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New design methodology - Using VHDL-AMS models to consider aging effects in automotive mechatronic circuits for safety relevant functions

Paper for final thesis 2018

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Abstract

For years, the scope of the functionality shown by electrical or electronic systems in motor vehicles is constantly increasing. With driver assistance systems and electric mobility the development trend is more and more expanding into safety related areas. Both the legislative (product liability or environment protection) as well as the customers (quality or safety expectation) provide highest expectations on the undiminished safety of these functions over the entire lifecycle.

Failures can occur at any time during the lifecycle in all possible condition. The environment in which a car can be used is quite broad. It reaches for example from temperatures of -40°C up to 125°C in the engine compartment. The applied architectures prevent that a first error in a function running on an electric control unit (ECU) is dangerous. In addition diagnosis is implemented in the ECU to detect a first error (e.g. broken components).

In case of a high risk classification a function redundant concept with independent controllers in the ECU architecture is chosen (lockstep concept). The correct processing of the controllers is monitored at many operating points by comparison, so that in case of deviations a possible failure state can be detected. This method can quickly and easily detect errors.

A hidden error in the ECU may occur. For this purpose, diagnosis measures are implemented to uncover these errors in time before a dangerous state occurs as a result of another error, without being revealed by diagnosis.

As part of the product development process (PEP) methods are used to avoid design errors. Also the operability of both the functions and the diagnosis is verified and validated. For this, a variety of methods and evidences are used. In the automotive industry the advanced product quality planning (APQP, Automotive Industry Action Group, USA) covers methods for the development process of engineering (like FMEA) and proofs with the production part approval process (PPAP, Automotive Industry Action Group USA) or the production process and product release (PPF, “Verband deutscher Automobilindustrie”, Germany) that fulfills the requirements. The PPAP includes environmental qualification results, like life time endurance or EMC tests. The qualification is assisted by industrial and organizational standards (ISO 16750-4). Also a yearly requalification (compare ISO 16949) during the series phase is required.

All these methods and tests ensure that the functions (or ECUs) are implemented flawlessly and with sufficient reserves against any environmental effects that are given from the outside.

It should be noted that today the used methods for design should consider all possible tolerances, circumstances and ensure the proper function. The product validation including also the requalification are carried out under the premise of a flawlessly implemented function. Due to temperature/aging/reliability effects, however, in the application hardware-related errors may occur that result in direct errors or reduce the robustness of the electronic control unit. As mentioned, error effects are identified and lead to safety-relevant reaction.

The loss of robustness of an electronic control unit can be examined under the influence of aging or environmental conditions, like temperature or different voltage level. In this work a methodology is described to support the hardware development phase on the one hand to reveal design weakness or to proof that the design fulfills the intended function in all environmental conditions and the needs of Functional Safety.

The new approach is to use a combination of aging FMEA and simulation models to design and validate circuits with special environmental aspects over the lifetime in conjunction with the needs of Functional Safety.

Keywords:
Functional Safety, aging effects, hardware-development, validation, VHDL-AMS simulation

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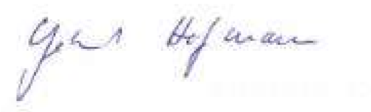
Declaration

I hereby submit for the examination and defense of doctoral studies at the Department of Applied Electronics and Telecommunications of the Faculty of Electrical Engineering at the University of West Bohemia in Pilsen. I declare that I have created this work independently, using the literature and resources listed, which is an integral part of it, and using legal copies of properly registered or freely available software. There are no sensitive or classified information subject to business secrets or requiring a special access regime. However, any use and application of these procedures and methods is possible only on the basis of the copyright agreement and the approval of the Faculty of Electrical Engineering of the University of West Bohemia in Pilsen.

In Pilsen on 15.9. 2018 M. Eng. Gerhard Hofmann



Glossary

ABS	anti-locking braking system
ASIL	automotive safety integrity level
DUT	device under test
E/E	electric/electronic
ECU	electronic control unit
E-GAS	electronic gas
EMI	electromagnetic interference
FEP	Fluorinated Ethylene Propylene
FMEA	failure mode and effect analysis
HIS	hardware interface specification
IEEE	institute of electrical and electronics engineers
ISO	international organisation for standardisation
PEP	product development process
PMHF	probabilistic metric for random hardware failures
PPAP	production part approval process
PPF	production process and parts approval
PSpice	PC form of Spice
RPN	risk priority number
SAE	Society of automotive engineers
SMD	surface mounted device
Spice	simulation program with integrated circuit
THT	through hole technology
VDA	Verband der Automobilindustrie e.V (= accociation of the automotive industrie)
VHDL-AMS	VHSIC hardware description language - analog mixed signals
VHSIC	very high speed integrated circuit

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1 Introduction /Motivation

Motivated by the climate discussion the main fields in the future automotive industry will be the introduction of electro mobility flanked with new technologies such as lithium-ion battery technology and lightweight components. Society aims at the reduction of motor vehicle accidents and requires new development of driver assistance systems toward autonomous driving and the increased networking of vehicles by Car-2-Car and Car-2-backend communication. The increase of these key functions is only possible by the use of more electrics / electronics (E/E). Studies show that up to 90% of the innovations in the automotive sector are only possible through the use of electronics and software[1]. This is partly possible because of the increased opportunities due to more powerful processors and sensors and, secondly, because of the ever-increasing use of software. Currently up to 90 control units[2] are fitted in a luxury car.

The complexity increase on the one hand faces an extremely high safety, quality and cost pressure on the other hand.

At the same time the share of recalls in the US in 2014 was at 34.1% in the field of electrics / electronics[3]. Therefore, the automotive industry is trying to find new development methods which support shorter development times, so that on the one hand the quality is high enough so that no safety risk arises for vehicle users and road transport and secondly, the testing effort remains affordable.

During the development phase, the focus is on the functional development. However, the range of diagnosis is important for areas such as the development, production and after sales in order to develop, manufacture and maintain the vehicle.

It is attempted in classic mechanical engineering to anticipate reality through virtual engineering before the creation of the vehicle. In electronics, especially in system and hardware development, the representation of reality is made possible by simulations. In the system as well as in hardware development simulation provides statements about the function and helps with the first investigations for example to find details for thresholds and tolerances.

