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A New Approach to Ensure Causality in Design-FMEA Based on the System Modelling of Generic Systems Engineering

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Abstract

Increasing failures of technical products have been a significant phenomenon since decades in industry. The major reason for this is the increasing complexity of product functions and structures. Different quality assurance methods are applied in modern product development processes to prevent failures. However, the established approaches are no longer sufficient to manage the increasing complexity of products.

Among numerous methods, Design-FMEA is the most widely applied ones for product development in the automotive industry. By analysing the approach of Design-FMEA, the root cause for the weakness of the established Design-FMEA approach can be derived: the missing causality in its failure analysis. The reason for that is the system modelling: only the model of functions and the model of system design are built up to identify potential design failures by Design-FMEA. However, the causal links between functions and product designs are defined by the physical effects, by which the functions of the product are fulfilled during the operation. Without analysis of these links, the causality in failure analysis cannot be ensured in Design-FMEA.

Systems engineering, as a scientific principle for managing complexity, can be applied to solve this problem. Generic Systems Engineering (GSE) is a new development of Systems Engineering, which uses four models: requirement, function, process and component to describe a system. This methodology to build system models can be applied to ensure causality in failure analysis in Design-FMEA.

Based on GSE, a new approach to improve Design-FMEA by ensuring the causality is developed. The structure-analysis, the function-analysis and the failure-analysis of the established Design-FMEA can be applied to set a focus of design risks for further analysis. The new methods to derive failure mode, to find root causes, and to define countermeasures are developed based on the problem-oriented modification of GSE system modelling. Moreover, a model-based review mechanism is created to empower cross-functional development teams for making optimal decisions.

The new approach of Design-FMEA is applied in a worldwide leading automotive supplier for its product development projects. The improvement of Design-FMEA is confirmed there.

Zusammenfassung

Die zunehmenden Fehler technischer Produkte sind seit Jahrzehnten ein signifikantes Phänomen in der Industrie. Der Hauptgrund dafür ist die steigende Komplexität der Produktfunktionen und -strukturen. Um diese Fehler zu vermeiden, werden in modernen Produktentwicklungsprozessen unterschiedliche Methoden der Qualitätssicherung eingesetzt. Die etablierten Ansätze reichen jedoch nicht mehr aus, um die zunehmende Komplexität der Produkte zu beherrschen.

Unter zahlreichen Methoden wird die Design-FMEA am häufigsten zur Qualitätsabsicherung in der automobilen Produktentwicklung angewandt. Eine Analyse des Ansatzes, konnte ein Defizit identifiziert werden. Das Resultat: Die fehlende Kausalität bei der Fehleranalyse der Design-FMEA. Der Grund dafür liegt in der Systemmodellierung. Hier werden nur das Funktionsmodell und das Modell des Produktdesigns in der Fehlanalyse betrachtet. Die kausalen Zusammenhänge zwischen Funktion und Produktdesign sind jedoch durch die physikalischen Effekte beschrieben. Heute werden die Modellierungen dieser physikalischen Prozesse bei der Anwendung der Design-FMEA jedoch vernachlässigt.

Bei dieser Problematik kann das Systems Engineering, als ein wissenschaftliches Prinzip zur Beherrschung der Komplexität, eingesetzt werden. Das Generic Systems Engineering (GSE) ist eine Weiterentwicklung des Systems Engineering, welches vier Modelle verwendet: Anforderung-, Funktion-, Prozess- und Komponente-Modelle, um ein System zu beschreiben. Bei der Anwendung dieser Modellierungsansätze, kann die Kausalität in den Analysen der Design-FMEA sichergestellt und neue Methoden entwickelt werden.

Die Struktur-Analyse, die Funktions-Analyse und die Fehler-Analyse der etablierten Design-FMEA können weiterhin eingesetzt werden, um die Design-Risiken für die weiteren Analysen festzulegen. Die neuen Methoden zur Ableitung des Ausfallmodus, zur Ursachenfindung und zur Definition von Gegenmaßnahmen werden auf der Grundlage der problemorientierten Modifikation der GSE-Systemmodellierung entwickelt. Darüber hinaus wird auch ein modellbasierter Auswahlmechanismus geschaffen, der die funktionsübergreifenden Entwicklungsteams in die Lage versetzt, optimale Entscheidungen zu treffen.

Dieser neue Ansatz der Design-FMEA wurde bei einem weltweit führenden Automobilzulieferer in der Produktentwicklung eingesetzt. Die Verbesserung der Design-FMEA kann dort bestätigt werden.

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List of Abbrieviations

ABS	Anti-Lock Braking System
AIAG	Automotive Industry Action Group
BDW	Brake Disc-Wiping
BRM	Boost Recuperation Machine
DeCoDe	Demand Compliance Design
DMU	Digital Mock-Up
DoE	Design of Experiment
ECU	Electronic Control Unit
ESP	Electronic Stability Program
ETC	Electronic Thonttle Contral
FEM	Finite Element Method
FFDM	Function-Failure Design Method
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode Effects Criticality Analysis
FTA	Failure Tree Analysis
GSE	Generic Systems Engineering
HBA	Hydraulic Brake Assist
HDC	Hill Drop Control
HHC	Hill Hold Control
IEEE	Institute of Electrical and Electronic Engineers
INCOSE	International Counsil on Systems Engineering
KPI	Key Performence Indicator
MFP	Module-based Failure Propagation
MVM	Münchener Vogehensmodell
NASA	National Aeronautics and Space Administration
NVH	Noise, Vibration, and Harshness
OEM	Original Equipment Manufacturer
PDP	Product Development Process
PLC	Product Life Cycle
QFD	Quality Function Deployment

RE	Requirements Engineering
RPN	Risk Priority Number
SE	Systems Engineering
SPC	Statistical Process Control
TCS	Traction Control System
VDA	Verband der Automobilindustrie
VDMA	Verband Deutscher Maschinen- und Anlagenbau

1 Introduction

1.1 Motivation

Industry 4.0, the Internet of things, autonomous driving and alternative powertrain technologies of vehicles…, modern industry has been undergoing a great transformation for decades. Today, the success of technology companies depends on their degree of innovation, the efficiency of the organization, and, especially, the quality of their products.

The downfall of Takata in 2017 proves the fact that quality problems of a single product can ruin a world market leader. Takata Corporation, once the biggest manufacturer of airbags, was founded in 1933 in Shiga Prefecture, Japan. The company held 20 percent of the worldwide market for airbags in 2014. Because of a design failure, Takata was forced to make the largest auto recall in the history of the automotive industry: 53 million automobiles had to go back to car dealers or to workshops to get their airbags replaced. On June 25, 2017, Takata filed for bankruptcy in the USA and Japan, and the company was then sold to its largest competitor [Editorial 2017].

The increasing quality problems of technical products is a worldwide trend in recent years. In 2016 and 2017 alone, 108 million vehicles in the USA were recalled by their manufacturers. The statistic in Figure 1 [Center of Automotive Management 2018] demonstrates the increasing recall-rates, i.e., the ratio of the number of recalled and sold cars, from 2005 to 2017, in this leading automotive nation.

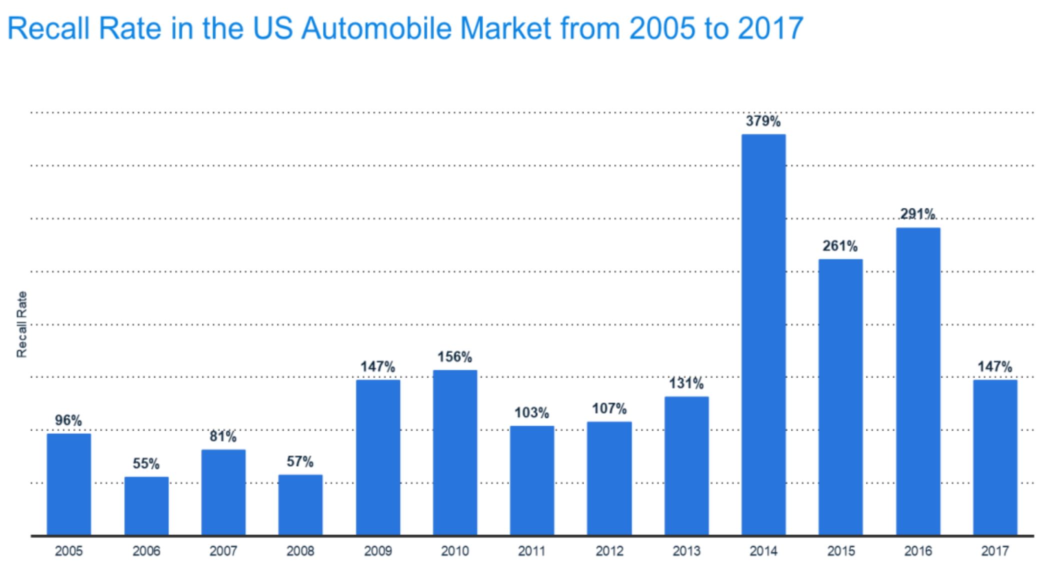


Figure 1 Recall-rate in the automotive market in the USA from 2005 to 2017 [Center of Automotive Management 2018]

Where do those quality problems arise? To answer the question, we should take a closer look at the process of product engineering. In modern industry, the product engineering process is apportioned in different phases. Running parallel to the main process, the quality assurance process, has a decisive influence on quality of to be developed products [Feldhusen and Grote 2013].

Figure 2 [Gamweger et al. 2009] illustrates a typical product engineering process with different phases: innovation, planning, conception, development, pre-series and series production. The quality assurance process begins in the conception phase, for the product design will be developed and the functional sample will be realized and validated as early as in this phase [Ehrlenspiel and Meerkamm 2017].

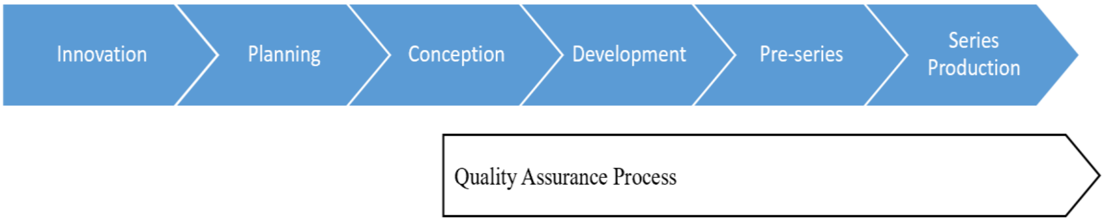


Figure 2 A typical Product Development Process (PDP) and the quality assurance process [Gamweger et al. 2009]

Studies from industral practice show that approx. 70% of all failures occurred as early as the conception phase, whereas 80% of those failures are corrected by the end-users. Figure 3 [Schmitt and Pfeifer 2015] presents the frequency distribution of generation and correction of product failures in different phases of Product Life Cycle (PLC). A study of Verband Deutscher Maschinen- und Anlagenbau (VDMA) with the subject of quality-related costs confirms the result [Witte 2016].

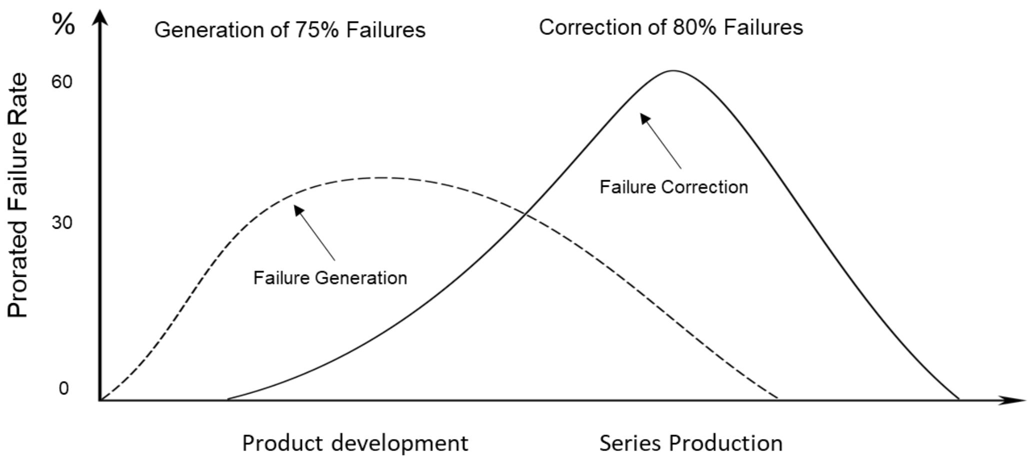


Figure 3 Generation correction of failures of product in PLC [Schmitt and Pfeifer 2015]

Related to the costs of failure correction in different phases of PLC, a phenomenon so-called "Rule of Ten" is observed in practice. It means that the cost of failure identification, tracking and correction increases exponentially at every later phase of PLC, i.e., if failures are not avoided during the conception and development phases, but are found after production or even by customers, the cost can be 1,000 or even 10,000 times higher for the manufacturer of the product. Figure 4 [Schmitt and Pfeifer 2015] illustrates the effect of "Rule of Ten" in different phases of PLC. From this point of view, the failure elimination should be done as early as possible in the conception phase.

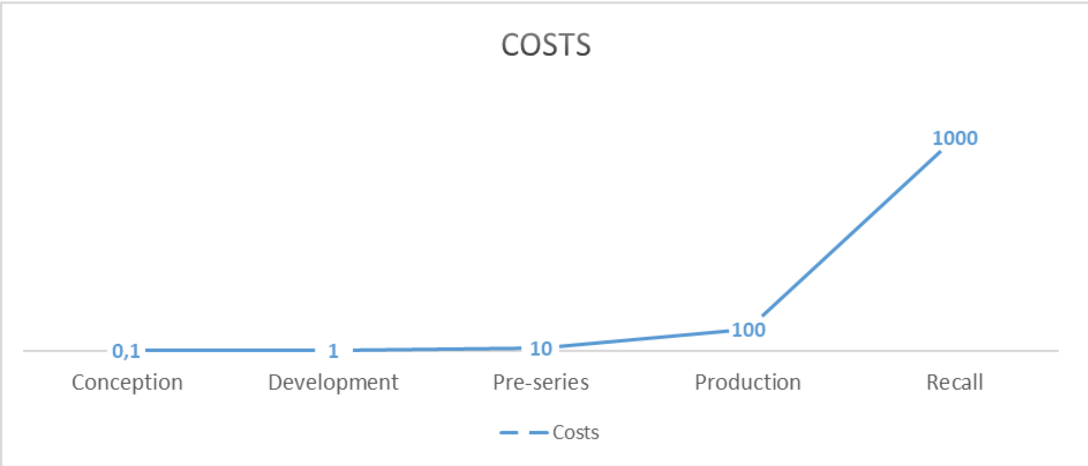


Figure 4 Rule of Ten for costs for correction of failures in PLC [Schmitt and Pfeifer 2015]

Why are failures made during product development by the developers? Due to the human brains' characteristics, such as the limitation of rational thinking, the shortages of long-term and short-term memory capability, it is natural for engineers to make mistakes during the solving of complex problems, according to Ehrlenspiel [Ehrlenspiel and Meerkamm 2017]. To find and eliminate such failures, quality assurance methods are indispensable during product development, despite applying systematic approaches of product development process [Schmitt and Pfeifer 2015].

In the automotive industry, different methods have been established and standardized for decades to eliminate failures of product design, such as Failure Mode and Effects Analysis (FMEA), Quality Function Deployment (QFD), Fault Tree Analysis (FTA) and Design of Experiment (DoE) to avoid failures in the conception phase [VDA Band 14: 2008]. Why are failures of technical products still increasing? The goals of this thesis are to analyze the root causes of this problem, and to derive a technical solution to improve the established methods. In the next section, the influencing factors for the increasing product failures, as well as the approach of the established quality assurance methods of product development, are analyzed to identify the shortcoming of the current quality assurance methods.

1.2 Problem analysis

The transformation of industry and the increasing demands of end-users lead to the increasing complexity of technical products [Winzer 2014a]. The increasing complexity of products consists not only in their increasing functionalities, but also in the increasing system structure and components. Especially, the combination with mechanical, electronic and software components, the so-called mechatronic system, is the most important driving force of innovation in the automotive industry [Reif 2014a]. Today, mechatronic products comprise 30 percent of manufacturing costs and offer 90 percent of all new functions in a modern passenger car with 200 megabytes of software, which is running in around 75 Electronic Control Units (ECU) [Czichos 2015].

The start-stop function, which has been becoming a standard system of passage cars in Europa since the 2010s, is a representative example of this trend. To reduce fuel consumption and emissions, the start-stop function switches the combustion engine off, temporarily, without the driver having to turn off the ignition key. The engine will then restart automatically, as soon as the driver is ready to resume driving [Reif 2014a]. Compared to a conventional starter, the complexity of the start-stop system increases not only due to an additional ECU with the control software, but also due to higher requirements of its components, such as more ignition times over the lifetime, as well as the interactions between its subsystems, such as the influence of the battery voltage on the starter motor.

In the results of different studies, the complexity of system structure and behaviors, as well as the dynamic interactions between elements in a system are identified as the major reason for increasing quality problems, which lead to the high quota of recalls [Dittes 2012; Meyer et al. 2007; Mamrot 2014]. It is, therefore, a great challenge for the quality assurance process in product development to manage the increasing complexity of technical products.

Another influencing external condition is the division of competence, the specialization of working packages and the globalization of development organization [Winzer 2016a]. For instance, as a world-leading engineering and electronics company and the biggest automotive supplier with its headquarters in Germany, Robert Bosch GmbH has 125 product development locations worldwide [Robert Bosch GmbH]. It is common in the automotive industry to spread cross-functional product development teams across different countries: e.g., the platform development in Germany, the customer application in China, the simulation and software teams in India and the purchasing department in Singapore. The decentralization of the product development origination, competence and locations increases the demands of communication, which leads to more failures during the product development process.

The hard competition of markets requires a shorter time for product development. The term “Time to Market” means that a company can make more turnover and profit than its competitors if it can develop a product more rapidly than others and bring it to the market early [Feldhusen and Grote 2013]. The fact is that this competition leads to less time for product development teams to solve more complex technical problems.

To summarize the decisive factor and the influencing conditions are: the increasing complexity of technical products, the distribution and globalization of development teams, as well as “Time to Market”. They have been changing the way of product development and lead to the increasing product failures in modern industry.

The goal of the quality assurance process in the product development is to find out the design failures and to define countermeasures to eliminate product failures by using different methods, as Figure 5 illustrates.

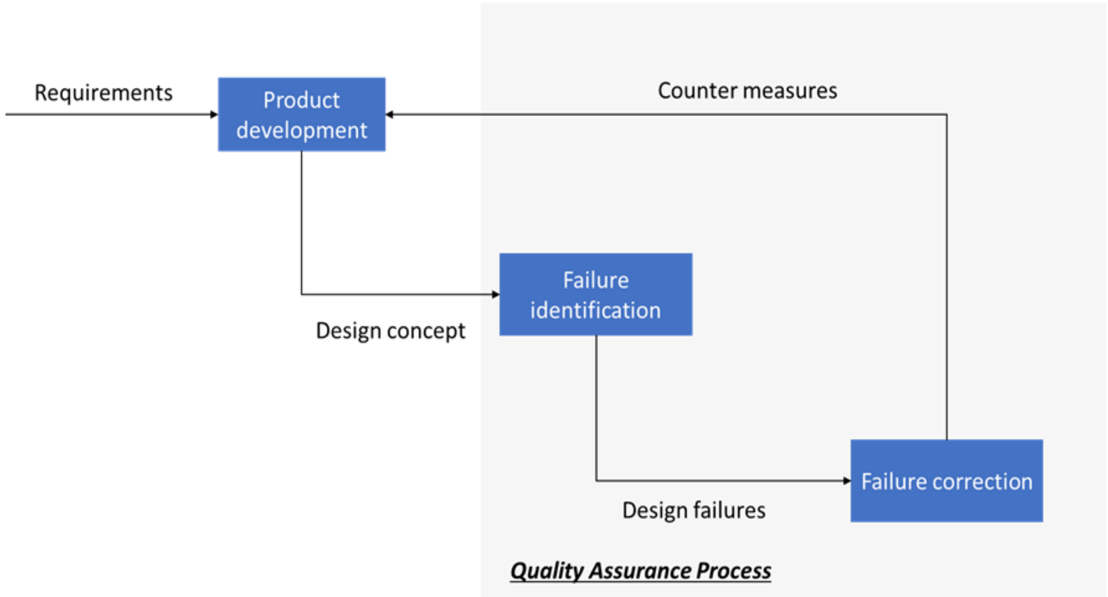


Figure 5 The goal of the quality assurance process in the product concept phase

FMEA is the most widely applied quality assurance method in product development, especially in the automotive industry. According to a survey showed in Figure 6 [VDA Band 14: 2008], all manufacturing companies of the German automotive industry apply this method regularly.

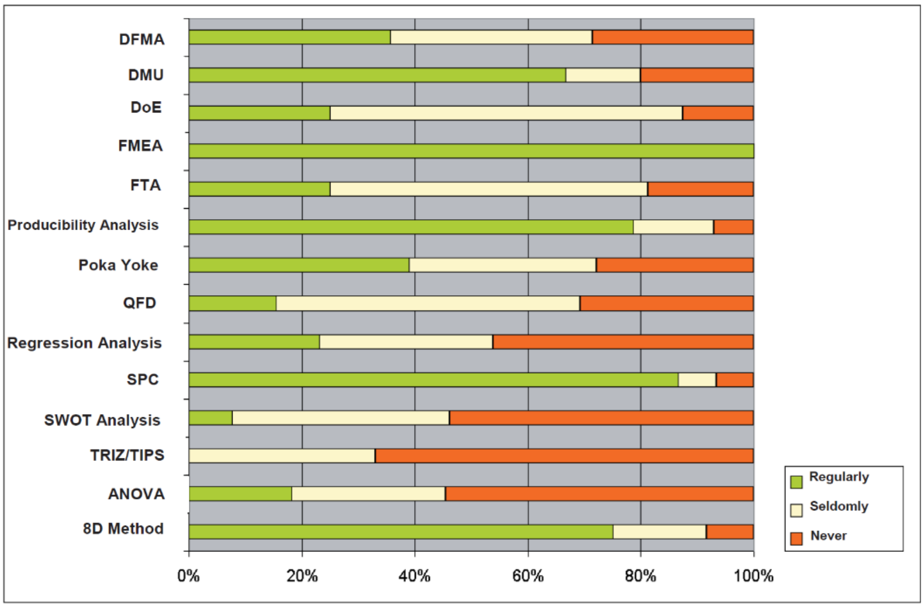


Figure 6 Frequency of quality methods used in the German automotive industry [VDA Band 14: 2008]

After comparing different established methods of quality assurance in this thesis, FMEA is proven as the most effective and efficient one to eliminate product design failures among those.

Regarding the increasing quality problems of technical products, Winzer draws the conclusion that it is necessary to improve the established quality assurance methods or even to develop new approaches to fulfill the increasing challenges in modern industry [Winzer 2014b]. This hypothesis can be confirmed in this thesis by analyzing the standard approach of Design-FMEA in the automotive industry.

The root cause for the problem of Design-FMEA is the missing causality of its failure analysis. According to the laws of science, the prerequisite of causality analysis is the cause-and-effect relation of the failures. It means the physical effects during the product operation, which are leading to failures. However, during the analysis of Design-FMEA, only the models of the product structure and functions are built up.

Due to the missing causality of the failure analysis, the failure mode analysis, the root-cause analysis of Design-FMEA cannot lead to an effective countermeasure systematically. To improve the methods of Design-FMEA, building the causal chain from failures to countermeasures is the prerequisite, as Figure 7 shows.

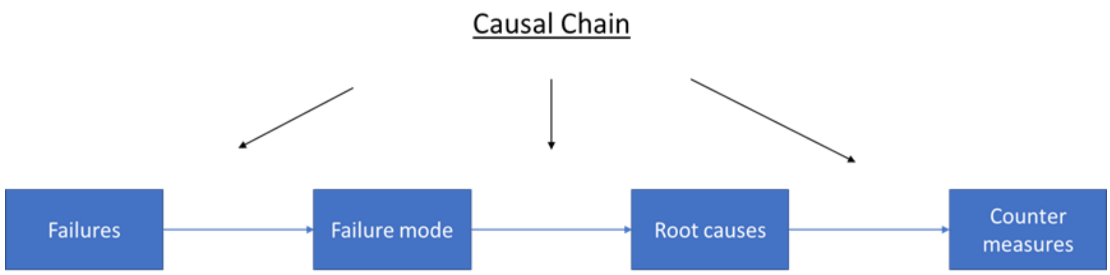


Figure 7 The causal chain from failures to counter measures

Moreover, the review and the decision-making mechanism are not introduced by the standard approach of Design-FMEA. The validations and decision-making processes often require many recursions in industrial practice. Product develop teams claim the missing integration of all competencies of product engineering, the incorrectness of the countermeasures, and the missing approach to ensure the transparency by the communication of decision process. These effects are intensified with the distribution and globalization of the development organizations.

To develop solutions of these problems, Systems engineering (SE) and science of product development are applied as the scientific principles. In the next section, the approach of problem-solving is explained in detail.

1.3 Derive solution

In the modern product development, physical effects are used deliberately to fulfil product- and component-functions [Pahl et al. 2007]. As early as the 1800s, theories of kinematic as a scientific principle were already applied systematically to build machines [Otto and Wood 2001]. The physical processes to operate functions of technical products can only be realized by using physical principles [Koller 1985]. Those physical processes build bridges of causality between product functions and product design. To make a causal analysis of product failures, the models of functions, of physical processes and of product design parameters should be defined and built, firstly.

The universal SE approach is a philosophy to solve complex problems. It includes, on the one hand, the Systems Thinking, on the other hand, the Systematic Acting to generate a problem-solving process [Haberfellner 2015]. Figure 8 [Haberfellner 2015] illustrates the generation of a problem-solving process based on the SE-approach.

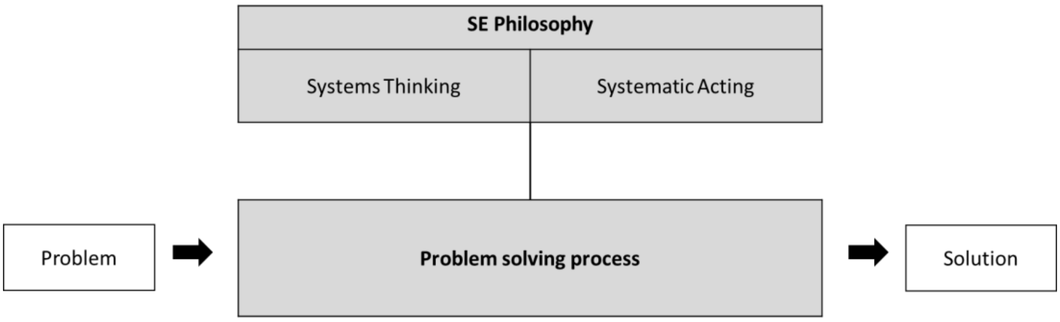


Figure 8 The SE-Concept based on Haberfellner [Haberfellner 2015]

Analyzing different implementations of SE-methodology, Winzer develops the Generic Systems Engineering (GSE), which consists of a newly developed Systems-Thinking-Model, as well as a Systematic-Acting-Concept. The major advance of the GSE-Thinking-Model in the context of product development is that it describes a system with the requirement-, function-, component- and process-models.

The Acting-Concept includes project management-, goal-building-, analyze- and construction-modules. Moreover, the GSE ensures the interaction between the Systems-Thinking-Model and the Systematic-Action-Concept by developing problem-solving processes [Winzer 2016a]. To develop requirement-, function-, process- and component-models of a system, as well as to describe the interactions between those models, Sitte and Winzer developed Demand Compliant Design (DeCoDe) and the corresponding tools [Sitte and Winzer 2011].

Describing a product with four models can ensure the causality of the Design-FMEA. This hypothesis is confirmed in Chapter 4 by analyzing the relationships between product functions, physical effects, and the product design based on science of product development. The conclusion is that to solve the missing causality problem of the Design-FMEA, the process-model of the product must be added to the Design-FMEA by the failure analysis.

Based on result of the analysis, GSE is applied in this thesis to develop a new approach to improve Design-FMEA. The general DeCoDe-models are specified and quantified based on mathematical logic, physical laws, and the science of product development. With the newly developed, problem-oriented DeCoDe-models, the methods of failure mode analysis, of root-cause analysis, as well as the method to select countermeasures are developed to improve Design-FMEA.

Figure 9 illustrates the combination of the structure analysis, function analysis and failure analysis of the standard Design-FMEA approach in the automotive industry with the newly developed methods to ensure the causality of Design-FMEA. The idea is to set the focus of further analysis, i.e., potential risks of product design, with results of the current failure analysis of Design-FMEA; the new methods provide a deep analysis to identify potential failure mode and root causes, subsequently, to derive optimal countermeasures for the failure elimination.

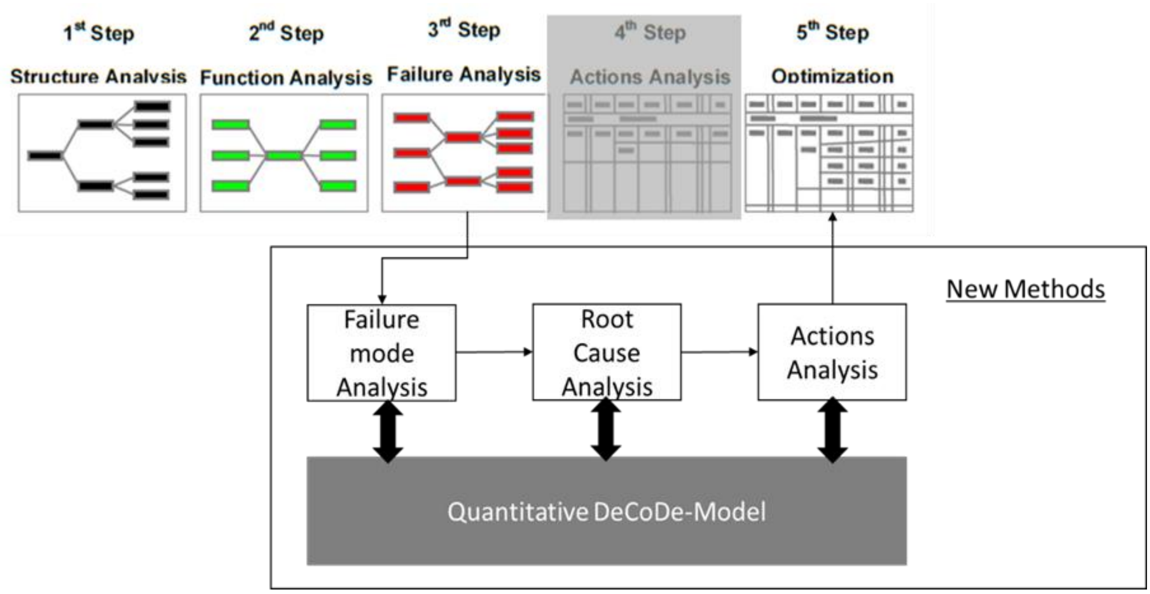


Figure 9 Develop new methods of failure mode analysis, root-cause analysis and action analysis for FMEA based on modified DeCoDe-Model

Different analytic methods and tools are developed for each step of the new approach, such as Function-Process-Design Diagram, Design-Risk-Table, and Decision-Matrix. These methods and tools can empower product development teams to manage the complexity of the problem solving, to reduce the lead time by pinpointing the focus of the further analysis and the validations. Moreover, due to the transparent way of the presentation and the newly developed review mechanism, the process of the decision-making by the cross-functional development teams becomes more effective than the established approach of FMEA.

The value-added of new methods of Design-FMEA for the industry are, among others,

- to improve the correctness of failure assurance,
- to improve the coordination of cross-functional development teams of product development,
- and to decrease the lead time of validation and verification by reducing recursions.

In the scientific domain, the innovation of this thesis consists in the combination of product development science and Generic Systems Engineering to improve Design-FMEA. With this interdisciplinary combination of scientific domains, a new way of problem-solving in product development is made.

The validations of the new methods are introduced in a division of a leading automotive supplier, which develops and produces complex technical products for automobiles with more than 1,000 development engineers worldwide. By implementing the methods, a rollout plan is made firstly, which includes different training phases, the concrete training plan, the route map of the implementation, and the Key Performance Indicators (KPI) to monitor the implementation in the organization. The rollout begins with the training for the engineering leaders and then for the product development teams. The improvement of Design-FMEA in product development is confirmed by feedbacks from different development projects. The new approach has been, since then, a standard approach in this organization.

1.4 Structure of the thesis

Corresponding to the applied scientific approach, this thesis consists of 7 chapters. Chapter 1 introduces the analysis of the increasing quality problems of technical products and the deficits of quality assurance methodic of product development, as well as the overview of solution development. In Chapter 2, the question, "why the quality assurance methods are essential for product development?", is answered. And, the requirements of such methods are derived. Based on these requirements, the state-of-art approaches of industry and in the scientific domain are analyzed in Chapter 3. The result shows that those approaches, especially Design-FMEA, cannot fulfill the above-developed requirements with full scope. The root cause is that the causality is not ensured by the procedure of problem-solving. In Chapter 4, the Systems Engineering, especially Generic Systems Engineering are introduced as scientific principles to manage complexity. The question: "why GSE is applied as the problem-solving principle in this thesis?", is also answered. The new methods to ensure causality of Design-FMEA are developed in Chapter 5. Followed by Chapter 6, the validation of the new methods with two chosen examples from the automotive industry. Chapter 7 summarizes the thesis and gives an outlook on further research demands. Figure 10 depicts the structure of the thesis.

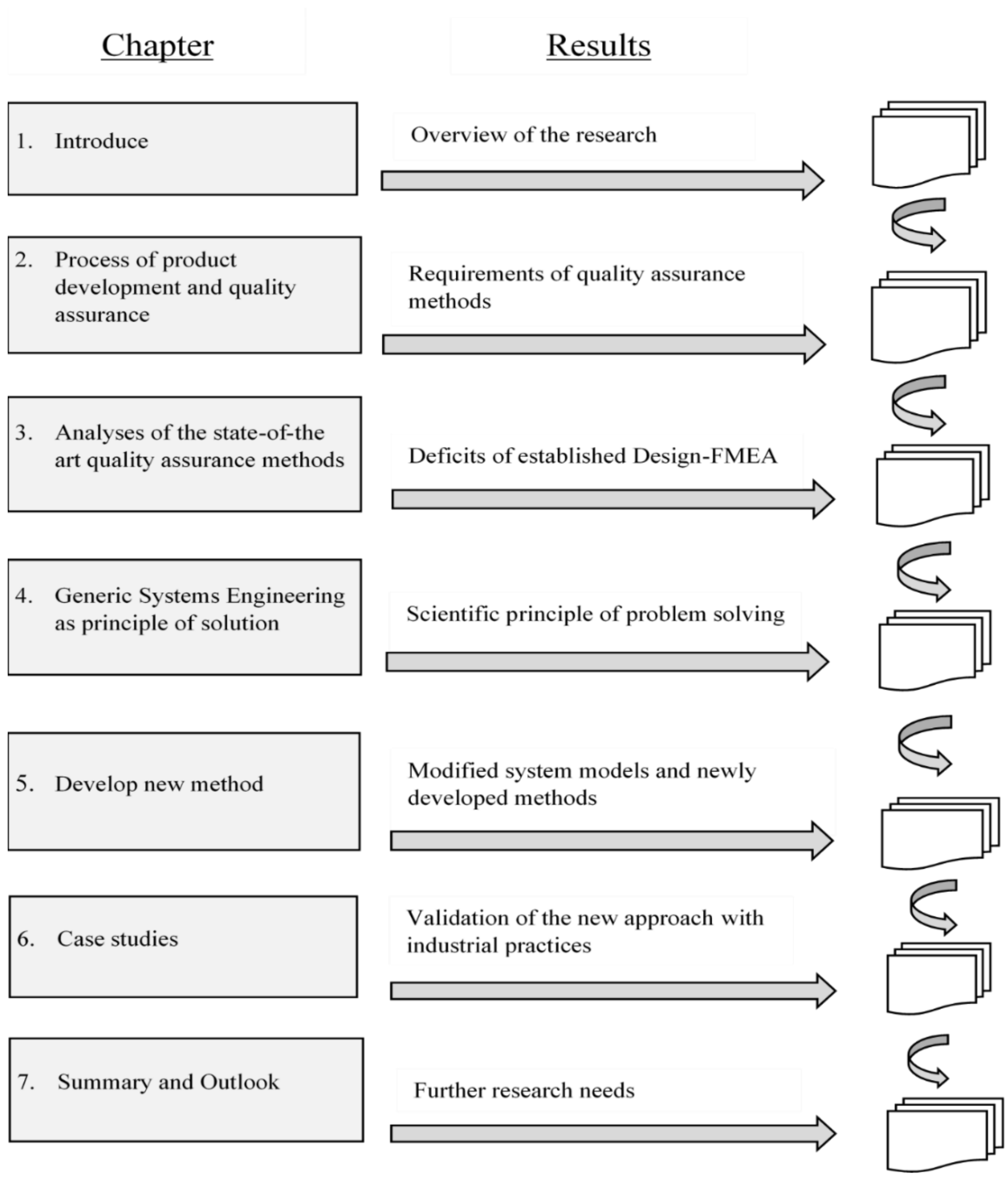


Figure 10 The structure of the thesis

2 Process of product development and quality assurance methods

Before developing a solution, the root causes of the problem should be analysed. To analyse the root causes, the problems should be clearly identified first. The goal of Chapter 2 is to identify the problem in the modern product development process, which leads to the increasing failure rate of technical products. To achieve this goal, different models of product development process are analysed. Based on the results, the requirements of the quality assurance methods for product development are derived. These requirements are then applied to evaluate the established quality assurance methods in the industry to identify their deficits.

2.1 Product development in the Product Life Cycle

The typical business model of technology companies, such as automotive OEMs (Original Equipment Manufacturer) is to develop, produce and distribute products for their customers [Ehrlenspiel and Meerkamm 2017]. Product Life Cycle (PLC), which consists of Requirements Engineering (RE), product planning, product, and process design, manufacture, operation, and recycling [Eigner and Stelzer 2013; VDI 2221:1993], is the core process of the business model in those companies.

The term "process" means a sequence of activities under the use of information, knowledge as well as material resources to change inputs to the defined outputs [Lindemann et al. 2009]. The goal of the product development process is to generate functioning and manufacturable products to fulfill the customer's needs [Ponn and Lindemann 2011]. The inputs of the product development are the requirements and outputs are the intellectual product. In this context, requirements mean the requested features of the product [Ponn and Lindemann 2011]; and the intellectual product includes all models of the product, which are necessary to define the product [Eigner and Stelzer 2013], e.g., product architecture, drawings, material specifications, 3-D models, assembly drawings, software architecture, software programs, analysis of risks etc.

In the conception phase of product development, the fulfillment of product functions has the highest priority [Lindemann 2005], therefore the inputs of product development can be considered as product functions, as Figure 11 depicts.

Figure 11 The black-box Model of the product development process

To understand how failures of product concept can occur during the product development process, different process models in industry are analyzed in the next section.

2.2 Processes of product development

To understand the mechanism of quality assurance methods in product development, the approaches of product development should be analyzed.

It is typical for technology companies to structure line organizations for product development with different competencies, e.g., hardware construction, software development, system design, reliability engineering, quality management, etc. According to scientific management, which is also known as Taylorism, this specialization of expertise in enterprises can improve economic efficiency and increase productivity [Schlick et al. 2018]. On the other hand, teams of technical product development are getting more organized as projects in the modern industry [Bullinger and Warschat 1997]. Different from line organizations, projects are the one-off undertakings with defined start and end dates with given resources to achieve a defined goal [Bullinger and Warschat 1997]. Figure 12 presents a simplified project organization for product development of mechatronic products.

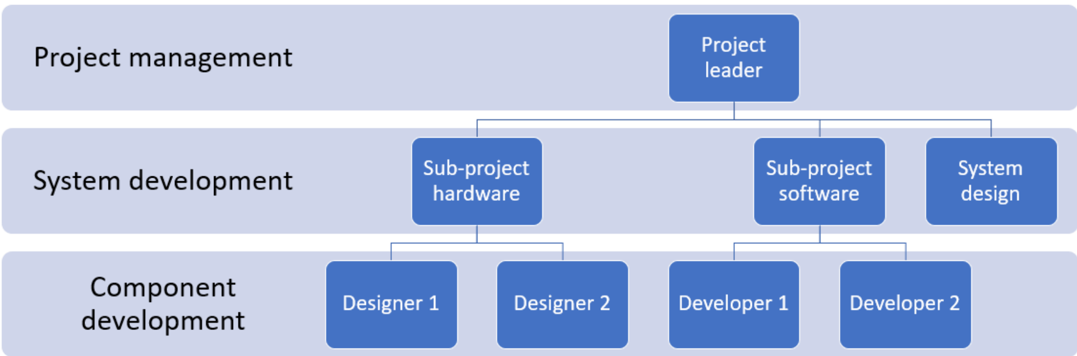


Figure 12 A simplified project organization for product development in modern industry

Depending on numerous determining factors, e.g., grade of innovation, the complexity of products, volumes of production, product developments processes vary widely from each other. As a tool to help planning, conducting, and controlling product development, processes break down product development into manageable steps of actions [Lindemann 2005]. According to the different levels in development teams from the project manager, to the single developer, those process models can be classified in three catalogs,

- Phase model of whole project,
- Model of development of the technical system,

- Operative model of product components development.

Haberfellner calls views of the different problem-solving levels macro-logic and micro-logic [Haberfellner 2015].

The project leader takes responsibility for the whole project. His main tasks consist of, inter alia, the overall time schedule, the budget of the project, communications, and outputs of work packages. Figure 13 [Gamweger et al. 2009] illustrates a phase model of a product development project of a leading technology enterprise in the automotive industry. The project phase model is a tool to manage the whole project by defining inputs and outputs of each phase of the project with quality gates, as checkpoints of each step and releases for the next steps. Belonging to the domain of total project management, this model deals with the macro-logical aspect of product development.

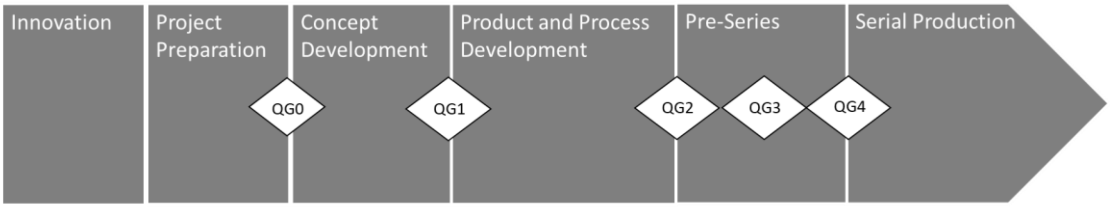


Figure 13 Project phase model with quality gates as milestones [Gamweger et al. 2009]

Technical sub-project leaders for system, hardware and software work closely together. They focus on the realization of product requirements by designs of system architecture, hardware specifications, and software architecture. Beginning in software development in the 1980s, the V-model is established in the automotive industry as a tool for the development of complex technical systems [VDI 2206:2004]. At the level of the technical sub-projects, the V-model is often applied to plan and to conduct complete system development.

Figure 14 [Reif 2015] depicts an interpretation of the V-model in the automotive industry. The left side of the V-model describes the principle of top-down construction, i.e., from system to subsystems and then to components. Its right side presents the principle of bottom-up validation, i.e., from components to subsystems and then system. The interactions between design and tests are an essential part of product development. The V-model introduces which tasks and in which order the product development is to be done, but it doesn't answer the question: how to design a product and its components.

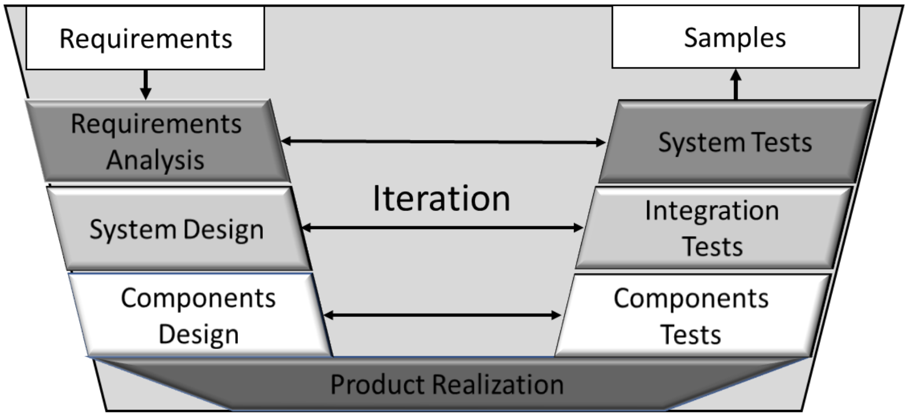


Figure 14 V-model of product development based on "Bosch Automotive Handbook" [Reif 2015]

Based on similar systematic approaches by Rodenacker (1991), Roth et al. (1971), Hubka (1976) and Pahl/Beitz (1977), VDI 2221 introduces a generic process to develop a product or its components, as shown in Figure 15 [VDI 2221:2018]. It indicates concrete steps of the product design, i.e., from requirements per functions, work principles to the product design solution and adjoining the cross-check, as the quality assurance of results. The transition from the functions to the working principles, and then to the product designs, builds the causal chain of the product development. This model can be considered as a micro-logic of product development.

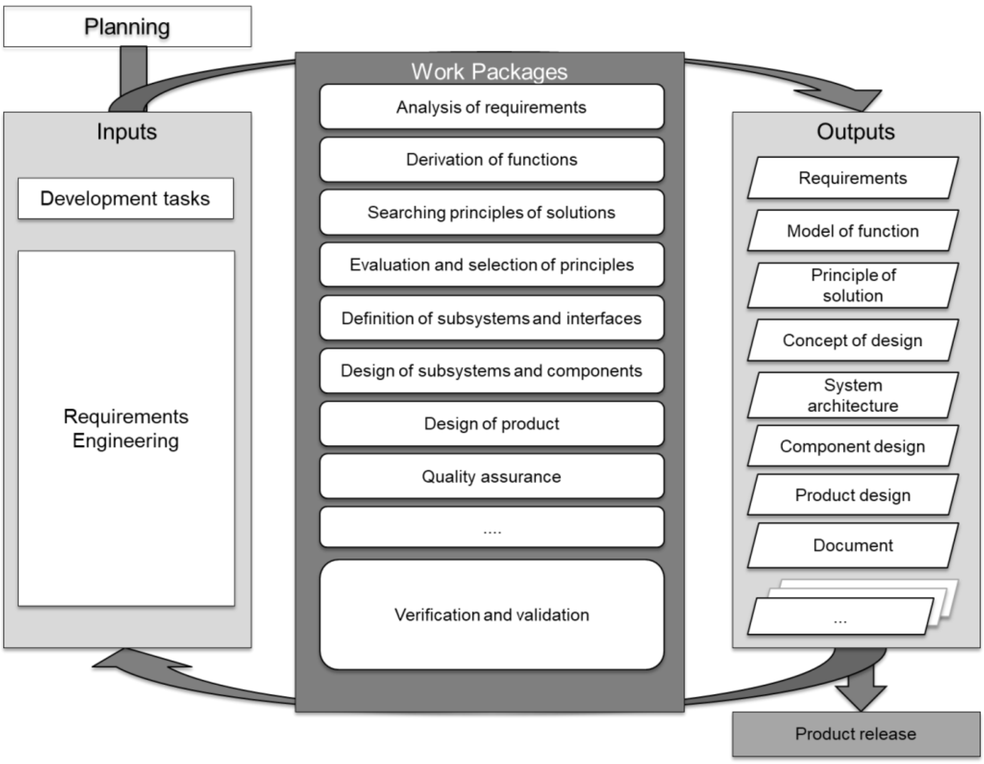


Figure 15 Generic model of product development based on VDI 2221 [VDI 2221:2018]

Figure 16 illustrates the integration of all action models from macro-logic to micro-logic in the conception phase. The phase model guides the whole project of product development, the technical product development process in every single phase follows the V-model, and the designing of components and system follows the generic process based on the causal chain:

- system developers analyze the requirements and design the structure of the product as well as derive the requirements for hardware and software design;
- according to the hardware and software requirements, the hardware and software developers construct the hardware and software components;
- according to the results, sample shops will produce components;
- the components will be validated by component tests;
- the deviations of tests will be analyzed, and countermeasures and the improvements of components designs will be taken accordingly;
- after assembling components which include hardware and software parts, the first test of the system will be made;
- the first adjustment of product structure and components should be made according to the results;
- some more tests of the product will be made to test all main functional requirements of the products;
- the product design will then be finalized [Reif 2015; VDI 2221:2018].

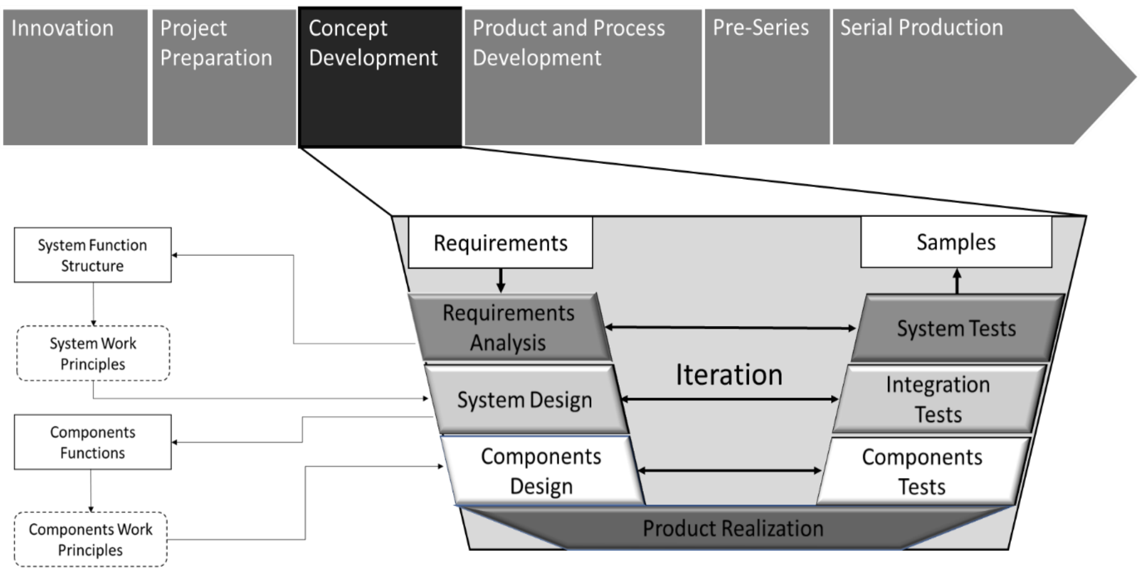


Figure 16 Integration of different action models in concept development phase [Reif 2015; VDI 2221:2018]

To summarize the integration of different models in the product development:

- The phase model defines the steps of the whole project;
- V-model is applied in every phase of the product development to structure the single step;
- The causal chain from functions per the working principles to the product design parameters should be applied with every step of the V-model [Reif 2015; VDI 2221:2018].

The causal chain of the product design is essential for the quality assurance approach in product development. In the next section, the term “failure” of the product development is discussed and precisely defined, so that the requirements for the quality assurance methods of technical product development can be derived.

2.3 Failures of product design

In ISO 9000 Quality management systems, “quality” is defined as “degree to which a set of inherent characteristics of an object fulfills requirements”, in opposition to “quality”, “failure” is defined as “non-fulfillment of a requirement”, which is called “nonconformity” in this norm [ISO 9000:2015]. However, in another international standard of the automotive industry, ISO 26262 Road vehicles – Functional Safety, “failure” is defined as “termination of the ability of element, to perform a function as required” [ISO 26262:2011]. The “element” means, in that context, hardware or software components of a system, however, there is no specification of the term “function” in this norm.

What is the difference between “to fulfill a requirement” and “to perform a function”?

Product development always starts with a list of tasks which come from stakeholders, e.g., law-makers, governments, own company, especially customers [Pahl et al. 2007]. This list is the requirements of the product to be developed. Ponn et al. define “requirements” as required characteristics of the product to be developed [Ponn and Lindemann 2011]. The requirements can be classified into two groups: functional and non-functional requirements. Suh names them functional requirements and constraints [Suh 2001]. The functional requirements describe the usages of the product, through which the demands of customers are to be satisfied. Such kind of requirements are essential for product developments in the conception phase [Pahl et al. 2007].

The functions of products are derived from the functional requirements. Pahl/Beitz defines functions as solution-neutral descriptions of tasks of a product [Feldhusen and Grote 2013].

Functions can be described, shown in Figure 17 [Pahl et al. 2007], as a black-box model, which converts energy, material, or signals from one value to another defined value.

Figure 17 The Black-Box model of the function of a technical product [Pahl et al. 2007]

Figure 18 [SG 2019a] shows a modern starter of passenger cars. Its major task is to start internal-combustion engines with electrical direct current from the battery in the car. To ignite a combustion engine, a high initial torque is required to overcome the engine's initial resistance to rotation and to accelerate the masses in the engine [Robert Bosch GmbH (Ed.) 2014].

Figure 18 A starter of passage cars [SG 2019a]

Figure 19 illustrates the function of starters applying the black-box model, the input is the electrical current from the battery, and the output is the kinetic energy, i.e., the torque and the rotation movement to start the engine.

Figure 19 The function of the starter in a vehicle

In the conception phase of product development, the first step is to choose a design of starters, which are able to start the combustion engines of a certain type of vehicles. The non-functional requirement, such as costs, labeling, packaging, etc. would be considered in the next development-steps. If the design of the starter cannot fulfil the functional requirement at all, the optimization of the design to fulfil non-functional requirement makes no sense for product development. Therefore, in the concept development phase, the fulfillment of the functional requirements has the highest priority [Lindemann 2005]. The focuses of quality assurance methods in this phase are to eliminate failures of product functions.

Considering the logic of the V-model, failures in the product concept mean either the system design, or the component design, cannot fulfill at least one of the product functions, as illustrated in Figure 20. This definition of failure of product design will be applied in this thesis.

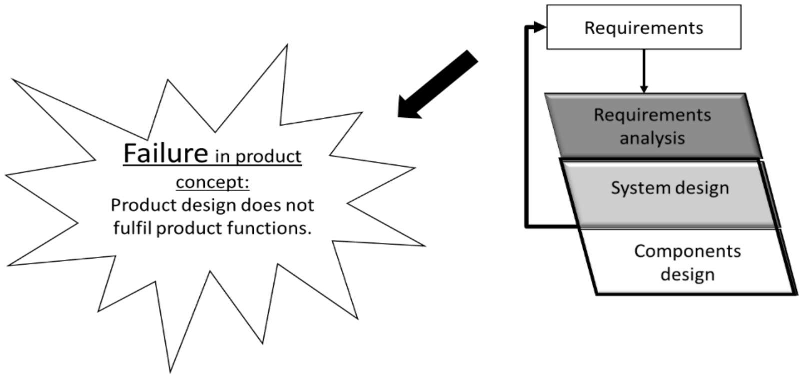


Figure 20 The definition of Failure in the product concept phase

As Friedrich Krupp once said: “He who works, makes mistakes. He who works a lot, makes a lot of mistakes. Only those who don’t work at all, put their hands in their laps, don’t make mistakes.” Besides external factors such as lack of knowhow, unsuitable methodology, incorrect communication, it is human nature for engineers to make mistakes when solving complex problems. The reason is the human brains’ characteristics, such as the limitation of rational thinking, the shortages of long-term and short-term memory capability [Ehrlenspiel and Meerkamm 2017]. Accordingly, the quality assurance methodology with goals to identify failures of the product design is indispensable in the product development process [Schmitt and Pfeifer 2015].

The goals of the quality assurance process are to identify and to eliminate failures of product design. Methods of failure identification and correction is a reverse process of product development. The failure identification analyzes the product functions and the product design to find failures in the product design. The methods of failure correction analyze the failures to derive possible corrective measures. Figure 21 illustrates the inputs and outputs of these methods with the black-box model.

Considering the quality assurance process in combination with the V-Model, as shown in Figure 22, the right side of the V-Model represents different tests as methods to identify failures of product design from component level to system level. Are they sufficient and efficient for the failure identification of product development?

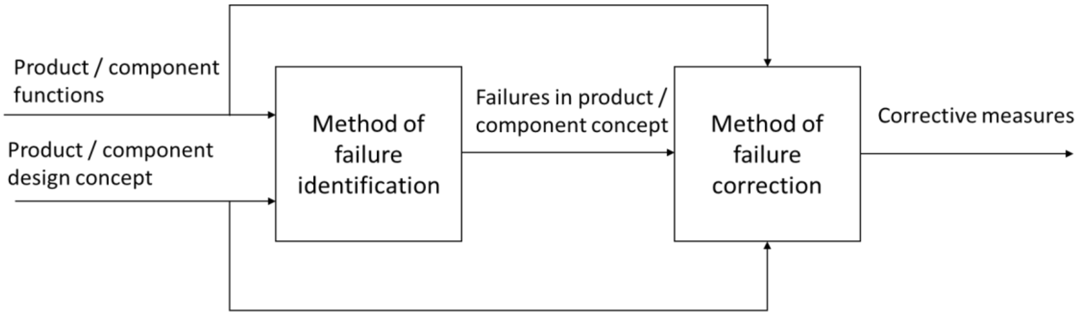


Figure 21 A black-box model of methods for failure identification and correction in the product concept phase

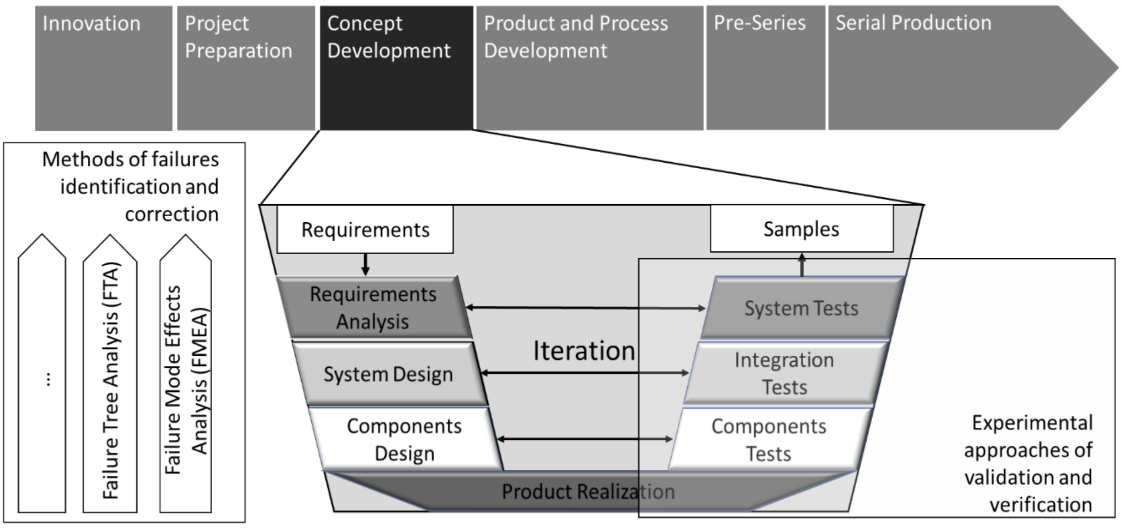


Figure 22 Methods of failures identification and correction in the concept development

In product development, different tests are applied, for example, to simulate the real situations of product use-cases. According to the use-cases, the test cases are specified. However, tests are always linked with high financial and time expenditures. The endurance tests of automotive products take, overwhelmingly, a couple of months to validate the product functions over a lifetime. According to a statistic, one-third of the total budget of product development is planned for tests in the industry [Pfeifer and Schmitt 2014]. Even with such an effort, it is impossible to cover all use-cases with the range of all the environment's conditions through the tests.

To ensure the efficient validation and verification of product design, therefore, analytical methods shall be applied to plan tests and to analyze results of tests [Pfeifer and Schmitt 2014].

Which requirements should these analytical methods fulfill in the product conception phase?

Requirement 1: the methods should be able to analyze the functions and the design of the product and components to find out design failures depending on the black-box-model of function.

Requirement 2: correctness of the results should be ensured, otherwise, the loss to the company could be high according to the “Rule of Ten”.

Requirement 3: the implementation of methods should only focus on design risks, due to the requirements of “time to market” and costs pressure in the industry.

Requirement 4: the completeness of finding the design risks should be guaranteed based on the available know-how and experience of the team. Failures due to misunderstanding or ill-treatment should be avoided, to reduce the recursions in the quality assurance process.

Requirement 5: methods of failure identification should be able to find out the root-causes of the failures to derive possible measures to correct the failures sustainably.

Requirement 6: facing the increasing complexity of product development organizations with different functionalities and locations, methods should empower and authorize the cross-functional team members to review and decide countermeasures according to their competencies, so that optimal solutions for the company can be chosen.

Can the standard quality assurance methods fulfil the above-developed requirements? In the next section, the state-of-the-art quality assurance methods of product development in industry are evaluated based on these requirements.

2.4 Evaluation of the standard quality assurance methods

Numerous methods for quality management are applied in the industry. The results of a survey in 2004, based on the analysis of German automotive OEMs and suppliers, show the frequency of quality assurance methods used in the product development and production departments of those companies, as Figure 6 [VDA Band 14: 2008] depicts.

Considering the results, the following methods should be analyzed closely:

- DMU (Digital Mock-Up)
- DoE (Design of Experiment)
- FMEA
- FTA
- Poka Yoke

- QFD
- SPC (Statistical Process Control)
- 8D method

DMU is a virtual 3D-Model of technical products, which presents the structure and dimensions of the product and its components [Feldhusen and Grote 2013]. DMU is applied, for instance, to simulate possible dimensional conflicts of different components by assembling the product virtually. Compared to a physical assembly trial, DMU can reduce time and financial costs. However, the DMU simulations are based on the corresponding numerical models of physics, e.g., dimensional, mechanical rigidity, thermodynamics. For complex technical products, it requires enormous efforts and wide expertise to build all necessary numerical models. Moreover, changing characteristics of products, such as material fatigue are difficult to be added to DMU models. DMU is an effective supporting tool to analyze failures of product concepts in certain domains. For example, the Finite Element Method (FEM) can be used to analyze the strength of components to find out the potential breaking points of components.

DoE is a systematic approach to deploy experiments for determination of the mathematical models for cause-effect relations between design and functions. However, the physical effects and laws are not taken into consideration [Gamweger et al. 2009]. It is used during the product development process, as well as a quality assurance method. For instance, the mathematical models derived by DoE can be applied in methods of failure identification to increase their effectiveness and efficiency.

According to the survey, FMEA is the most deployed quality assurance method in the German automotive industry, 100% of companies participating in the survey apply this method. The approach of FMEA is originally described in the US Armed Forces Military Procedures document [Military Standard MIL-STD-1629A]. Its goal is, among others, to identify design failures at the early stages in order to avert their occurrence in later phases of PLC. Moreover, the occurrence possibilities of the failures are also estimated, and the effects of the failures of the product are derived as well. Based on the analysis, the failures can be monitored and corrected [VDA Band 4:2013].

FMEA is not only a widely used method for product development and manufacturing; but also required and accepted by stakeholders. Different stakeholders, such as the Automotive Industry Action Group (AIAG) in the USA, its counterpart “Verband der Automobilindurstrie” (VDA) in Germany, laws of product liability and safety, etc. require automotive OEMs and suppliers to apply FMEA during their product development and for the production. Figure 23 gives an overview of the situation for the application of FMEA in the industry.

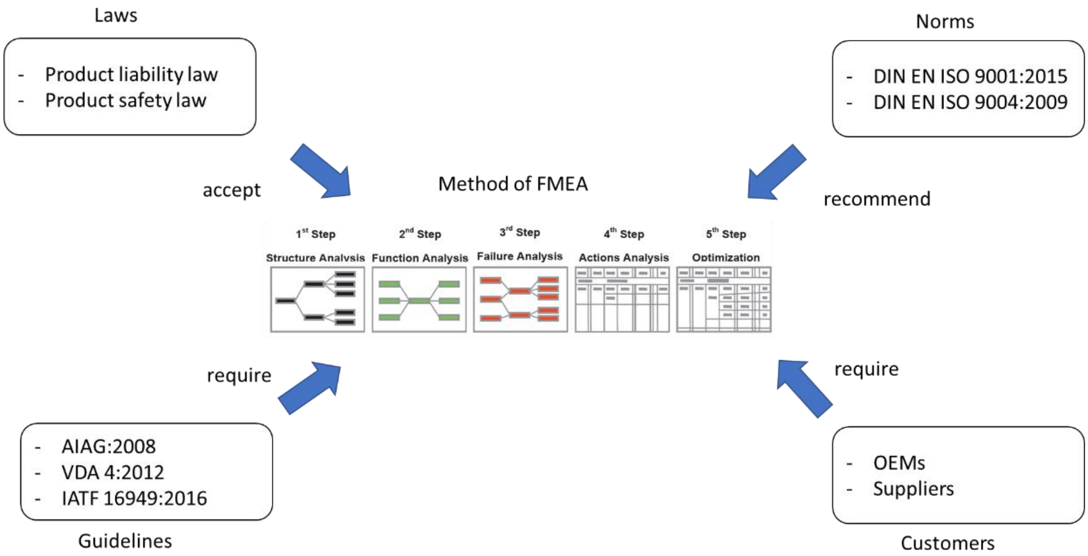


Figure 23 The application of FMEA in the industry

In contrast to FMEA, the method of FTA applies deductive analysis, which means to start with all potential failures of the product level, and to analyze the possible causes down to the components’ level. The goal is to identify all failures, and the corresponding causes, of the product and to predict their frequency of occurrence as well as the consequences to the end-users [VDA Band 4:2003].

To achieve Zero-Failure-Production, Shigeo Shingo developed the Poka-Yoke concept as a part of Toyota-Production-Systems [Syska 2006]. The Poka-Yoke technique is an approach in production with special devices, which can prevent the occurrence of certain failures. The philosophy of Poka-Yoke is that if defects of product reach customers, they would become failures. If those defects are unavoidable in production, they should be detected 100% of the time before they reach customers [Segismundo and Augusto Cauchick Miguel 2008].

QFD dates back to Toyota as well. In 1966, Yoji Akao introduced this method to map customers’ requirements in four steps, to characteristics of the product firstly, and then to design parameters of its components, followingly process parameters of production, and finally to quality assurance measures of production, using four 2x2 matrices [Gamweger et al. 2009]. QFD is an instrument helping to plan, to conduct, and to control a requirement-oriented product development process. However, no approaches are defined to analyze the causality between those domains, especially between the functions and the design parameters.

SPC forms a control loop of the manufacturing process to ensure the production quality before failures are revealed. This approach is based on a sample check between the defined time intervals. The results will be then evaluated in special form sheets with a coordination system and the defined control limits, so-called Quality Control Chart. If the evaluation shows an exceeding of the limits, an adjustment measure should be undertaken to steer the process in the opposite direction. Because the control limits are generally beneath the required tolerances of the product, this preventive quality method can support achieving the Zero-Failure-Target of production [Pfeifer and Schmitt 2014].

Especially in the automotive industry, failure complaints of customers must be managed with high urgency and precision. 8D method standardizes an action plan with 8 defined steps to handle failure complaints in an organization. It includes

- build a core team,
- describe problem,
- containment action,
- root cause analysis,
- plan corrective action,
- take corrective action,
- stop reoccurrence, and
- report closure [Behrens et al. 2007].

All those methods are evaluated for their applicability to failure identification and correction in the product concept phase in Table 1. The evaluation is based on the derived requirements in 2.3. Poka Yoke, SPC, and 8D are methods which are applicable in production rather than in product development. QFD is an effective method for quality assurance in product development and provides qualitative correlations between requirements and design parameters. These correlations can support identifying failures in product design. However, no methods for analyzing the causality between different models of the product are available in the approach of QFD. DoE is an experimental method to analyze the cause-effect-relation between design parameters and functions, which can be used not only for product development, but also for failure identification in product concept. Because the analysis of FTA starts with possible failure effects at the product level, unknown risks of the products to the team could be ignored by applying this method.

Table 1 Evaluation of established quality assurance methods of product development

Requirements \ Methods	DMU	DoE	FMEA	FTA	Poka Yoke	QFD	8D
1. Analyze design concept and product functions	No	No	Fully	Fully	No	Fully	No
2. Ensure correntness of the failure analysis	No	No	Partially	Partially	No	Partially	Partially
3. Focus on design risks	Partially	Fully	Partially	Partially	Fully	No	Fully
4. Ensure completeness of design risks analysis	No	No	Fully	Partially	No	Partially	Partially
5. Ensure root-cause-analysis of failures	No	No	Partially	Partially	No	Partially	Partially
6. Empower and authorize communication and decision making of cross-functional team	No	No	Partially	No	No	Partially	Partially

Table 2 gives detailed explanations of the requirements' fulfillment. The evaluations make it clear that the improvement of the FMEA approach should be made to increase the effectiveness, as well as to ensure cross-functional team coordination. Is any approach already made in those directions by current scientific research? In the next chapter, the state-of-the-art scientific research of FMEA are analyzed in detail.

Table 2 The evaluation of the fulfillment of the requirements for FMEA in the product concept phase [Gamweger et al. 2009]

Requirements of methods	Evaluation of FMEA
Requirement 1: the methods should be able to analyze the functions and the design of the product and components to find out design failures.	Fully: - inputs: product design concept and function - procedure: analyzing product structure and function structure - outputs: potential failures of product design and measures for detection and correction
Requirement 2: correctness of the results should be ensured, otherwise, the loss to the company could be high according to the “Rule of Ten”.	Partially: - bottom-up analysis - analysis based on the expertise of the reviewer - no methods are introduced for failure mode analysis, root-cause-analysis, and corrective measures
Requirement 3: the implementation of methods should only focus on design risks.	Partially: - analysis based on experiences and expertise of the team - goal-oriented review workshops with cross-functional competencies - no causal analysis between failure mode, root causes, and corrective measures
Requirement 4: the completeness of finding the design risks should be guaranteed based on the available know-how and experience of the team. Failures due to misunderstanding or ill-treatment should be avoided, to reduce the recursions in the quality assurance process.	Fully: - the systematic comprehensive analysis covers all product structure and function structure - comprehensive use of knowledge of the organization
Requirement 5: methods of failure identification should be able to find out the root-causes of the failures to derive possible measures to correct the failures.	Partially: - no methods are introduced by FMEA - use the existing method like the fishbone diagram, which only define what to do but not how
Requirement 6: methods should empower and authorize the cross-functional team members to review and to decide measures according to their competencies to ensure the optimal solutions for the company.	Partially: - reviews of analysis for finding potential failures by a cross-functional team - no approach for reviewer to ensure a systematic decision-making process

3 State-of-the-art approaches of Design-FMEA

3.1 The standard approach of Design-FMEA in industry

FMEA can be applied to the product design, as well as for the manufacturing process. The goal of Design-FMEA is to find out the potential failures of the product design, and to derive the countermeasures to eliminate the failures. Different approaches of Design-FMEA are published by different organizations, such as AIAG or VDA, but the objectives and approaches of different Design-FMEA methods are mostly identical in the automotive industry.

By applying Design-FMEA, the responsible persons of the product design, the experts in reliability, in material, and in NVH (Noise, Vibration, and Harshness), the engineering managers, as well as a moderator will be invited to an FMEA workshop. During the workshop, potential failures of the design, the root causes, and the consequences of the failures, are identified, discussed, reviewed, and documented. Additionally, the severity of failure consequence, the probability of failure occurrence, and the probability of failure detection are quantified. Finally, measures of failure correction are defined with responsibilities and deadlines.

To standardize the general approach of Design-FMEA, VDA published "VDA Band 4: Product- and Process-FMEA", which is considered as the standard in the German automotive industry. The logic and the approach are representative of the FMEA method in the automotive industry worldwide. According to VDA Band 4, FMEA is carried out in five steps, as shown in Figure 24 [VDA Band 4:2012].

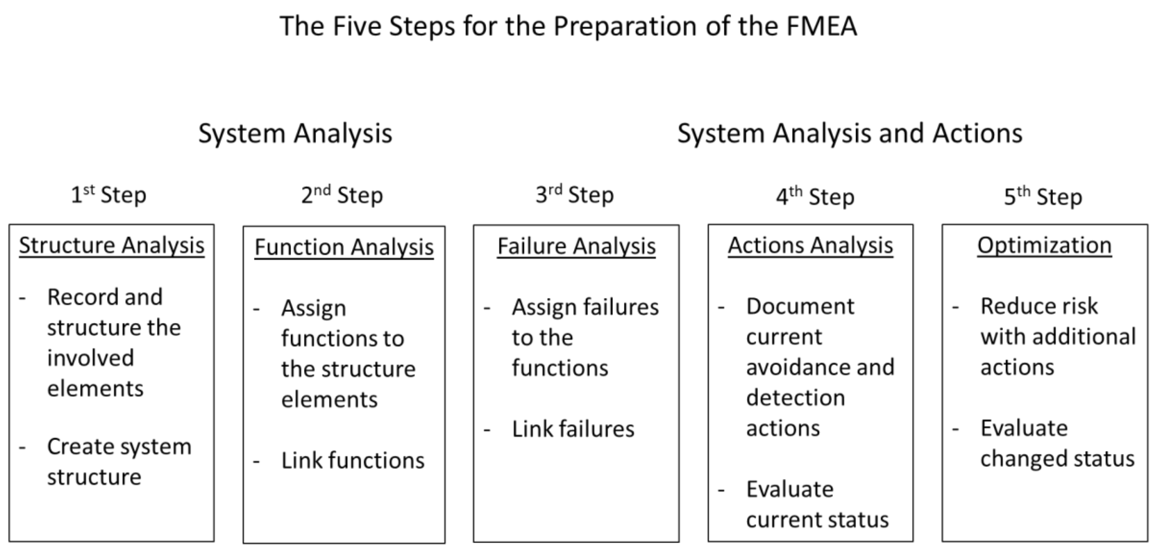


Figure 24 Five steps of the method of FMEA according to VDA [VDA Band 4:2012]

Using the example of the throttle positioner of a Drive-by-Wire system, the principle of the design-FMEA is evaluated. The throttle positioner controls the open angle of the throttle plate, which is depicted in Figure 25 [Reif 2015b] to manage the air quantity of combustion processes in gasoline engines for ensuring the required air/fuel mixture.

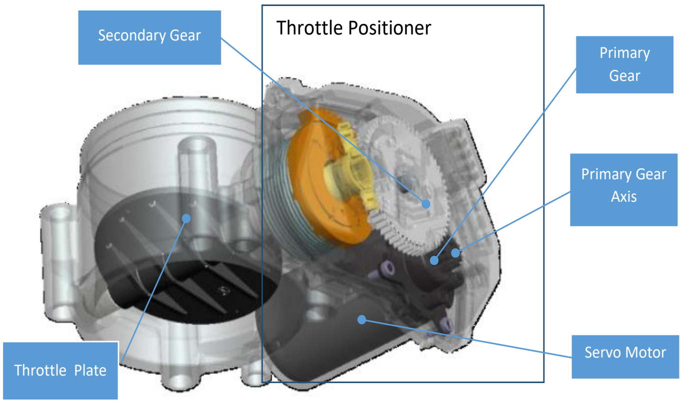


Figure 25 The throttle positioner of a brake-by-wire system [VDA Band 4:2012]

In this system, ECU gives signals to the servomotor to actuate the opening and closing of the throttle plate. The two-step gearbox transmits torques from the motor to the plate with a defined ratio. The hardware structure of the throttle positioner is presented in Figure 26 [Reif 2015b].

1. Air and fuel vapor
2. Canister-purge valve
3. Connection
4. Returned exhaust gas
5. EGR valve
6. Air-mass flow
7. Air-mass flow
8. Fresh-gas charge
9. Residual-gas charge
10. Exhaust gas
11. Intake valve
12. Exhaust valve
13. Throttle valve
14. Intake manifold

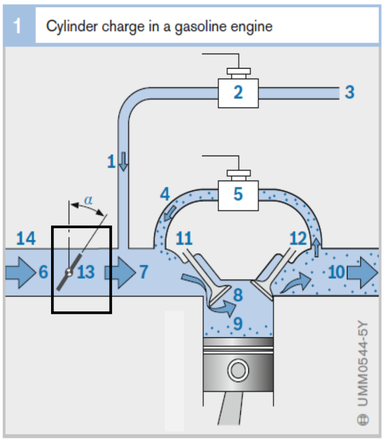


Figure 26 Components and process of the cylinder charge with the throttle plate (13) [Reif 2015b]

In the first step, the model of components of the throttle positioner is built up in a hierarchical tree structure. The root node represents the product itself, which has three children, i.e., its three subsystems: the servo motor, the transmission, and the throttle plate. The components of subsystems, such as primary gears, primary gear axle, the secondary gear, build the next level of leaves of the tree with all design parameters. According to the product structure, functions of the system, subsystems, and components are derived and added in the tree. Figure 27 [VDA Band 4:2012] presents the tree structure as the results of the structure and the function analysis.

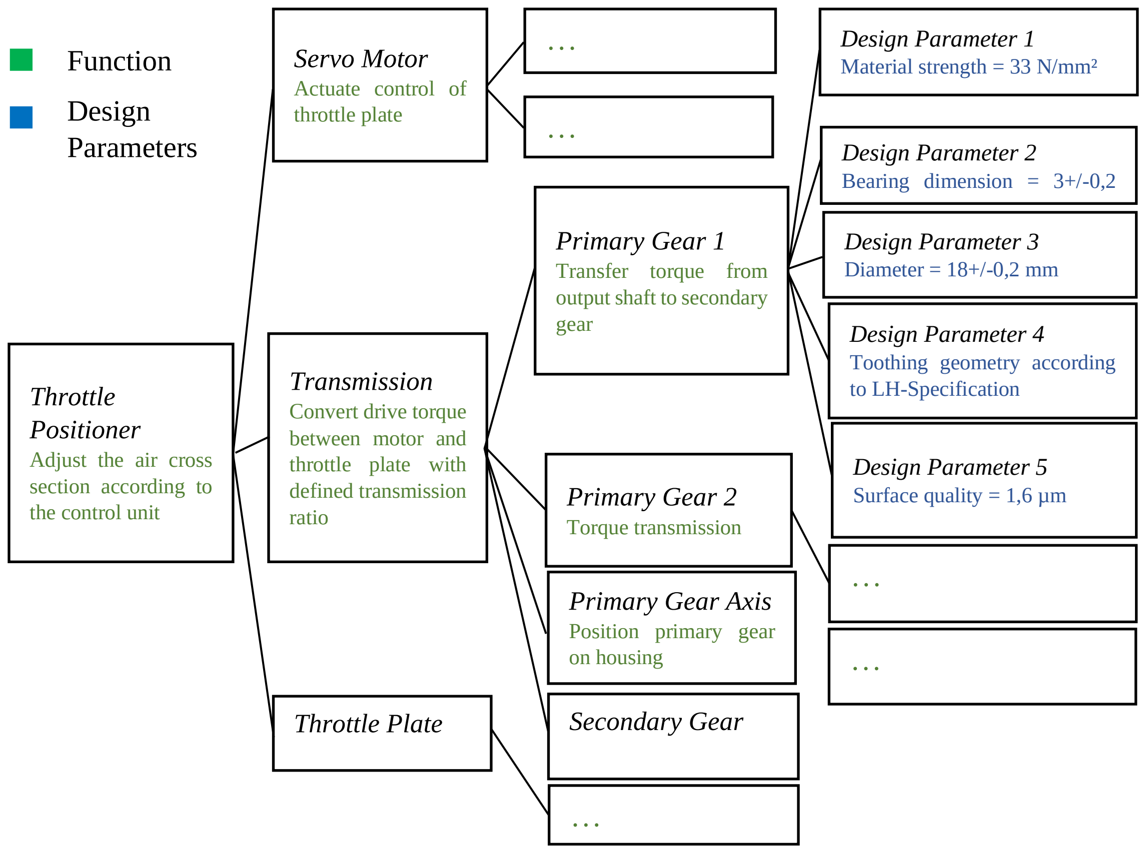


Figure 27 Example of product structure and function analysis for FMEA of throttle positioner of an E-Gas-System based on VDA [VDA Band 4:2012]

Based on the product component structure and the function structure, the comprehensive failure reviews are conducted to derive potential failures and the failure mode according to the available experience, knowledge, and expertise of participants of the workshop. The failure structure, depicted in Figure 28 [VDA Band 4:2012], represents the chain of failure modes i.e., causes of the failure, potential failures of components, and failure consequences of the product.

In the next steps, measures of failure correction and detection are developed. Based on the effectiveness of these measures, the probabilities of failure occurrence and failure detection are derived, correspondingly. The FMEA-sheet is then fulfilled with that information, as showed in Figure 29 [VDA Band 4:2012]

The inputs of the throttle positioner FMEA are the product design, and functions of the product, subsystems, and components. The outputs are the probabilities of failure detection and occurrence and the corrective measures. Because the available knowledge and expertise and different competencies of the organization are comprehensively used by FMEA-workshops, the method can ensure the efficiency of the failure finding process. During the systematic analysis of the product design structure as well as the structure of functions, the completeness of the identification of potential failures is ensured according to the available information. The approach of FMEA delivers the comprehensive result of the risk awareness of the product design concept based on the competency of the organization.

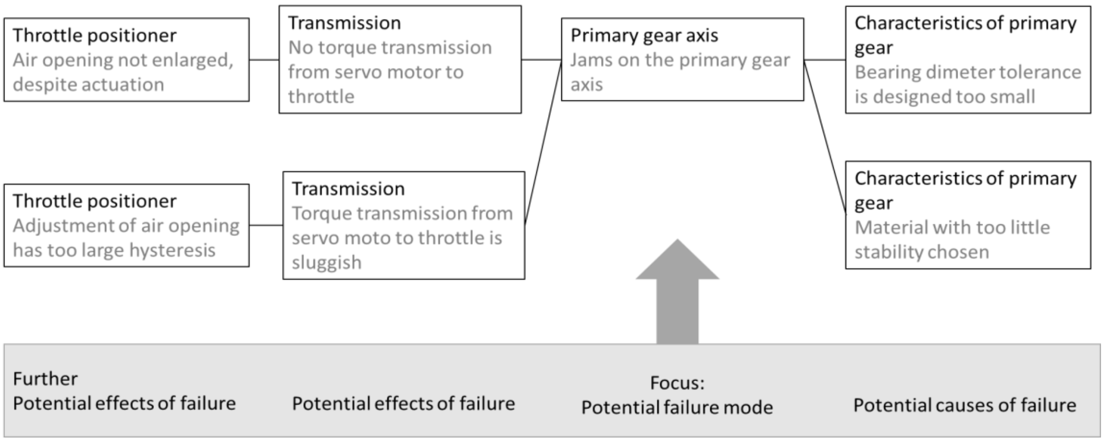


Figure 28 Failure structure of the throttle positioner [VDA Band 4:2012]

Design-FMEA Failure Mode and Effects Analysis										
Potantial effects of failure	S	Potential mode of failure	C	Potential cause of failure	Preventive actions	O	Detection actions	D	RPN	R/DL
Transmission No torque transmission from Servo motor to throttle	10	Primary Gear James on the primary gear axis		Characteristics of the Primary Gear Bearing diameter tolerance is designed too small	Design according to tolerance caculation to the value +/- 0.1 mm Miller CW 24 completed	2	Sample part function test Smith CW 25 completed	6	120	
>> Throttle Positioner Air opening not enlarged despite actuation	10						Wear analysis after endurance testing in changing temperature operation	(2)	(40)	Jones, CW 27 not implemented
Transmission Torque transmission from servo motor to throttle sluggish	9			Characteristics of the Primary Gear Material with too little stability chosen	Material stability corresponding to manufacturer recommendation for load case chosen Miller, CW 24 completed	3	Deamaged part analysis after endurance testing with excessive load Smith CW 24 completed	1	30	
>> Throttle Positioner Adjustment of the air opening has too large hysteresis	9				Using reinforced PP Smith, CW 24 completed					

Figure 29 FMEA sheet of the throttle positioner [VDA Band 4:2012]

Nevertheless, why doesn't the approach of FMEA fully fulfill the requirements of the quality assurance methods in the product concept phase?

VDA defines the term failure mode as "within the terms of a description of a failure by the supplier, this is the description of the type of failure or the more precise circumstances which have led to the failure" [VDA QMC].