In the course of this work, the consideration of the simulation is focused on the point of view of aging and Functional Safety. In conjunction with Functional Safety diagnosis plays an important role, because malfunction should be detected in time by diagnosis. A methodology will be introduced, that is aimed to test the compliance with safety goals by the use of aging models in the early phase of development.

The basic aim of this work is to combine the classic environmental factors, such as aging with the aspects of Functional Safety, through the introduction of a methodology based on the application of FMEA and VHDL-AMS simulation, and to define opportunities for a reasonable use. In the first step only simple electronic components are simulated so that it can be attempted to map the effects of environmental influences. In the second step a simplified model for the throttle valve of

[1] Compare http://www.springerprofessional.de/elektronik-und-software-beherrschen-innovationen-im-auto/5097588.html accessed on 30.12.2015

[2] Compare [Richter_2009], page 4

[3] Compare http://de.statista.com/statistik/daten/studie/224054/umfrage/gruende-fuer-das-zurueckrufen-von-fahrzeugen/ accessed on the 30.12.2015

an E-GAS is simulated and it will be investigated whether they have an impact on the Functional Safety at certain border locations or proof the compliance with the safety goal.

The work is partitioned as follows. In the first approach the state of the art is presented in chapter 2. It starts with the development process and a life cycle of a product in the automotive industry. It continues with a definition of mechatronic and an explanation of reliability including the Arrhenius equation. These are followed by the basics of Functional Safety, with the focus on hardware development. The conclusion of the basic part deals with the simulation and especially with a comparison of PSPICE, Matlab and VHDL AMS.

In chapter 3, the current problem situation and the derived goals are described in detail. In addition, the hypothesis that will alleviate the problem situation is presented. The chapter closes with an assessment of usability and relevance of the proposed methodology.

In the following chapter, the methodology of the work (chapter 4) and the proposed methodology (chapter 5) as well as the practical application on a throttle valve in the E-Gas (chapter 6) are shown. As part of the theoretical approach the mathematical equations for the aged model are described. In the practical approach a resistor as a simple basic component is modelled. This paper closes with a current conclusion and a forecast on the future work.

2 State of the Art

2.1 Product life cycle in the automotive industry

In the automotive industry, a typical product life cycle is divided into three main areas, which is shown in the next figure:

a) Product development process
b) Series production
c) Product life cycle of a car

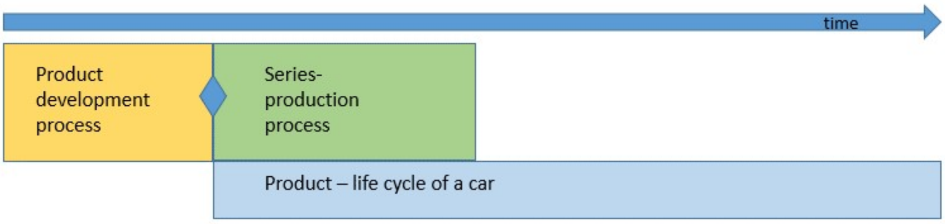

Figure 1 Product life cycle phases

The development process is divided into several phases (see next figure). In the definition of objectives, the vehicle targets, such as weight or consumption are defined. In the concept phase the architecture is specified and the specifications are created. In the series development a product is developed and validated by the various stages of construction. In the area of series startup the qualification of the production process and training of the personnel are carried out. With the start of production (SOP) the production of customer vehicles starts.

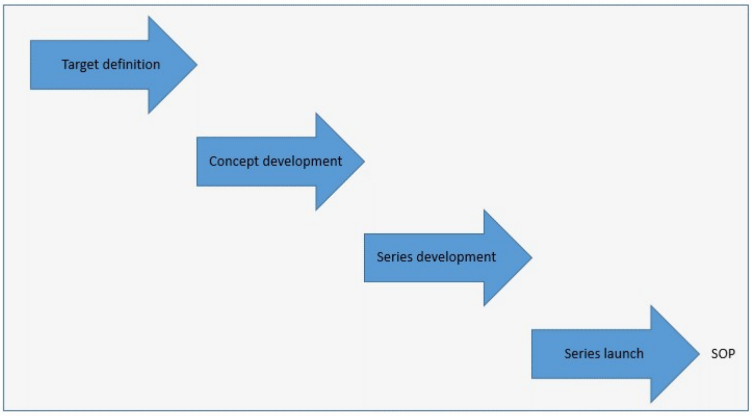

Figure 2 Reference model of the product development process[4]

The development process in Germany ends with a production process and product release (PPF). In VDA Volume 2, this objective is defined. "The PPF process provides before the start of series to prove that the agreed specifications fulfill the customer requirements (e.g. component specifications, drawings, standards, packing instructions, change status, color sample boards, capacity and flexibility) and other requirements (e.g. laws, standards)."[5] Specifically, the fulfillment of the environmental conditions is detected by specific environmental tests, this is often done with

[4] Compare [Schulz_2014] page 5
[5] [VDABd2_2012] translated from German, page 10

a small quantity (<25 units). In addition, there are only i.O. samples checked in an environmental test.

In mass production, which begins after start of production (SOP), vehicles for the customer are produced. It must be ensured over the test plan, that the vehicles meet all specified requirements. In terms of environmental tests and endurance tests a requalification is requested in the ISO 16949 certification[6]. The contents thereof shall be determined in accordance with the standards and the customer.

The product life cycle of a vehicle begins after the delivery to the customer. The standard LV 124 assumes a useful life of 15 years[7]. Producers are obliged delivering spare parts for more than 10 years after the end of series production. During the use phase, the electronic control units are exposed to a wide variety of stresses, such as vibrations, temperature changes or chemical stresses. These loads are trying to simulate environmental qualification tests. The scope of the tests is set in the LV124: 2010 - "Electrical and electronic components in motor vehicles up to 3.5 tons; General requirements, test conditions and tests". There you can find the possible temperature ranges, the extreme range is between -40C and 140C[8].

2.2 Mechatronic

“Mechatronics consequently uses the synergies from the interaction of the classic engineering sciences mechanical engineering, electrical engineering and information technology“[9] The following figure visualizes this definition.