As an example of the failure mode definition, the following case is added:

"The CD player mechanism is sluggish at temperatures below -10°C and this causes a mechanical overload on the loading mechanism" [VDA QMC].

The conditions under which the failures of products occur are the key elements for the failure mode analysis. In the case of the example is "-10°C" the boundary condition of the failure. It implies that the CD player should operate faultlessly at least at the temperature of -10°C. If the CD player mechanism is sluggish at temperatures below -10°C, for example, -20°C, this defect cannot be accepted as a failure of the CD player, because this temperature exceeds the limit of the requirement.

Considering the failure mode in Figure 30 [VDA Band 4:2012], "Jams on the primary gear axis", the boundary conditions, e.g., temperatures, external loads, loads cycles, lifetime, are not specified, therefore a quantitative root-cause-analysis is not possible. The quantitative analysis description is essential for the correction of failures of product design, because the countermeasures to eliminate the failures should be quantified in the design parameters. To identify the failure of the design means to find quantitative failures in the design parameters and all failure conditions.

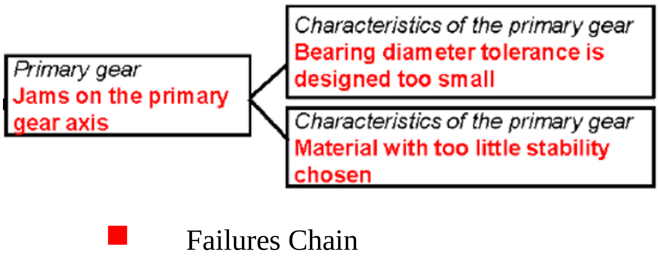


Figure 30 The potential causes of the failure "Jams on the primary gear axis" [VDA Band 4:2012]

According to the mechanical reliability theory, "jams on the gear axis" can be explained by the stress-strength-analysis of the material. In this case, the local stress of the bearing exceeds the strength of the material in the area of damage. Figure 31 depicts the distribution of the local stresses which is determined by the distribution of the tolerances and external loads; as well as the distribution of the strength of the material which is determined by the quality of the material. The area of the intersection of both curves, which equals the probability of the failure, is determined by the external loads profile, quantitative design parameters: the diameter of the gear axis, and the quality of the material. A failure of design can only be fixed, and be corrected, by analyzing values of the design parameters.

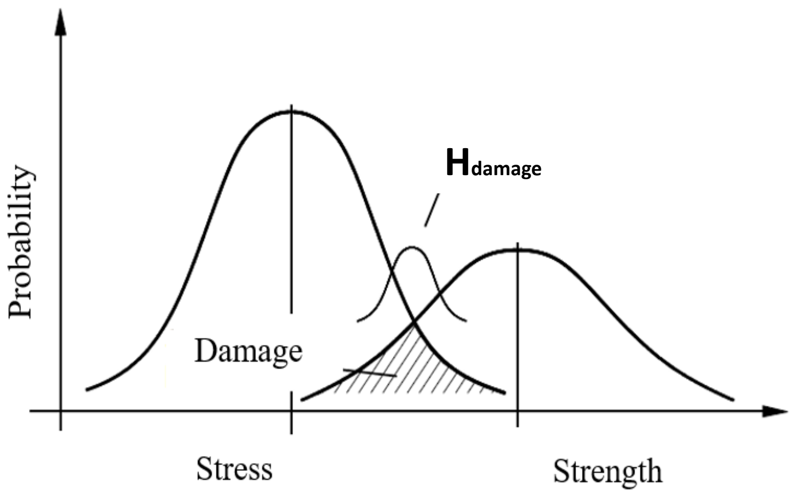


Figure 31 Failure mechanism based on stress-strength analysis

In the context of product development, the causality means the cause-effect relation of the physical effects during the products' operation. Design-FMEA of VDA Band 4 does not explain how to derive root causes of failures based on causality between design parameters and physical effects. In industry practices, several methods are applied to conduct the root-cause-analysis, such as "5 x why" or Brainstorming. However, those methods only guide developers to find a certain logical chain during analysis, but none of them offers the approach for how to make the causal analysis for product design failures in detail. Due to different experiences and knowledge, other conclusions may be drawn for the same problem by different teams or on different occasions. The correctness of the result is, therefore, not ensured.

For example,

- bearing diameter tolerance is designed too small,
- material with too little stability chosen

are listed as the root causes for "jams on the gear axis" [VDA Band 4:2012]. Obviously, the direct causality between the causes and the effect are missing. Due to a comprehensive physical analysis, the following causes of the effect can be taken into consideration based on the reliability theory:

- External loads profile of the related components,
- Dimensions including tolerances of those components,
- Environments conditions, e.g., temperatures, humidity, vibration, external medium like oil or particle, etc.
- Characteristics of the material

- Lifetime, wear status, …

All those influencing factors can lead to a decrease in the strength or an increase of the stress, so that the failure “jams on the gear axis” occurs.

The goal of Design-FMEA is not only to identify failures of design, but also to correct them before they occur in products’ operation. As the measure of correction to the failure “Jams on the primary gear axis”, “design according to tolerance calculation to the value 0.1mm” is introduced by the FMEA approach [VDA Band 4:2012].

Firstly, the effect of this measure cannot be explained without analyzing the causal chain of failure. Does it lead to a link or left shift of the stress- or strength-curves in Figure 31? Secondly, different strategies can be applied to solve the problem. For instance, using the same material with small distribution of strength, or changing to a different material with a better strength can also be the solution besides reducing the tolerances according to reliability engineering. It is important to provide a method to derive the countermeasures based on causal analysis, so that development teams can select an optimal measure.

The analysis of the single steps proves that the current approach of Design-FMEA gives a comprehensive analysis of the product design concept risks according to the available expertise and knowledge of the development teams. However, the standard methods of Design-FMEA provide no systematic approaches for failure mode analysis, root-cause-analysis, as well as a method to derive optimal countermeasures.

What is the root-cause of these shortcomings of Design-FMEA?

Firstly, the formulation of functions and failures in the combination of an active verb and a noun, e.g., “transfer torque”, or “convert drive torque”, make it impossible to analyze boundaries between failure and non-failure, quantitatively. This quantitative limit is the key element, not only to estimate the probability of failure occurrence, but also to derive the effective corrective measures.

The second reason is the direct mapping between functions and product designs by the failure analysis. Experienced engineers and experts may recognize the correlation between the failure “jams on the bearing position in the housing” and the cause “bearing diameter tolerance is too small” instinctively, according to their experience. However, without analyzing the physical effects, with which the functions are not fulfilled, causality between the force leading to jams and the tolerances of bearing cannot be derived. Different from the principle of the model-based product design, the approach of Design-FMEA does not analyze the physical effects between the function and the design parameters.

In recent years, numerous developments of the FMEA approach have been made in the industry and in the scientific domain to improve approaches of FMEA. In the next section, the state-of-the-art industrial standards and influential research papers are reviewed and evaluated to check if any solutions exist already to eliminate these shortcomings.

3.2 Evaluation of state-of-the-art approaches of Design-FMEA

3.2.1 State-of-the-art stands in industry

In 2019, AIAG and VDA published the *FMEA Handbook* to synchronize the Design- and Process-FMEA approaches of the automotive industry in the USA and Germany. These approaches are considered as the standard of FMEA worldwide, because the members of both organizations include the most influential OEMs and suppliers in automotive industry. From beginning of 2021, this standard is replacing the VDA Band 4 in German automotive industry successively.

Adapting the Design-FMEA approach of VDA, the new approach kept five main steps: structure-, function-, failure-, risk-analysis and optimization with two new steps: “planning and preparation” and “results documentation”. Among numerous changes, four major ones are affected by the Design-FMEA:

- introduce the Block/Boundary Diagram to analyze interfaces of the product and its periphery systems;
- introduce the Parameter Diagram to specify the functions;
- clarify the detection and prevention control measures to eliminate failures;
- set action priority according to the values of Severity, Occurrence, and Detection.

The Block/Boundary Diagram is a new method of Design-FMEA for the structure analysis of products and their interfaces to environment and periphery systems. Figure 32 [AIAG 2019] depicts a model of the window lifter system of vehicles with the system elements and their interfaces to the environment. It is a useful tool to build system models including the interactions between different elements, but it cannot ensure the causality by applying failure analysis due to the missing approach of quantification of the models.

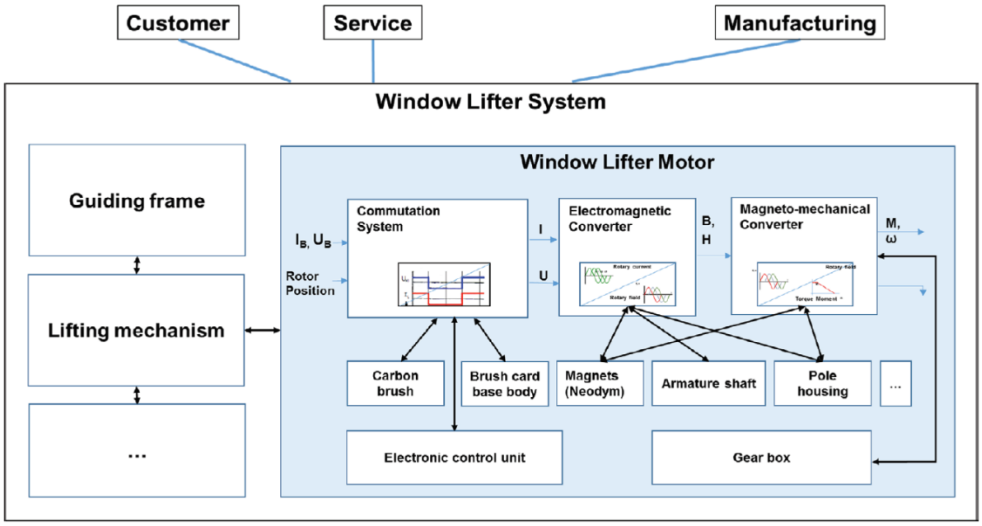


Figure 32 An example of the Block/Boundary Diagram for window lifter system [AIAG 2019]

Figure 33 depicts a Parameter Diagram of window lifter motor [AIAG 2019]. It visualizes the product function with a traditional black box model combined the so-called noise factors, which summarize different influence factors of the product function fulfillment. They can help to guide completion of failure analysis. However, this approach is a type of brainstorming, because those factors are not classified, and the analysis process is not systematically structured. Therefore, the value-added of this method for Design-FMEA is limited in ensuring the causal analysis.

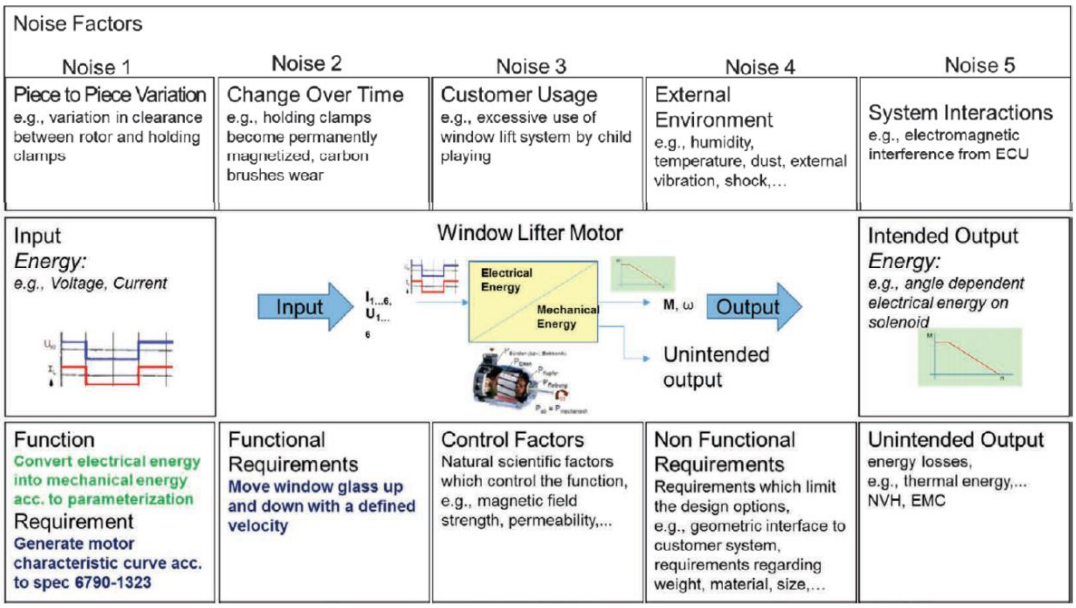


Figure 33 An example of the Parameter Diagram for window lifter motor [AIAG 2019]

The clarification of the detection and prevention controls is an improvement for the derivation of countermeasures by Design-FMEA. This approach guides development teams to structure the possible countermeasures in detection and prevention measures. Away from the controversial Risk Priority Number (RPN), the new action priority method defines the priority of actions based on the value of Severity, Occurrence and Detection in Action Priority Table. These new approaches can increase the efficiency of Design-FMEA by different prioritization of already defined measures.

The analysis shows that the latest development in the industry can improve the effectivity of Design-FMEA in industrial practice, but those improvements cannot solve the problem of missing causality in the failure analysis of Design-FMEA.

3.2.2 Latest researches of FMEA in scientific domain

Are there some solutions of the latest research in the scientific domain? To answer this question, extensive searches are conducted in the scholarly database, Scopus, with two steps:

- search overview of FMEA researching with the set of key words, “FMEA” & “review”;
- search research about how to ensure the causality of FMEA approach for failure mode analysis, root-cause-analysis and derivation of countermeasures with four sets of key words, “FMEA” & “causality”, “FMEA” & “failure mode” & “product development”, and “FMEA” & “root cause” & “product development”;

in the fields of article titles, abstracts, and keywords, separately.

In the first step, 311 publications are found, which include conference papers, articles, and books. Among those opuses, the comprehensive review of Huang et al. in 2020 gives an overview of the latest FMEA research’s results and trends in the future. After a systematic review of 263 papers from 1998 to 2018 with FMEA of 105 journals, six major research fields of FMEA are identified by Huang [Huang et al. 2020]:

- healthcare failure mode,
- risk ranking,
- extended FMEA,
- gray theory,
- risk evaluation,
- and fuzzy inference.

FMEA research in the field of healthcare focuses on the prospective risk analysis and assessment for healthcare technology and treatment processes [Liu 2019]. The research of risk ranking tries to improve the shortcomings of a traditional RPN approach. According to this research, the method of RPN leads to different uncertainties by risk determination. Different methods are introduced to replace the method, such as the action priority table of AIAG and VDA [AIAG 2019], or the evidential downscaling method for risk evaluation suggested by Liu [Liu 2019]. Moreover, some different action models are suggested to extend the traditional FMEA approach. For example, the Failure Mode, Effects and Criticality Analysis (FMECA) methodology is a widely recognized tool for the study and reliability analysis of product design, which adds the Criticality Analysis to the traditional FMEA approach to rank each failure mode according to the combined influence of the severity and the probability of occurrence [Carmignani 2009]. Because not all information is available at the concept phase of product development, gray theory and fuzzy inference are two representative approaches to manage this uncertainty, for example, to estimate the rates of failures, so that the design risks can be evaluated quantitatively [Sharma et al. 2008; Braglia et al. 2003; Wang et al. 2016]. None of the above-mentioned research fields are related to the improvement of the causal analysis of Design-FMEA.

To find out more possible results relating to causal analysis of Design-FMEA, the second step of searching is carried out. With the key words, “FMEA” & “causality”, 11 published papers are found; with the key words, “FMEA” & “failure mode” & “product development”, 170 papers are found; and with “FMEA” & “root cause” & “product development”, 8 papers are found from 2000 to 2020.

Among those researches, Stone et al. developed the Function-Failure Design Method (FFDM) to couple intended product functions and historical product failures of the similar products in the product concept phase [Stone et al. 2005]. Applying the functions-failure-matrix, the mapping between the historical product failures and the intended product functions can be derived, and corrective actions can be defined. However, the direct coupling of functions and failures cannot ensure the causality in failure analysis, because the cause-effect-relation, i.e., the physical effects leading to failures, are not analyzed by the method.

Noh et al. improved the failure analysis of Design-FMEA with the Module-based Failure Propagation (MFP). The MFP consists of four elements: a model for describing functions and their relations; a model for describing module interactions; function rule for describing behaviors; and failure rule for describing failures [Noh et al. 2011]. Mapping function and its failures with the physical phenomenon, the MFP model tries to build a causal chain for the failure mode of Design-FMEA. However, the different models of the product are not defined quantitatively, so that the causality of Design-FMEA is not ensured.

After analyzing the state-of-the-art research of Design-FMEA, the conclusion can be drawn that there is no research providing the solutions to ensure the causality of Design-FMEA. A new product modeling approach and new methods to ensure the causality to improve Design-FMEA should be developed. To achieve this goal, new methods should be developed based on the current standard FMEA approach to make the best value-added effect for industry.

The next chapter introduces why Systems Engineering, especially Generic Systems Engineering, is applied as the scientific principle in this thesis to build up a solution approach.

4 Systems Engineering as a tool to manage complexity

4.1 Complexity in modern technical products

The increasing complexity of technical products is a trend in the industry. Much research show that this trend is the major cause of increasing product failures [Winzer 2016a; Lindemann et al. 2009; Ehrlenspiel and Meerkamm 2017; Feldhusen and Grote 2013]. According to this research, the way to manage the complexity of technical products plays an essential role in reducing failures in the product conception phase. Why can complexity lead to failures of products? To answer this question, the meaning of the term “complexity” in product development should be clarified.

Gomez et al. differentiate the terms “simple problems”, “complicated problems” and “complex problem” [Gomez and Probst 2007]. According to their definition, simplicity means a low number of influential factors and fewer linkages between them, whereas complication indicates a large number of influential factors and many linkages between these, which stay stable over a period of time. Complexity, however, is characterized by the dynamic of the influence factors and their interactions.

These definitions can be adopted in the domain of product development. Mamrot pointed out that the complexity of technical products consists in their complex structure and in their dynamic behaviors, as well as the interactions between the product and its environment [Mamrot 2014].

With the example of mechatronic products, the meaning of complexity in the domain of technical products can be clarified. Figure 34 represents a system model of mechatronic products. The word “mechatronics” is the combination of mechanics and electronics, which indicates that the mechatronic system consists of mechanic, electronic, and software elements. Using a synergy with mechanics, electronics and software, mechatronic products are able to project more functionalities at a lower cost, less weight, smaller size and better quality [Reif 2015].

The ECU, on which the software is running, is the command center of mechatronic products. It receives signals from sensors, which detect the demanded information from environments, from man-machine interfaces, as well as from interfaces with other system elements. After calculating the inputs with a defined algorithm, the ECU gives control signals to actors to drive a defined mechanism of the products.

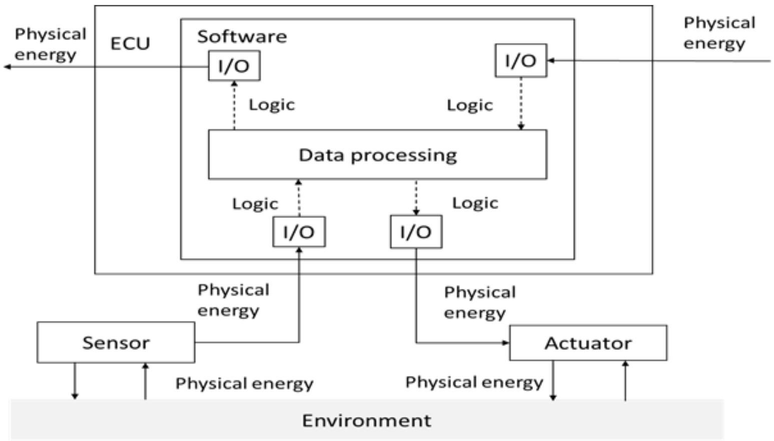


Figure 34 Basic structure of a mechatronic system

Not only the components, interfaces, environment but also the defined mechanisms change over the lifetime of the product. For example, the aging processes of the starter leads to a change of the output torque, or the changing ambient temperatures cause a variation of the current-voltage and internal resistance in a start-stop system. Such dynamics behaviors, the complex elements, as well as the interactions between them, are the main reasons for the increasing quality problems of technical products.

It is a big challenge to deal with those factors in product development. Systems Engineering (SE) is regarded as a common tool to manage complexity, especially in the technical domain. In the next section, the philosophy of SE is explained.

4.2 The scientific principle of Systems Engineering

SE is a widely-used term in the domains of science and industry. Different SE-implementations can be classified in domain-specific and universal approaches [Winzer 2014a].

The International Council on Systems Engineering (INCOSE) defines SE as “an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal” [INCOSE 2015]. While, the National Aeronautics and Space Administration (NASA) describes SE as “a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system” [NASA 2017]. The definitions of these two organizations summarize the different activities and processes in the domain of engineering.

In the domain of science, universal SE is treated generally as a philosophy to manage complexity. Haberfellner sees SE as a methodology for generic problem-solving, whereas he defines a problem as differences between the actual and the required status, which is depicted in Figure 35 [Haberfellner 2015].

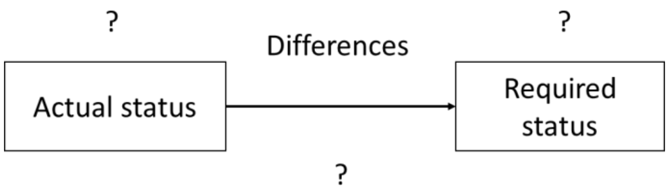


Figure 35 Problem as differences between the actual and the required status [Haberfellner 2015]

To achieve this goal, the SE-concept includes, on the one hand, Systems Thinking to structure the necessary information for problem solving, on the other hand, Systematic Action to generate the solution with causal and transparent steps, so Haberfellner [Haberfellner 2015].

Why are Systems Thinking and Systematic Action necessary for the solving of complex problems? The reason are characteristics of the organ of thinking, the human brain. Ehrlenspiel summarizes four weaknesses of human thinking in the context of product development:

Insufficient functionality, e.g., limited capacity of short-term and long-term memories;

- Lack of capability of abstract and logical thinking;
- Minimizing effects and time in practice;
- Risk aversion, i.e., the developers tend to be averse to new solutions [Ehrlenspiel and Meerkamm 2017].

For instance, the limited capacity of short-term memory means that after receiving too much new information in a short period of time, some old ones will be lost. This weakness of our brains makes it impossible for developers to solve complex problems intuitively. Therefore, problem-oriented filtering of information, as well as rational and systematic actions, are logical strategies to overcome such weaknesses. The target is to reduce the complexity of the problem, e.g., to break a big problem into small ones or to concentrate on the essentials of the problem in order to understand the cause-effect-relation.

The foundation of Systems Thinking is to build models of the system [Winzer 2016a]. A system is a group of interconnected elements that has a clear border to its environment. Figure 36 [Haberfellner 2015] depicts a system with its elements and the boundary to its peripheral system and environment.

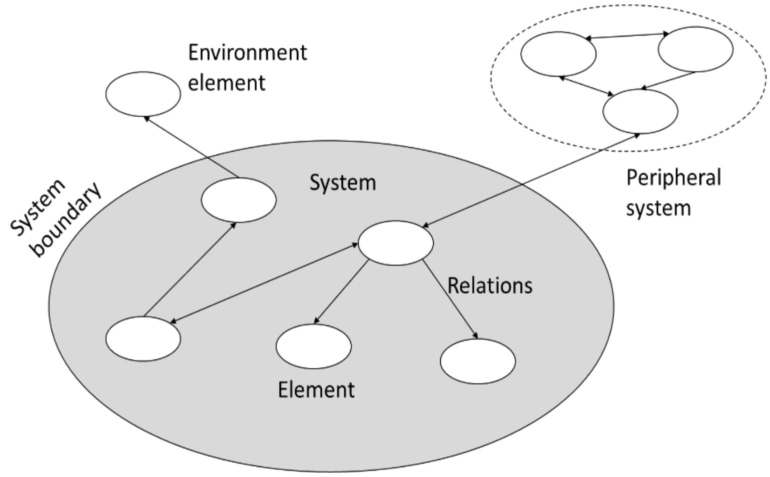


Figure 36 The principle of Systems Thinking [Haberfellner 2015]

System elements are components of a system, which possess certain characteristics or physical properties such as dimensions, material or color. Every element carries out some functions. In a system, its elements are, somehow, linked with each other with some relationships. These relationships could be information, energy or logical relationships depending on the type of the system. Some system elements are not only linked to elements inside a system, but also linked to its peripheral systems and environmental elements outside the system boundary. The elements and their relations build up the structure of a system [Haberfellner 2015]. Another unneglectable aspect is the changes of the system's status under different circumstances, e.g., time and environment. Such changes are called System Dynamic [Sterman 2000].

There are different kinds of systems depending on types of its elements, relations inside the system and to its environment, for example, technical, socio-technical, or social systems [Ehrlenspiel and Meerkamm 2017]. According to Winzer, a technical system is a product system which interacts with human as its environment elements [Winzer 2016a]. The domain of this thesis is focused on the technical system. Hereafter, systems in the context refer only to a technical system.

A model is a simplified representation of an object to fulfill intended purposes. According to Stachowiak, a model is characterized, at least, by three features:

- representation of the object;

- simplification of the original;
- to fulfill intended purposes [Stachowiak 2013].

Due to the reduction of unnecessary details, models of systems help humans to recognize the relevant features of objectives. Figure 37 illustrates a start-stop system with a model. The model consists of an ECU, a starter, a battery voltage sensor and a combustion engine as its system elements. These elements are connected with each other with physical values, such as signals or kinetic energy. The brake pedal, the battery, and the information lamp belong to its peripheral systems. By reducing the unnecessary details, this model describes the working principle of the start-stop system very clearly. This example shows that Systems Thinking is the right approach to simplify the complexity of technical products.

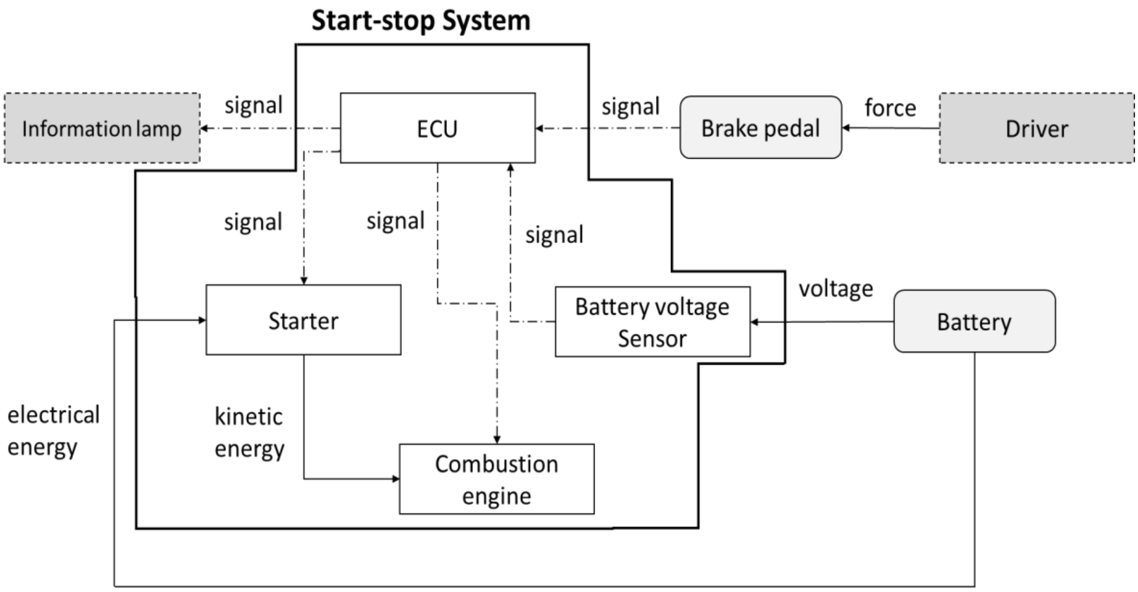


Figure 37 The system model of a start-stop system

However, in the domain of product development, different modeling methods are applied to describe technical products. For instance, Pahl/Beitz used four different models of the clutch of a machine: Function-, Working-Principle-, Construction-, and System-model in product development, as Figure 38 [Pahl et al. 2007] depicts. These models represent different aspects of the product, which are applied to solve different problems. How many models should be used to describe a product by the product development? Winzer analyzed different approaches of the system modeling and draws the conclusion that a technical system should be described with requirement-, function-, process- and component-models, so that the different requirements in product development can be fulfilled [Winzer 2016a]. The research of this thesis confirmed these four models of technical products are indispensable to ensure the causality of Design-FMEA. The analysis is conducted in the next section.

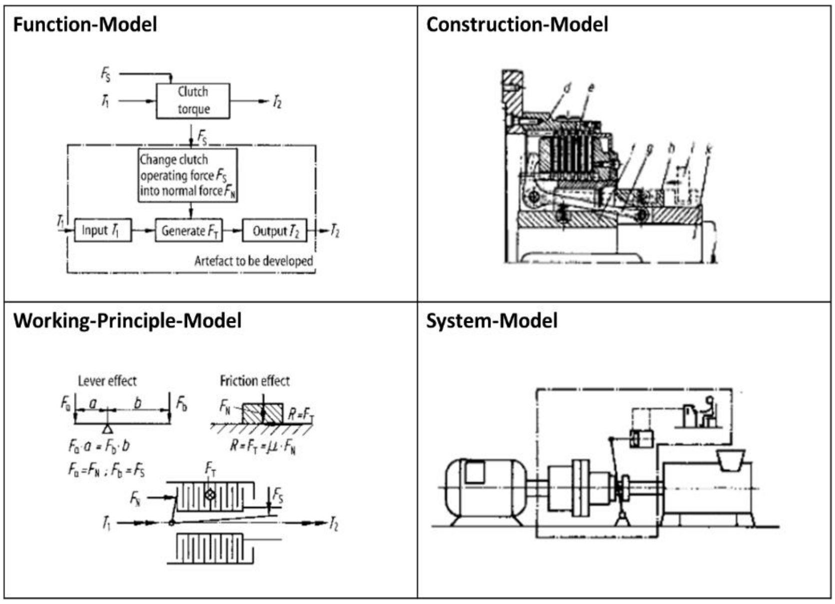


Figure 38 Different models of a clutch of a machine [Pahl et al. 2007]

Thinking and action are rotating activities of the problem-solving process. Systematic Action means a methodic, rational and problem-oriented procedure to reach a defined target. Generally, it answers questions such as:

- What is the problem?
- What are the goals?
- How can the solutions be found?
- What are the possible solutions?
- How can these possible solutions be evaluated?
- How can the chosen solution be validated?
- How can the whole process be organized?

Regarding the weaknesses of the human brain, Systematic Action provides many advantages over intuitive action, which means an unconscious and experience-oriented approach [Ehrlenspiel and Meerkamm 2017].

Several SE-approaches including different models of Systems Thinking and processes of Systematic Action have been developed by different researchers and institutions, e.g., Haberfellner, Ehrlenspiel, Lindemann, Pahl/Beitz, INCOSE, NASA, VDI. Among those SE-approaches, the concepts of Generic Systematic Action describe procedures of universal problem-solving, while the concepts of specific ones focus on a certain field of work, for example, product development.

After analyzing the applications of SE-approaches in different domains, Winzer summarizes the general requirements for the generic approach of SE:

- Thinking in systems;
- A system model can be used in all scientific disciplines;
- Cross-functional applicability, transparent, and traceability of action;

The problem-oriented implementation of principles in the building of system models and systematic action [Winzer 2016a].

Based on these requirements, Winzer investigates different SE-approaches and concludes that the existing SE-approaches can only fulfill a part of their requirements. Especially, the interaction between Systems Thinking and Systematic Action is missing in many of those approaches. This shortcoming leads to a new development of SE, including new action approaches and new methods of system modeling, i.e., Generic Systems Engineering (GSE) and Demand Compliant Design (DeCoDe). In the next section, the approaches of GSE and DeCoDe will be introduced in details. Moreover, the question: why GSE and DeCoDe are the right approach to ensure the causality in Design-FMEA is also answered.

4.3 Generic Systems Engineering and Demand Compliant Design

4.3.1 GSE – A new development of Systems Engineering

Analyzing the deficits of the existing SE-approaches, Winzer develops a new methodology of SE, “Generic Systems Engineering”, which consists of a concept of systematic action and a new approach of system modeling. As revealed by the name “Generic”, GSE is developed as a universal approach, which can be applied not only for technical, but also for socio-technical as well as for social systems [Winzer 2016a].

Figure 39 [Winzer 2016a] depicts the elements of GSE, i.e., the concept of action and system modeling, which interact throughout the problem-solving procedure. The system modeling consists of four different models of a system, i.e., requirement-, function-, process- and component-models. The concept of action includes four modules:

- Goal setting
- Analysis

- Solution development
- Project management consists of
  - Planning phase
  - Execution phase
  - Control phase.

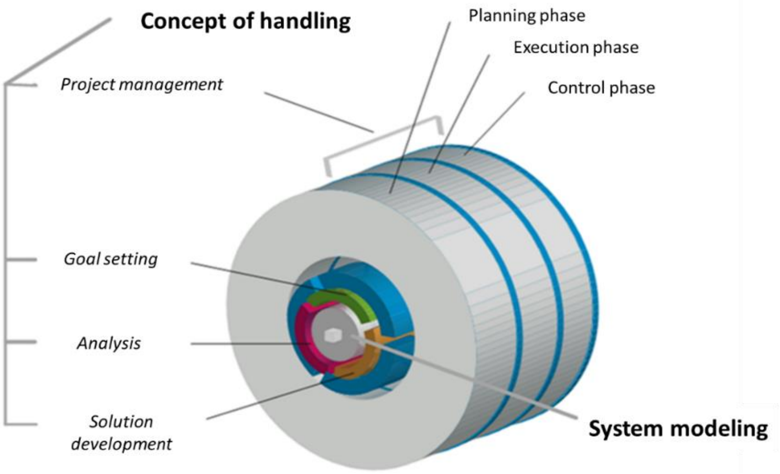


Figure 39 The methodology of GSE [Winzer 2016a]

Comparing such system modeling approaches only with three models, i.e., requirements-, functions-, and components-models, Winzer argues that the processes-model is an indispensable element [Winzer 2016a].

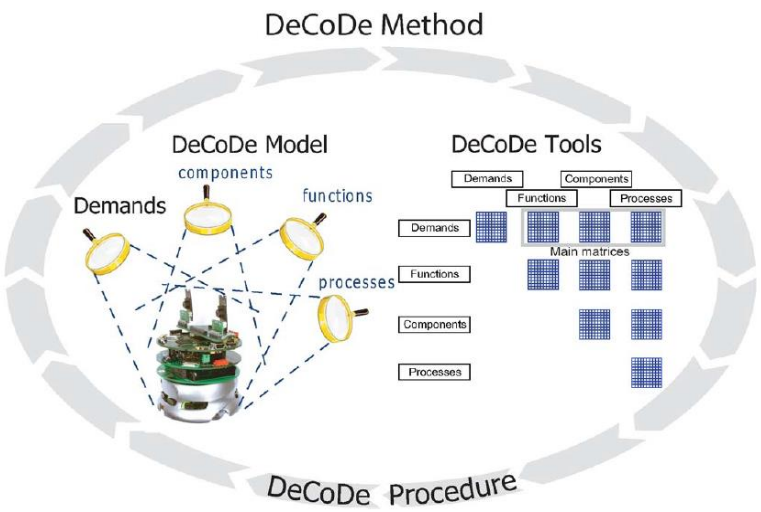


Figure 40 DeCoDe-concept of system modeling [Sitte and Winzer 2011]

Based on this conclusion, Sitte and Winzer developed Demand Compliant Design (DeCoDe) to build up those models and their interactions, especially for technical systems [Sitte and

Winzer 2011]. Moreover, DeCoDe provides a set of tools and methods such as DeCoDe-Matrices, showed in Figure 40 [Sitte and Winzer 2011], to build up GSE system models. The definitions of these models for a technical system are listed in Table 3 [Winzer 2016a].

Table 3 Definition of DeCoDe-System-Models [Winzer 2016a]

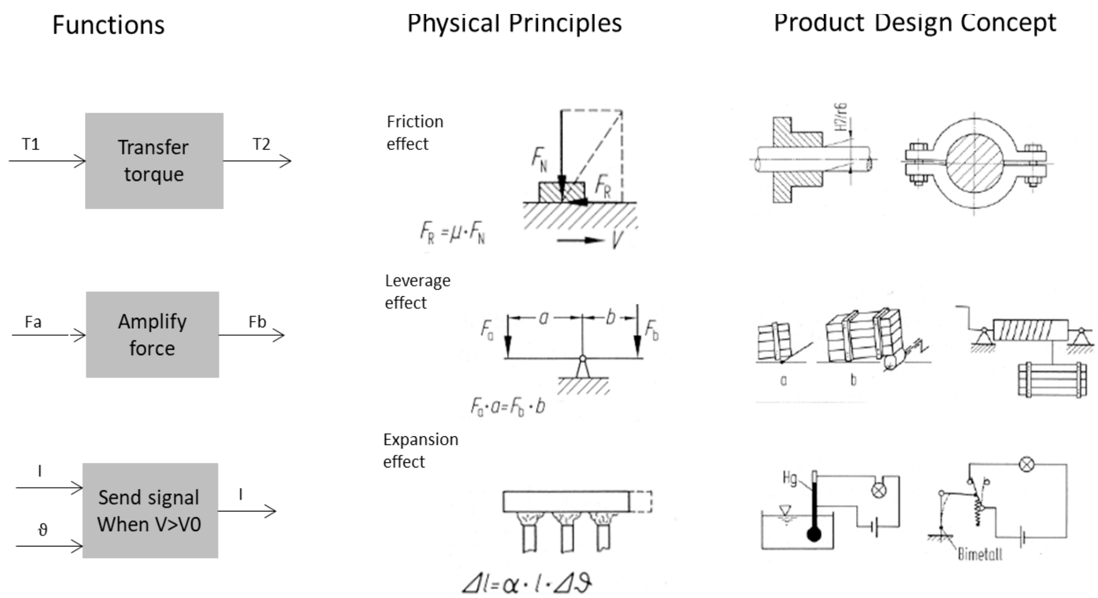
View of a technical system	Definition
Requirements	Requirements are expectations or requisites of a system, which are defined by stakeholders, and usually obligatory.
Functions	Functions describe purposes or tasks which a system has to fulfill by converting its inputs into outputs in a target direction. Functions describe “What” a system or its components should perform.
Processes	Processes describe how inputs of a system convert into outputs, i.e., how functions of the system are realized. The fulfillment of system functions is realized by the fulfillment of functions of its components with processes.
Components	Components are physical or logical, single or united parts of a system.

In the domain of product development, different approaches and methods are developed based on GSE. Among other, Ott integrated DeCoDe-models with every step of product development process and introduced the interactions between DeCoDe-models and different methods during product development [Ott 2009]. Mamrot argued that system models are sources of information for the action of problem solving, and provide a data structure to achieve the results of the process as well [Mamrot 2014]. However, the relation between the causality in product development and DeCoDe-models are still not analyzed by those former researches.

The starting point of product development is the list of requirements to be fulfilled, and product design is the technical solution of those requirements [Gamweger et al. 2009]. To understand causal chain through whole product development, let us go back to explain the basic meaning of “engineering”. According to the American Engineers’ Council for Professional Development, engineering is “the creative application of scientific principles to design or to develop structures, machines, apparatus, or manufacturing processes, or to work utilizing them singly or in combination; …” [IAENG 2014].

The internal processes to operate functions of technical products can only be realized by using physical principles [Koller 1985]. In modern mechanical engineering, physical effects are used deliberately to fulfil product- and component-functions. As early as the 1800s, theories of kinematic as a scientific principle were already applied systematically to build machines [Otto and Wood 2001]. Table 4 [Feldhusen and Grote 2013] illustrates the fulfillment of three functions with different physical effects, as well as their realizations with different product design concepts.

Table 4 Fulfillments of functions by realization of physical effects [Feldhusen and Grote 2013]



This scientific approach of product development indicates that it is essential to build up Requirement-, Function-, Process-, and Component-models to ensure causality during product development process. Figure 41 depicts these interactions between system models and product design.

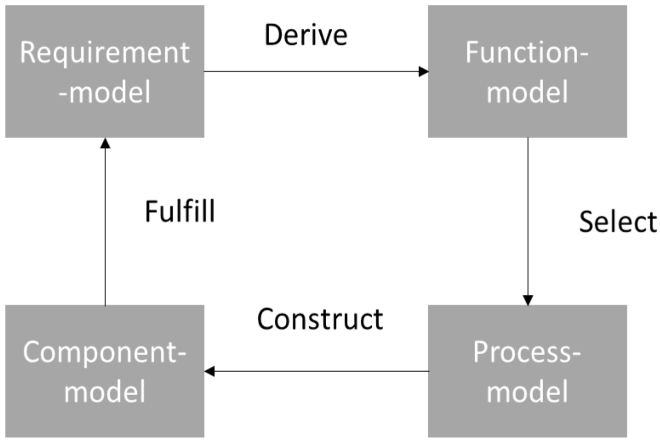


Figure 41 Causal loop of product development based on DeCoDe-Models

To explain this principle in the context of product development, an example from industrial practice will be analyzed in the next section.

4.3.2 Causality of product development

Considering the function "transfer torque", the friction effect is chosen as the physical principle to fulfill this function. Amontons' Law of dry friction describes the relationship between the normal force F_N and the friction force F_R with μ as the coefficient of friction:

$$F_R = \mu \cdot F_N \qquad (2.1)$$

To generate the normal force, an interference fit, i.e., a connection between a bigger shaft, with diameter T_W, and a smaller hole with diameter T_B, is developed, as showed the situation c in Figure 42.

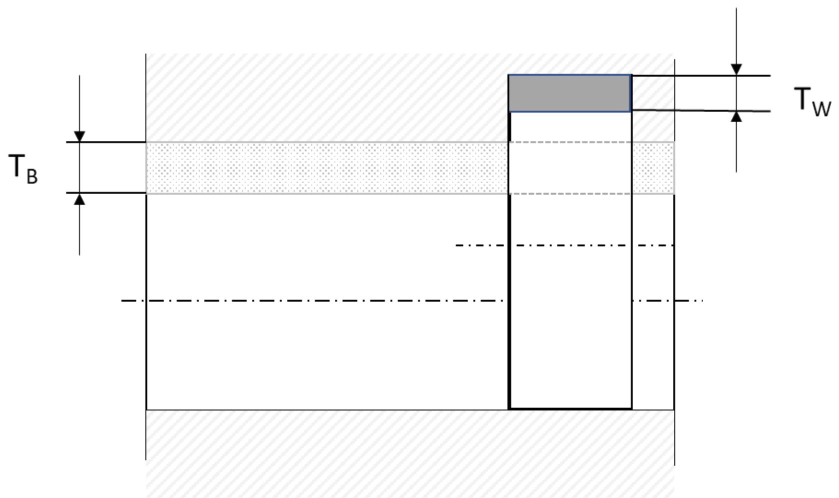


Figure 42 interference-fit with T_W: tolerance of shaft T_B: tolerance of hole

According to Hooke's Law, an elastic deformation of metal is proportional to the force exerted on it:

$$F = E \cdot A \cdot \varepsilon \qquad (2.2)$$

F is the exerting force; E is Young's modulus of the metal; A is the area of the contact surface; ε is the strain, i.e., change in length divided by the original length of the metal.

Assuming the maximal input torque T_{1max} is proportional to F_R with

$$T_{1max} = k \cdot F_R \qquad (2.3)$$

Replacing F_N in 2.1 with F in from 2.2 and then substituting 2.1 into 2.3, we get

$$T_{1max} = k \cdot E \cdot A \cdot \varepsilon \qquad (2.4)$$

Figure 43 [Feldhusen and Grote 2013] depicts an interference-fit connection with the design-parameters D, the diameter of the shaft after assembly; and l, length of the contact surface. Therefore, it obtains

$$A = \pi D \cdot l \qquad (2.5)$$

Substituting 2.5 in 2.4, it gives

$$T_{1max} = \pi k \cdot E \cdot D \cdot l \cdot \varepsilon \qquad (2.6)$$

$$\text{With } D = f_d(Tw, T_B),\ \varepsilon = f_\varepsilon(Tw, T_B) \qquad (2.7)$$

With the design parameters:

- materials of shaft and hole with $k\ and\ E$,
- diameters of hole T_B and shaft T_W,
- as well as the contact l,

the maximal input and output of the interference connect are determined, as formulae 2.6 and 2.7 show.

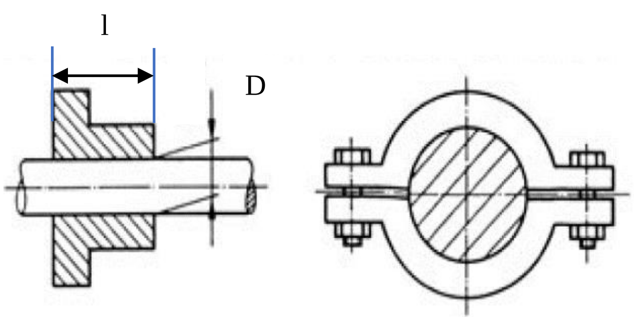


Figure 43 An interference-fit connection [Feldhusen and Grote 2013]

The physical causal chain indicates the quantitative relation between product design parameters and product functions. In this case, T_B, T_W, and l are the design parameters, and the elastic deformation and the friction force are the internal physical processes, which finally perform the function, transfer torque.

Causality is one of the most foundational notions of physics. In the physical domain, causality means that the causes and their effects can only be determined by physical laws [Bunge 2012]. With the explored physical cause-effect-relationship, the mechanism of the product design is understood. The possible failures of the design and the effective corrections can be model-based derived and implemented.

Without the physical processes, a direct mapping between functions and design cannot build a causal chain. As the case of the abovementioned interference connection, it is impossible for the developers to calculate the maximal transfer torque based on the diameters of the hole and shaft without understanding the physical processes. Therefore, the processes-model of products is necessary to derive causality between product designs and functions. The missing processes-model of product is the root cause of the deficit of the current Design-FMEA approach for failure identification and correction.

DeCoDe-models provides a scientifically grounded tool to create the solution in this thesis. However, the current tools of DeCoDe only show a yes-or-no relation between two elements; the models of function, process, and component are not quantified in the form of physical and mathematical logic to ensure the causality of failure analysis in Design-FMEA.

4.4 Interim conclusion and requirements for further method development

4.4.1 Interim conclusion

The growing demands of markets lead to the increasing complexity of technical products in recent decades. A phenomenon correlating with this trend is the increasing failure ratio of industrial products. A representative piece of evidence for that is the increasing recall rate in the automotive industry. According to different studies: increasing complexity, changing development organization, and the pressure of “time to market” are the major reasons for the increasing quality problems of technical products.

Industrial research shows also that most of those failures are already generated in the product concept phase of product development. According to the “Rule of Ten”, the earlier a failure of the product can be corrected, the smaller the financial loss will be for the business. It is important for the industry, therefore, to identify and to correct failures, as early as possible in the product concept phase.

Making mistakes in solving complex problems is a natural phenomenon of the human brain. Different methods to identify and to correct failures are already established in the product concept phase. Among those methods, FMEA is widely accepted and the most applied approach in the automotive industry. In spite of its efficiency in identifying potential failures of product design concepts, the shortcomings of failure analysis reduce its effectiveness to derive countermeasures.

The goals of the thesis are

- to explain why the standard approach of Design-FMEA is not sufficient to reduce the failures of technical products,
- to derive the root causes of this problem,
- to define the solution approaches,
- to improve the methods of FMEA,
- to validate the improvement for industrial practices.

To identify the problems of the FMEA approach, the research begins with the analysis of different product development processes. Considering the approaches of the process and the environment conditions, the requirements of methods for failure identification and correction in the product concept phase are derived. The next step is to analyze the approach of Design-FMEA of VDA Band 4, as the standard of the German automotive industry. The result shows that the Design-FMEA is an efficient method because with this approach the expertise and knowhow in the organization are comprehensively used. With a comprehensive analysis of product structure and functions, the potential risks of product design can be found by the current FMEA approach.

However, the current approaches of FMEA do not introduce systematic methods to analyze the root-causes and to derive countermeasures. The failure analysis of Design-FMEA is not effective, because the causality between the causes and effects in different product models are not ensured. The reason is the direct mapping of the product design and function models.

To make an overview of the state-of-the-art research in the scientific domain and in industry to find out the possible solutions of the problem, a comprehensive search in the latest standard FMEA approach of AIAG and VDA as well as the publications in international journals from 2000 to 2020 is made. After analyzing major researching fields, the conclusion can be drawn that some researchers tried to solve the problem with the missing causality of Design-FMEA, such as FFDM and MFP models, by introducing the physical effects in failure analysis. However, none of those methods can provide an effective solution due to the decoupling of the system modeling of those methods.

Systems engineering is a scientific discipline to manage the complexity of problem-solving, especially, in the domain of product development. Systems Thinking and Systematic action are the two supporting pillars of the SE-philosophy. Different implementations related to technical systems of SE have been developed in recent years. Analyzing those approaches and comparing their strengths and weaknesses, Winzer developed Generic Systems Engineering which includes four Systematic Action modules, i.e., analysis, goal-setting, solution development, and project management, as well as a model of Systems Thinking with four different models of requirement, function, process, and component to describe a system. To improve Design-FMEA in the concept phase, GSE is chosen as the theoretical foundation to develop a solution, because the four models of technical products ensure the causality in failure analysis of Design-FMEA.

Based on the established Design-FMEA approaches, the methods of failure mode analysis, of root-cause-analysis, and for the definition of countermeasures will be developed to ensure the causality of Design-FMEA. The prerequisite of the new methods is the problem-oriented modification of the function, process, and component models of DeCoDe.

4.4.2 Generic Requirements for quality assurance methods

The generic requirements of analytical quality assurance methods for product development are derived based on industrial practices in 2.4 are

- Requirement 1: the methods should be able to analyse the functions and the design of the product and components to find out design failures.
- Requirement 2: correctness of the results should be ensured, otherwise, the loss to the company could be high according to the "Rule of Ten".
- Requirement 3: the implementation of methods should only focus on design risks.
- Requirement 4: the completeness of finding the design risks should be guaranteed based on the available know-how and experience of the team. Failures due to misunderstanding or ill-treatment should be avoided, to reduce the recursions in the quality assurance process.
- Requirement 5: methods of failure identification should be able to find out the root-causes of the failures to derive possible measures to correct the failures.
- Requirement 6: methods should empower and authorize the cross-functional team members to review and decide countermeasures according to their competencies, so that optimal solutions for the company can be chosen.

According the analysis shown in Table 2, the established Design-FMEA approach of VDA fulfills the requirements 2, 3, 5, and 6 only partially. The root cause is, as analyzed in 3.1, missing causality by failure analysis. In Chapter 5, a new approach to improve Design-FMEA will be developed based on the science of product development and the principle of Systems Engineering to fulfil the abovementioned requirements.

5 Develop a new approach to ensure causality of Design-FMEA

5.1 Scientific principles to ensure causality of failure correction

Before developing the new approach to ensure causality of Design-FMEA, the questions to be answered firstly are:

- What are scientific foundations of sustainable problem-solving?
- Which additional steps should be made to ensure causality by applying Design-FMEA based on those scientific foundations?
- How can the new approach be integrated into the established process of Design-FMEA?
- The goal of applying Design-FMEA in the early phases of product development is to identify potential product design failures, and to define measures to correct them. To correct a failure effectively, the root causes of the failure should be derived [Fantin 2014].

To apply this principle of problem-solving in Design-FMEA, the following five steps are developed in this chapter, as showed in Figure 44:

- To focus the design risks for further analysis as the starting point of causal analysis;
- To quantify and to specify models of affected functions, physical effects and product design as basis of failure mode analysis;
- To analyze failure modes based on the product models as the prerequisite of root causes analysis;
- To derive root causes based on the failure modes;
- To define countermeasures based on root causes.

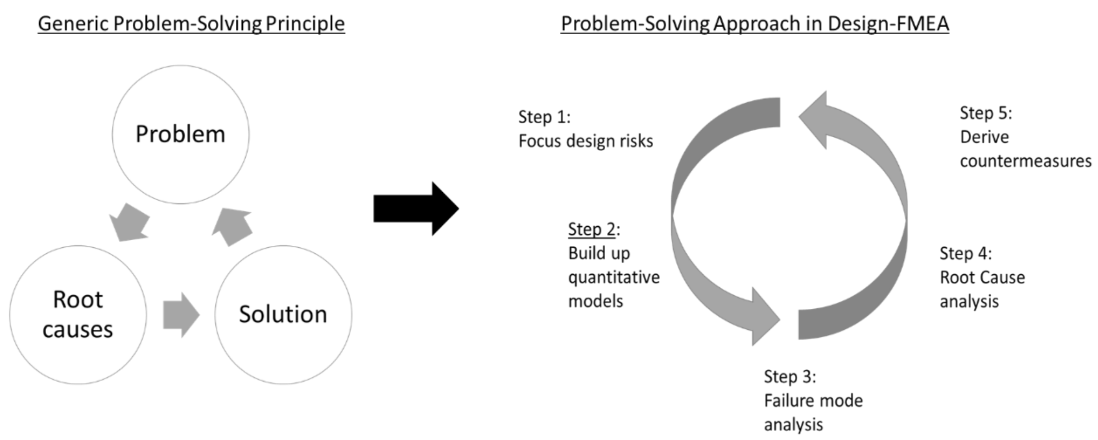


Figure 44 Applying generic problem-solving principle in Design FMEA

The first step is to select design risks for further analysis based on the failure analysis of Design-FMEA. Those design risks are the potential failures of product design which should be the inputs of the new approach.

To identify the root causes of those design failures, their cause-effect-relations, which are the so-called failure modes, should be analysed firstly [VDA Band 4:2012]. To understand failure modes, certain physical effects leading to the failure by the product operation should be clarified with

- Requirement 7: models of physical effects by product operation to fulfill product functions must be built up.
- Requirement 8: link between functions and the dedicated effects to fulfil those functions, as well as link between design parameters and the dedicated effects must be analyzed.

Because quantitative and mathematical description of cause-effect-relations builds the prerequisite of causality [Bunge 2012], the quantitative models of functions, physical effects and produce design should be modified before failure mode analysis with

- Requirement 9: models of functions, physical effects, and product design should be quantified, and be specified to enable causal analysis of Design-FMEA.

Industrial practice shows that building quantitative models and analyzing failure modes of technical products are often very time-intensive and expensive. For example, for a new development of generator in a passenger vehicle, it took the product development team several weeks with a couple of workshops to derive function of the screw connection of the generator, even if screw connection is widely used. Another example is that for a project of a new high-pressure pump of ESP, a special know-how must be acquired from a university to build models for the wear behavior of moving seals. The test to confirm its reliability took several months, even if the sealing concept was already applied for products of former generations.

In the time of high competition on costs and the challenge of time-to-market, it is essential for a development project to reduce the time of whole process. If the design risks are clearly evaluated, the focus of further analysis can be defined. It means that the deep causal analysis should only be applied to focuses of design risks,

- Requirement 10: focus of deep diving analysis for Design-FMEA should be defined.

The purpose of finding root causes is to define optimal countermeasures to correct the design failure. The current Design-FMEA provides no method to guide development teams to derive countermeasures from root causes. To improve this point, the requirement can be derived:

- Requirement 11: method to ensure the causal chain between root causes and countermeasures should be developed.

Moreover, as industrial practice shows that the competencies of different roles, e.g., engineering, manufacturing and purchasing, in development teams are needed to define an optimal solution, the requirement can be derived:

- Requirement 12: a tool to enable the cross-functional development team to select the optimal countermeasure should be developed.

The five steps of the new approach will be developed and integrated into the process of Design-FMEA, as Figure 45 depicts.

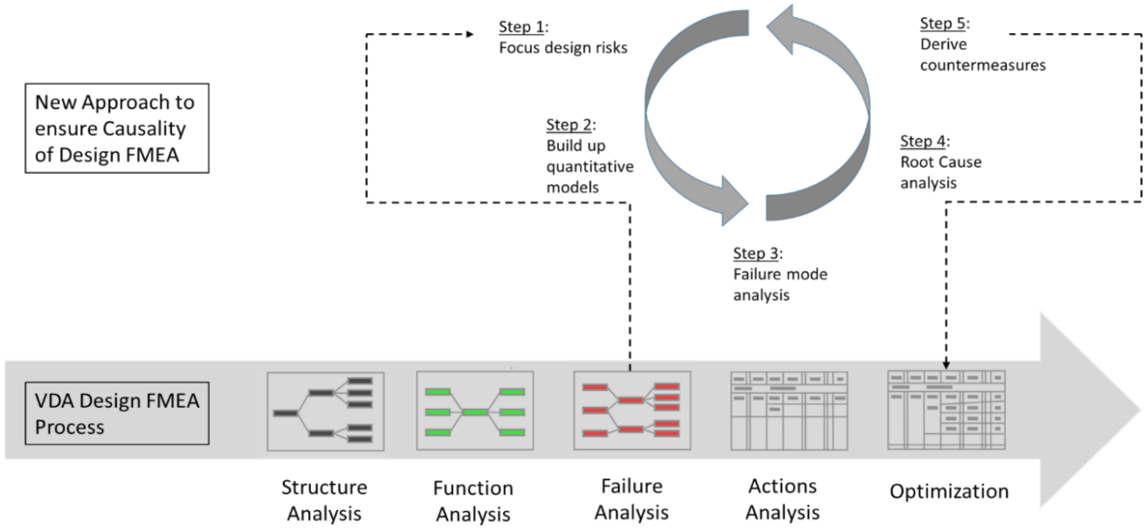


Figure 45 Integration of new approach to ensure causality into VDA Design FMEA process

5.2 Develop a new approach

5.2.1 Step 1: Focus design risks

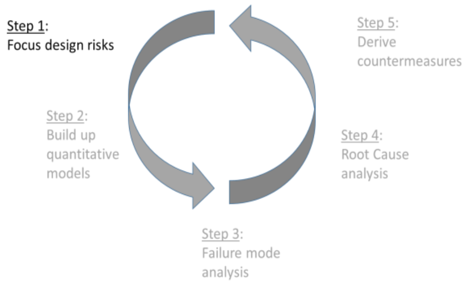


Figure Step 1

The Failure-Analysis of Design-FMEA provides a broad analysis to identify design risks.

Starting with the design risks, the purpose of this step is to select focuses for further analyses. To achieve this goal, Figure 46 introduces a standard approach with responsible persons, recommended methods and tools.

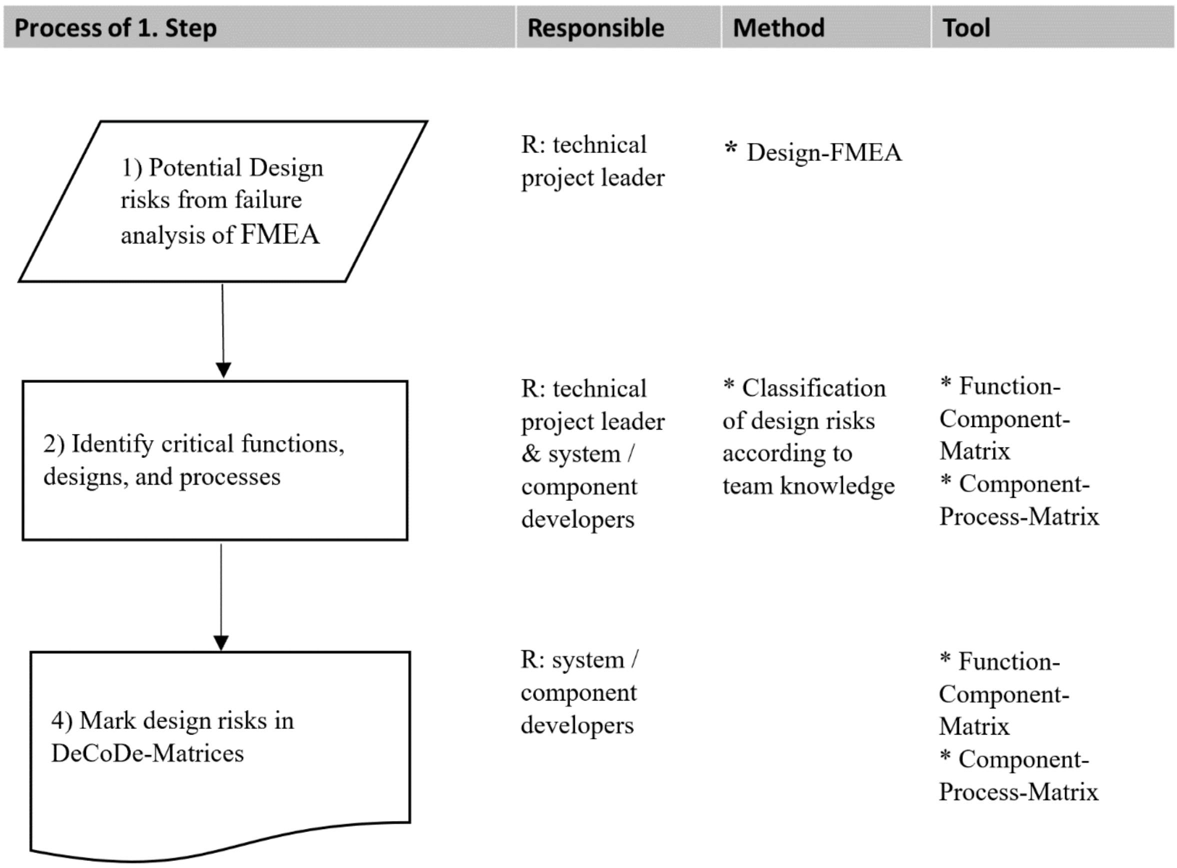


Figure 46 Process of focus design risks

Substep 1) The failure analysis of Design-FMEA underlines all possible design risks with evaluation of their severity, occurrence probability and detection probability [VDA Band 4:2012]. This information is the input of this step.

Substep 2) The critical design risks can then be classified into three different levels:

- validated component design,
- understood component design,

- risky component design.

The validated design means the design which is already validated by tests or by real operations. Typically, most new developments of innovative products are based on the old generations, or other proven design of components and subsystems [Feldhusen and Grote 2013]. In this case, the “old” design solutions, which have been used for years by end-users, can be regarded as the validated design, under the condition, all new requirements and new functionalities are also covered by former applications.

The understood design means that the cause-effect-relations of design parameters to functions are analyzed and well known. From the example of interference-fit, the relationship between the diameter of the shaft, D in an interference fit and the maximal transferable torque T_{1max} is well known as

$$T_{1max} = \pi k \cdot E \cdot D \cdot l \cdot \varepsilon$$

So that the shaft design can be regarded as an understood design, for instance. In this case, the design risks are relatively low, because the performance of the component can be calculated precisely even with new boundary conditions and requirements.

There are also some design solutions, which are not yet fully validated or understood, because of new functionalities or higher requirements of new products, for example, higher temperature of the use environment, or a longer lifetime. A new design solution, which has never been used before, belongs also to this category.

In the Start-Stop-System, for instance, the engine has a new function to start automatically after the driver releases the brake pedal, which leads to a long lifetime requirement of the starter due to the larger ignition cycles. Because of the long lifetime requirement, the design of carbon brushes of the starter is regarded as a risky design.

Generally, such design risks are only theoretically proven in the design concept, but the cause-effect-relation between design parameters and functions is, very often, still not analyzed completely, or the validation by the real operation is still open, or the side-effects are still not understood completely. To evaluate the causality of the design risks, physical processes affecting the critical components should identified and analyzed.

To select the focus of design risks, the DeCoDe-Function-Component-Matrix can be applied, as Table 5 depicts. According to the expertise of the product and components, and the results of conducted tests and analyses, the design risks, i.e., the affected functions and components can be identified.

Table 6 Function-Component-Matrix of DeCoDe demonstrates the correlations between functions and components to show risks of the product design concept

Components / Functions	Component 1	...	Component i	...	Component n
Function 1	x			x	x
⋮	x		x		
Function j		x			x
⋮			x	x	
Function m	x	x			x

■ Design risks ■ Understood / validated design

Modern product design science applies dedicated physical effects to fulfil product functions [Pahl et al. 2007]. According to GSE-system-modeling, the defined physical processes fulfil the function of technical products [Winzer 2016a]. Applying the DeCoDe-Component-Process-Matrix, Table 6, the critical processes of design risks can be identified. The responsible system and component developers should work systematically to analyze all affecting effects of the design risks over the lifetime, so that all root causes can be derived.

Table 5 Component-Process-Matrix of DeCoDe demonstrates the correlations between design risks and critical processes

Components / Physical processes	Component 1	Component n
Process 1	X	X
Process 2	X	
Process 3	X	X

■ Critical processes ■ Understood / validated processes

Substep 3) The results are documented in Table 5 and Table 6 with:

- x: the component influences the function, and affecting processes;
- green: the cause-effect-relations between component, processes and function are validated or understood;

- red: the cause-effect-relations between component, processes and function are not validated or understood;
- white: the component doesn't affect the function.

The focuses of further research are, consequently, the red marked functions and components. The visualization in the table facilitates the development team to plan and to track further analysis. So that "Requirement 10: focus of deep diving analysis for Design-FMEA should be defined" is fulfilled.

In the next step, the approach to analyze the cause-effect-relations of design risks is developed based on the quantified DeCoDe-models.

5.2.2 Step 2: Buildup quantitative DeCoDe-models

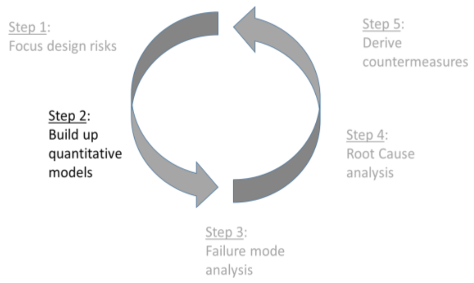


Figure Step 2

As already discussed, the prerequisite of causal failure analysis is the physical and mathematical relationship among design parameters, physical effects, and functions. The current Design-FMEA approach builds models of functions and design. However, those models cannot fulfil the requirement of causal analysis, due to three reasons:

- the function model uses an informal formulation of functions, i.e., natural language [Winzer 2016a] [Koller 1985];
- the model of physical effects is not available [Koller 1985];
- the model of design is not standardized to fulfill the requirements of causal analysis.

To solve those problems, DeCoDe-models of function, process and component can be applied. However, the generic DeCoDe-models should be quantified to ensure the causal analysis of product failures.

Figure 47 explains the process of building up quantitative DeCoDe-models in detail. The technical project leader is responsible for defining further analysis of risky designs. The related component designers get the information in the Function-Component-Matrix with the red marked functions and components. The task is to build the quantified DeCoDe-models of function, process and component.

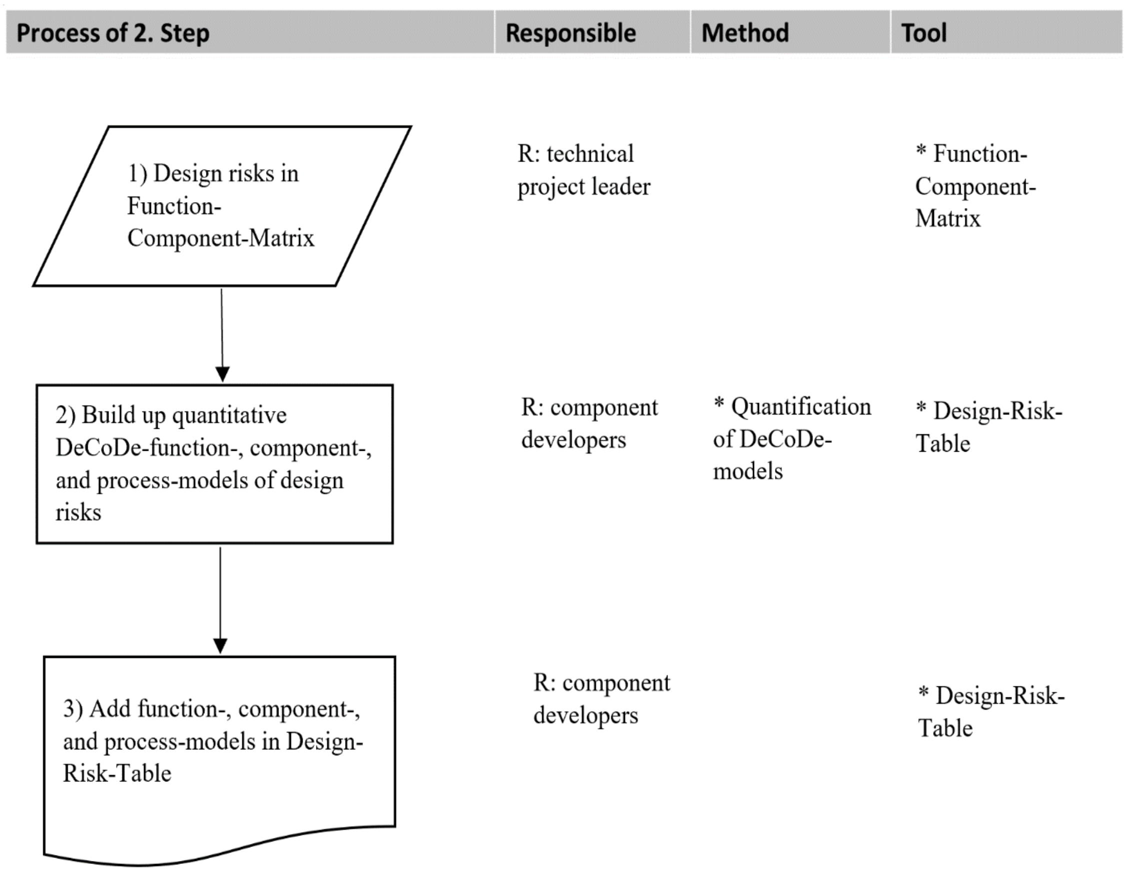


Figure 47 Process of buildup quantitative DeCoDe-models

Substep 1) The design risks from the Function-Component-Matrix should be transferred to the responsible component designers by the technical project leader. The tasks of building up quantitative DeCoDe-models should be defined and terminated.

Substep 2) The responsible component designers build quantitative DeCoDe-models according to following modification of generic DeCoDe modeling:

<u>Modification of Function-model</u>:

Functions describe the intended uses of products, and normally are formulated in words, as a combination of a verb and a noun [Hubka and Eder 2001]. The current Design-FMEA approach applies also this formulation of functions. To ensure the causality of failure analysis, however, the following elements should be considered:

- Mathematical relationships between inputs and outputs,
- Limitation of ranges of inputs and outputs of the function,
- All influencing factors of the function realization.

To fulfil those requirements, the Black-Box model, introduced by Pahl/Beitz, of function for product development is applied to build the function-model [Pahl et al. 2007]. Moreover, different information for developing a product and component design is standardized for the function-model from industrial practices. Figure 48 shows the quantified DeCoDe-Function-Model with five elements:

- Corresponding rule between inputs x and outputs y with limits: $y = f(x)$,
- Loads Profile: L with loads distribution over life time,
- Conditions: C e.g., installation interfaces,
- Use Environment E, e.g., temperature,
- Lifetime T [Pahl et al. 2007] [Otto and Wood 2001] [Koller 1985] [Bertsche and Lechner 2004] [Gamweger et al. 2009].

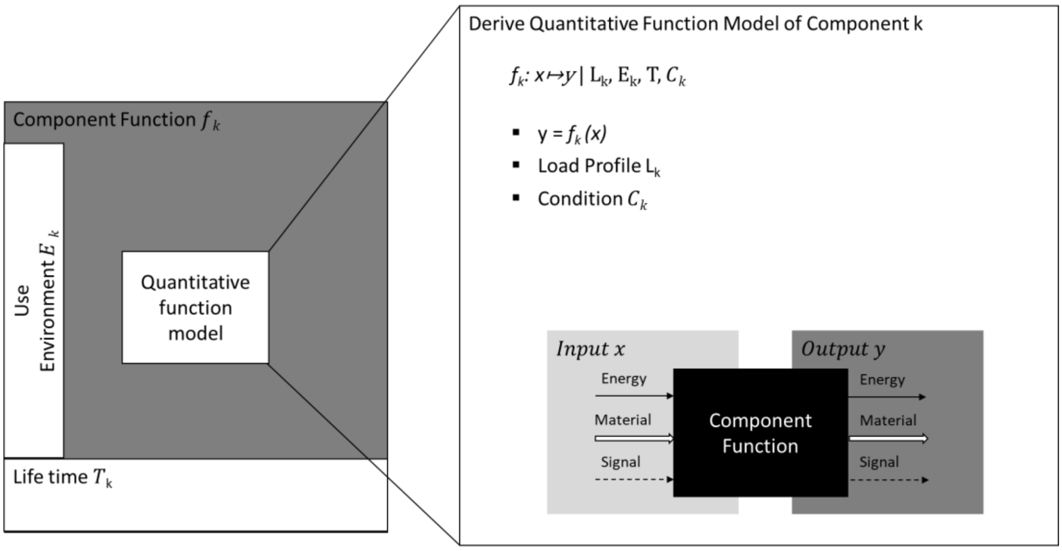


Figure 48 the modified DeCoDe-Function-Model

The Black-Box model is widely used by product developers in industrial practice to describe functions. The current approach of Black-Box model only defines the inputs and outputs of functions, but not the relationships between them. Therefore, the mathematical function definition is applied to improve this approach. In the context of mathematics, a function is defined as a relationship between a set of inputs and a set of permissible outputs with the property that each input is related to exactly one output. Applying the function theory of mathematic, the corresponding rule of the component function can be formulated as,

$$F: x \mapsto y$$

$$\text{Inputs } x \in (x_{min}, x_{max})$$

$$\text{Outputs } y \in (y_{min}, y_{max})$$

Every input should be transferred to an exactly defined output with defined ranges for product functions. This relationship is the mathematical formulation of the intended task of a component or of a product. This formulation in formal language with the mathematical relationship builds the first step of causal analysis. The ranges of the inputs and outputs define differences of failures of the product and its misuses. If the inputs exceed the defined range, defects of the component will not be accepted as failures, rather as misuses of the product.

High stresses of components caused by extreme loads are common reasons for component failures [Bertsche and Lechner 2004]. The loads profile is, therefore, the core part of the function model, especially for mechanical components.

Moreover, conditions C, use of environment E and lifetime T, under which the product should operate, must also be included in the model of functions. For product development, that information is essential to derive the product design parameters. Vice versa, this information is also essential for failure analysis of product design. Failures of products happen probably under boundary conditions, in a bad environment, and near end of the lifetime. For example, old cars have difficulty igniting their engines on extremely cold winter days.

To summarize the steps to build the function model, three steps will be conducted:

Step 1: transform the described physical tasks from informal formulations to mathematical sigmatic, syntactic and semantic;

Step 2: derive the domain and range, i.e., limits of the inputs and outputs of the responding rule the function;

Step 3: derive the loads profile, the environment, the lifetime and the conditions of the function.

Modification of Process-model:

Figure 49 illustrates that the inputs of a component function are transferred to the outputs by applying different physical effects. It is, therefore, indispensable to analyze those physical processes for identifying the root causes of the failure.

The key element of the process model is the physical laws applied to convert the inputs to outputs of functions, for example, Amonton’s Law and Hooke’s Law to fulfill the function “transfer torque”. Based on the physical laws, the second step is to identify the physical mechanisms, i.e., the mathematical relationship of the process, by operating the products, and then to quantify their parameters and variables. The causal chain of the physical processes can be then determined.

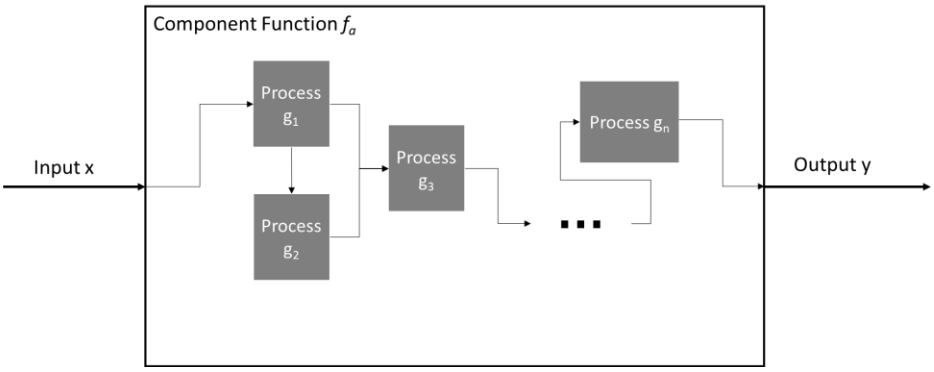


Figure 49 Fulfillment of a component function by realization of physical processes

Summarizing the procedure, the quantification of the process-model for the function, f_a can be conducted by applying different physical processes as:

$$g \in \{g_1, \dots, g_n\}$$

with n defined physical processes, as well as each process with

$$\{g_x | x \in \{1, 2, \dots, n\}\} := \{(M, \{i\}, \{p\})\}$$

with M: physical laws, {i}: variables, {p}: parameters, which are the triple of the process model.

The variables can be classified into the exogenous variables, which represent the inputs of this process determined by the former processes, and the endogenous variables, which represent the physical values determined by this process and as the inputs for the later ones. For example, the normal force between the shaft and the hole in the interference connection is one of the exogenous variables, whereas the friction force can be treated as one of the endogenous variables of the pressure process for the interference connection.

The parameters are, however, factors in the physical processes determined by the product design, like the contact area of the former example, which can define the relationship between the exogenous and endogenous variables of the physical process.

If n processes are needed to fulfill the function a, according to the rule of composition, it holds

$$y = f_a(x) = (g_1 \circ g_2 \circ, \dots, \circ g_n)(x)$$

as Figure 49 depicts.

After quantification of Function-, and Process-models, the quantitative model of the design parameters will be defined based on DeCoDe-Component models in the next section.

Modification of Component-model:

The outputs of the product design process are the intellectual product, which includes all models to define the product, e.g., product architecture, drawings, material specifications [Eigner and Stelzer 2013]. Which information among these models, and which data structure of product design, are necessary to ensure causality by identifying the failure modes?

Firstly, the structure of the product should be specified to clarify the layout of the components and their dependency to sub-systems and the product. Pahl/Beitz calls it construction structure of a technical product [Pahl et al. 2007]. Figurer 50 [Pahl et al. 2007] illustrates the construction structure of technical product with the data structure of a general tree, which is also applied by the structure analysis of Design-FMEA. The root of the tree is the product and its child nodes are the sub-systems, which can also possess their own sub-trees. The leaf nodes are the single components of the product, which are considered as the elementary units of the tree.

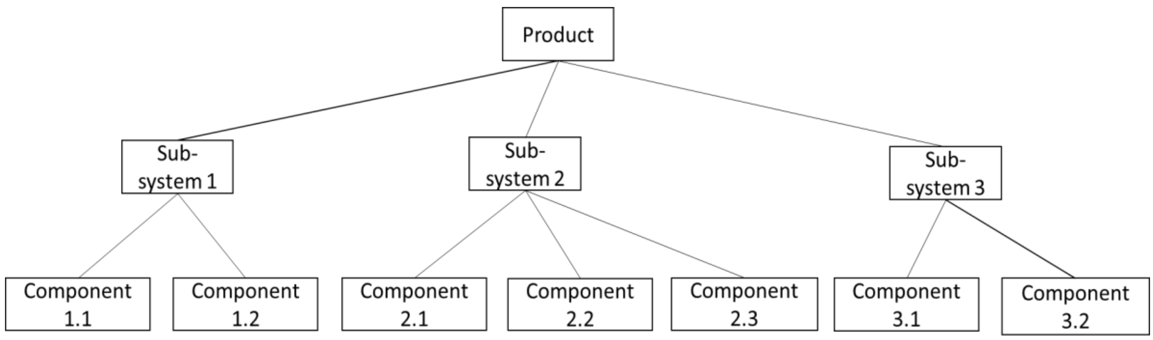


Figure 50 Product component hierarchy [Pahl et al. 2007]

Besides the overview of components and their dependency, the quantitative design parameters are also key elements for the causal analysis, because the parameters of physical processes are determined by those design parameters.

The design parameters of technical products can be described in a set:

$$\{p\} := \{\{p_0\}, \{p_1\} \dots, \{p_n\}\}$$

with

p: design parameter

$\{p_0\}$: design parameters to define the relations of the system elements (sub-systems or components)

$\{p_1\}, \dots, \{p_n\}$: design parameters to define the system elements

The product structure and the design parameters are also elements of Design-FMEA. However, the characteristics of the components, like the yield strength, Young’s modulus, and thermal conductivity, etc. are not considered by Design-FMEA. It is one of the reasons why causal analysis of failure mode cannot be conducted systematically. The new component model includes also the characteristics of components as design parameters.

Figure 51 describes the modified product component model of the DeCoDe with product structure in a general tree format combined with the quantitative design parameters including the characteristics of components. With the quantification of the product structure, the product design concept can be described by the quantitative component-model to provide all necessary information for the causal analysis.

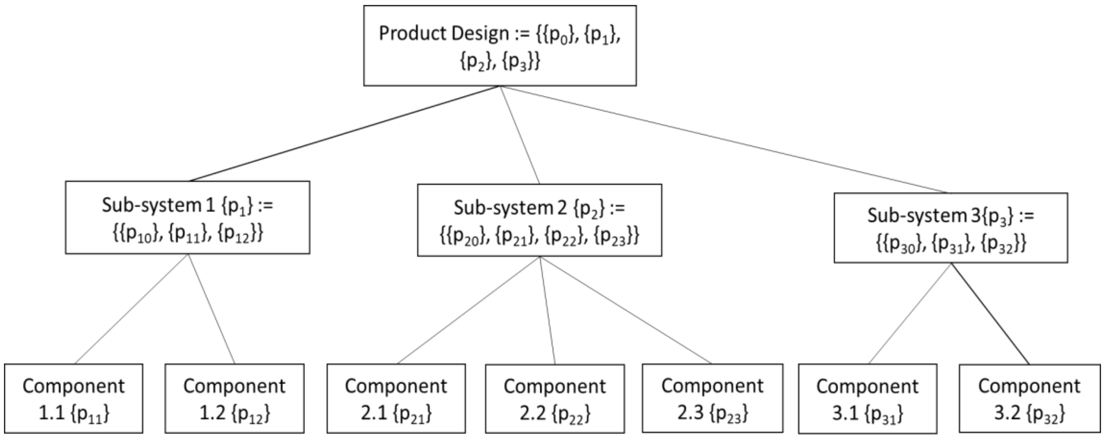


Figure 51 Product component model with quantitative design parameters

Substep 3) After building quantitative function-, process-, and component models by component developers, the information will be added into Design-Risk-Table, Table 7.

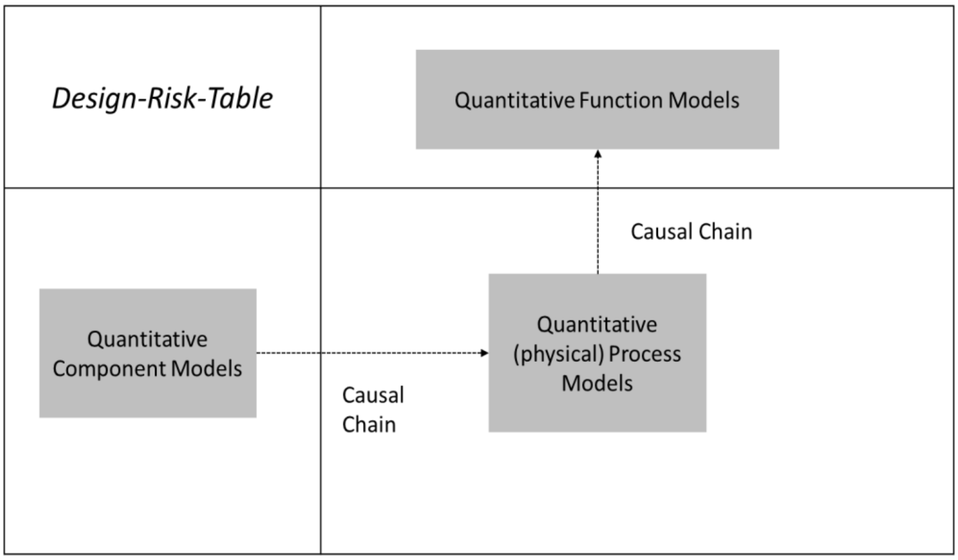
With this step,

"Requirement 7: models of physical effects by product operation to fulfill product functions must be built up."

"Requirement 9: models of functions, physical effects, and product design should be quantified and be specified to enable causal analysis of Design-FMEA." are fulfilled.