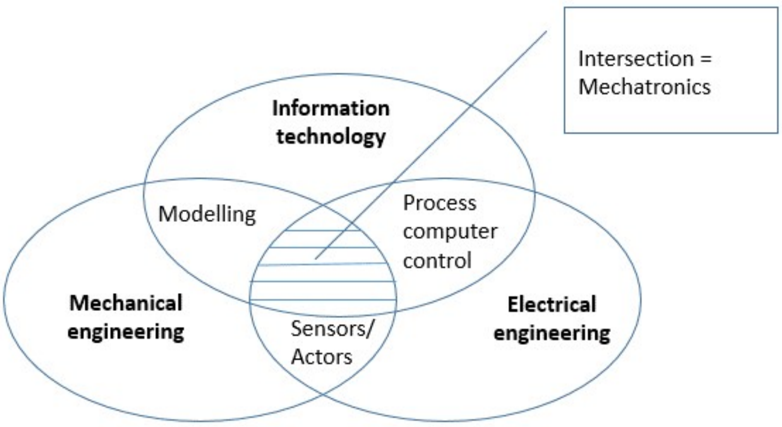

Figure 3 Mechatronics as intersections from different sciences[10]

The Intersection with all three disciples is the mechatronic. The intersection with only two disciples shows other competences. If you combine Sensors/Actors and process computer control you get

[6] Compare [ISO16949_2009] page 72
[7] [LV124_2010], page 65
[8] [LV124_2010], page 135
[9] [VDI2206_2004] page 10
[10] Compare [Heimann_2015] page 14

an automatic control system. A system is a picture of reality and describes it on the interfaces with information-, power- or material flow.[11] This approach is similar to the idea of entity in VHDL. Examples for automotive mechatronic components are the anti-brake system, modern headlamps and all the new driving assistant systems, which combine radar, ultrasonic and video signals to assist the car steering.

Mechatronics overcomes the differences of the different engineering disciplines by considering the different technical solutions on a system level with mathematic equation. For example a mechanical system with dampers and springs can be described with a differential equation, with a similar equation a LC Resonator can be described. The system can be described as a black box with input variables and output results. The transfer function models the system.[12] These properties are the reason why mechatronic systems are so suitable for simulation especially with VHDL.

2.3 Reliability and Arrhenius equation

Terms and definitions

2.3.1.1 Reliability

In daily life reliability is mostly present if there is an event of non-reliability, like a car break down. In the German DAT-report from 2017 the criteria reliability is - together with the price - the top criteria for used car buyers.[13]

For the term reliability exist several definitions:

- "Reliability is a characteristic of the item, expressed by the probability that it will perform its required function under given conditions for a stated time interval"[14]
- The term reliability is seen as part of quality and it can be described as quality over time.[15]
- In the DIN 40041 there is a hint that in the meaning of the standard the translation "dependability" is more precise than the term "reliability", because the term reliability has a focus on functionality and that the components survive over the life time.[16] In this work – the term reliability will be used in the meaning of Birolini.

As reliability is focused on a function it has to be cleared under which circumstances it should work. "Operating conditions have an important influence on reliability, and must therefore be specified with care."[17] Due to this requirement reliability is strongly linked to aging effects of the components.

Reliability is focused on the function – where safety is defined as "the ability of the item not to cause injury to persons, nor significant material damage or other unacceptable consequences during its use. Safety evaluation must consider the following two aspects: Safety when the item functions and is operated correctly and safety when the item or a part of it has failed. The first aspect deals with accident prevention, for which a large number of national and international

[11] Compare [Heimann_2015] page 16
[12] Compare [Roddeck_2016] page 8ff
[13] Compare [DAT_2017] page 22
[14] [Birolini_2014] page 2
[15] Compare [Linss_2016] page 1
[16] Compare [DIN40041_1990] page 2
[17] [Birolini_2014] page 3

regulations exist. The second aspect is that of technical safety which is investigated using the same tools as for reliability"[18]

In the recall statistic of the Federal Motor Transport Authority in Germany shown in the figure below there is a steady increase of recalls – which is an indicator that the product vehicle is affected by less reliability.

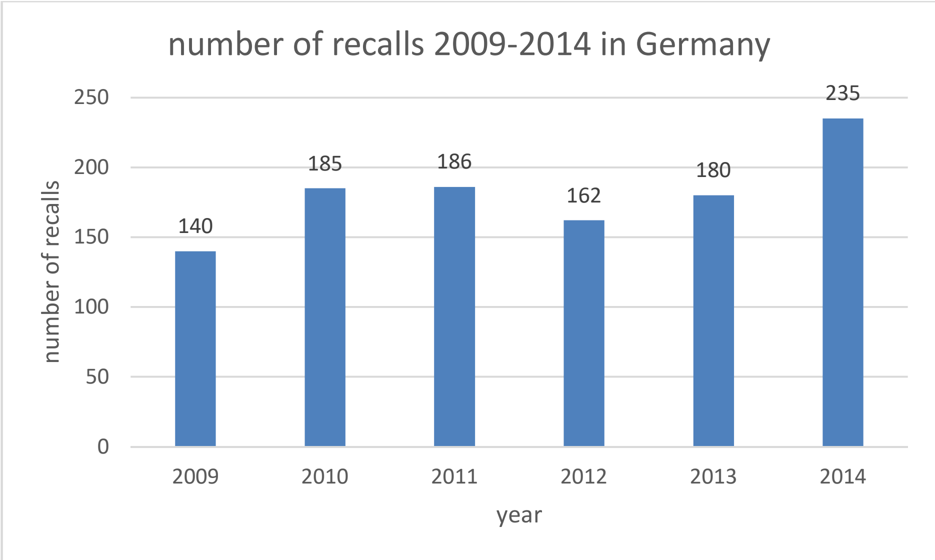

Figure 4 German recall statistic[19]

2.3.1.2 Fault, error and failure

In this work the focus is on hardware. With other words the big field of software quality and testing is not considered.

The German language is ambiguous with respect to the term error - in English, there is the distinction is visualized in the next figure.

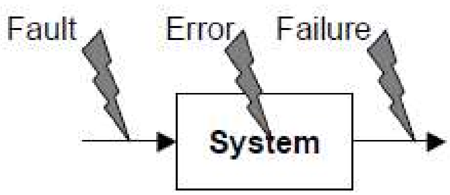

Figure 5 Meaning of fault, error and failure[20]

The term **fault** describes the root cause. The fault causes an **error** in the system that is visible in the system. This error results in a so called **failure** in the expected output.