Based on the newly modified models, the causal analysis to derive failure modes can be developed in the next section.

Table 7 The Design-Risk-Table with the DeCoDe function-, process-, and components-models



5.2.3 Step 3: Failure mode analysis

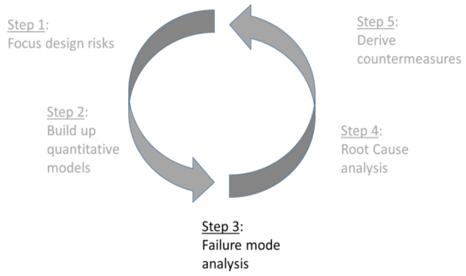


Figure Step 3

The purpose of this step is to derive failure mode of the potential design failures. The failure mode in this context means the physical principles, as well as the boundary conditions lead to those failures. To achieve this goal, the relationship among the quantitative DeCoDe-models should be analyzed, so that the causal chain from design, through physical effects to functions can be derived. Figure 52 introduces the process of failure mode analysis in five substeps.

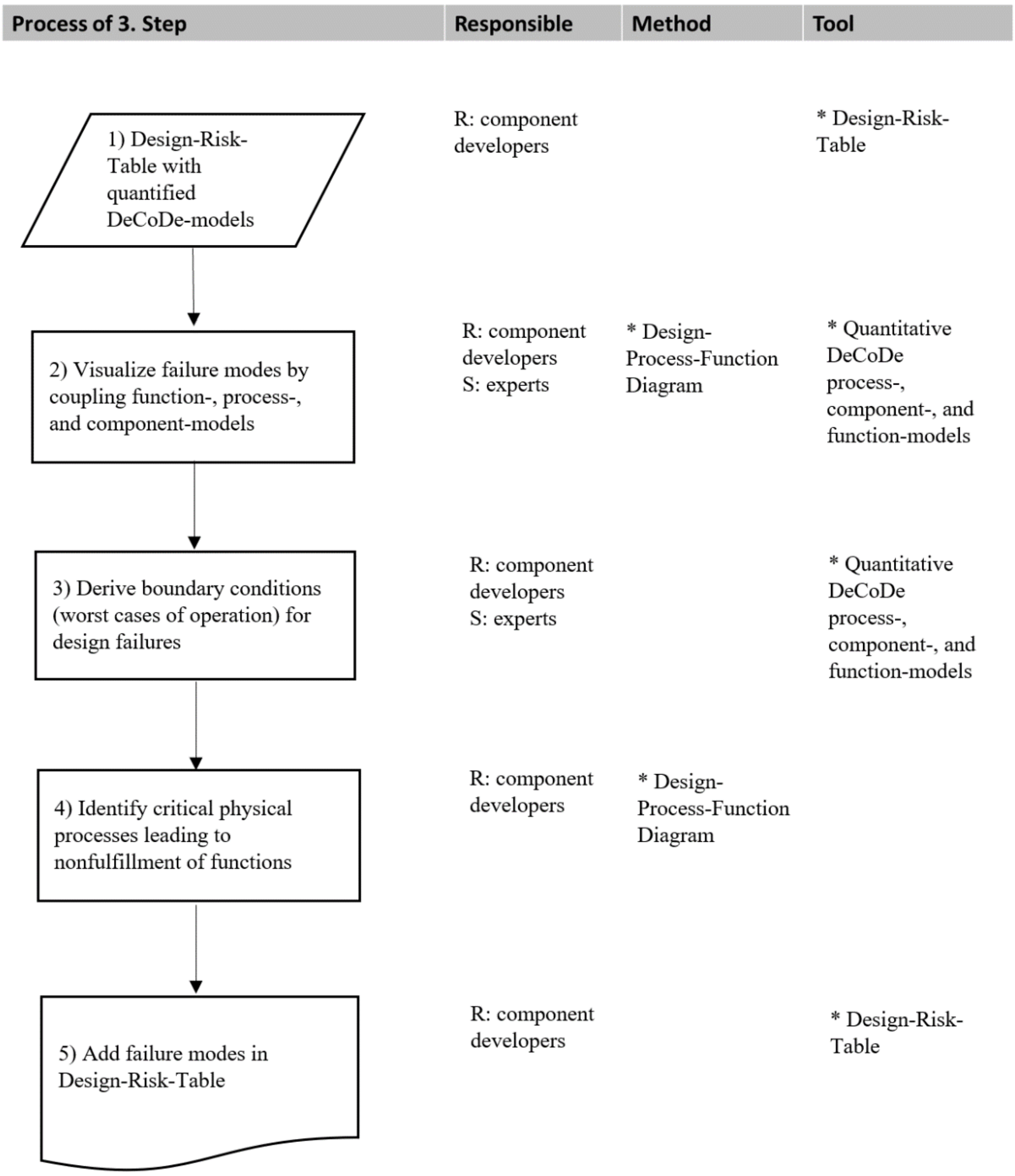


Figure 52 Process of failure mode analysis

Substep 1) Starting points of the analysis are the quantitative function-, process-, and component-models of design risks from the Design-Risk-Table in Table 7. Because the causal chain is through the three models, the essential information should be crystallized to build the failure mode.

Substep 2) To derive the failure mode from the quantitative process-, component-, and function-model in the Design-Risk-Table, Table 7, failure of product design should be defined mathematically.

Failures of product design mean the nonfulfillment of product functions even if all product features are within the defined tolerances of all design parameters.

If the product function is defined by five elements, corresponding to rule f: $x \mapsto y$, loads profile L, conditions C, use environment E, and lifetime T, as

$$f: x \mapsto \mathrm{y},\ \forall x\ \in X,\ \forall y\ \in Y\ |\ L, \mathrm{C, E, T}$$

The design concept of products is defined as

$$P = \{p|\{p_0\}, \ldots, \{p_n\}\}$$

with P is the set of all design parameters.

According to the theory of design engineering, the functions are fulfilled by the defined physical effects. And those effects are realized by the quantitative geometries of working surfaces and structure of the product [Pahl et al. 2007]. If any physical process exists which leads to a nonfulfillment of any function, then the design parameters which cause such physical processes are the failures of the design concept. The failures of product design can be, therefore, formulated as

$$\exists \mathrm{g(x)}\ \neq \mathrm{y} = \mathrm{f(x)}|\ \forall \mathrm{x}\ \in \mathrm{X}, \qquad \forall \mathrm{y}\ \in \mathrm{Y}|p_e \in \mathrm{P}$$

If any physical process of the Process-model leads to an output of the function, which is not equal to the output defined in the Function-model, then the design parameters p_e leading to the process is a failure of the product concept.

VDA defines failure mode as “the precise circumstances which have led to the failure” [VDA QMC]. In the context of product development, failure mode can be defined as the boundary conditions the failure p_e.

Even this mathematic definition provides prerequisite of causal analysis of failure mode, the complex relationship among three quantitative models cannot guide engineers to find the right failure mode easily by losing key information. Industrial practices show that the visualization of such models can reduce the complexity by analysis [Gamweger et al. 2009].

To crystallize the physical processes and function, as well as the influences of physical processes from design parameters, the so-called Design-Process-Function-Diagram in Figure 53, by linking all the information in one single diagram is developed.

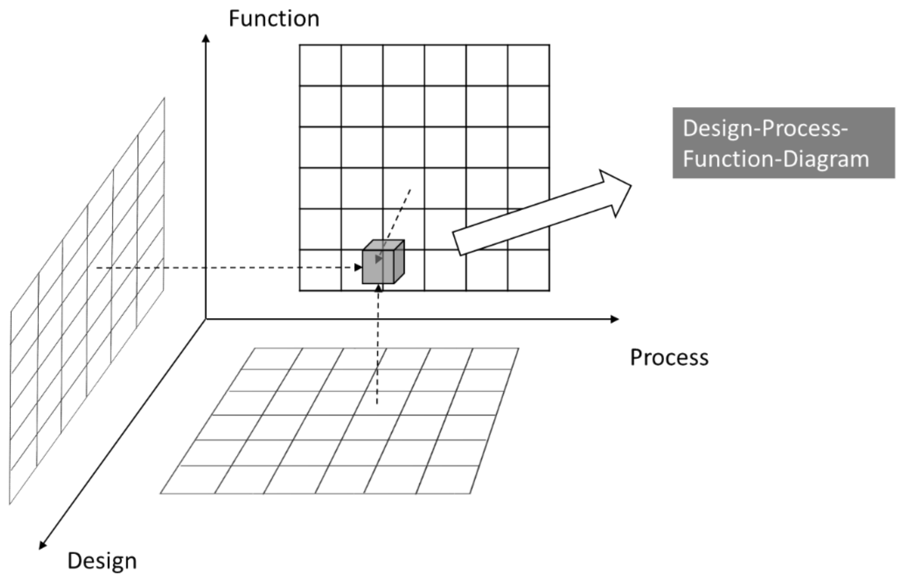


Figure 53 Design-Process-Function-Diagram

For building of the Design-Process-Function-Diagram, the affected functions of quantitative Function-model and the critical physical processes of the Process-model are visualized in the same coordinate system. The technique to visualize functions is to build a graph of functions with pairs (x, f(x)) with all input values x in the domain of the function in the Cartesian coordinate system. If the graph is built up, the area of admissible values of the function and the failure area should be marked.

The visualization of the critical processes should be applied to the full range of the f(x), which links to the corresponding outputs of the function in the same Cartesian coordinate system. The curve of the physical processes, however, are determined by the related design parameters, which can be identified in the Component-model.

Substep 3) The next substep is to check if the critical processes can lead to product failures, especially under the boundary conditions, or under worst-case scenarios. Usually, product failures happen under extreme conditions, such as under high mechanical loads, at high or low temperatures, at end-of-life phase. To analyze that systematically, the sets of

- Loads profile L,

- Use environments E,
- Conditions C,
- Life time T,
- as well as ranges of the function inputs, x ∈ (x_{min}, x_{max}),

should be analyzed systematically.

After the affected functions and the critical processes are visualized in Design-Process-Function-Diagram, the worst-case scenario of the critical physical processes should be added in the diagram. The conditions of worst-cases can be low temperature, maximal loads, end of life due to fatigue, etc. They lead to a shifting of the critical processes in the diagram, which can cause failures. Figure 54 illustrates an example of the Design-Process-Function-Diagram, to demonstrate its application in an industrial practice.

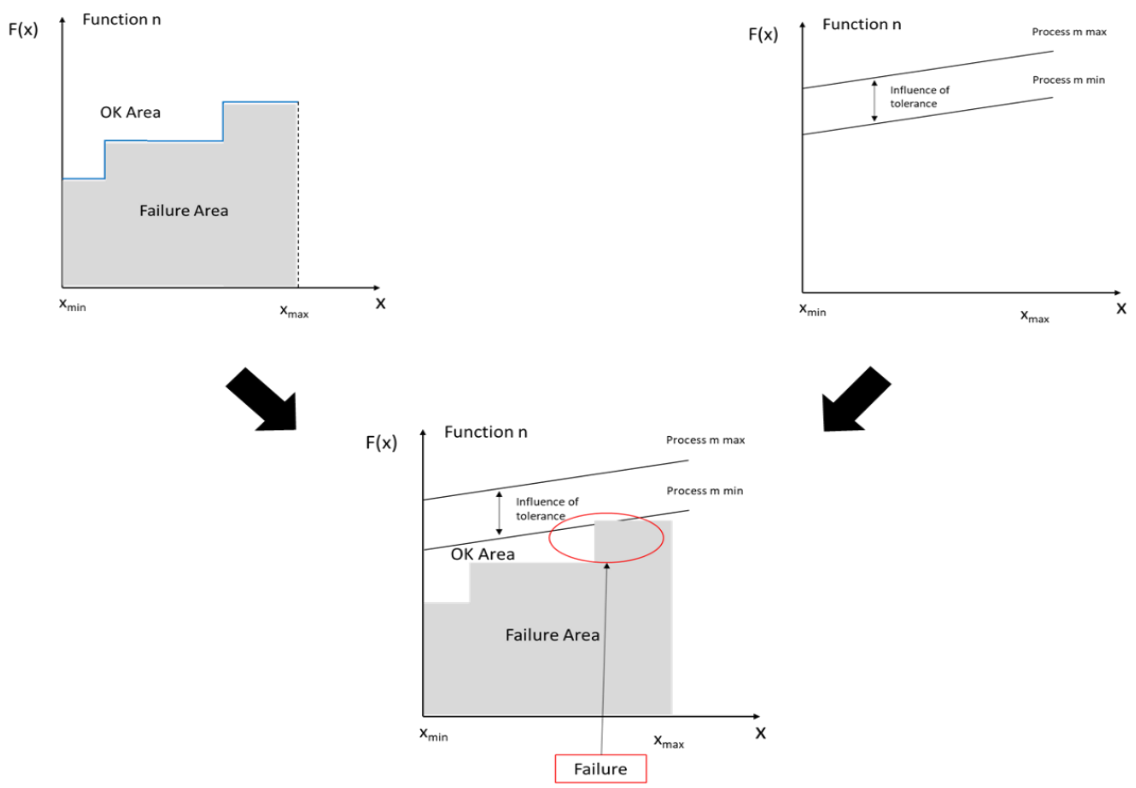


Figure 54 An example of the Design-Process-Function-Diagram

Substep 4) The visualized failure mode can be, therefore, formulated with three key elements based on Design-Process-Function-Diagram:

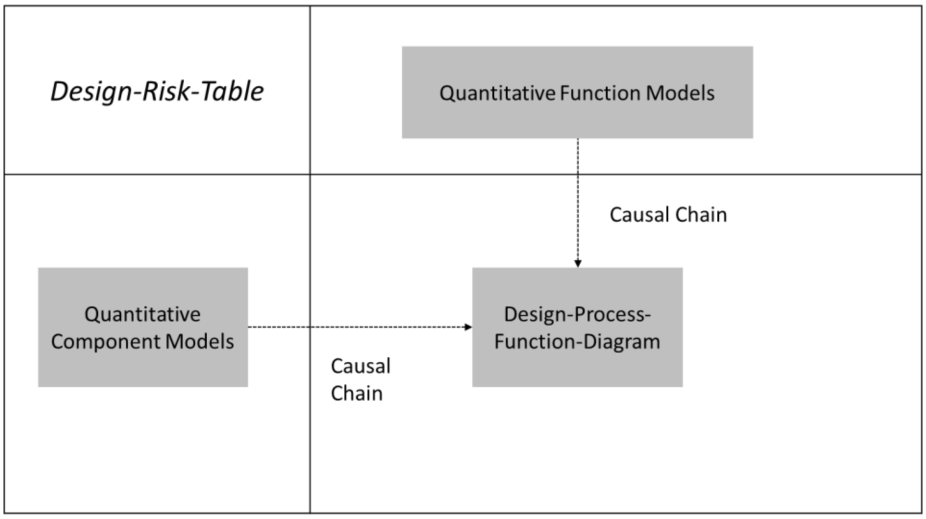
- the range of the function,
- the critical processes with different scenarios,

- and the conditions of the worst-cases [Gamweger et al. 2009].

Substep 5) The Design-Process-Function-Diagrams are then recorded in the Design-Risk-Table, as shown in Table 8, by this substep.

Based on the failure mode, a method of root-cause-analysis will be developed in the next section.

Table 8 Design-Risk-Table with Design-Process-Function-Diagram



5.2.4 Step 4: Root cause analysis

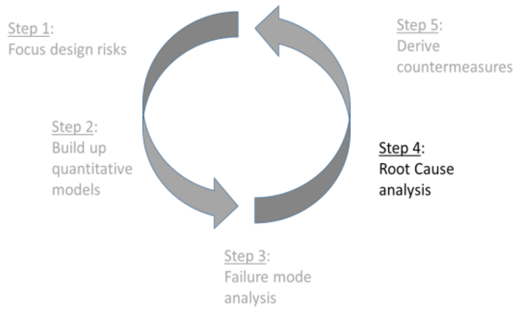


Figure Step 4

In common sense, the root cause is the initiating cause at the highest level leading to a problem [Andersen and Fagerhaug 2006]. The highest-level means that the root cause stands at the end of the causal chain to create the problem. Finding out the root causes of a failure is the prerequisite for the effective elimination of it. Root cause analysis, therefore, is widely applied during problem solving processes by product development in industry. To ensure the causality in root cause analysis of product development, however, the method should link to different level of product models. In this step, DeCoDe-model-based "5 x why" is developed to improve it of Design-FMEA.

Figure 55 illustrates the process of root cause analysis.

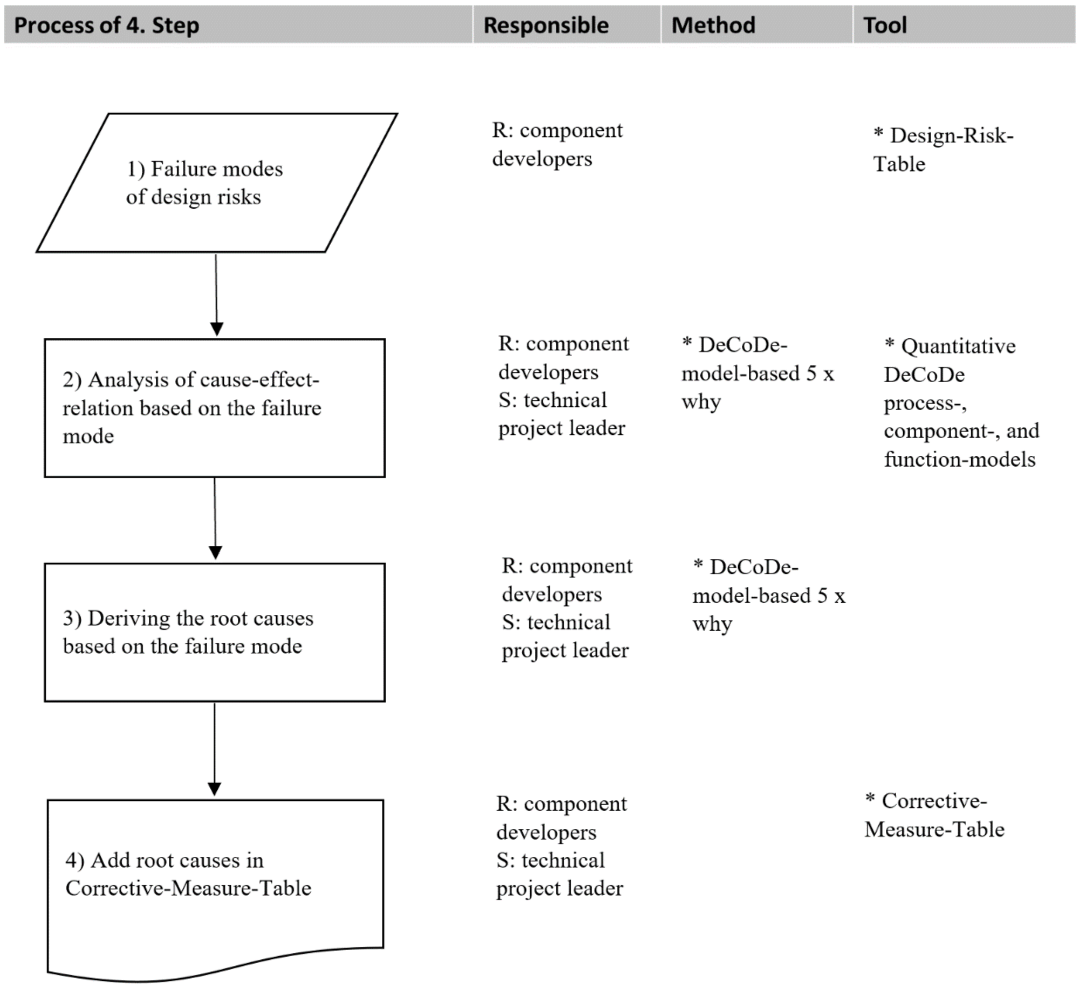


Figure 55 Process of root cause analysis

Substep 1) The failure modes and the quantitative DeCoDe-models are the inputs of root cause analysis. To conduct the effective root causes analysis, the question: "What does the root cause mean in the context of product development?" must be answered at first. Applying quantitative DeCoDe-models, this question can be answered physically: root causes are the design parameters, which lead to non-fulfilment of certain functions by product operation. As the mathematical definition of product design failure in 5.2.3 shows

$$\exists g(x) \neq y = f(x) | \; \forall x \in X, \; \forall y \in Y | p_e \in P,$$

the set $p_e \in P$ is the set of root causes of the product design failure.

Why can only those design parameters be considered as root causes, not other influencing factors in the failure modes? According to failure modes, the external factors, like extreme environment, high load, or in certain interval of life time play decisive roles in causing product failures. Why can they not be root causes?

If the requirements are all correct and accepted, the worst-case conditions, within the defined range cannot be considered as the root causes of the failure, because the product is expected to be used under those conditions. If the conditions are out of the range of requirements, then the product is misused. Therefore, even different factors can influence the physical processes leading to failures, but only the design parameters can be regarded as root causes, as Figure 56 illustrates.

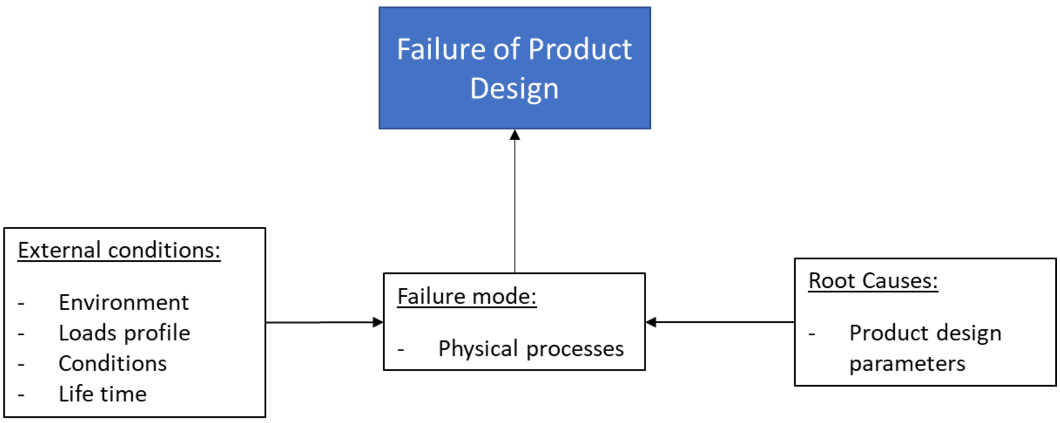


Figure 56 Causes and root causes of product design failure

Substep 2) Based on this scientific principle, the goal of this substep is to derive root causes by applying newly developed DeCoDe-Model based "5 x why".

"5 x why" developed by Sakichi Toyoda is a widely used method to derive root causes in the automotive industry. The technique of "5 x why" is to ask the question "why does the problem occur?" firstly. The answer to this question will be the next question. This procedure will be conducted interactively until the root cause is identified so that causal chains from the root causes of the problems can be built [Gamweger et al. 2009].

However, the general approach of the "5 x why" method does not provide an orientation of the "whys" for the analysis of the product design concept. If the application of "5 x why" follows common sense in the context of the product development, it could lead the root-cause-analysis in a ridiculous direction.

The problem is missing orientation by applying "5 x why". To solve this problem, a model-based "5 x why" is developed for the product development based on the DeCoDe-models. The idea is to define the domains of different levels of whys based on different DeCoDe-models. depicts the interaction between the DeCoDe-models and the "5 x why" method. The defined levels in different product-models ensure the causal chain of failure leading to the influencing design parameters, as the root causes.

Substep 3) Applying DeCoDe-model based "5 x why" in three phases:

- To formulate failures of the function,
- To analyze failure mode
- To identify influencing design parameters,

the root causes can be derived. In the practices, each phase can consist of different steps, so that the analyses aren't limited of "5 times". Figure 57 depicts the interactions between the function-, process-, and component-models and different phases of "5 x why".

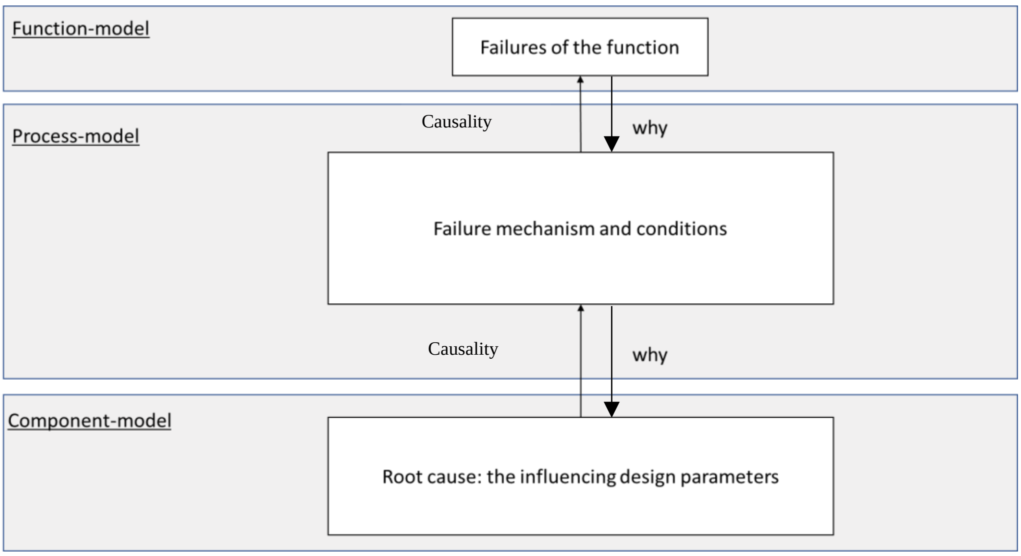


Figure 57 DeCoDe-model based "5 x why"

Substep 4) The derived root causes should be added in Corrective-Measure-Table, Table 11, which give an overview of failure modes and root causes. Based on this information, the method for deriving countermeasures can be developed in the next step.

With Step 3 and 4,

"Requirement 8: link between functions and the dedicated effects to fulfil those functions, as well as link between design parameters and the dedicated effects must be analyzed to derive failure mode."

is fulfilled.

5.2.5 Step 5: Decision of countermeasures

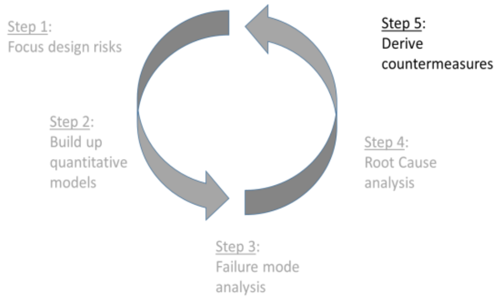


Figure Step 5

The purpose of root cause analysis is to derive effective countermeasures to eliminate failures. In industrial practice, it is important to make an optimal decision for the company among all possible choices of countermeasures. Based on best practices from the automotive industry, this step targets how the best solution of countermeasures can be made according to the competencies of engineering, purchasing and manufacturing in a project team. Figure 58 depicts the procedures of this step.

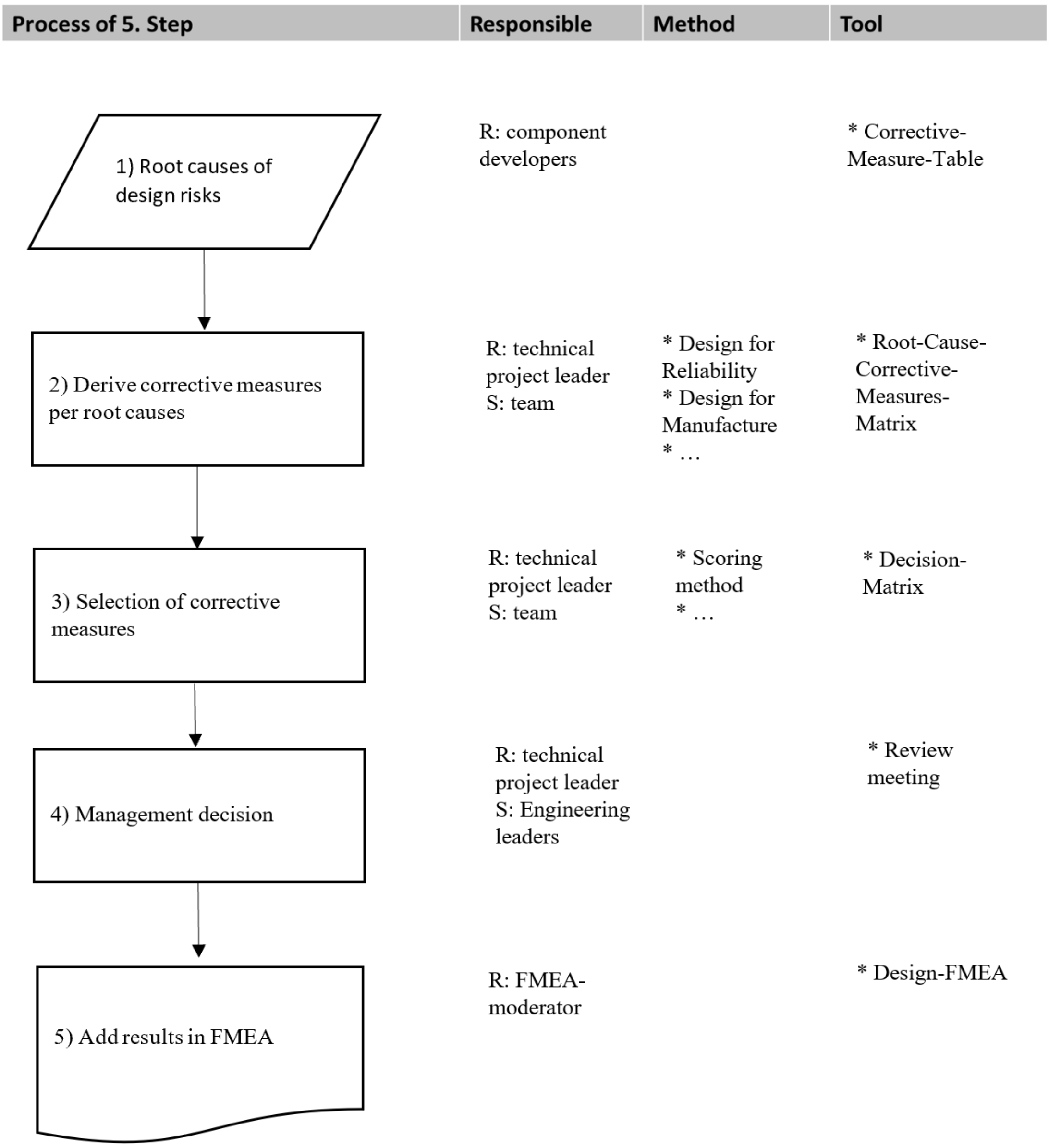


Figure 58 Process of derive countermeasures

Substep 1) The root causes from Corrective-Measure-Table are the foundations to derive possible countermeasures. The root causes should be reviewed by all competencies and responsibilities of the project team to achieve the optimal solution. One of the best practices is a workshop with all necessary roles, such as the system developer, all component developers, reliability engineer, manufacturing coordinator, purchasing engineer, organized by the technical project leader.

Substep 2) Based on the root causes, different countermeasures can be driven by applying necessary methods, such as Design for Reliability or Design for Manufacture. Besides the measures directly linked to product design parameters, the measures of manufacturing or testing can also be applied. For instance, it is possible to reduce the tolerances of components by using a machine with higher machine capability.

To give a good overview of this process, the results can be added in the Root-Cause-Corrective-Measures-Matrix, Table 9. All root causes are listed in the first row of the table and all possible measures are added in the column.

Table 9 Root-Causes-Corrective-Measures-Matrix

	Root cause 1	**Root cause 2**	**...**	**Root cause n**
1	Countermeasure 1.1	Countermeasure 2.1	...	Countermeasure n.1
2	Countermeasure 1.2	Countermeasure 2.2	...	Countermeasure n.2
...	...	...	...	...

Substep 3) To achieve an optimal countermeasure, the joint review should be made by the cross-functional team, as experience from the automotive industry shows. Engineering is responsible for the effectivity of the measure, whereas manufacturing should check their technical feasibility, and purchasing should communicate with suppliers, if they are also involved. Project controlling is, in some cases, important for evaluating the finical efforts of different countermeasures.

Typically, the review meeting is conducted by technical discussions. To ensure a systematic decision-making process, serval methods can be applied, such as SWOT-Analysis or Chance-Risk-Analysis [Pfeifer and Schmitt 2014].

The Scoring-Method can be applied as a quantitative approach to simplify technical discussion in this thesis [Eisenführ et al. 2010]. One of the key elements in conducting the Scoring-Method successfully is to define goal-oriented criteria [Pfeifer and Schmitt 2014]. For instance, engineering ranks different measure according to their effectivities; manufacturing follows the feasibilities, purchasing evaluates the acceptances of suppliers, and the controlling checks their costs for the project. The Decision-Matrix-of-Countermeasures can be used to document the results, as Table 10 shows. The value "1" means the best measure according to the defined criteria for one role, "2" means the second-best measure, and so on. According to totally ranking result, the suggestion of the best measures can be derived.

Table 10 Decision-Matrix-of-Countermeasures

Criterion / Measures	**Manufacture**	**Engineering**	**Purchasing**	**Controlling**	**Ranking**
Measure 1	2	3	1	1	2
Measure 2	1	2	4	3	3
...	...	...	...	...	...

Best solution — Worst solution

1	2	3	4	5

Substep 4) The final decision should be made by a review meeting with the managers and the development team together among the best solutions. The reason is that a decision may affect not only one project, but also play a role for the overall business of the company, for example, an extension of existing product modules. The managers of engineering, manufacturing or purchasing jointly with the project leader should bear the responsibility of the final decision.

Substep 5) After the definition of the countermeasures, the validations should be derived to ensure the effectiveness of the measures and to identify the unknown side effects. The common methods of the validation depending on the measures can be function test, simulation, endurance test, machining trial, etc. The Corrective-Measure-Table can be applied to document the results of the analysis, and to make a review for the management board. As Table 11 shows, it includes the failure mode, root causes, countermeasures, and the validation results. After the conduction of the validations, the results can be documented in the FMEA-sheet.

Table 11 Corrective-Measure-Table

Failure Mode	Root Cause Analysis	Counter Measures	Validation
- Effected functions (Function-Model) - Conditions of failures (Function- and Process-Model) - Possible use scenarios of failures conditions (Process-Model) - Effects of product functions (Process- and Function-Model)	- DeCoDe-based 5 x why - Causal chain from design parameters to the failure (Function-, Process- and Component-Model)	- Finding all design parameters which can affect failures in failure models (Component-, Process- and Function-Model) - Finding other measures to find or eliminate failures (Requirement-, Component-, Process and Function-Model)	- Define evaluations of counter measures (via effect, effort and cost) - Define tests, simulation, DOE or other measures to validate the selected measure

With Step 5,

“Requirement 11: method to ensure the causal chain between countermeasures and root causes should be developed.”

and “Requirement 12: a tool to enable the cross-functional development team to select the optimal countermeasure should be developed.”

are fulfilled.

5.3 Summary

The goal of the development of a new approach is to ensure causality by applying Design-FMEA to eliminate potential design failures. The key element to solve the problem is to use physical cause-effect-relationship, which is essential approach of modern product development [Feldhusen and Grote 2013]. To implement this principle, GSE, especially the DeCoDe-modeling, is applied to develop the new approach. Figure 59 summaries five steps of the new approach and methods and tools, which can be applied by different steps.

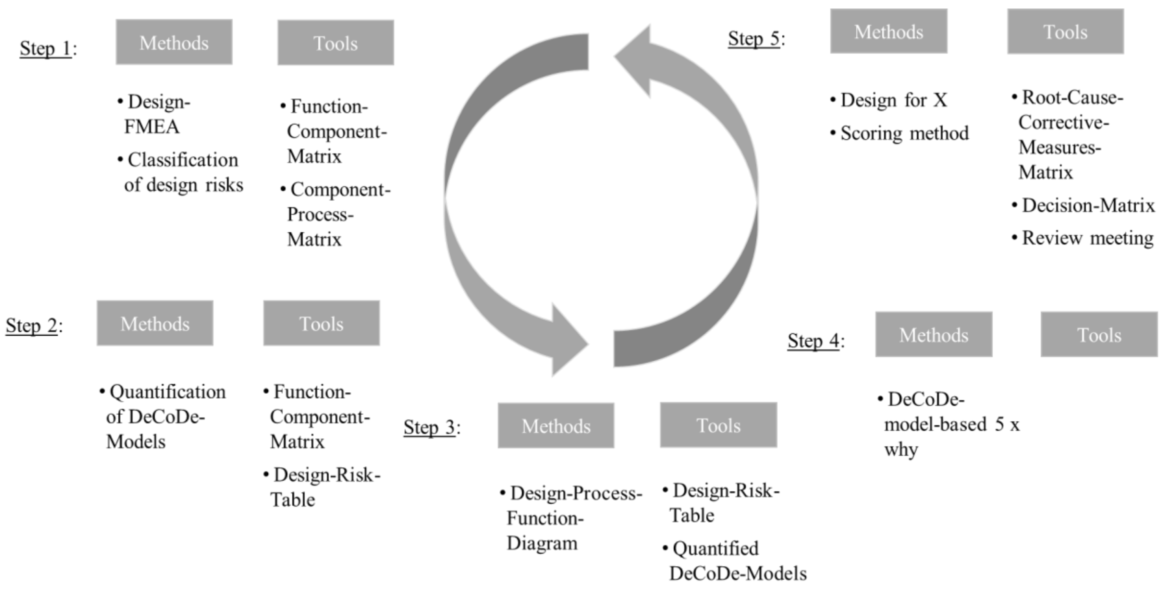


Figure 59 Overview of the new approach with the details of methods and tools for every step

The new approach integrated in the established Design-FMEA concludes following five steps:

Step 1 Focus design risks;

Step 2 Buildup quantitative models;

Step 3 Failure mode analysis;

Step 4 Root cause analysis;

Step 5 Derive countermeasures.

Figure 60 shows the combination of the new approach and Design-FMEA including the inputs and outputs of every single step.

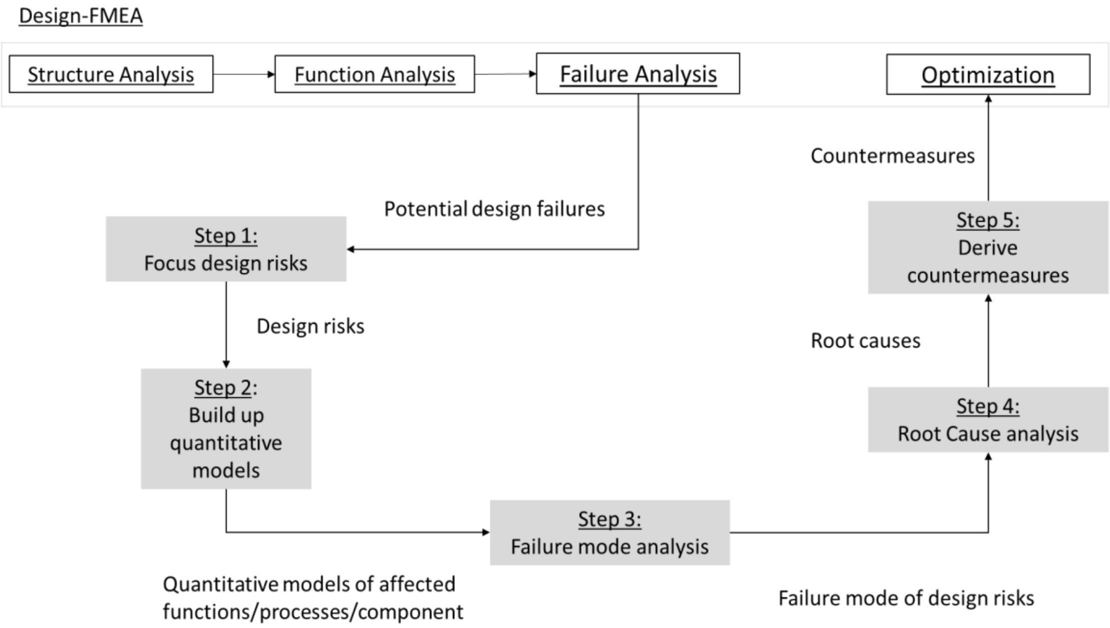


Figure 60 The combination of the new approach and Design-FMEA

With these steps, the new approach fulfills the specific requirements of the quality assurance methods, which is developed at the beginning of this chapter. Table 12 shows the fulfillment with the different steps of the new approach.

Table 12 Fulfillment of the specific requirements of new approach

Requirements \ Steps	Step 1: Focus design risks	Step 2: Build up quantitative models	Step 3: Failure mode analysis	Step 4: Root Cause analysis	Step 5: Derive countermeasures
Requirement 7: Model of physical effects		Fulfilled			
Requirement 8: Link between physical effects and functions			Fulfilled		
Requirement 9: Quantification of produce models		Fulfilled			
Requirement 10: Focusing analysis	Fulfilled				
Requirement 11: Causal analysis					Fulfilled
Requirement 12: Enable cross-functional collaboration					Fulfilled

Combined with the established Design-FMEA, the new approach can ensure systematic derivation of root causes, and enable cross-functional collaboration in product development teams, significantly. The new approach is implemented as a standard by applying Design-FMEA in a leading supplier of the automotive industry, two case studies are chosen to show the improvement of Design-FMEA in the conception phase in the next chapter.

6 Validation of the New Approach in Design-FMEA

FMEA is the standard method of the German automotive industry for product development and production [VDA Band 4:2012]. As the responsible manager for the development methods and the coach of the engineering team in a division of an automotive supplier, the author can implement the newly developed approach within Design-FMEA of different development projects. To ensure the effectiveness of the implementation, the worldwide engineering leaders and development teams are trained in the new approach before the ramp-up.

Two cases are chosen to be introduced in this thesis to present the application of the new approach by two product developments. With these case studies, the applicability of the approach and the improvement of Design-FMEA are validated. Considering the protection of technical data, the unnecessary technical details which play no roles in showing the validation of the methods are blanked out.

In the next sections, the application of the new approach for the throttle positioner of electronic gas control for modern gasoline engine management, and for the screw sleeve joint of a new generation of alternator for hybrid vehicles are presented.