[18] [Birolini_2014] page 9
[19] https://www.kba.de/SharedDocs/Publikationen/DE/Jahresberichte/jahresbericht_2013_14_pdf.pdf?__blob=publicationFile&v=5 page 63
[20] Compare [Benz_2004] page 28

Further it is distinguished between **systematic** and **random** failures. A random hardware failure is a failure "that can occur unpredictably during the lifetime of a hardware element and that follows a probability distribution"[21] and a systematic failure is "related in a deterministic way to a certain cause, that can only be eliminated by a change of the design"[22] The benefit of the new methodology is to minimize systematic hardware errors with the aspect of aging.

Further failures can be distinguished when they occur. The sum of all failures looks like a bath tub. Over all areas are random failures possible. The increase shortly after the beginning is often caused by assembly failure, and the increase in the last segment is often caused by wear out and aging effects. The curve in the blue area below is called the bath-tub diagram (shown in the figure).

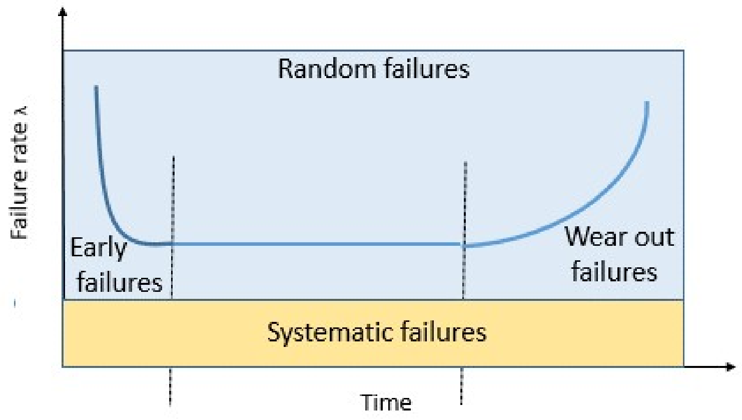

Figure 6 Bathtub diagram[23]

Reliability testing

During a design project so called qualification tests are required. The idea behind these tests is to shorten the test time by increasing different stress factors. "A qualification test includes characterization at different stresses (for instance, electrical and thermal for electronic components), environmental tests, reliability tests, and failure analysis."[24]

In the automotive industry it is required at the end of a design project to proof that electrical components pass the required qualification test. This has to be confirmed in the production process and product release (PPF) according the VDA Standard 2. Also the big German car manufacturers agreed on a common qualification standard LV 124 " electric and electronic components in motor vehicles up to 3.5t – general component requirements, test conditions and test"[25] Also the family of the IEC 60068 describes the different conditions and tests.

Technically the function and the location inside the car determine the temperature range and the conditions of the test. The focus of the test is on reliability. The life time endurance test shortens the test time on basis of the Arrhenius equation.

21 [ISO26262_2011] part 1, page 13
22 [ISO26262_2011] part 1, page 17
23 Compare [Eberlein_2014] page 12
24 [Birolini_2014] page 81
25 [LV124_2010] - https://wenku.baidu.com/view/68967ff9fab069dc502201fe.html accessed 30.04.2018

2.3.1.3 Arrhenius equation

Basis for the acceleration is the Arrhenius equation. "The device-to-be-tested consists of electronic components, whose reliability is believed to be influenced mainly by temperature, vibration and humidity."[26]

The Arrhenius equation is

$$v = v_0 e^{\frac{-E_a}{kT}}$$

v rate coefficient,
v_o: pre-exponential factor,
Ea: activation energy in [eV]
k: Bolzman gas constant (Bolzmann = 8.617x 10-5 eV/K)
T: thermodynamic temperature in [K].[27]

The pre-exponential factor can be considered as the factor which is needed without accelerating with a temperature increase. In case you do not start from absolute zero temperature you have a starting state temperature at T_{normal} and a test temperature at T_{test}. Further assuming that there is a linear time dependency between normal state and test state, than the following equation is valid.

$$v_{normal} t_{normal} = v_{test} t_{test}$$

Out of these equations you can calculate the acceleration factor

$$\frac{t_{normal}}{t_{test}} = \frac{v_{test}}{v_{normal}}$$

Defining the accelerating factor A – you get the following equation

Accelerating factor A = $\frac{t_{normal}}{t_{test}} = e^{-\frac{E_a}{k}\left(\frac{1}{T_{test}} - \frac{1}{T_{normal}}\right)}$[28]

For the activation energy the value for a resistor is chosen with E_a=0,56eV (see table below)

Component	Activation Energy /eV
Transformer	0.5
Capacitor	0.6
Resistor	0.56
Diode	1.5
Triode	1
MOS Device	1.2
Charge-coupled Photodiode	1

Table 1 Activation energy of electronic components[29]

[26] [Qi Li_2015] page 1
[27] Compare[Birolini_2014] page 329
[28] Compare [Birolini_2014] page 330
[29] [Qu Li 2015] Table I – page 2

As an example the usage temperature is 30°C and the test temperature is 150°C and the activation energy for a resistor is used with 0,56eV – the acceleration factor is approximately 436. If we assume a lifetime in a car is 15 years (≈131400h) than the minimum simulation time is $\frac{131400h}{436} = 301h.$

The existing publication which mention the usage time of an engine is between 2300h and 3400h – so for our simulation 2000h (approximately 2,8 months) were chosen.[30]

2.4 Aging behavior

General aging mechanism for passive components

In the literature there are different standards for aging. Unfortunately they deal with plastic material like the DIN 50035. There aging is defined as the sum of all irreversible chemical and physical processes inside the material over time. [31]

In order to reduce complexity the simplest electronic component was chosen to develop the new methodology, a resistor.

Aging Behavior of resistors

A resistor is a component which follows the ohm's law R = U/I. The main characteristics of a resistor are:

The resistor value R in ohm.
The power dissipation in Watt.
The tolerances of the nominal value in %.
The temperature coefficient in ppm/Kelvin.
The stability over time is the parameter which is mainly important for aging. In data sheets there are for example high temperature exposure in % mentioned.[32]

There exist different designs with

- the wire wound resistor for high power consumption
- the carbon film resistor as a low cost version and tolerances from +/-5%
- the metal film resistor for higher precision with tolerances up to +/- 1%

Further it is distinguished how the resistor gets mounted. The main types are the through hole technology (THT) and surface mounted device (SMD) types.

If the resistance layer has a size between 5µm and 50 µm the resistor is called a thick film resistor. If the layer is smaller than 5µm it is called a thin film. The thick film resistors are mainly used for higher resistance values.[33]

[30] Compare https://www.tqu-group.com/we-dokumente/Themen/dokumente_themen/Zuverlaessigkeit.pdf?r=249418510 accessed on 30.04.2018 page 5 lifetime for an engine
[31] Compare [DIN50035_2012] page 3
[32] Compare https://www.vishay.com/docs/30099/wsl3637.pdf accessed on 05.09.2018
[33] Compare [Stiny_2015] pages 38ff

In Forlani's paper "Electrical Conduction by Percolation in Thick Film Resistors," he describes a phenomenon that the resistance is a nonlinear function of the temperature, but he does no further research on time dependencies.[34]

In a paper over thin film resistors the stability in a 2000 h Test at 125°C is mentioned in a table. The exact values can be seen in the table below. Unfortunately only the end result and not the trend is mentioned.

Table 2 Stability range of different resistor types[35]

	Discrete carbon film resistor	Discrete metal film resistor	Thin film resistor
Stability (2000h, 125°C) in %	0,5..5	0,2…0,5	0,1

In another paper from deMay the influence of pulsed power dissipation is investigated and he shows there that an aging effect is observed after 20 weeks. The probe A was only DC powered, the probe B was pulse powered and air cooled, the probe C was DC powered and liquid cooled and the probe D was pulse powered and liquid cooled. The results of the measurement are shown in the figure below. [36] Here a linear aging behavior is visible.

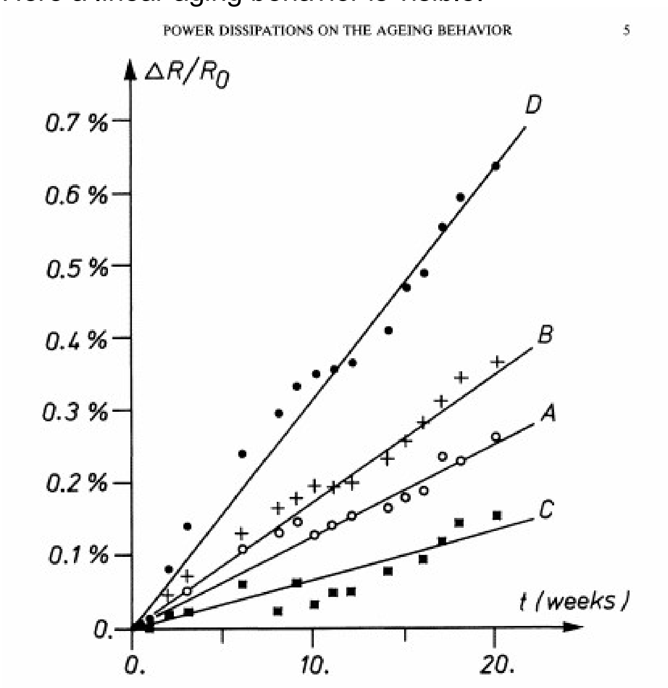

FIGURE 3 Ageing behaviour of 4 set of thick film resistors. A: DC power and air cooling. B: pulse power and air cooling. C: DC power and liquid cooling. D: pulse power and liquid cooling.

Figure 7 Aging behavior of 4 sets of thick film resistors[37]

[34] Compare [Forlani_1976]
[35] Compare [Heywang 1975] page 62
[36] [deMey_1993] page 6
[37] [deMay_1993] page 5

The physical reason for aging dependencies lies in an internal behavior. “Stress relief, internal oxidation, and perhaps precipitation are dominant mechanisms in producing resistance change”[38] There is not a general formula which describes these mechanisms.

2.5 Functional Safety

Basics

“The ISO 26262 treats Functional Safety of electrical / electronic systems for motor vehicles with a gross vehicle weight up to 3.5 tons. The standard covers all aspects of a product's lifecycle. The analysis starts with the so-called "Item Definition". As part of a hazard and risk analysis an "Automotive Safety Integrity Level (ASIL)" assignment for the functions described in Item definition occur. The ASIL classification takes into account the **severity**, which can be caused by the consequences of a possible accident, the probability of the driving situation in which the hazard may occur due to an error, considered under the aspect **probability of exposure** and the **controllability** by the driver. Starting from the ASIL classification, the standard requires the creation of a safety concept including safety goals (Part 3). In Part 4, the methods needed for system design are presented. Part 5 deals with the hardware development. The requirements for the software development are presented in Part 6, depending on the ASIL classification. The areas of production, operation and decommissioning are dealt with in part 7. In part 8 supporting processes such as requirement-, configuration- or change management are described. In part 9 a safety analysis is presented and in part 10 a directive on the application of the standard is given.” [39] Actually the valid ISO 26262 from 2011 gets updated. In the 2nd edition are also a part 11 for motorcycles and a part 12 for semiconductor planned. For trucks and buses is no separate part – they changes to adapt the standard are done in the existing parts. So the limit to 3.5 tons is in the new edition invalid.[40]

The corresponding relations of the individual part of the current ISO 26262 are shown in the next figure.

In principle, the concept phase is starting with the item definition. Than the hazard and risk analysis is performed and the ASIL classification is determined. The safety goals are derived, which are implemented in a Functional Safety concept. The concept provides the Functional Safety requirements, from which the technical safety concept is developed. Depending on the ASIL classification the individual requirements of the various processes and the system design are derived.