6.1 Throttle Positioner of Electronic Gas Control

Gasoline engines are the engines most commonly fitted to modern motor vehicles. It burns a mixture of gasoline and air to transfer chemical energy to kinetic energy to drive vehicles. The precise mixture of gasoline and air plays an essential role in the output torque and the emission of exhaust-gas, e.g., CO_2, which is an important factor leading to global warming.

To comply with the growing legislation governing exhaust-gas emission limits and to increase the efficiency of the fuel consumption, the fuel injection technique is widely used to replace the carburetor for the fuel supplement. Electronic throttle control (ETC) is used to control the throttle-valve for the fuel injection.

Figure 61 [Reif 2015b] illustrates the structure and the operating principle of ETC. If drivers press the accelerator-pedal, the travel distance of the pedal will be measured by a position sensor (Pos. 1). This signal will be sent to the Engine ECU (Pos. 2). According to this signal and the signal of the throttle valve (Pos. 5) position, which is measured by the throttle-valve-angle sensor (Pos. 3), the Engine ECU calculates the actuation signal to the throttle-valve drive system (Pos. 4) to open or to close the throttle valve to a certain degree.

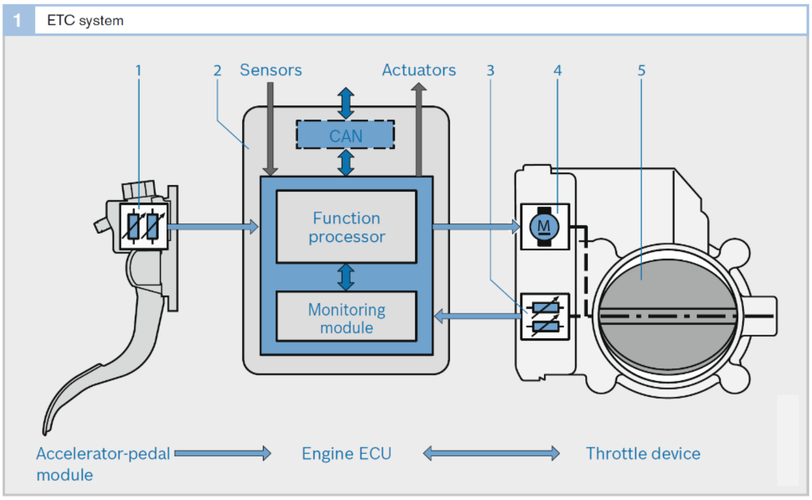


Figure 61 Electronic throttle control system [Reif 2015b]

The throttle-valve drive system includes a throttle-plate and a throttle-positioner. The throttle-positioner consists of a servo motor and the transmission unit. The task of the throttle positioner is to drive the throttle plate to the defined opening angle based on the signal from the engine ECU, and the task of the transmission unit is to transfer the rotating power from the servo motor throttle plate and to reduce the rotating speed, as Figure 62 depicts.

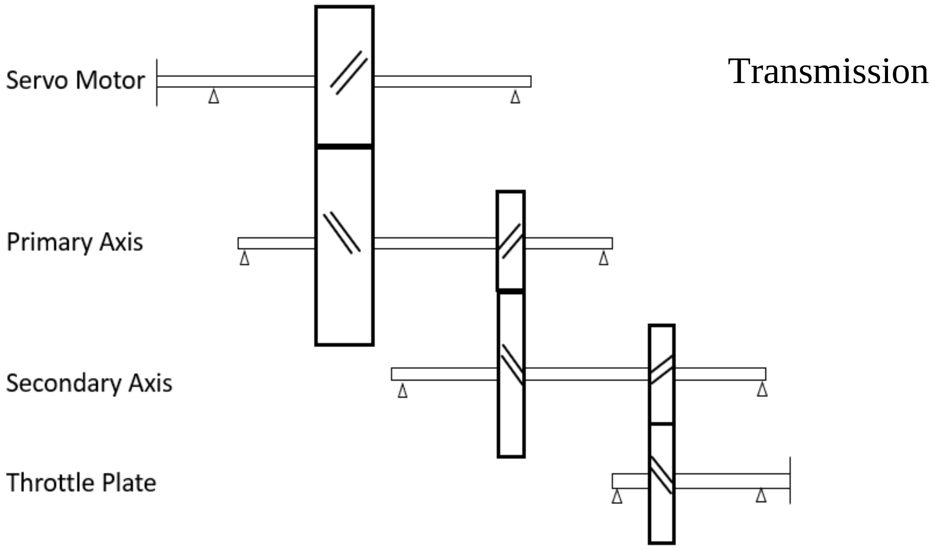


Figure 62 Structure of transmission of throttle-positioner

Based on the analyses of the Design-FMEA [VDA Band 4:2012], the new approach is applied to analyze the failure mode, the root causes and to derive the countermeasures. The case serves as training material for development teams worldwide in the abovementioned company.

6.1.1 Step 1: Focus design risks

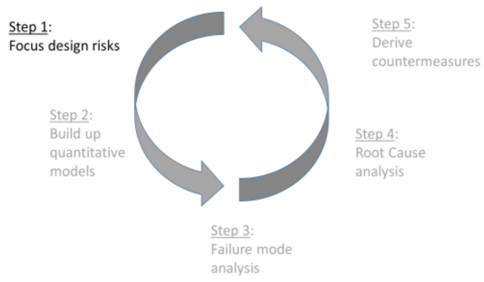


Figure Step 1

Substep 1) Based on the structural analysis and the function analysis of Design-FMEA, Figure 63, the team identified different design risks according to the experiences of former generation and tests of samples:

- Primary gear: Jams on the primary gear axis,
- Primary gear: Breaks of gear axis,
- Primary gear: Jams on the bearing in the housing.

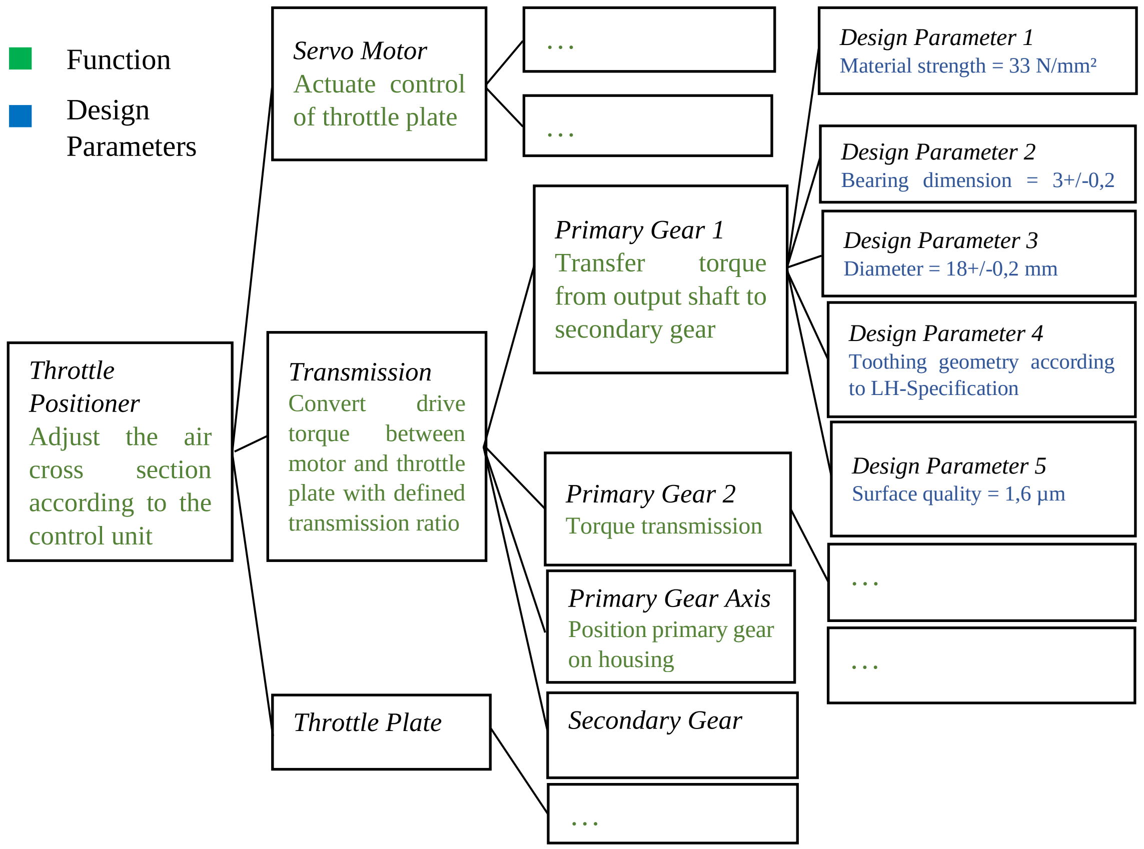


Figure 63 Function analysis of Design-FMEA for throttle positioner of an E-Gas-System based on VDA [VDA Band 4:2012]

Substep 2) Among those design risks, "Jams on the primary gear axis" and "Jams on the bearing position in the housing" are already validated by endurance tests of the former generation. By comparing requirements of old and new generations, the team identified those two risks as not critical: if jams or break of the transmission happen, the servo motor can detect the drop or increase of the torque to protect itself. The function of the position sensor is not affected by the potential failures. The gears, the housing and the bearings are holdovers from the product of the former generation, which have no design failures identified in operations during years.

The primary and the secondary axis are newly designed based on the last generation, whereby the secondary axis has a very high safety factor relating to the external loads profile and the dimension of the gear axis. The calculation, the simulation of Finite-Element-Method, as well as function tests confirm the assumption. Therefore, the focus of further analysis is the primary gear axis. Figure 64 depicts the failure effect of throttle positioner due to the failure "Breaks of gear axis".

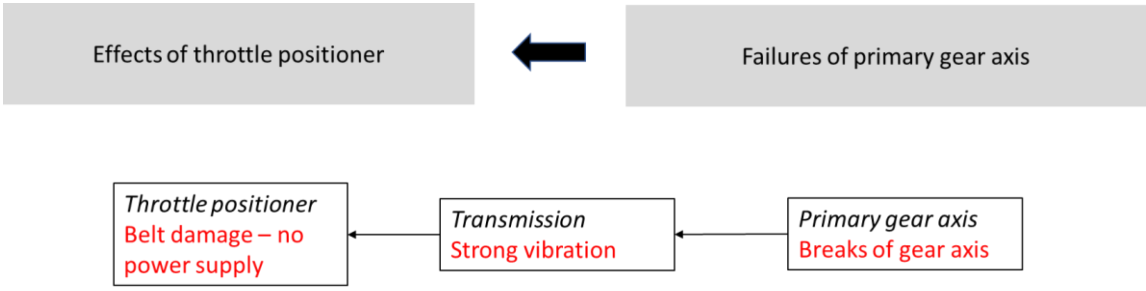


Figure 64 Focus of design risks based on the failure analysis of Design-FMEA

To identify the affected functions and components, the Function-Component-Matrix is applied by the team. The throttle positioner can be treated as a system with three different sub-systems:

- Servo motor,
- Transmission,
- Position sensor.

The sub-systems have different functions, which can be deployed from the system function, as Figure 65 shows. Adding functions of sub-systems and components, the Function-Component-Matrix can build in Table 13. The risk evaluation of the functions and the components are marked for transmission function and all components of transmission in the Function-Component-Matrix. Due to the known cause-effect relationship of other components, only primary gear axis is focused for the further analysis in Table 13.

After setting the focuses of transmission function and primary gear axis, the responsible developers analyzed all physical effects of primary gear axis. The result is documented and evaluated in Table 14. The criterion of the evaluation is whether they are critical to fulfilling the function or not. Among these processes, the understood or validated ones are marked with green and the not understood and validated ones are marked with red.

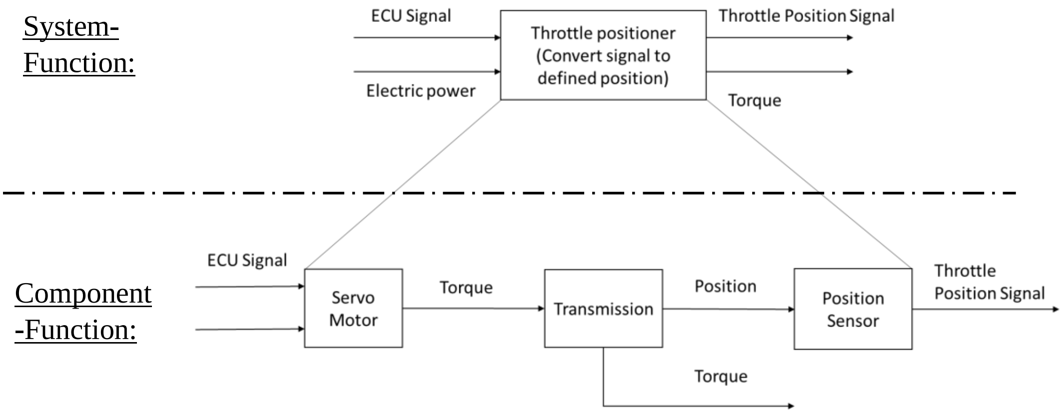


Figure 65 Black-box model of functions for the throttle positioner and its components

Table 13 The Function-Component-Matrix of the throttle positioner with risk evaluation

Components / Functions	Servo motor	Primary gear	Primary gear axis	Secondary gear	Secondary gear axis	Bearing	Position sensor	Housing	Plug
ECU Signal, Electric power → Servo Motor → Torque	X	X	X	X	X	X		X	X
Torque → Transmission → Position, Torque	X	X	X	X	X	X		X	X
Position → Position Sensor → Throttle Position Signal							X	X	

■ Design risks ■ Understood causality

Table 14 The DeCoDe Component-Process-Matrix of Primary Gear Axis

Physical effects (processes) \ Components	Primary Gear Axis
Bending effects after assembling	Critical
Mechanical power transmission	Not critical
Thermal effects by temperature changing	Critical
Fatigue effects	Critical
Wear out effects of connect surfaces	Not critical
Corrosion effects	Not critical

■ Critical processes ■ Uncritical processes

The bending effects after assembling cause the increasing stress, especially, in shafts. According to the experiences of former generation, the increasing stress can lead to failure during operation. The mechanical power transmission process is not critical due to the mechanical model and the results of Finite-Element-Method. Other critical processes are the thermal effects of temperature changes in combination with the fatigue effects of the gear axis due to the temperature requirement -20°C to 105°C, as well as the 10^8 load cycles of the life. Both effects are critical for the former generation. The wear-out effects and the corrosion effects are not critical according to the experience of the former gear axis design, and the new functional requirements.

Substep 3) The results of focus analysis are, therefore documented in the DeCoDe Function-Component-Matrix, Table 13, with the focus function “transmission” and the focus design “primary gear axis”, as well as in the DeCoDe Component-Process-Matrix, Table 14, with critical processes “thermal effects” and “fatigue effects”.

6.1.2 Step 2: Build quantitative DeCoDe-models

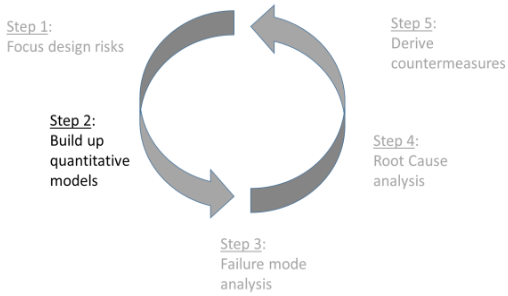


Figure Step 2

Substep 1) The DeCoDe Matrices, which include the design risks and the critical processes are discussed by the team. The component designers received the tasks to quantify the models of focus functions and design parameters, as well as the critical processes.

Substep 2) According to the defined models, the designers quantified the functions, the product designs and the physical processes supported by the product experts.

1) Function-model

Based on the function analysis of the Design-FMEA and the functional requirements, the five elements of the transmission function are derived:

- Corresponding rule:

  Convert torque with given ratio with

$$M_{out} = M_{in} \text{ x } R, -M_{in\_max} < M_{in} < +M_{in\_max},$$

$$\text{Input torque } M_{in},$$

  Output torque M_{out}, with

$$-M_{in\_max} < M_{in} < +M_{in\_max},$$

  Gear transmission ratio R,

$$N_{ot} = N_{in} / R, -N_{in\_max} < N_{in} < +N_{in\_max}$$

  Speed of revolution N.

Figure 66 illustrates the corresponding rule between the input torque M_{in} and the output torque M_{out} with the domain of the both parameters.

- Loads profile

The loads profile is not included in the document of the Design-FMEA. Even though the loads profile should be one part of the technical requirements from the customer [Gamweger et al. 2009], it is often not the case in industrial practice. If the loads profile for the function is unknown, it can be measured or be derived from different use cases of the gearbox, to get the torque amplitudes and their frequency over the lifetime.

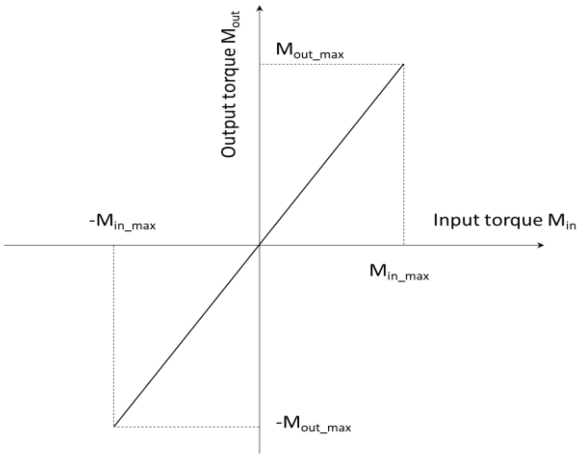


Figure 66 Corresponding rule of the transmission function

Figure 67 depicts the load profile of the gearbox derived from the worst-case scenario of the normal driver behaviors. It means a typical mixture of highways, country roads and city streets,

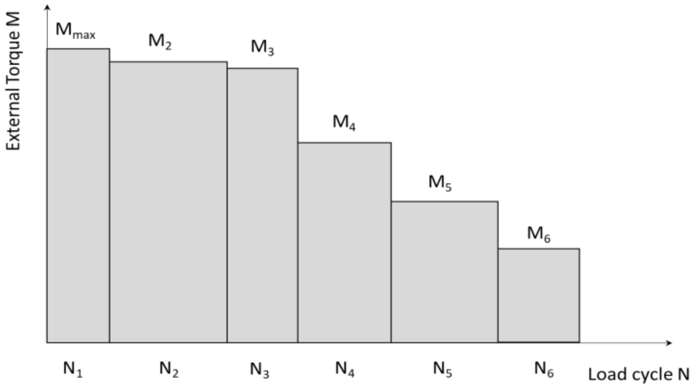


Figure 67 The loads profile of the gear box

which covers 80% of all drivers in Germany over 15 years or 300,000 km.

- Conditions

The gasoline engine, the housing of the throttle positioner, the servo motor, etc. are the peripheral conditions defined in advance. This information is not documented in the Design-FMEA either. Among that information, the vibration of the gasoline engine with 50 G-force of three directions, defined by ISO 16750, is important for the gearbox function model [ISO 16750-3:2012].

- Use environment

The typical environment of the road vehicle components, which are agreed with the customers:

- Temperature -20°C to + 105°C,
- Humidity 0-100%.

- Lifetime

The typical lifetime of the road vehicle is 15 years or 300.000 km. For the throttle positioner, the lifetime is

$n = 10^8$ cycles,

with the worst-case scenario to cover 80% drivers in Germany.

- Process-model

1) Thermal expansion effect

Because of the high-temperature range of the operation, the expansion of the gear axis in the axial direction leads to high thermal stress of the material. Regarding the coefficient of linear expansion α, and with the assumption the thermal expansions in the axial direction of the housing and the bearing are ignorable, the relation between the thermal stress and the temperature of the gear axis is illustrated in Figure 68. If there is no thermal stress in the primary gear axis in the assembly, then the thermal stress increases with increasing temperature during the operation, and vice versa.

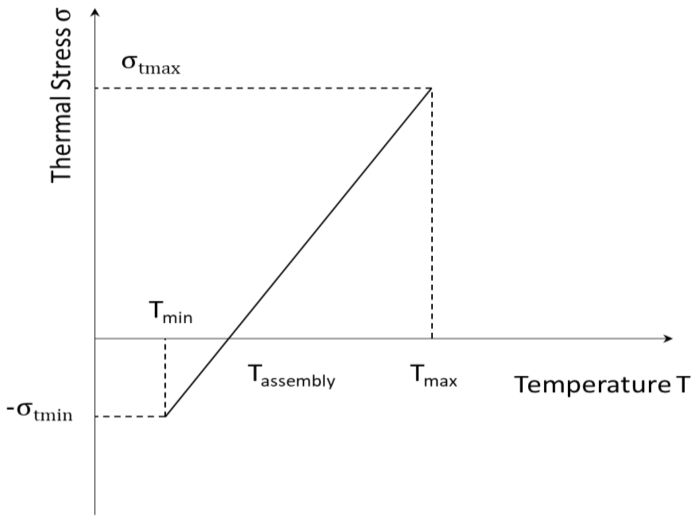


Figure 68 The thermal stress in the primary gear axis

2) Fatigue effects of the primary gear axis material

Because of the high load cycles over the lifetime, the fatigue effects of the material play an important role in the function fulfilment. The Smith diagram indicates the permanent strength area of torsion, of tension and pressure, as well as of bending. Because the loads of the primary gear axis are combined with bending, tension and torsion, the Gough-Ellipse of the material reliability is applied, as a conservative approximation, to define the permeant strength area of the primary gear axis [Schlottmann and Schnegas 2016]. Figure 69 depicts the Smith diagram as well as the Ellipse of material reliability.

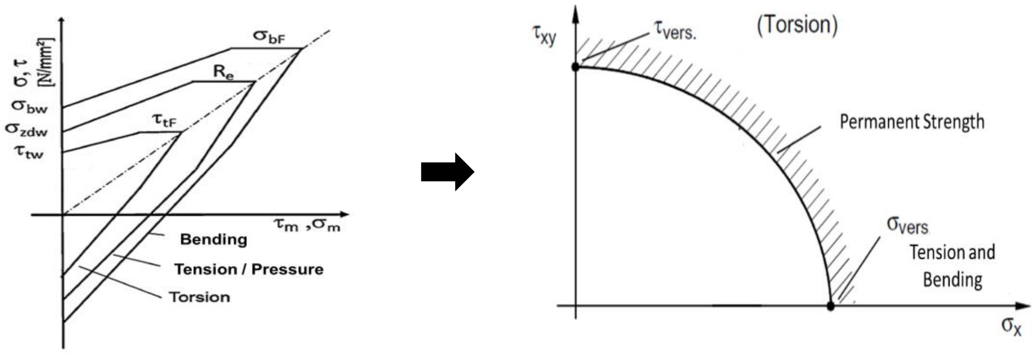


Figure 69 The Smith diagram and the Ellipse of material reliability for the primary gear axis material

3) Bending effects

The contacts of the tooth cause the bending force of the axis in the gearbox. The torque transmission generates the torsion stress in the axis, as well. Therefore, the stresses in the primary axis are the combination of bending and torsion stresses. Figure 70 illustrates the bending and torsion stress combination of the servo motor axis and primary axis. The developers applied a test with limit samples to measure the maximal bending stress. The limit samples are built with the components on the tolerances limits to measure the maximal bending stress after assembly. The maximal bending stress after assembly according to the limit samples is σ_{ben}.

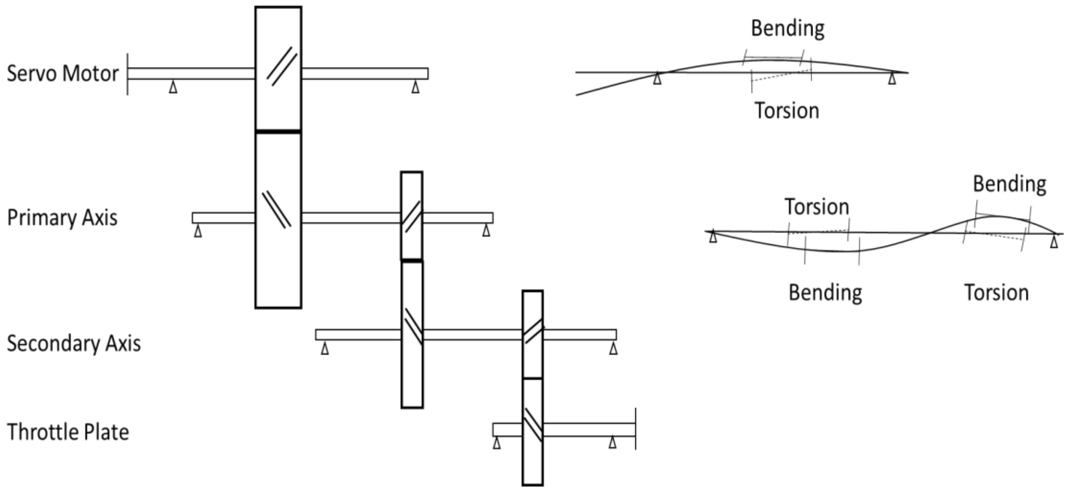


Figure 70 The stress model of the primary axis by operation

- Component model

Figure 63 depicts the structure of components of the primary gear axis. The design parameters, like material strength and the diameter of the primary gear axis, are listed in the structure. Furthermore, some material characteristics play an essential role in the fulfillment of functions, which are not mentioned in the conventional Design-FMEA. After analyzing all design parameters and material characteristics, the development team lists the effected parameters related to the fulfillment of the gearbox function in Table 15. An important assumption is the normal distribution of material with limits of both ends, as Figure 71 depicts.

Table 15 The design parameters and material characteristics of the primary gear axis

Component	**Design parameters**
Primary Gear Axis	Dimensions **{p}**
	Roughness of surface **{R}**
	Chemical Composition **{C}**
	Modulus of Elasticity **E**
	Ultimate Strength $\mathbf{R_m}$
	Yield Strength $\mathbf{R_e}$
	Fatigue Limit Tension and Bending **σ**
	Fatigue Limit Torsion **τ**
	Coefficient of Linear Thermal Expansion **α**
	Distribution of strength
	...

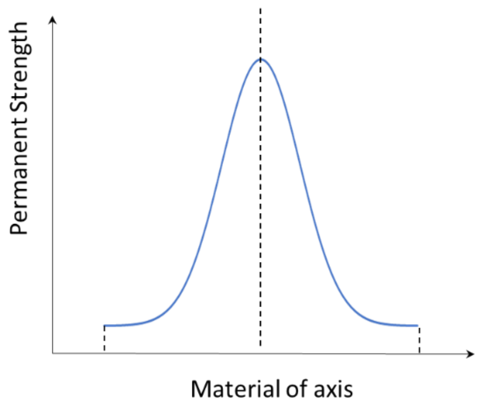
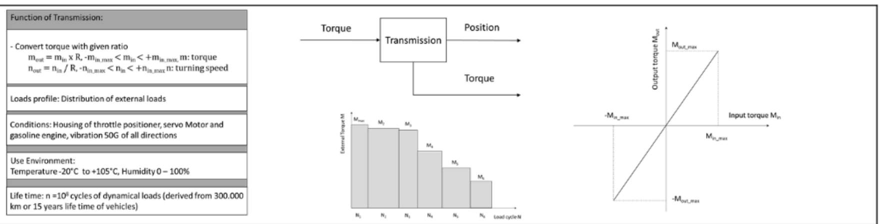
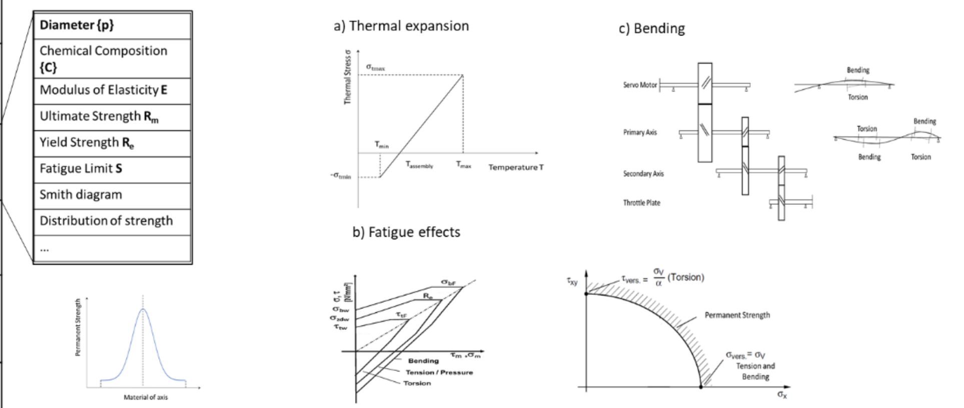


Figure 71 Distribution of the primary axis material

Substep 3) The quantitative DeCoDe-models are added in the Design-Risk-Table, Table 16, which is the central document of failure mode analysis. With the quantified DeCoDe-Model as the inputs, the failure mode will be derived in the next section by analyzing the causal relationship between the design parameters and the physical processes related to the primary gear axis.

Table 16 The Design-Risk-Table with quantitative DeCoDe-models

Design-Risk-Table	
Servo Motor	
Primary gear	
Primary gear axis	
Secondary gear	
Secondary gear axis	
Bearing	
Plug	
Position sensor	

6.1.3 Step 3: Failure mode analysis

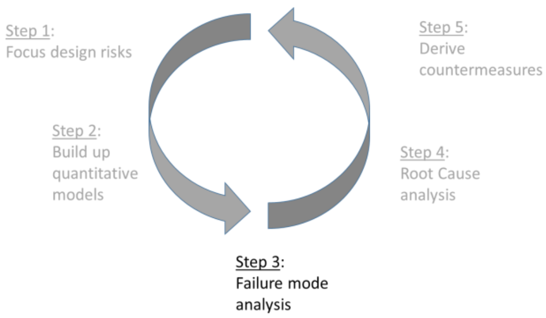


Figure Step 3

Substep 1) After the quantification of function-, process-, and component-models in the Design-Risk-Table, the component developer started to derive the Design-Process-Function Diagram to analyze the failure mode supported by the reliability engineer.

Substep 2) Based on the preliminary analysis, the biggest concern of the transmission function with the failure "breaks of gear axis" is the combination of bending, torsion and tension stress under the defined design parameters.

The task is to visualize the effects combination in a Design-Process-Function Diagram.

- Bending after assembly

The bending effects after assembly lead to bending stress of the primary gear axis. The maximum of bending stress can be marked in the Design-Process-Function-Diagram, Figure 72, with 1. Working point.

- Transmission function

Figure 72 depicts that the range of torsion of the primary gear axis in depending of loads profile of the transmission. The loads profile and the range of the input and output torque are also considered in the calculation. The torsion of the axis is proportional to the input of mechanical torque. The maximal torsion stress is τ_{max}, which is marked as the 2. Working point in Figure 73.

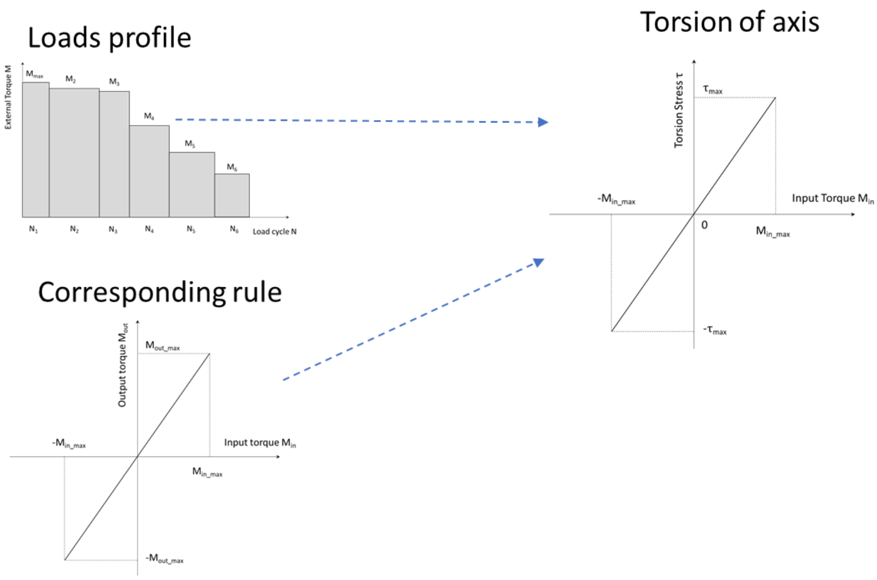


Figure 72 Torsion of the primary gear axis due to mechanical transmission

- Thermal effects

As already in Figure 68 depicted, the tension stress of thermal effects is proportional to temperature, and the maximal thermal tension stress is σ_{tmax}. It is marked as the Working point 3.

- Distribution of material

According to the Figure 71, the minimal torsion permanent strength and the minimal tension and bending strength should shrift to the Working point 4 in Figure 73.

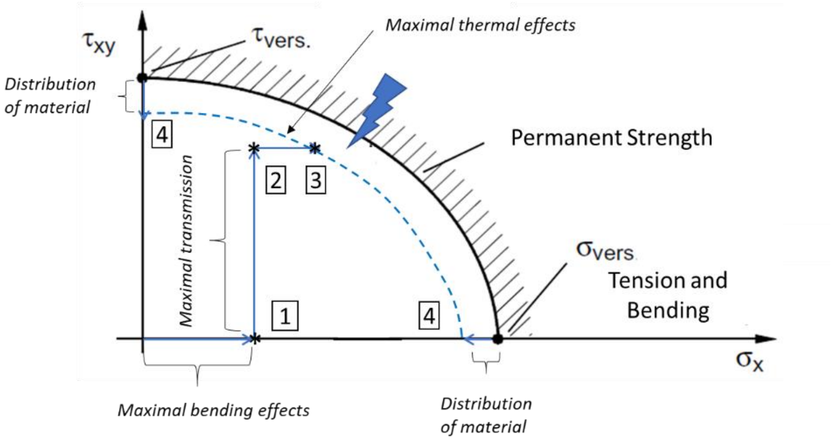


Figure 73 The Design-Process-Function-Diagram of "break of gear axis"

Substep 3) Summarizing all influencing factors, the potential failure of the product design concept can be derived: The combination of tension/bending and torsion stress on the primary gear axis (σ, τ) exceeds the limit of permanent strength of the material, as Figure 73 depicts.

Substep 4) The potential failure is that a certain percentage of primary axes break within the lifetime, i.e., 10^8 loads cycles, as Figure 74 depicts. The failure rate is estimated according the material distribution, the loads profile, the machine capability for the tolerance distribution, and ambient temperature by operations.

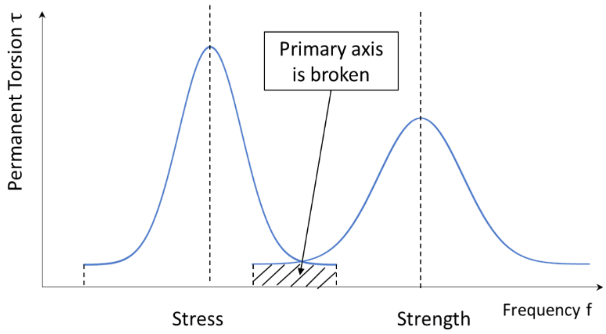
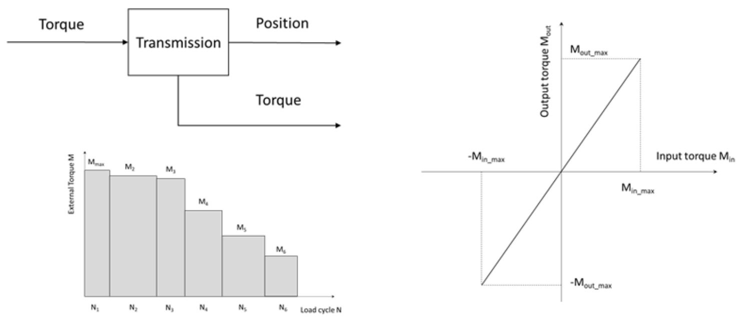
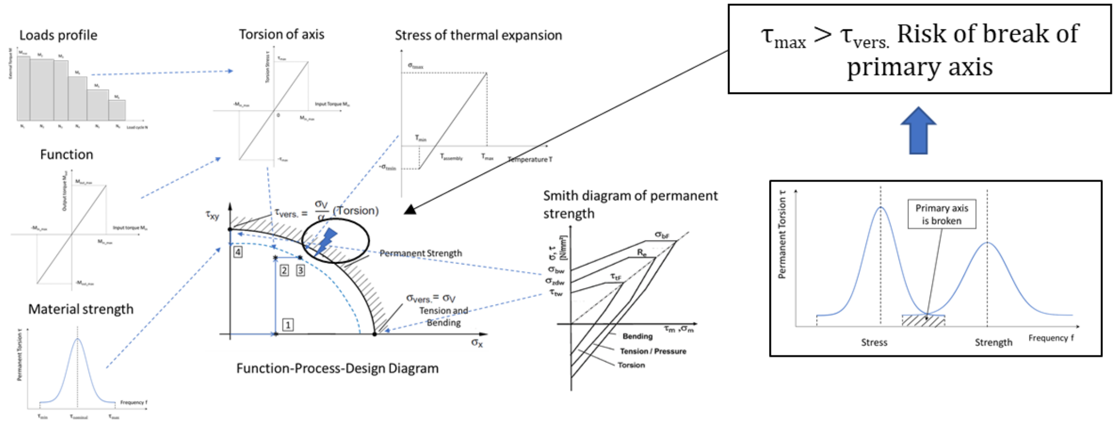


Figure 74 The potential concept failure of the primary gear axis

Substep 5) The responsible developer created the Design-Risk-Table, as shown in Table 17, which includes all information of the analysis, to prepare a review with the development team and the engineering managers to derive the root causes.

Table 17 The Design-Risk-Table of throttle positioner

Design-Risk-Table	Function of Transmission: - Convert torque with given ratio $m_{out} = m_{in} \times R$, $-m_{in\_max} < m_{in} < +m_{in\_max}$ m: torque $n_{out} = n_{in} / R$, $-n_{in\_max} < n_{in} < +n_{in\_max}$ n: turning speed Loads profile: Distribution of external loads Conditions: Housing of throttle positioner, servo Motor and gasoline engine, vibration 50G of all directions Use Environment: Temperature -20°C to +105°C, Humidity 0 – 100% Life time: n =10[8] cycles of dynamical loads (derived from 300.000 km or 15 years life time of vehicles) 
Servo Motor	**Diameter {p}** Chemical Composition {C} Modulus of Elasticity **E** Ultimate Strength $\mathbf{R_m}$ Yield Strength $\mathbf{R_e}$ Fatigue Limit **S** Smith diagram Distribution of strength ...  1 Bending stress due to position 2 Torsion stress due to the torque 3 Thermal stress due to the temperature 4 Change of permanent strength due to material quality
Primary gear	
Primary gear axis	
Secondary gear	
Secondary gear axis	
Bearing	
Plug	
Position sensor	

6.1.4 Step 4: Root cause analysis

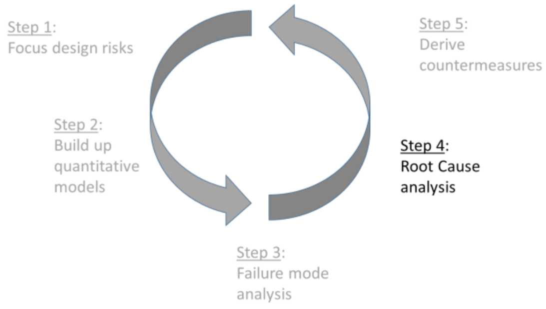


Figure Step 4

Substep 1) Based on the failure mode, the root causes of the failure are analyzed by applying DeCoDe-model-based "5 x why". The root causes are according to the causality between the function-, the process- and the component-models of the primary gear axis in the Design-Risk-Table, Table 17.

Substep 2) The failure, "primary gear axis breaks during operation" is the starting point of the analysis. The second step is to derive the physical causes of the failure. According to the theory of mechanical reliability, the reason for the mechanical failure is that the local stress exceeds the strength of the material, as shown in Figure 75.

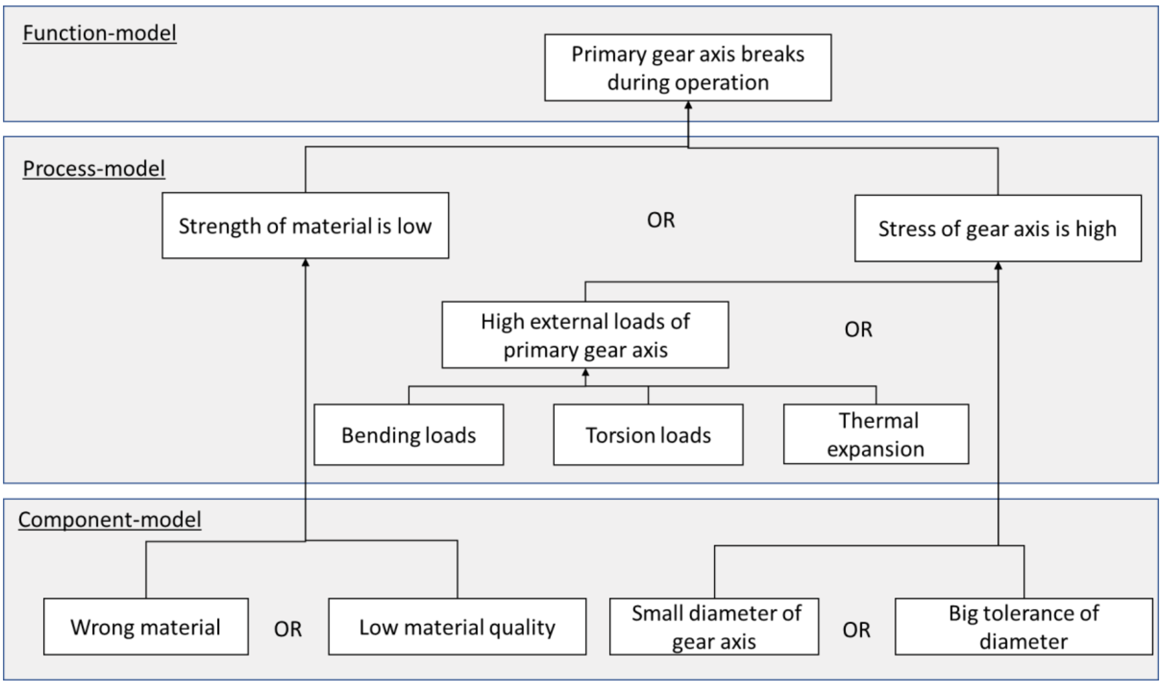


Figure 75 The DeCoDe-model-based "5 x why"

The causes of low material strength are either the wrong material or low material quality. The first case means that the nominal or the mean value of the strength distribution curve is too low. It is a problem with the characteristic of the chosen material. The second case means, on the contrary, the large variance of the strength curve. The problem can be the low quality of the manufacturing process of the material.