[38] [Best_1964] page 63

[39] Compare [Hofmann_2015a] chapter 2

[40] Compare https://www.elektronikpraxis.vogel.de/update-zur-iso-26262-funktionale-sicherheit-fuer-strassenfahrzeuge-a-563904/ accessed on 12.09.2018

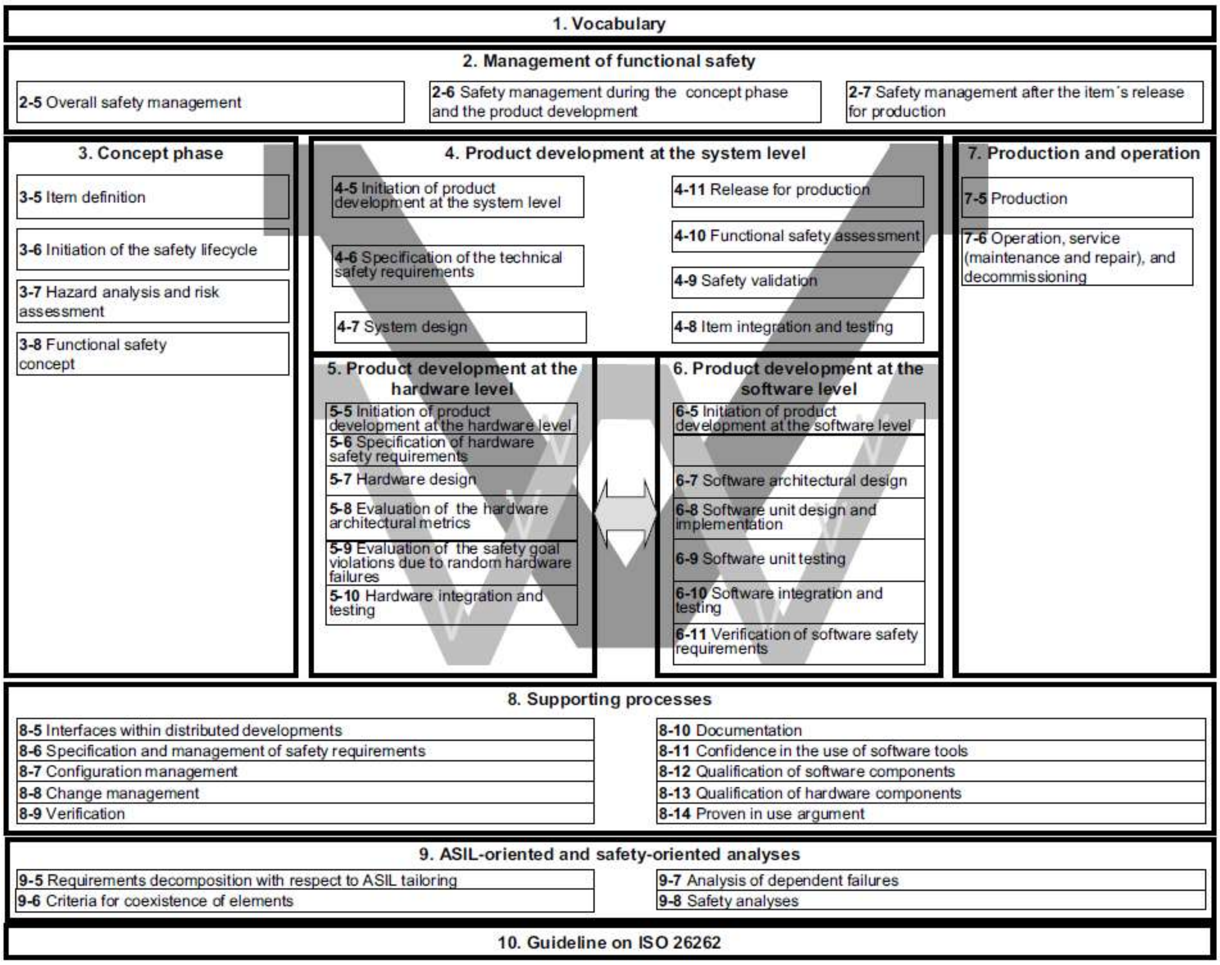

Figure 8 Content of the ISO 26262:2011[41]

Product development at the hardware level

2.5.1.1 General

The ISO 26262 part 5 “deals with the "product development at hardware level". Starting from the safety plan (ISO 26262 part 4) a "planning of hardware-specific activities"[42] becomes necessary. In clause 5 three main activities are enumerated:

- “the hardware implementation of the technical safety concept;
- the analysis of potential hardware faults and their effects; and
- the coordination with software development.”[43]

Based on a technical safety concept (ISO 26262 part 4) hardware safety requirements are derived. Starting from there evidence must be found that the hardware safety requirements are complied with. This is carried out through metrics for the hardware architecture (clause 8) and on the

[41] [ISO 26262_2011] part 5, page vii
[42] [ISO 26262_2011] part 5, page 3
[43] [ISO 26262_2011] part 5, page 4

estimation that random hardware faults lead to a safety hazard. Two methods are described for the safety hazard: first, whether the safety goals specified in part 3 are achieved or, as described in the standard as objective, "the residual risk of a safety goal violation, due to random hardware failures of the item, is sufficient low". The first method uses a rating based on failure rates metric, called "probabilistic metric for random hardware failures (PMHF)" The second method evaluates each single-point failure, residual failure and related dual point failures. … For this purpose, proof is provided that a single fault does not exceed the thresholds of the standard. The residual risk of a failure is evaluated by considering "the occurrence of a fault and the efficiency of the safety mechanism". The occurrence is expressed with a failure rate class and the efficiency of safety mechanism is expressed by diagnosis coverage. Dual point failures are evaluated similar to residual faults, with different limits. Part 5 closes with requirements on the hardware integration and testing." [44] The relation of the single clauses is shown in Figure 9 Content of ISO 26262 part 5 requirement for the hardware.

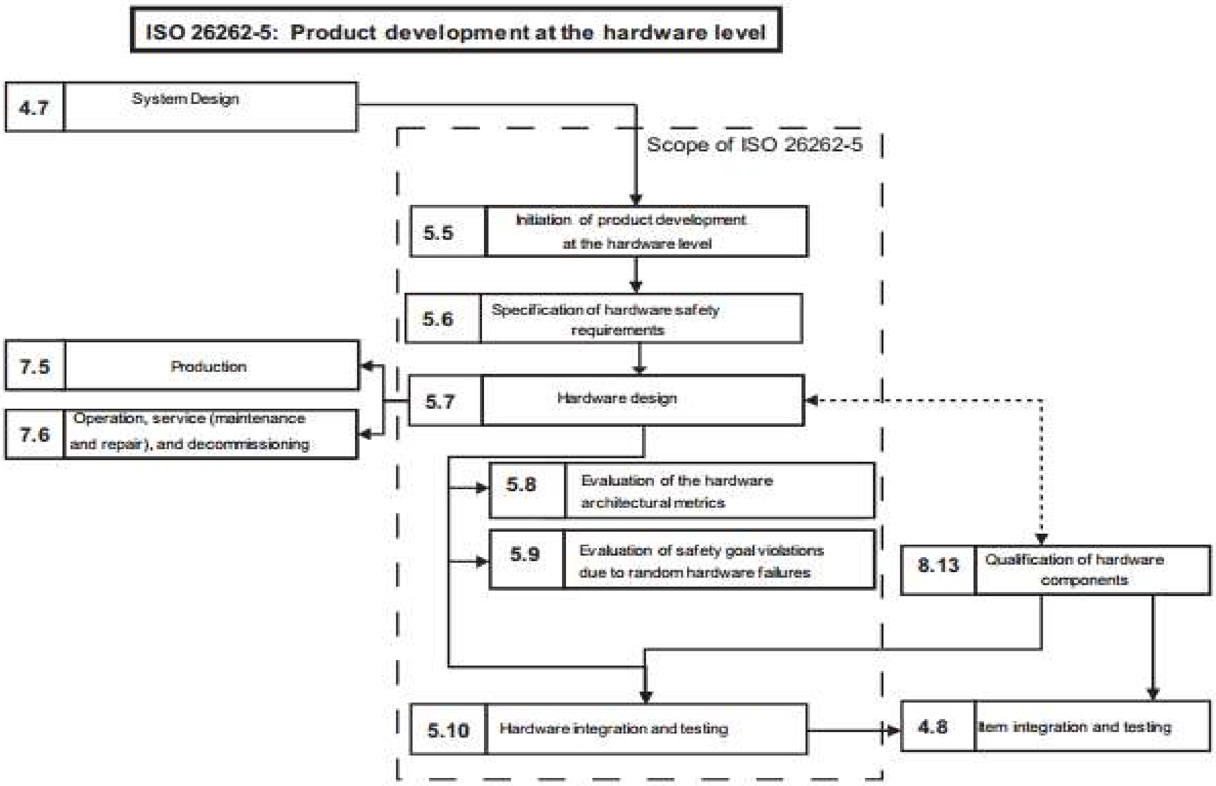

Figure 9 Content of ISO 26262 part 5 requirement for the hardware[45]

As part of the hardware integration, the ISO 26262 mentions functional testing, fault injection testing and electrical testing[46]. In the current integration test under the footnote it is mentioned, that fault injection is difficult on a hardware product level. In table 12 "hardware integration tests to verify robustness and operation under external stresses" of the standards "environmental

[44] [Hofmann_2015b] chapter IIB

[45] [ISO 26262_2011] part 5, page 4

[46] Compare [ISO 26262_2011] part 5, page 28

testing with basic functional verification" [47] is mentioned. Here is the reference to the ISO 16750-4 standard "Road vehicles - Environmental conditions and testing for electrical and electronic equipment - Part 4: Climatic loads"[48] This, however, is aimed at the proof of real experiments with a small sample size.

An indication of effects of environmental conditions is already given in the ISO 26262 "The criteria for design verification of the hardware of the item or element shall be specified, including environmental conditions (temperature, vibration, EMI, etc.)" [49]. As the pure evidence of the real pattern is not enough, the approach of this work is to reflect the aging influence in a simulation.

2.6 Simulation

In recent years, the usage of simulation models has increased significantly by the increased computing power. Simulation models try to represent an image of reality and are used when a real test is impossible, too expensive or because the large number of variants is not feasible.

The simulation models attempt to represent an image of the real system. For this purpose it is necessary in some places to simplify.

There are two approaches to develop models. The first attempt is based on an analytical model. Here a mathematic description of reality exists, like energy conservation or the Kirchhoff'sche laws. The second approach is to perform experiments and transform the collected data in a mathematical description, this is the so called experimental model [50]

The objective of simulations is to get better results in a faster way. "Simulation can shorten time of development, because only few optimal variants need to be validated and loops of hardware development can be avoided"[51].

Basics

Simulations can be performed on an abstract level of the system description. It is called **black box** testing, if only the system boundaries and the system behavior are known, but not the realization within the system.

In contrast, the **white box** tests represent the concrete realization of the system. This work falls under the white box testing, because a detailed circuit design already exists.

In the automotive sector both **hardware in the loop** (HIL) testing as well as **software in the loop** (SIL) tests are performed. In HIL tests a real control unit is operated in a virtual environment and in SIL tests the software is tested in a real environment, but not yet on the final hardware but mostly by an emulator. If neither the controller nor the environment is real, you call it a **system simulation.** In this work, only a system simulation is used. The delimitation of the various simulations is shown in the next figure.

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[47] [ISO 26262_2011] part 5,page 29
[48] [ISO16750-4_2010]
[49] [ISO 26262_2011] part 5, page 7
[50] Compare [Heimann_2015] page 20
[51] https://www.cst.com/content/events/2015automotive/Electromagnetic-Compatibility-Simulation.pdf accessed 17.12.2015, page 8

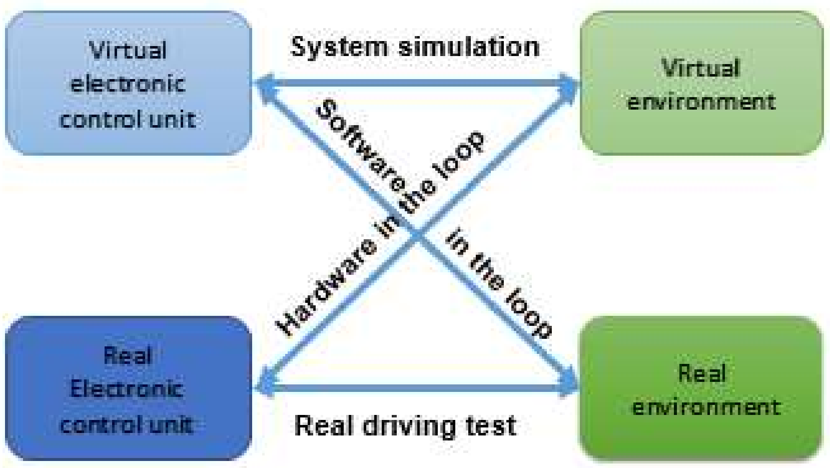

Figure 10 HIL, SIL and system simulation[52]

Simulation is also required as a method from the ISO 26262 to verify the hardware compliance, where an analytical method is not sufficient.[53]

There are different ways to simulate electronics. The three most common tools are PSpice, Matlab and VHDL-AMS simulators.