The local normal and shear stresses, σ, τ of the primary gear axis are determined by the normal force, F_n, the sheer force, F_s and the cross-sectional area, A with

$$\sigma = \frac{F_n}{A} \text{ and } \tau = \frac{F_s}{A}$$

Therefore, the reasons for the high local stress are high loads or small cross-section.

The bending, torsion and thermal expansion due to the large operation temperature range are also the reasons for the high loads. However, the range of the operation temperature are the given environment condition of the transmission function. While the small mean value or big tolerance of the gear axis diameter are the design parameters, which can be modified. And the material of the primary axis is also design parameter.

Substep 3) The possible root causes of the failure are, after applying the DeCoDe-model-based "5 x why",

- wrong material,
- low material quality,
- the small diameter of the gear axis,
- big tolerance of gear axis diameter.

With the identified root causes, countermeasures are derived by the cross-functional development team.

Substep 4) The derived root causes are added in the Corrective-Measure-Table, Table 20, which gives an overview of failure modes and root causes. Based on this information, the countermeasures can be derived at Step 5.

6.1.5 Step 5: Decision of countermeasures

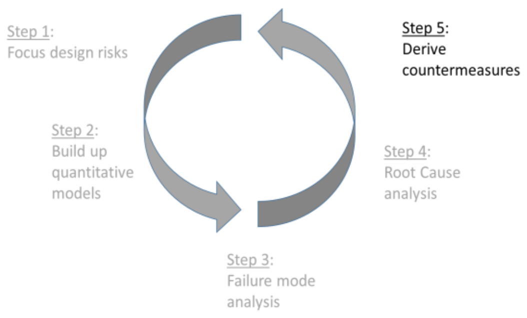


Figure Step 5

Substep 1) Based on the root causes, the project team organized a workshop with different roles to derive the possible countermeasures.

Substep 2) Increasing the material strength by heat treatment or by replacing with material of higher strength leads to the right shifting the strength curve, so that the overlap of the stress- and strength-curves can be eliminated, as depicted in Figure 76.

Another measure is to increase the diameter of the primary gear axis to reduce the local stress. This measure leads to a left shifting the stress curve so that the overlap of the stress- and strength-curve can be avoided as well, as Figure 77 illustrates.

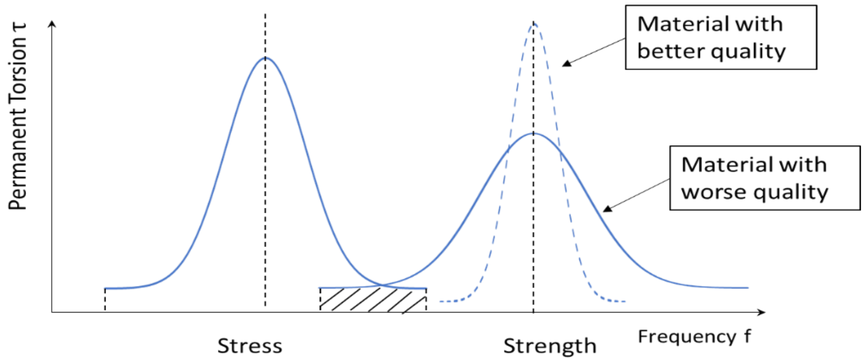


Figure 76 Reducing the variance of the strength curve by using material with better quality

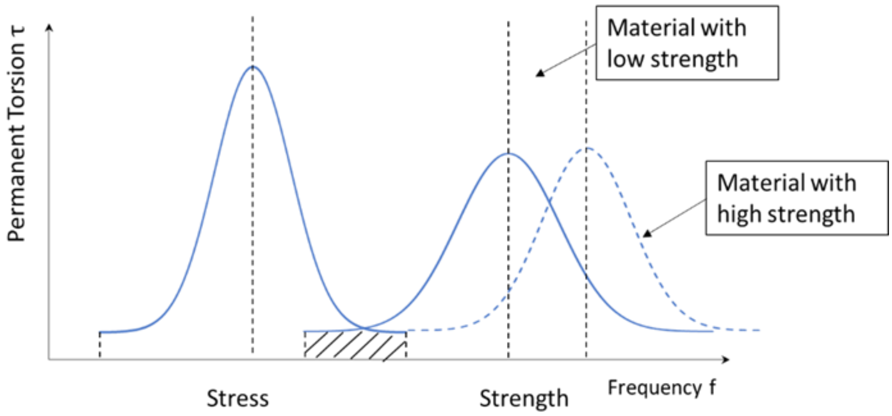


Figure 77 Shifting the strength curve due to better material

To increase the material quality, i.e., to reduce the variance of the material distribution, shown in Figure 78, is also a possible solution to the problem.

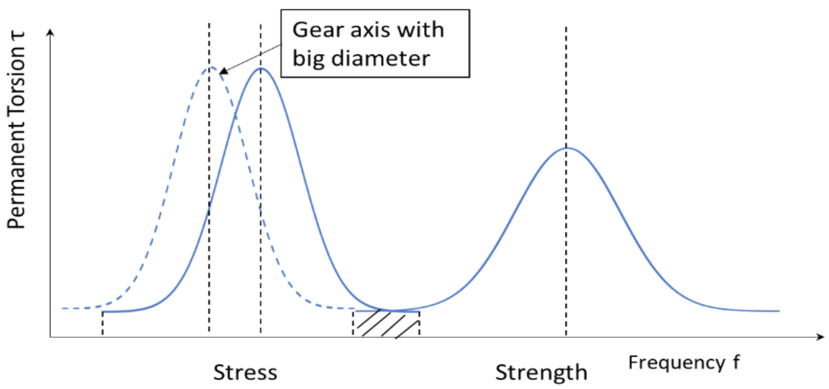


Figure 78 Shifting the stress curve by increasing gear diameter

The problem can also be solved with manufacturing measures. By measuring the dimensions of the primary gear axis after machining, the axis can be sorted out with a limit of the diameter to eliminate the overlap of the stress- and the strength curve. Figure 79 shows this effect of the reliability diagram.

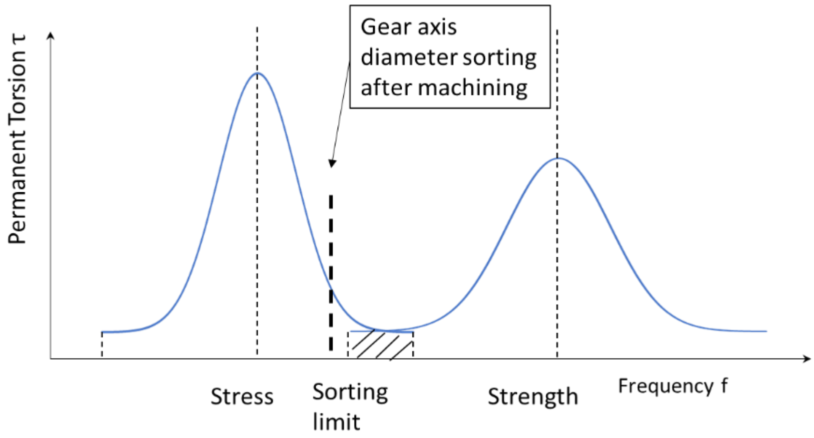


Figure 79 The effect of the diameter sorting of the gear axis

All possible countermeasures depending on the root causes are listed in the Countermeasure-Table, Table 18.

Table 18 Counter measure table based on the root-cause analysis

	Wrong material	Low material quality	Small diameter of gear	Big tolerance of diameter
1	Change material A with higher Strength	Change material supplier	Change dimensions of gear and axis / set 1	New machine with higher machine capability
2	Change material B with higher Strength	Heat treatment	Change dimensions of gear and axis / set 2	Selection by measuring after machining
...				

Substep 3) To define the optimal measures to correct the failure, different roles in the development team, i.e., manufacturing, engineering, and purchasing, discussed the pros and cons of each measure. The measures are ranked according to the efforts for the implementation. For example, changing material suppliers to get material with less variance of the strength is the best solution for the manufacturing department, because the efforts of the organization are minimal to implement this measure. Whereas, this measure means high effort for the purchasing organization due to the search for new suppliers, as well as for releasing the supplier and the

material. For purchasing, the best solution is to sort diameters after machining, because their efforts are minimal. But this measure requires high costs and manpower to be committed by the manufacturing department because the manufacture process flow should be redesigned according to the new process step. Since costs always play a central role in product development, it is also treated as a separate criterion in the decision matrix, as Table 19 shows.

Table 19 The decision matrix of corrective measures

	Manufacture	**Engineering**	**Purchasing**	**Costs**	**Decision**
Change material with higher Strength	2	6	6	6	20
Change material supplier	1	4	5	2	12
Heat treatment	4	5	4	3	16
Change dimensions of gear and axis	3	3	3	1	10
New machine with higher machine capability	6	1	2	5	14
Selection by measuring after machining	5	2	1	4	12

Best solution — Worst solution

1	2	3	4	5	6

Adding all ranking together, the decision column shows the overall ranking of the countermeasures considering different interests and criteria, the three top measures are suggested by the cross-functional development team:

Top 1: change material supplier to get the same material with less deviation of material strength,

Top 2: increase the diameter of the primary gear axis and redesign the related chain dimension,

Top 3: sort the primary gear axis with a diameter limit by measuring after machining.

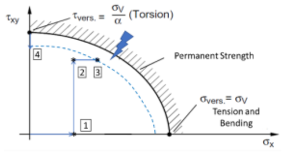
Substep 4) Considering the optimum result for all projects and the long-term interest of the company, the engineering leaders chose the top 1 countermeasure.

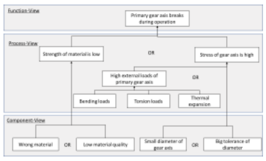
To validate this measure, the following tasks are defined:

- material analysis,
- supplier release,
- material release,
- endurance test with the new material.

Substep 5) These tasks are planned and followed up by the project leader. The Design-Evaluation-Table, Table 20, summarized and documented the failure analysis and the countermeasure. The FMEA document is updated accordingly.

Table 20 The Design-Evaluation-Table of the primary gear axis

<table>
<tr><th>Failure Mode</th><th>Root Cause Analysis</th><th>Counter Measures</th><th>Validation</th></tr>
<tr>
<td>

- The combination of bending stress, point 3, dynamical torsion stress, point 2 and thermal stress, point 1, near the border of the permanent strength area
- Due to the deviation of material permanent strength, the maximal stress can exceed the minimal permanent strength
- The primary gear breaks
- The life time 10^8 of the primary gear axis function is not fulfilled</td>
<td>

- Wrong material
- Low material quality
- Small diameter of gear axis
- Big tolerance of gear axis diameter</td>
<td><table>
<tr><th></th><th>Wrong material</th><th>Low material quality</th><th>Small diameter of gear</th><th>Big tolerance of diameter</th></tr>
<tr><td>1</td><td>Change material A with higher Strength</td><td>Change material supplier</td><td>Change dimensions of gear and axis / set 1</td><td>New machine with higher machine capability</td></tr>
<tr><td>2</td><td>Change material B with higher Strength</td><td>Heat treatment</td><td>Change dimensions of gear and axis / set 2</td><td>Selection by measuring after machining</td></tr>
<tr><td>…</td><td></td><td></td><td></td><td></td></tr>
</table>
<table>
<tr><th></th><th>Manufacture</th><th>Engineering</th><th>Purchasing</th><th>Costs</th><th>Decision</th></tr>
<tr><td>Change material with higher Strength</td><td>2</td><td>6</td><td>6</td><td>6</td><td>20</td></tr>
<tr><td>Change material supplier</td><td>1</td><td>4</td><td>5</td><td>2</td><td>12</td></tr>
<tr><td>Heat treatment</td><td>4</td><td>5</td><td>4</td><td>3</td><td>16</td></tr>
<tr><td>Change dimensions of gear and axis</td><td>3</td><td>3</td><td>3</td><td>1</td><td>10</td></tr>
<tr><td>New machine with higher machine capability</td><td>6</td><td>1</td><td>2</td><td>5</td><td>14</td></tr>
<tr><td>Selection by measuring after machining</td><td>5</td><td>2</td><td>1</td><td>4</td><td>12</td></tr>
</table>
- Change material supplier
- Change dimensions of the primary gear axis
- Selection by measuring after machining
⇨ Change material supplier</td>
<td>- Material analysis
- Supplier release
- Material release
- Endurance test with new material</td>
</tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>

6.2 Screw Sleeve Joint of a motor vehicle alternator

The alternator, depicted in Figure 80 [Robert Bosch GmbH (Ed.) 2014], plays a central role in the modern electrical system of motor vehicles. It converts the kinetic energy of the combustion engine to the electrical energy to charge the vehicle batteries. The batteries supply power to the electrical equipment, such as the starter to start the vehicle engine, the ignition and fuel-injection system, the electronic control units, the safety and comfort and convenience electronics, and the lighting. Besides the conventional functions, the modern alternator, so-called Boost Recuperation Machine (BRM) can also take over the starter function to start the combustion engine and to boost the combustion engine through driving [SG 2019].

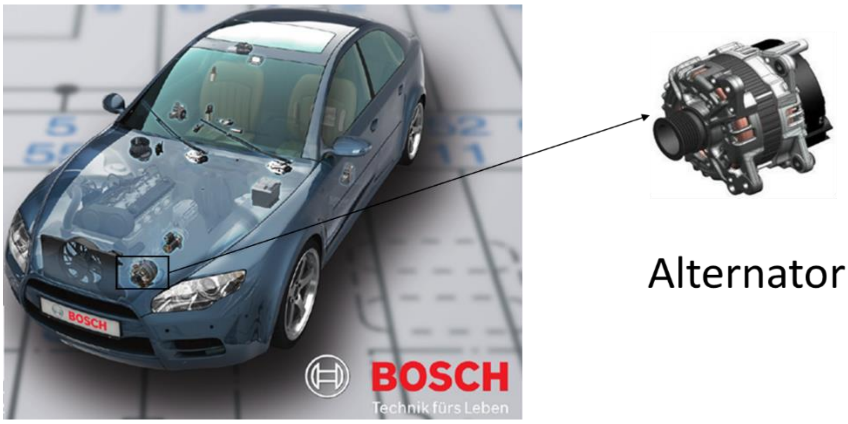


Figure 80 A generator of a modern passenger vehicle [Robert Bosch GmbH (Ed.) 2014]

Figure 81 depicts the working principle of the alternator. The alternator is fixed on the engine block and connected to the engine with a fan belt. The fan belt transfers the rotation movement of the engine to the alternator. With the turning rotor and magnet field excited by a stator of the alternator, electrical power is generated to charge the battery.

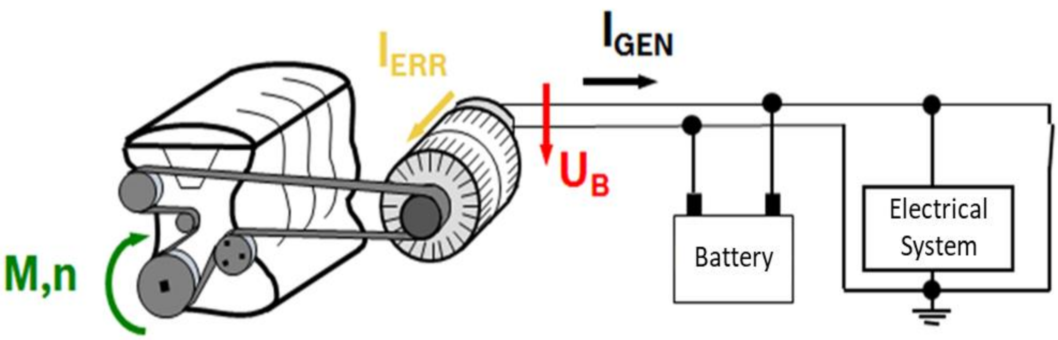


Figure 81 The working principle of the alternator

The alternator is fixed on the engine block by two screws with the pretension force F_V, as Figure 82 [Reif 2013] depicts. The fixation should resist vibrations of the engine, impacts of the road in driving, and the operation force of the belt over the lifetime.

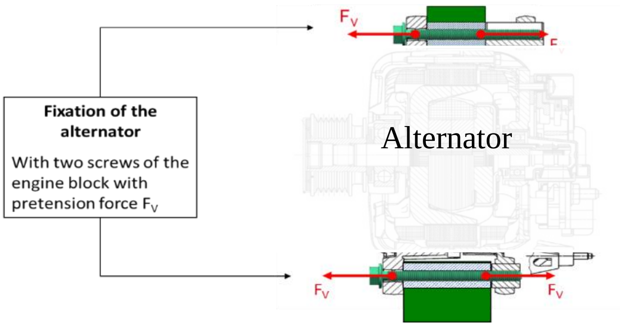


Figure 82 The fixation concept of the alternator based on Reif [Reif 2013]

For a new generation of alternator with higher required output power for the new functionality, e.g., boosting for hybrid vehicles, the new development of the alternator design concept is commenced. Because of the increasing weight and the increasing belt force, the development team modified the concept of fixation. The structure- and function-analysis of FMEA are done. The failure-analysis is done according to the function test result and the experience of the team based on the last generation.

Applying the new approach, the development team conducted the failure mode analysis, the root-cause analysis, and defined the countermeasures. In the next section, the procedure will be introduced step by step. To concentrate on the methodical approach, some technical details are omitted. To protect the intellectual property of the company, the design parameters and the specified information of the company are anonymized.

6.2.1 Step 1: Evaluate the design concept risks

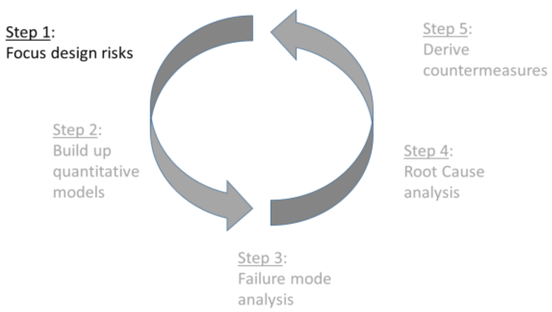


Figure Step 1

Substep 1) Figure 83 presents the simplified structure of the screw sleeve joint of the alternator. The screw sleeve comprises the bolt, the upper- and under-block, and the nut. The upper-block can be treated as the alternator in this case, and the under-block as the engine block. This model is simplified to the basic structure of the connection without the technical details.

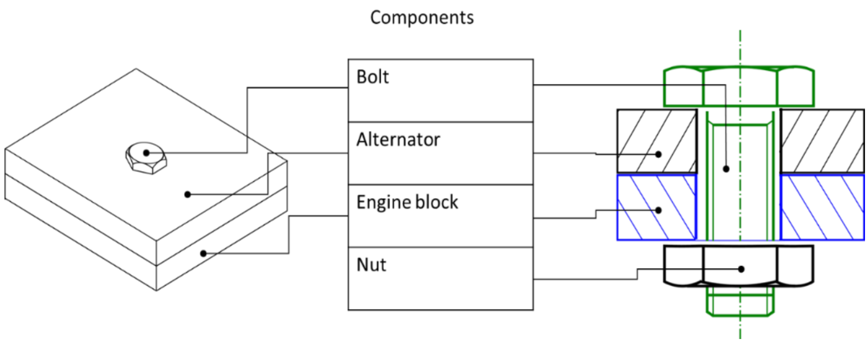


Figure 83 The simplified structure of the screw sleeve joint of the alternator

Due to the increasing weight of the alternator and the large belt force, the following changes comparing to the last generation are identified:

- diameter of the bolt is increased;
- internal diameter of the nut is increased;
- outer diameter of the nut is increased;
- pretension torque of the screw is increased.

The stress-strength calculation and the FEM-simulation showed a positive result not only for the static loads, but also for the dynamic loads. The first function test related to the screw sleeve joint is completed without any failure.

According to the internal product development process, the FMEA of the product design concept for the new alternator is conducted. Figure 84 illustrates the structure- and function-analysis of the Design-FMEA. Based on the experience of the team from the former generation of the alternator, two typical failures are mentioned: the broken bolt and the loosened nut during operation.

Figure 85 depicts the failure analysis of the Design-FMEA. The customer complaints over the years indicate those weak spots of the product. Therefore, even the calculation and the simulation confirmed the screw sleeve joint design with high safety factors and the first function test showed no deviations, the development team decides to focus on the potential failures to make further analysis.

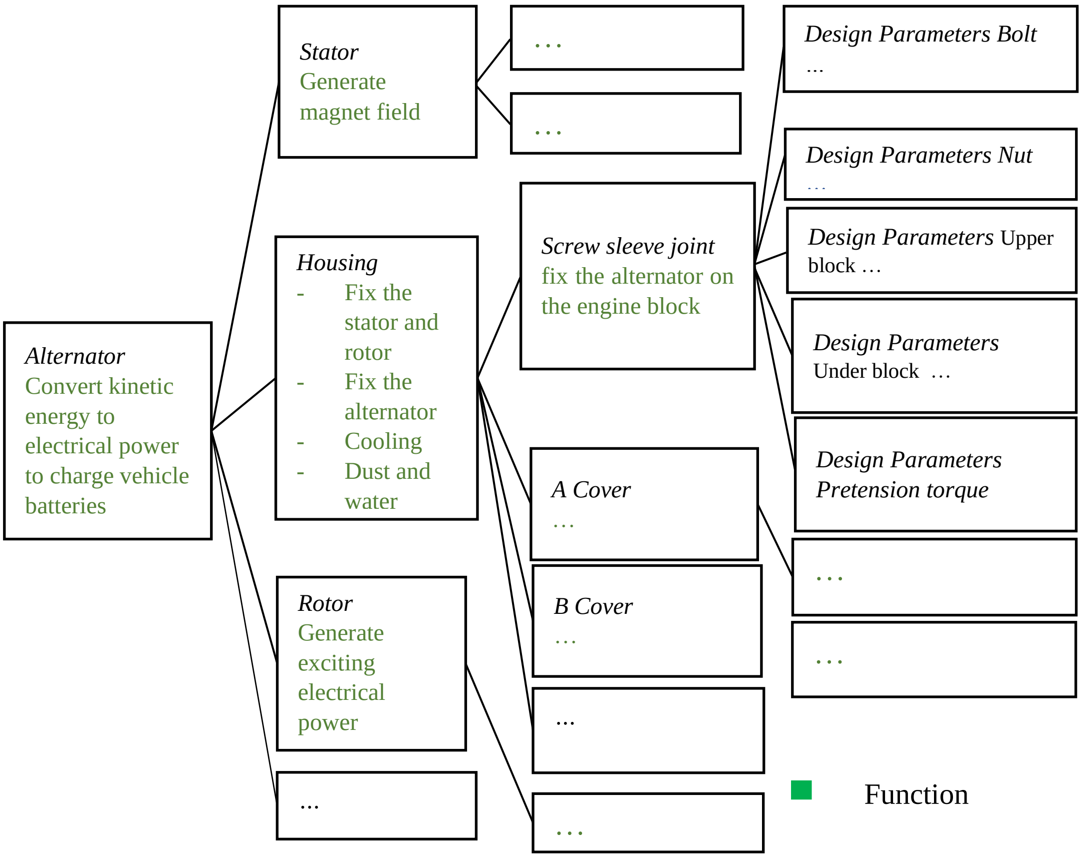


Figure 84 The structure and function analysis of the Alternator FMEA

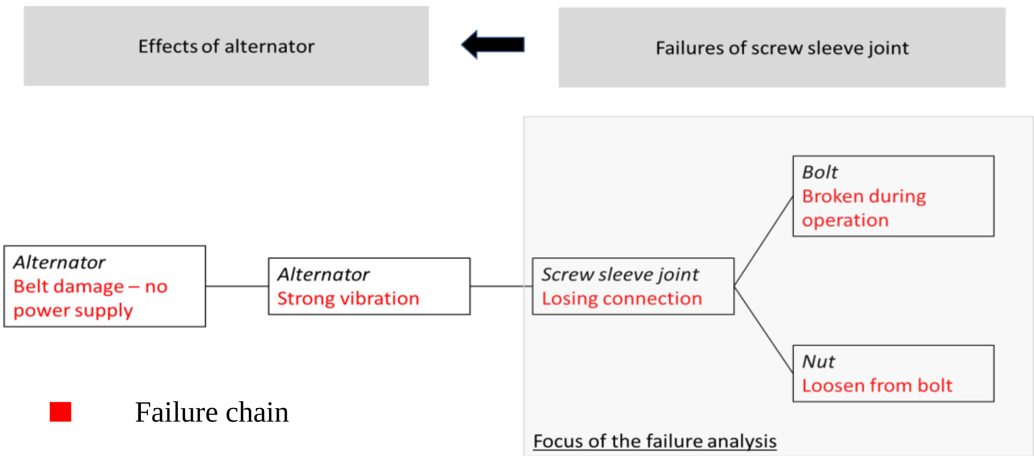


Figure 85 The failure analysis of the Design-FMEA

Substep 2) The development team analyzed all components of the screw sleeve joint to identify the design risks and affected function. The DeCoDe-Function-Component-Matrix, Table 21, shows the result: the bolt is a design risk, because of different customer complaints about the broken bolt for the last generation of the alternator. Whereas, other components are regarded as not critical.

Table 21 The DeCoDe-Function-Component-Matrix of screw sleeve joint

Functions \ Components	Bolt	Upper block	Under block	Nut
Fixation of alternator on engine block	Critical	Confirmed by simulation and tests		

■ Design risks ■ Understood causality

The development team used the DeCoDe-Process-Component-Matrix, Table 22, to derive the critical processes leading to the possible failure. As Table 22 shows, the processes: assembly, disassembly, and corrosion effects are well understood or validated. The focus processes are static fixation, dynamic fixation and fatigue effects. Therefore, even if the first calculation confirmed the bolt design, a deep analysis should be undertaken before starting the endurance test with the dynamic loads over the lifetime, which lasts more than several months.

Table 22 The Component-Process-Matrix of Screw Sleeve Joint

Physical effects (processes) \ Component	Bolt
Static fixation	Critical
Dynamic fixation	Critical
Assembly	Not critical
Disassembly	Not critical
Fatigue effects	Critical
Corrosion effects	Not critical

■ Critical processes ■ Uncritical processes

To study the dynamic connection processes, the following physical effects of this process are analyzed, the causality between the effects and the design parameters are derived. After that, the Function-Process-Design Diagram is built up to derive the failure mode.

Substep 3) The results of focus analysis are, therefore documented in the DeCoDe Function-Component-Matrix, Table 21, with the focus function "fixation of alternator on engine block" and the focus design "bolt", as well as in the DeCoDe Component-Process-Matrix, Table 22, with critical processes "dynamic fixation".

6.2.2 Step 2: Build quantitative DeCoDe-model

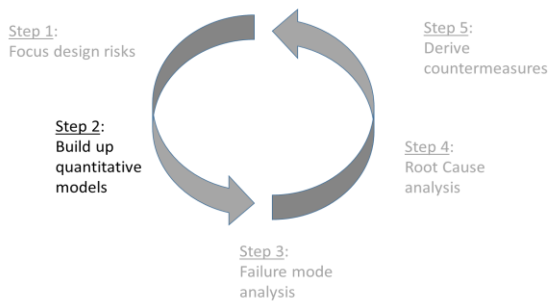


Figure Step 2

Substep 1) The DeCoDe Matrices, which include the design risks and the critical processes are discussed by the team. The component designers received the tasks to quantify the models of focus functions and design parameters, as well as the critical processes.

Substep 2) According to the defined models, the designers quantified the functions, the product designs and the physical processes supported by the product experts.

1) Function-model

Based on the functional requirements of the screw joint, the five elements of the function are derived and quantified:

- Corresponding rule:

The task of the screw sleeve connection is to fix the alternator on the engine block. To derive the corresponding rule of the function the physical meaning of the fixation should be analyzed.

The fixation means that there is no relative movement allowed between alternator and engine block during the operation. Figure 86 illustrates the working principle of the screw sleeve joint.

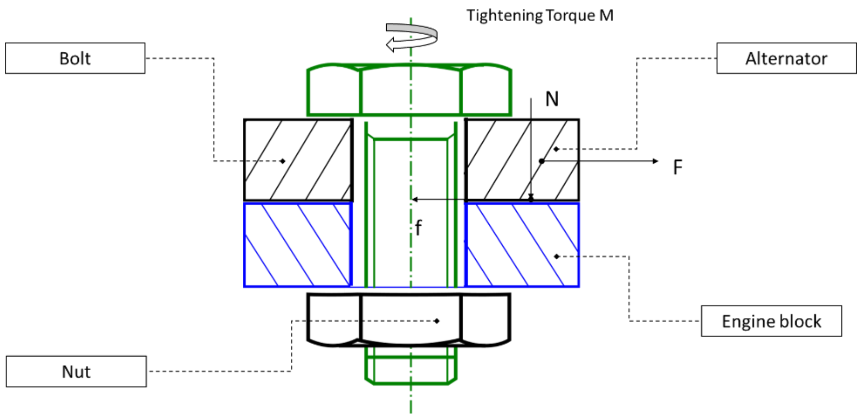


Figure 86 The physical explanation of the screw sleeve connection of the alternator

Besides the belt force, the weight of the alternator, the vibration of the engine and the impact of the vehicle, all these drive forces should be compensated by the clamping force x, which is generated by the normal force N of the screw sleeve connection, so that the resultant force between the alternator and the engine block should be zero. In this case, there will be no relative movement between the alternator and the engine block according to Newton's first law.

Figure 87 shows this relation:

$$y = x \text{ with } x: = F_f + F(t),$$

Input loads: x

Clamping force: y

Static loads: F_f

Dynamic loads: F(t)

Time: t.

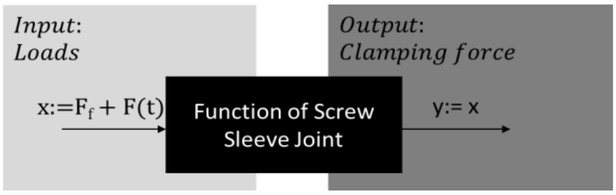


Figure 87 The block box model of the screw sleeve joint function

- Loads profile

The range of the inputs is defined by the range of the static load F_f and the dynamic loads F(t), which is a changing variable depending over the time. Figure 88 illustrates the range of output of clamping force f responding to the resultant force of all external loads.

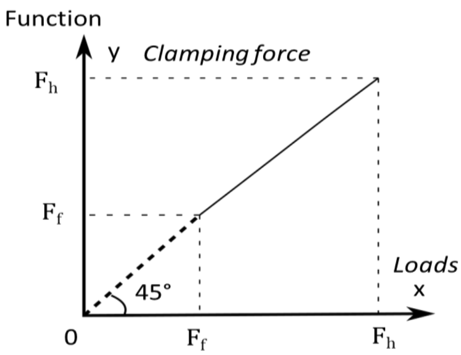


Figure 88 The range of the loads

The dynamic loads F(t) are decisive for the screw sleeve function. As the load profile is not required in the document of the Design-FMEA, and it is not provided by the customers either, the development team decided to measure it with the real driving mode with a mixture of highway, country road and city road. The different driving situations, such as engine starting, which generates high vibration, are also considered.

Figure 89 depicts the model of the loads profile of the screw sleeve joint depending on the time. The dynamic loads over time can be simplified with the shape of the sine wave.

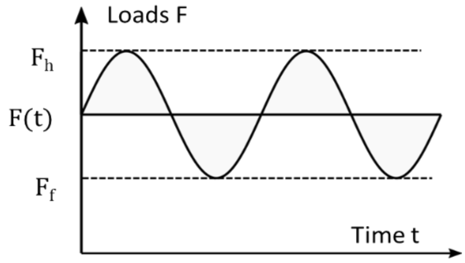


Figure 89 The simplified loads profiles of the screw sleeve joint

The other relevant loads are loads of the screwing process, i.e., the tightening torque during the alternator assembly and the loads from the unscrewing process. These loads belong also to the function loads profile, which are analyzed by the development team. However, they are not considered in this thesis.

- Conditions

Because the interface of the engine block is defined by customers, it should be taken into account by designing the connection.

- Use environment

The typical environment of the road vehicle components, which are agreed with the customers:

- Temperature -20°C to + 105°C
- Humidity 0-100%
- The corrosive environment, which should be verified by the salt spray test with 48 hours.

- Lifetime

The typical lifetime of the road vehicle is 15 years or 300,000 km. For the screw sleeve joint, the deployed lifetime is

$$n = 10^{10} \text{ dynamic cycles.}$$

2) Process-model

- Static fixation

Figure 90 illustrates the physical model of the screw sleeve static connection. After the screwing, the sleeves, i.e., the upper- and under-blocks are compressed, whereas the bolt is tensioned. Both behaviors can be considered as balanced springs.

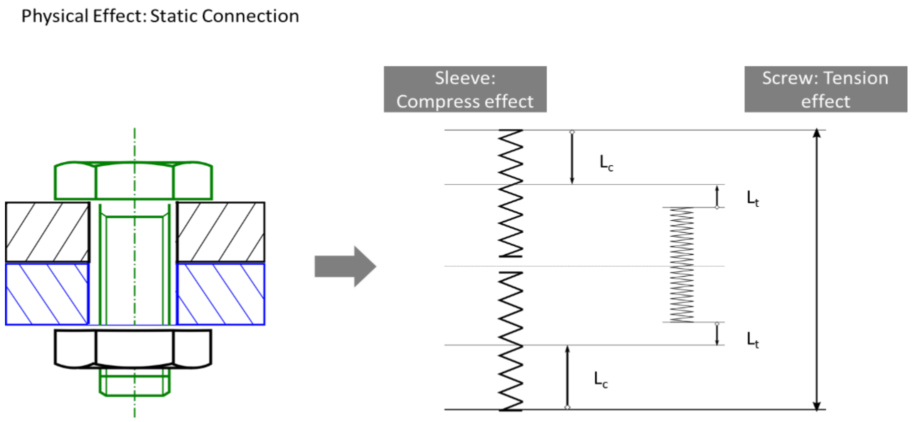


Figure 90 The physical effect of the screw sleeve static connection

Based on the model, the relations between the compression and tension forces can be derived. The tension force of the screw and the compressing force of the sleeve are equal F_v, which acts as the clamping force of the connection. The L_t is the deformation of the screw, whereas the L_c is the deformation of the sleeve. They form a force-deformation balance of the screw sleeve system after assembly.

- Dynamic fixation

The dynamic loads, as Figure 91 shows, cause a dynamic tension/pressure stress in the screw and the sleeve, which have the form of a sine wave.

- Fatigue effects

Figure 92 depicts the stress-strain curve of the bolt and block materials with the ultimate strengths, i.e., R_{m1} and R_{m2}. These values are listed on the material data sheet from the material suppliers. Due to the high frequency dynamic loads cycles, the permanent strengths of both materials are taken into account instead of ultimate strengths. Figure 93 shows the permanent strengths S_1 and S_2, which are identified with material tests.

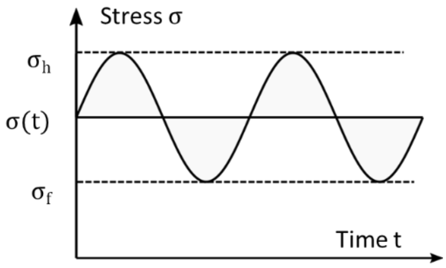


Figure 91 Dynamic loads of the screw sleeve joint

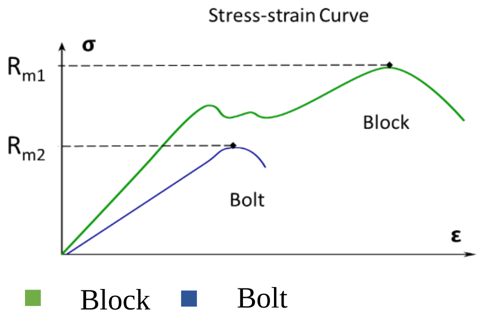


Figure 92 The stress-strain curve of the bolt and block materials

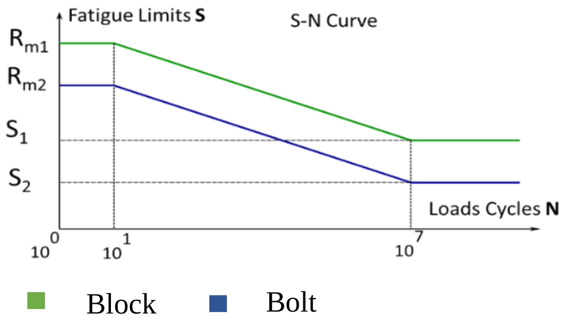


Figure 93 The fatigue effect of the bolt and block materials

- Component-model

Besides the dimensions of the components, like the length and diameters of the bolt, the chemical composition as well as the physical characteristics of the material belong also to the design parameters. Figure 94 presents a list of the design parameters and component characteristics, which are relevant for the function fulfillment.

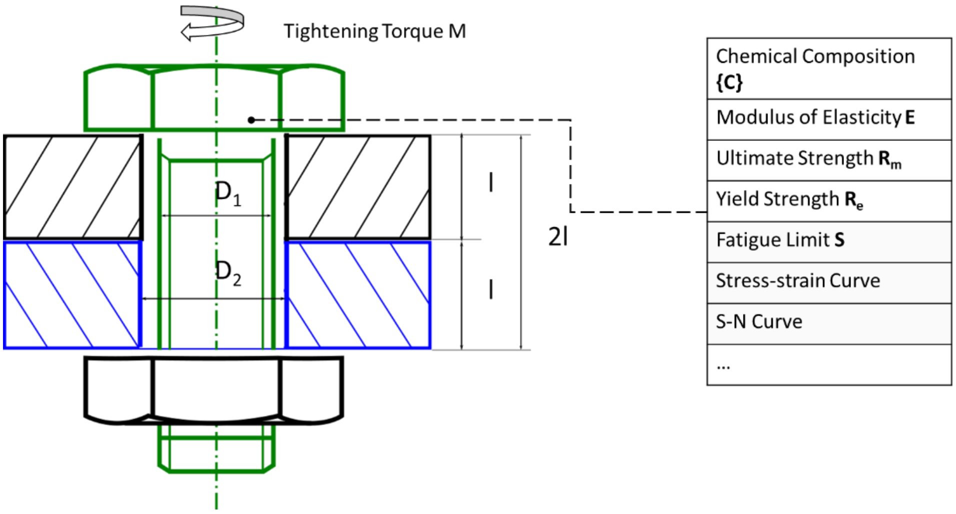


Figure 94 The design parameters of the screw sleeve joint

6.2.3 Step 3: Failure mode analysis

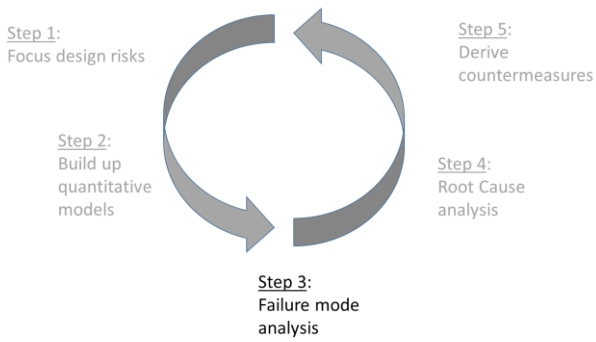


Figure Step 3

Substep 1) After the quantification of function-, process-, and component-models in the Design-Risk-Table, the component developer started to derive the Design-Process-Function-Diagram to analyze the failure mode supported by the reliability engineer.

Substep 2) Different physical processes were combined with the function in the Design-Process-Function-Diagram to derive possible failure mode.

1) Static fixation and Stress-strain curve

The curve of static fixation depicts the behaviors of tension of the sleeve and pression of the screw. During the screwing process, the curve should be the same as the stress-strain curve of materials. It means the tension of screw can be replaced by the stress-strain curve of bolt material, whereas, the pression curve can be replaced by the stress-strain curve of sleeve material by turning the curve from right to left.

2) Dynamic fixation

If the screw is fixed by assembly process, the dynamic loads by the operation causes additional stress in the bolt and sleeve.

The Design-Process-Function-Diagram can be derived from these three effects as well as the function, as Figure 95 shows.

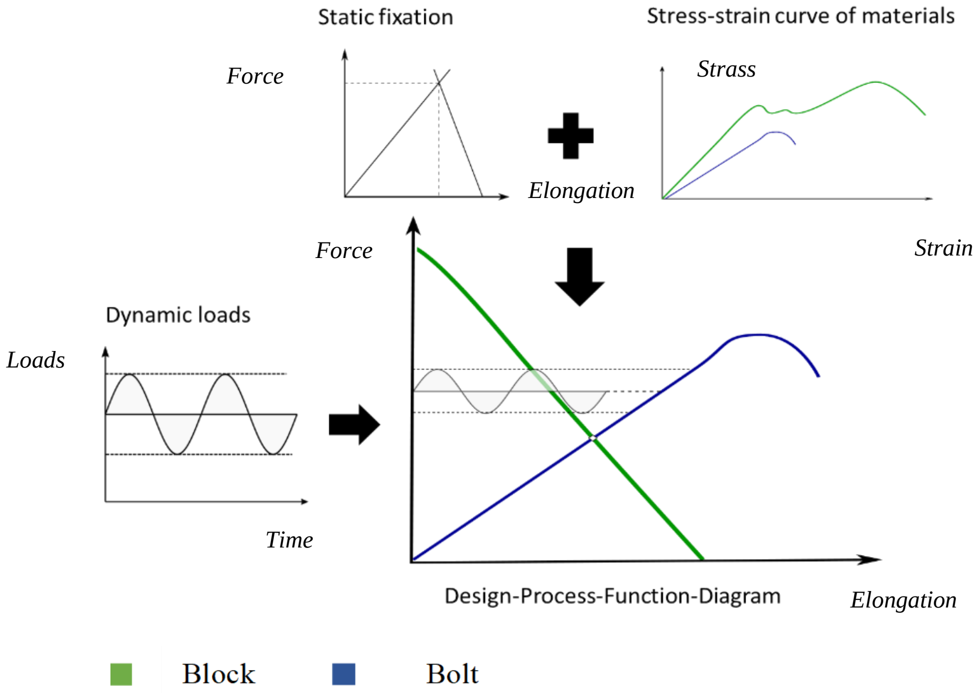


Figure 95 Deriving Design-Process-Function-Diagram from DeCoDe-models

3) Fatigue effect

Considering the fatigue effect, as Figure 93 depicts, the explanations of different working points are presented in Figure 96 in details:

1. Point is the balance point for the stress of the bolt, the blocks and the nut after assembly;

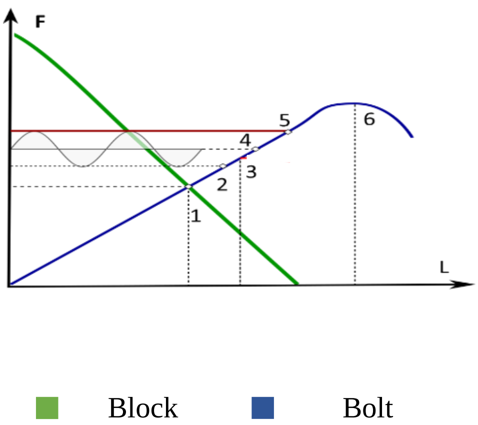
2. Point shows the stress increase due to the lower limit of the dynamic loads;

3. Point presents the permanent strength of the bolt material;

4. Point shows the stress increase due to the mean value of the loads;

5. Point depicts the stress increasing because of the higher limit of the dynamic loads;

6. Point illustrates the ultimate static strength of the bolt material.



1	Balance point after assembly
2	Lower limit of working loads
3	Ultimate tensile strength after aging
4	Mean value of working loads
5	Upper limit of wokring loads
6	Static tensile strength

Figure 96 The dynamics of the physical processes due to different influence factors

The failure mode of the screw sleeve joint can be described as following:

- increasing the stress of the bolt due to the dynamic loads,
- decreasing the strength of the bolt due to the dynamic loads cycle from the ultimate strength to the permanent strength,
- the maximal dynamic stress exceeds the minimal permanent strength,
- the bolt breaks within the defined lifetime.

Figure 97 illustrates the failure mode in the Function-Process-Design Diagram.

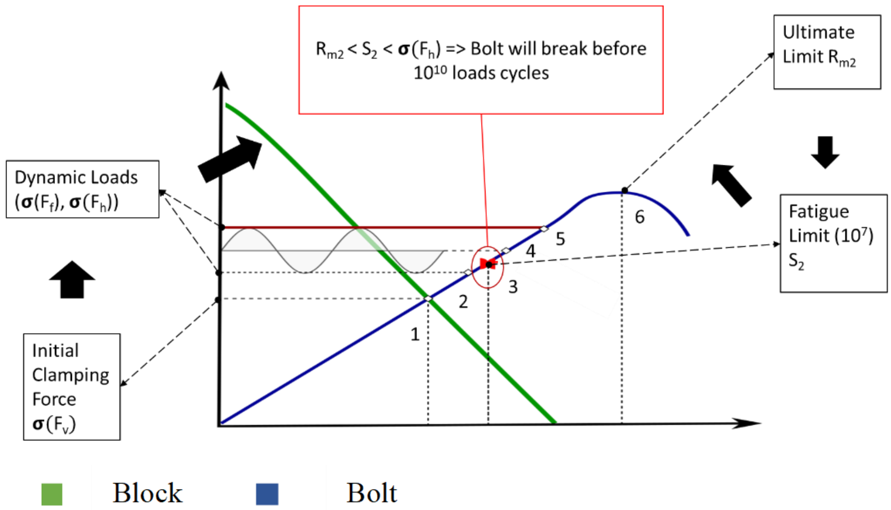
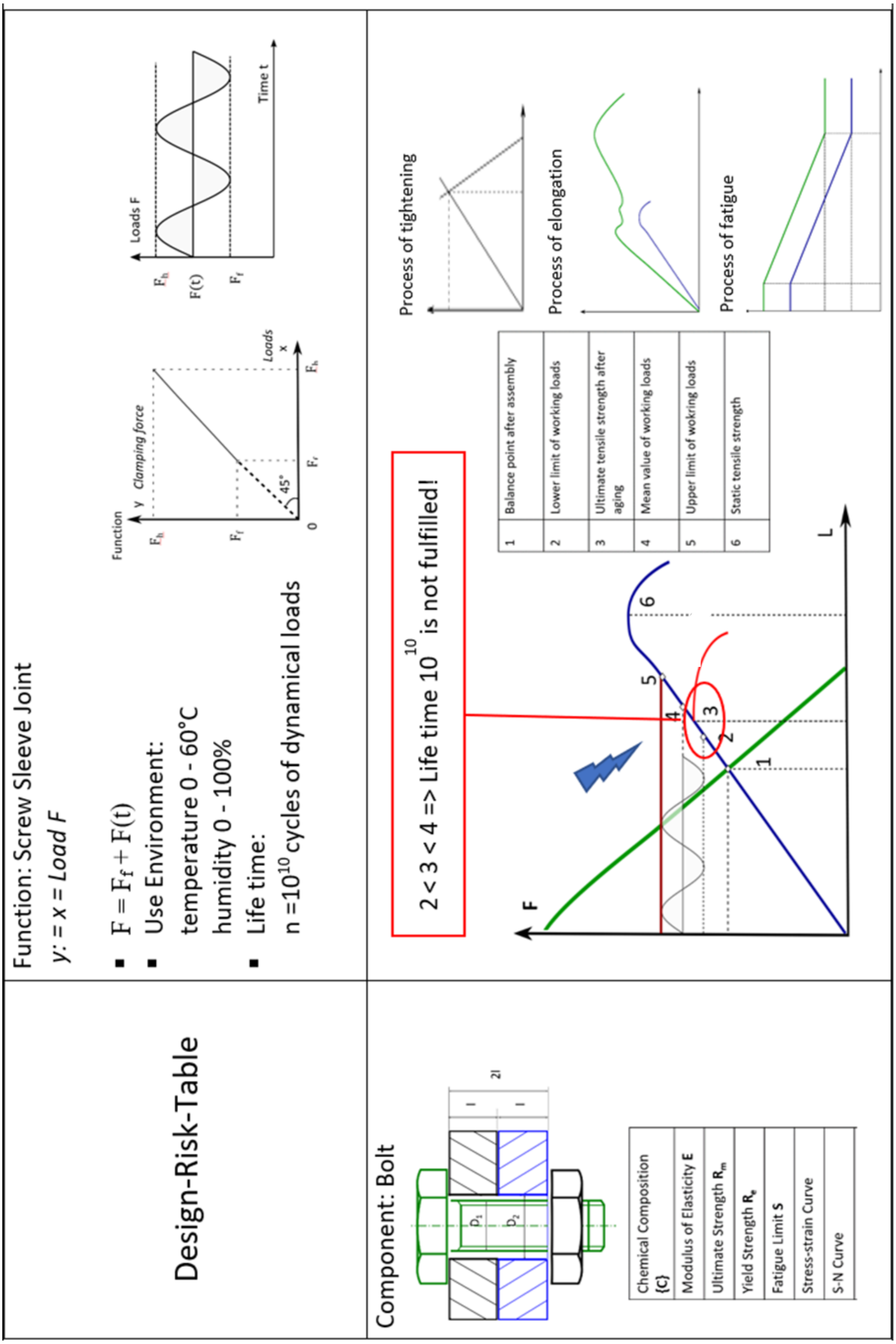


Figure 97 The failure mode of bolt broken within the defined life time

Substep 3) The development team reviewed the result, and documented it in the Design-Risk-Table in Table 23. The next step is to analyze the root causes of the potential failure.

Table 23 The Design-Risk-Table of the alternator screw sleeve joint



6.2.4 Step 4: Root cause analysis

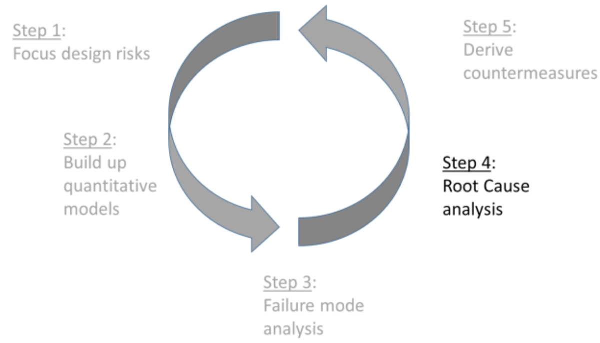


Figure Step 4

Substep 1) Based on the failure mode, the root causes of the failure are analyzed by applying DeCoDe-model-based "5 x why". The root causes are according to the causality between the function-, the process- and the component-models of the screw sleeve joint in the Design-Risk-Table, Table 23.

Substep 2) As Figure 98 depicts, the failure, "bolt will break before 10^{10} loads cycles" is set as the starting point. The second step is to derive the physical causes of this failure. According to the theory of mechanical reliability, the reason for the mechanical failure is that the maximal stress of the bolt exceeds the minimal strength of the bolt material. And the reasons of high stress and low strength can be derived from the process models.

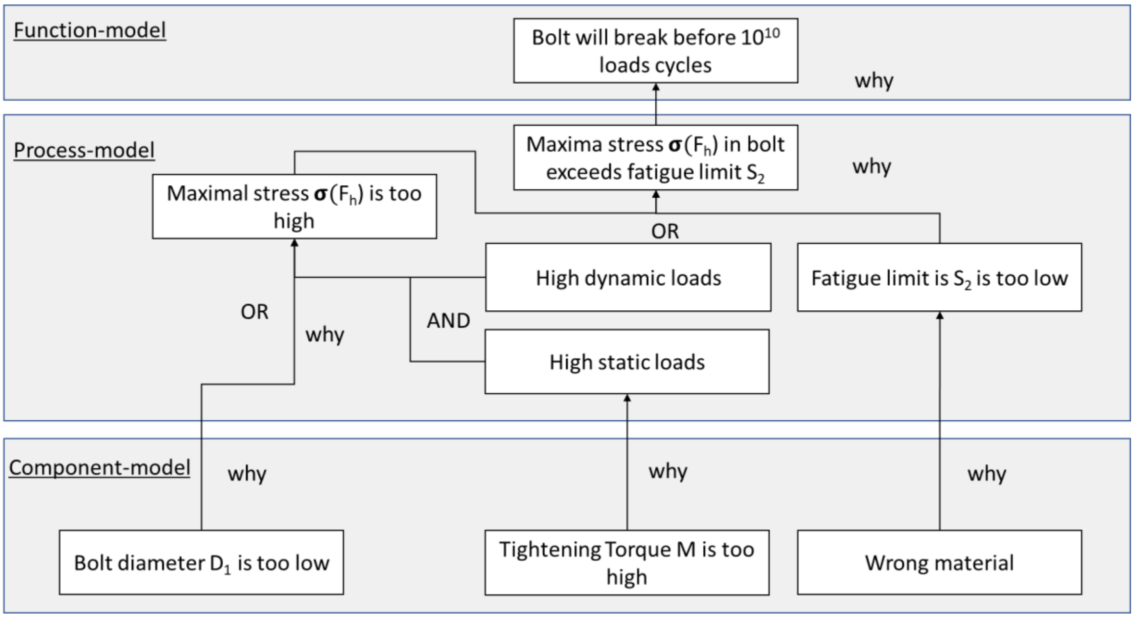


Figure 98 The DeCoDe-Model-Based "5 x why" for the potential failure of the alternator screw sleeve joint

The third level of the root causes analysis is to find the causes in the design parameters based on the affecting processes. Because the fatigue limits and permanent strength are the characteristics of the chosen material, they can be one of the root causes. The other reason is the high maximal stress in the bolt during the operation. Because the stress σ of the bolt is determined by the loads, F, and the cross-sectional area, A with

$$\sigma = \frac{F}{A}$$

therefore, the reasons for the high stress can be high loads or small cross-section.

The small bolt diameter is the design parameter, which is fixed by the developer. Therefore, it belongs to the root causes of potential failure. The causes of the high loads are on one hand the high dynamic loads, on the other hand, the high static load. The dynamic loads are the external loads which are part of the defined function. However, the high internal load is caused by the high tightening torque M, which is a design parameter, so that it is another possible root cause.

Substep 3) The development team summarized the root causes as follows:

- Bolt diameter is too low
- Tightening torque is too high
- Material with low permanent strength is chosen.

Based on the root causes, countermeasures are derived by the cross-functional development team in the next step.

Substep 4) The derived root causes are added in Corrective-Measure-Table, Table 28, which give an overview of failure modes and root causes. Based on this information, the countermeasures can be derived at Step 5.

6.2.5 Step 5: Decision of countermeasures

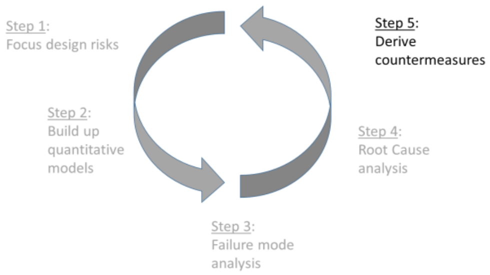


Figure Step 5

Substep 1) After identifying the root causes of the potential design failure, the development team derived all possible countermeasures the failure mode. The responsible developers and the reliability, material experts organized serval workshops to derive those measures. The results are documented in the countermeasure table, Table 24.

Substep 2) Increasing the bolt diameter is one of the countermeasures to eliminate the failure, shown in Table 25. With the increasing cross-section of the bolt, the tension curve is turned left, because of the increasing stiffness constant of the bolt, as following formulas show:

$$F = Kx,$$

$$K = E(\frac{1}{4}\pi D^2), \text{ and}$$

$$\sigma = \frac{4F}{\pi D^2}$$

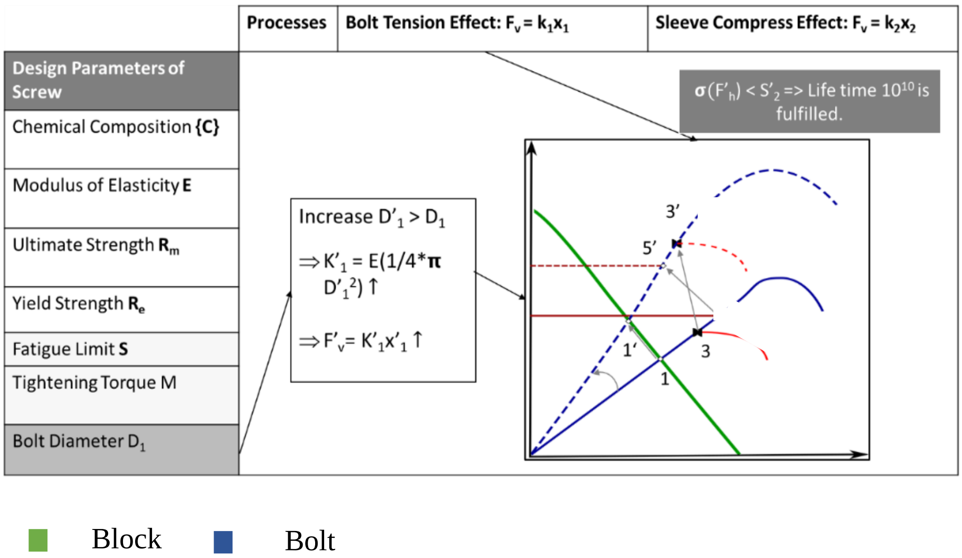
F: the tension force of the bolt, K: the stiffness constant of the bolt, E: Young's modulus, σ: the tension stress of the bolt.

Table 24 Evaluation of decreasing the tightening torque

Root Causes	Bolt diameter D_1 is too low	Tightening Torque M is too high	Wrong material
Solutions	Increase bolt diameter	Decrease tightening torque	Change bolt material
Comments	Possible	Possible	Not possible – bolt material is standard

Possible solutions

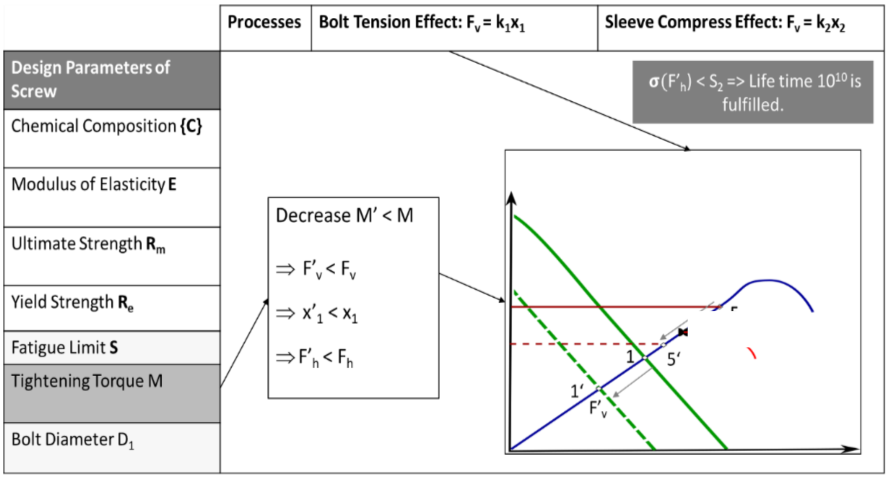
Table 25 Evaluation of increasing the bold diameter



Moreover, the maximal dynamic tension stress of the bolt decreases due to the increasing cross-section of the bolt. Both effects lead to the improvement of the bolt lifetime.

Another idea is to decrease the static tension stress of the bolt to improve its life time performance. This measure leads to a left shifting the tension curve of the bolt, so that the maximal tension stress decreases from F_V to F'_V as well, as Table 26 shows.

Table 26 Evaluation of decreasing the tightening torque



Block Bolt

To change the bolt material to one with higher permanent strength is not possible, because the material of the bolt is standardized on the market. To change the material means a cost explosion of the product development. Therefore, this option is not followed further.

Substep 3) To define the optimal measures for the project, the different roles of the development team, i.e., manufacturing, engineering, and purchasing, discussed the pros and cons of each measure. The measures are ranked, as Table 27 shows. The measure to decrease the tightening torque is the preferred measure from all roles of the development team. Only engineering has a concern that with a small pretension the screw sleeve can loosen during the operation. Therefore, the tolerance of the pretension torque should also decrease, and the screwing process should be controlled to ensure the process capability as well.

Table 27 the decision table of the counter measures

	Manufacture	**Engineering**	**Purchasing**	**Costs**	**Decision**
Increase Screw Diameter $D'_1 > D_1$	2	2	2	2	8
Decrease Tightening Torque $M' < M$	1	1	1	1	4

Best solution	Worst solution
1	2

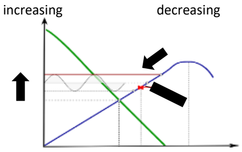
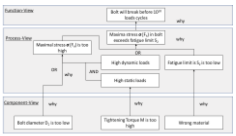
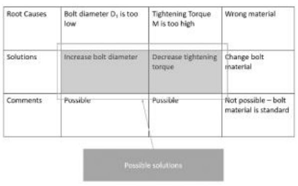
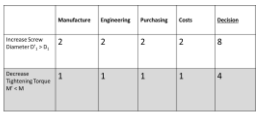
Balancing all pros and cons, the engineering leader decided to follow the suggestion of the team to decrease the pretension torque in the screwing process, as well as to reduce the tolerance of the pretension torque.

Substep 4) To validate this measure, the following tasks are defined:

- Analytical stress and strength calculation,
- FEM-simulation with dynamic loads,
- Endurance test according to the loads profile over the lifetime,
- Assembly trail by the manufacture, especially to confirm the process capability.

Substep 5) These tasks are planned and followed up by the project leader. The Design-Evaluation-Table, Table 28, summarized and documented the failure analysis and countermeasures. The FMEA document is updated accordingly.

Table 28 Evaluation of decreasing the tightening torque

Failure Mode	Root Cause Analysis	Counter Measures	Validation
 - Function join two blocks cannot be fulfilled - Conditions of the failure is dynamical loads more than 10^{10} cycles - Strength decreases due to dynamical loads - Stress increases due to dynamical loads - Stress of bolt exceeds his fatigue strength - Effect of the product is that bolt will be broken	 - Diameter of bolt is low - leads to high stress - Tightening torque is high leads to high stress - Wrong material of bolt leads to low fatigue limit	 - All possible counter measures  - Decision: decrease tightening torque M	- Analytical stress and strength calculation - Simulation with dynamical loads - Endurance test according to loads profile over lifetime - Assembly test by manufacture

6.3 Summary of the industrial application

The application of the new methods to improve Design-FMEA in the automotive industry brings benefits for product development projects, which are confirmed by two case studies.

The quantitative DeCoDe-models enable the teams to focus on the critical points of the product design, for example, the thermal expansion effects for the primary gear axis of the throttle positioner in combination with the fatigue effect of the gear material in the first case. This critical point would be overlooked without the quantitative function analysis.

The causal analysis of the function-, process- and component-model make it possible to analyze the failure mode, to derive the root causes and to define the countermeasures in a very effective and efficient way, for example, the reducing tightening torque for the screw sleeve joint to solve the bolt broken problem in the second case. Without the causal analysis crossing the different models of the screw sleeve, the team would not identify the optimal countermeasure so efficiently.

The chosen examples are only a small part of the applications of the new approach. With the comprehensive implementation of the approach in combination with Design-FMEA in worldwide development locations of the automotive supplier, the improvement of Design-FMEA during the product development can be confirmed by the development teams, as Table 29 shows. However, the implementation of the method depends on the maturity of the method application.

Table 29 Improvement of Design FMEA in combination with the new approach

Methods / Requirements	Design FMEA VDA	Design FMEA VDA + New approach
1. Analyze design concept and product functions	Fully	Fully
2. Ensure correntness of the failure analysis	Partially	Fully
3. Focus on design risks	Largely	Largely
4. Ensure completeness of design risks analysis	Fully	Fully
5. Ensure root-cause-analysis of failures	Partially	Fully
6. Empower and authorize communication and decision making of cross-functional team	Partially	Fully

7 Summary and outlook

Autonomous driving, reducing greenhouse gas, the internet of things, …, increasing customer needs lead to greater complexity of technical solutions. Meanwhile, the conditions of product development have been undergoing radical changes. On the one hand, the industrial organization for developing and for manufacturing technical products changes due to globalization. On the other hand, market factors, such as the decreasing life cycles of technical products, the aggressive competition on prices, require more efficiency in product development processes to reach the high product quality among intense competition. However, the quality problems of technical products have been increasing across different industry sectors in recent years. Those problems cause high costs for the manufacturing companies and damage to their reputation among customers.

Different scientific research reveals that one of the root causes leading to increasing product failures is the increasing complexity of technical products [Dittes 2012; Meyer et al. 2007; Mamrot 2014]. What does it mean in the context of product development? Because of the limitation of the human brain, engineers cannot avoid failures during the process of solving complex problems [Ehrlenspiel and Meerkamm 2017]. Therefore, quality assurance methods are one of the key elements of the product development process to identify and correct failures of product design [Gamweger et al. 2009]. The failures of product design mean such product design that leads to the non-fulfillment of the product requirements [ISO 9000:2015]. Among the established quality assurance methods, FMEA is accepted as the standard one in the automotive industry [VDA Band 14: 2008].

Trying to explain the phenomenon of the increasing failures of technical products, one of the hypotheses is that the established quality assurance methods in the product development process, for instance, FMEA, are not effective enough for managing the complexity of quality assurance in product development [Winzer 2014b]. The results of this research from industrial practice support this hypothesis.

Comparing the approach of Design-FMEA with the modern science of product engineering [Feldhusen and Grote 2013], this hypothesis is confirmed in this thesis. The root cause is that, different from the approach of product development, only the models of functions and of product design are analyzed by applying Design-FMEA [VDA Band 4:2013]. The direct coupling between the functions and the product design cannot ensure the causal analysis of failures and their root causes, because of the missing information regarding the physical effects of product operation. Figure 99 illustrates the disconnection of function and product design of the current Design-FMEA approach.

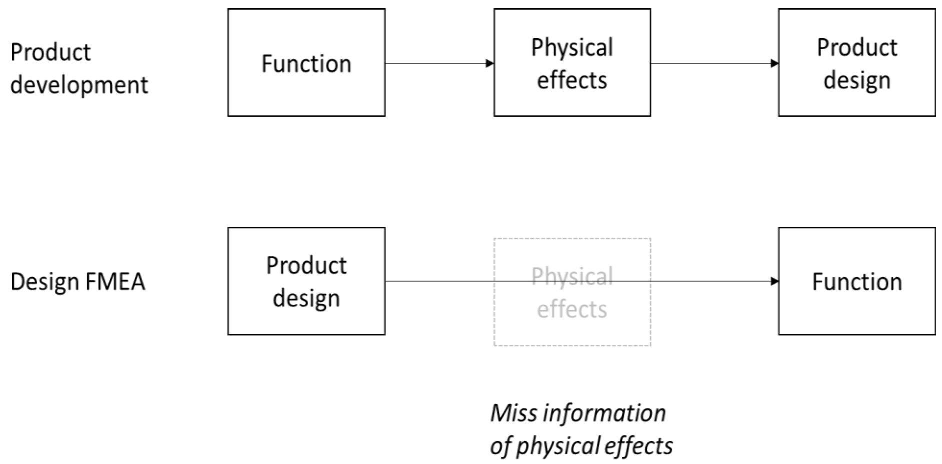


Figure 99 Root cause of infectivity and inefficiency of established Design-FMEA approach

To solve this problem, it is important to build the model of physical effects of the product's operation by applying Design-FMEA. Apply the theory of Systems Engineering (SE), especially Generic Systems Engineering (GSE), a problem solution approach is developed in this thesis.

SE is a philosophy to manage complexity [Haberfellner 2015]. The approach of SE is based on the coupling of the system models and the problem-solving concept. There are different implementations of SE, especially of different system modeling approaches [Winzer 2016a]. After analyzing the existing ones, Winzer points out that a system should be described with four different models, i.e., requirement-, function-, process-, and component-models to solve the complex problems [Winzer 2016a]. Thereupon, she develops Generic Systems Engineering (GSE), which is a general SE-approach with the four aforementioned system models coupled with the problem-solving approach.

Based on this scientific principle, only system modeling with function-, product design (component)- and physical effects (process)-models can ensure the causal analysis, this thesis applies GSE to develop a new approach to improve Design-FMEA for analyzing the failure mode, for deriving the root causes and for defining the countermeasures.

To achieve this goal, the approach with five steps combined with the established method of Design-FMEA are developed, as Figure 100 depicts:

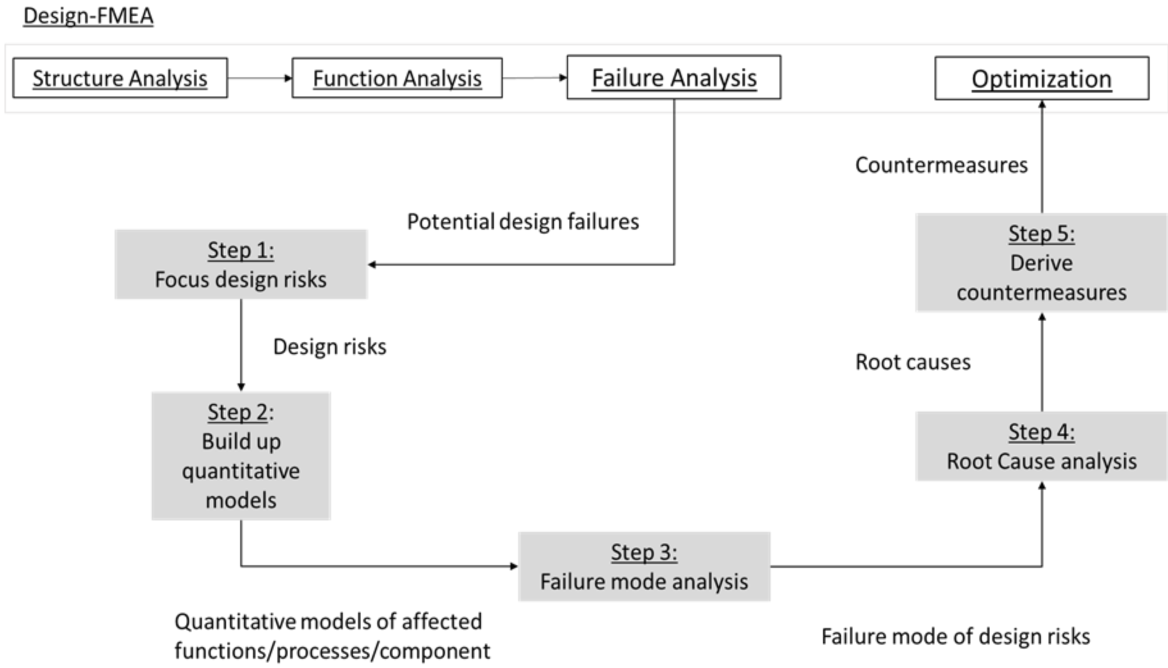


Figure 100 Combination of established Design-FMEA of VDA with the new approach including inputs and outputs of single steps

Step 1: Focus design risks

Adopting the failure analysis of Design-FMEA to identify risky designs and the affected functions, the focus of further analysis is derived;

Step 2: Build up quantitative DeCoDe models

Based on the focus design and functions, the quantified function-, process-, and component-models are built up;

Step 3: Failure mode analysis

Connecting the quantified function-, process-, and component models, causal chains of the failures are derived;

Step 4: Root cause analysis

According to the causal chains of failures, root causes will be derived by using the new developed DeCoDe-Modal-Based 5 x why;

Step 5: Derive countermeasures

Cross-functional development team defines the optimal countermeasures based on the defined criteria.

The key elements of the approach are the problem-oriented quantified system models of DeCoDe with the information of three scientific fields:

- Product development,
- Mathematical theories,
- Physical laws,

to ensure the causality of Design-FMEA.

Adopting the function definition in mathematics and of product development, the function model is quantified and modified with five key elements:

- Responding rule,
- Loads profile,
- Conditions,
- Environments, and
- Lifetime [Pahl et al. 2007] [Otto and Wood 2001] [Koller 1985] [Bertsche and Lechner 2004] [Gamweger et al. 2009].

The process-model is built to describe all physical effects which occur during products' operations. In addition, the characteristics of products and of their components are added to the component-model, besides common design parameters.

To ensure the interaction between the problem-solving concept and the thinking models, and to enable product development teams to apply the new approach, new methods and tools are developed for different steps. Figure 101 depicts the methods and tools applied to every single step of the approach.

The most important ones among them to ensure the causality in Design-FMEA are

- Design-Process-Function-Diagram
- DeCoDe-model-based "5 x why".

The Design-Process-Function-Diagram, Figure 102, is a newly developed tool to build failure mode from quantified function-, process-, and component-models. Using the visualization technique of information like:

- functional ranges,
- physical effects under extreme conditions and environments,
- worst-case-scenarios of functions,

the tool can reduce the complexity by analyzing physical causal chain comparing to use different 2 x 2 matrices.

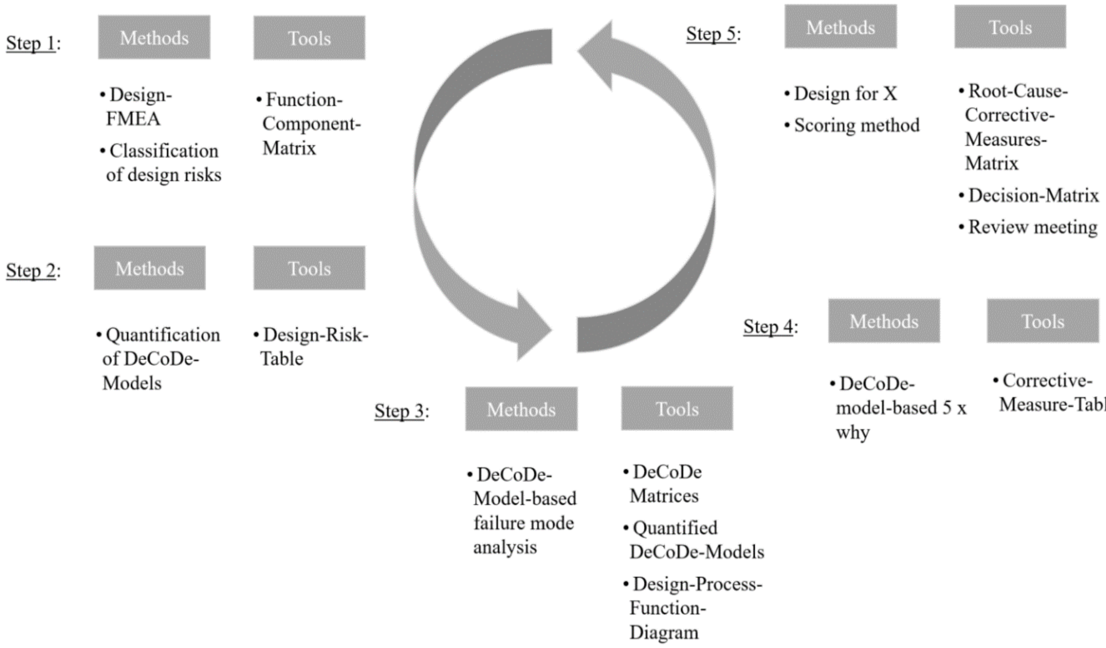


Figure 101 Overview of the new approach with the details of methods and tools for every step

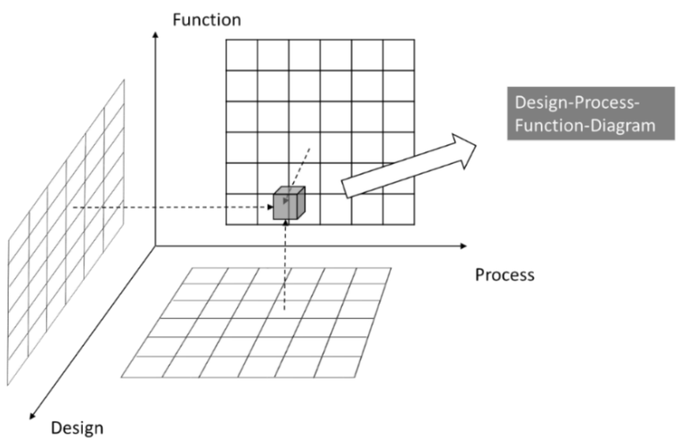


Figure 102 Design-Process-Function-Diagram is derived from DeCoDe-Product-Models

The DeCoDe-model-based "5 x why", Figure 103, uses function-, process-, and component-models as a foundation to guide the approach of root-cause-analysis. The starting point is unfulfilled functions in the function-model. Through physical effects in process-model, the root causes should be found in design parameters in the component-model.

Equipped with the defined processes and the dedicated methods and tools, the new approach is successfully applied in a leading automotive supplier to improve Design-FMEA. During the pilot phase, the new approach gains significant acceptance from the development teams, and has been since then established as the standards in the product development process in this company.

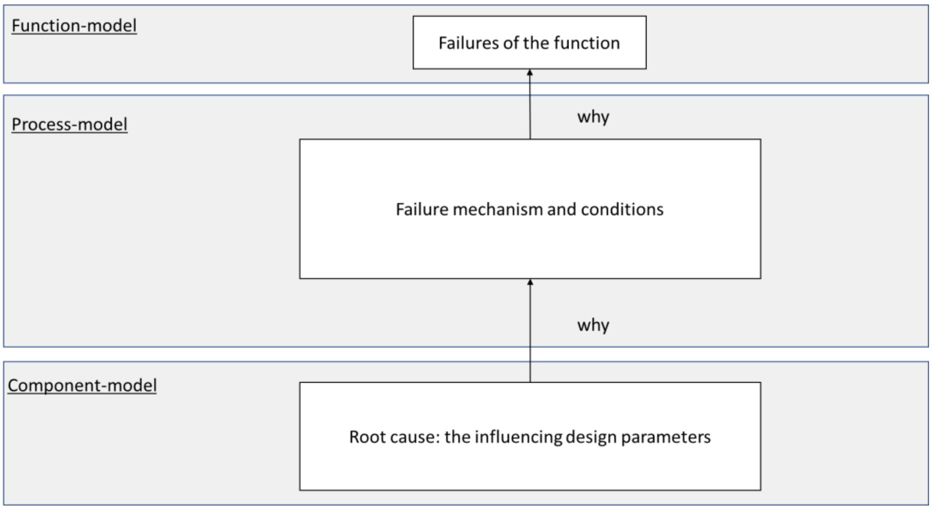


Figure 103 Interaction between "5 x why" and DeCoDe-Product-Models

Among numerous projects, two examples, i.e., the throttle positioner of the E-gas system and the screw sleeve joint for the new generation of vehicle alternator, are chosen in this thesis to represent the successful implementation of the new approach of product development. The improvements of Design-FMEA confirm the benefit of the new approach.

By implementing the new methods for different projects, the following experiences can be gained:

- Only defining form tables and descriptions of the process alone are not enough for a successful implementation of the new approach in practice. The prerequisite of the value-added application of the new approach is to change the way of thinking of the engineers. It means that the developers and engineering leaders should begin to analyze the function-, process-, and component-models by problem-solving of product development intuitively in their daily jobs, with the motto, "Thinking functionally! Thinking physically!"
- Profound technical expertise is essential to apply the causal analysis. If the necessary knowledge of the product is not available, the application of the approach will be superficial and not be effective in getting the optimal results;
- Task-oriented leadership is necessary for the successful implementation of the methods in an organization. The tasks of the leaders are not only to define the work packages and

to follow up the due dates. They should also guide the team to derive the analysis, to control the quality of outputs, to give feedback, and to make optimal decisions;

- The knowledge management system should be built up to manage the new knowledge gained by the application of the new approach. The document of the analysis should be archived, so that they are available for other development teams and for developments of next generations in the future.

During the implementation of the new approach, some needs for further research are also identified. The major findings are different deficits in applying the new approach for mechatronic systems. Figure 104 depicts the simplified model of the mechatronic system. The software runs on the ECU to process the data of signals getting from sensors. After calculation according to the defined logic, it sends the control signals to actuators.

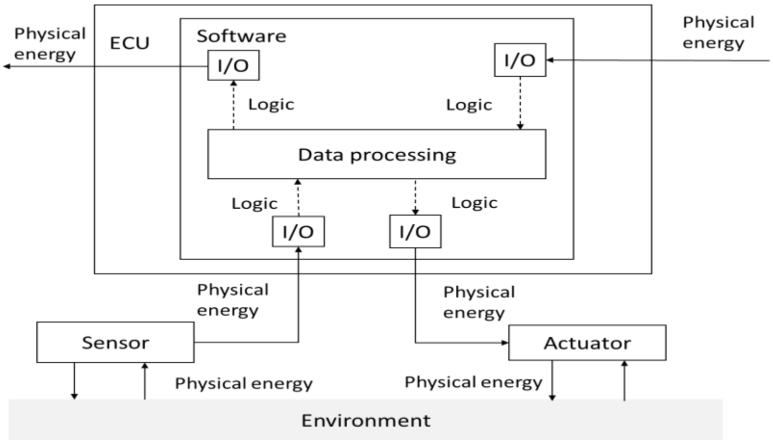


Figure 104 The simplified model of mechatronic systems

The software developers build software architecture with mathematical logic, whereas, the hardware engineers, e.g., the developers of the sensors and actuators, consider only the physical models of the product. The inputs and the outputs of the software model are digital and discrete. By contrast, the inputs and the outputs of the hardware are analogous and continuous.

For example, the software model regards the sensor signal as the logic model of information with status 0 or 1. However, the same signal is treated by the sensor developer as an electrical voltage impulse with concrete values. Moreover, the response time of the hardware is close to zero. Therefore, the reaction time is normally not considered in system modeling. The responding time of the software is often a critical point of software performance. The difference between hardware and software models leads to several quality problems of mechatronic products in industrial practices.

To solve these problems, following steps can be made to develop the DeCoDe system modeling for software of mechatronic system:

To define the function models of software based on the specified DeCoDe-function-model of hardware: the modified DeCoDe-function-model of technical products with five key elements cannot be applied directly to software. The lift time, loads profile and environment are, typically, irrelevant for software. The essential factors of a software are the inputs and outputs with defined logic as a regulator in a mechatronic system [Schäuffele and Zurawka 2013]. Figure 105 [Schäuffele and Zurawka 2013] demonstrates the software of PI-Regulator with outview and inside view with different data flow and internal logic.

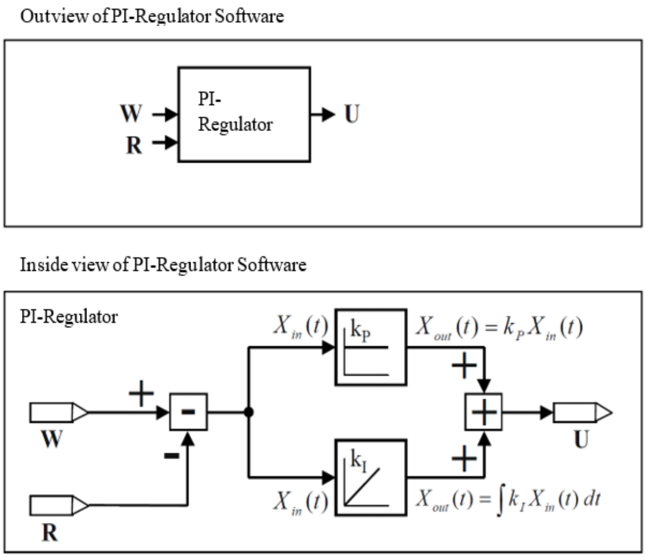


Figure 105 Outview and inside view of PI-Regulator Software [Schäuffele and Zurawka 2013]

Even functions of software have no restrictions of lift time, loads profile and environment, but as regulator, they play a decisive role for functions of their actuators, e.g., the life time for valves in ESP. Therefore, functions of software play also a decisive role for functions of the system. It means that the five elements of system and hardware should be considered, somehow, in the models of software function.

To consider the real-time requirements by building process models of software: the factor time is not considered in the DeCoDe models of technical product. Time, however, is, a critical factor in the context of software in a mechatronic system [ISO 26262:2011]. For instance, the reactions time of intervention of ESP is defined by the legal regulation for vehicles' safety [Reif 2014a].

To harmonize the software models and hardware models of a mechatronic system: the inputs and outputs of hardware models are analog and continuous physical values, whereases, the inputs and outputs of software are digital and discrete values. For the model-based product development, it is indispensable to harmonize both models by defining the interfaces.

With the implementation of the DeCoDe-software-models, the application field of Design-FMEA can succeed in all elements of mechatronic systems.

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