PSpice

PSpice is a simulator for analog and digital electronic circuits. "SPICE is a general-purpose circuit simulation program for nonlinear DC, nonlinear transient, and linear AC analyzes"[54] PSpice is further developed for the PC form of SPICE (simulation program with integrated circuit emphasis) which was developed at the University of California in mid-seventies. Accountable for the success of PSpice is on the one hand the availability in the public domain and on the other hand, that it was established quite early as an industry standard. SPICE calculates the circuit using nodal analysis. [55]

An application frequently used by PSpice is by the company Orcad[56], which consists of a Schematic Editor (capture), the simulation kernel (PSpice) and the result visualization tool (probe) together. [57]

[52] [Diermeyer_2008] translated from German page 19
[53] Compare [ISO26262_2011] page 12, table 3
[54] Translated from German http://www.eecs.berkeley.edu/XRG/Software/Description/spice2g6.html accessed on 07.02.2016
[55] Compare [Schulte_1995] page 1ff
[56] Compare http://www.orcad.com accessed on 07.02.2016
[57] Compare [Beetz_2008] page 7

Matlab and Simulink

Originally Matlab was developed by Cleve Moler in the late 1970s as a mathematical technique or exercise tool on a public domain basis. Mathworks transformed Matlab in a powerful engineering tool.[58] Nowadays Matlab und Simulink are products of the company Mathworks.[59] They are used for numerical handling of technical systems which can be described with vectors or matrices.[60] Simulink is a state flow oriented simulation environment and the script language of Matlab helps to solve technical systems which can be described with differential equations.[61] “Matlab is a numeric computation software for engineering and scientific calculations. Matlab is primarily a tool for matrix computations”[62]

VHDL-AMS

VHDL-AMS is a standardized description language by the IEEE "for digital, analog and mixed signal applications"[63]. It "support(s) the description of both behavior and structure"[64] Analog and digital circuits can be described, but also complex systems from other areas of physics, such as the mechanics or thermodynamics. VHDL-AMS is the abbreviation for "VHSIC Hardware Description Language - Analogue and Mixed Signal, and VHSIC for Very High Speed Integrated Circuit"[65]. The official name is IEEE 1076 which was published in 2009 under IEEE 1076-2008[66] is used. “The VHDL language was defined for use in the design and documentation of electronics systems. “[67]„It uses differential algebraic equations to describe different systems[68].

VHDL AMS allows a top-down approach. It can be described at a system level (high abstraction level), without knowing the details already. For this purpose, in the so-called **entities** the interfaces are specified. When a detailing of the function is happening in the continued later development process, this can be mapped in the **architectures** further in a refined or detailed way. This approach is similar to the idea of mechatronic with the information-, material- and power flow – where the entity specifies the interface and the architecture – behavior of the system inside.

The functionality in the architectures can either be described by the structure or the behavior. "It may be coded using a structural style of description, a behavioral style, or a style combining structural, and behavioral elements." [69]

With the modular design it is also possible to reuse the models and thus to create a comprehensive simulation environment and libraries.

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[58] Compare [Gander_2015] page xiv
[59] Compare http://de.mathworks.com/products/matlab/ accessed on 07.02.2016
[60] Compare [Pietruszka_2006] page V
[61] Compare [Pietruszka_2006] page VI
[62] [Okyere_1995] session 2c6
[63] [Christen_1999] page 1263
[64] [Christen_1999] page 1263
[65] [Herve_2006], page XV
[66] Compare [IEEE1076_2009] page IV
[67] [IEEE1076_2009] page 1
[68] Compare [Christen_1999] page 1264
[69] [Christen_1999] page 1264

“Ideally, models of later development phases are built up on models of earlier phases. Implementable specifications which in early development phases roughly describe the function of a system can be used for example for building up more detailed behavior models. Behavior models may be precepts for the geometrical configuration or else for software algorithms. It is appropriate for this so-called ”universality“ to be retained over all development phases up to the final system.”[70]

The following figure is an easy example (entity and architecture) of a VHDL-AMS Model for a resistor.

```
library IEEE;
use IEEE.ELECTRICAL_SYSTEMS.all;
use IEEE.std_logic_1164.all;

entity test1 is

  generic (
    r: RESISTANCE := 100.0
  );
  port (
    terminal e1: ELECTRICAL;
    terminal e2: ELECTRICAL
  );

end entity test1;

architecture default of test1 is

  quantity v across i through e1 to e2;

begin

  v==r*i;

end architecture default;
```

Figure 11 Simple VHDL AMS Model of a resistor

[70] [VDI2206_2004] page 47

Conclusion

According to Reisch he divides simulation tools in three categories in process and partssimulation, in circuit simulation and logic simulation. In the following figure the three categories are shown

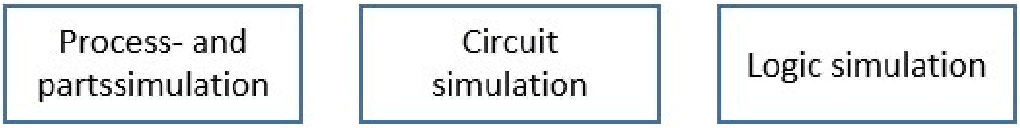

Figure 12 Categories of simulation tools [71]

In this categorization PSpice is more in the area of circuit simulation. Matlab is more in the field of the logic simulation and with VHDL – AMS it is possible to cover all categories.

Also inside VHDL Model – Pspice models are useable. Some component manufacturers provide SPICE models like TDK.[72]

For the further research the parts simulation with VHDL-AMS is focused on, because it is very structured and also flexible with the coding options. Also it can be used either with electronic circuits or other physical areas, like thermodynamic and it also provides the possibility to start with a black-box simulation and go further into details.

Simulation types

There are various types of simulation in this study; the transient simulation is used for aging simulation.

2.6.1.1 Transient simulation (aging and temperature)

In a transient simulation, the simulation is carried out over time, i.e., the described parameter changes over time. There are key parameters, such as resistance value or temperature changes over time.

In contrast to the transient simulation, there is the frequency simulation. Here the parameters will not be varied over time, but over frequency, this is specifically important in the signal processing and in the design of filters.

2.6.1.2 Different starting conditions (Tolerances)

In these simulations, a transient simulation is started, but each with different starting conditions. The variations of the initial conditions (t = 0) are performed by different component values within the tolerance band.

[71] [Reisch_2007] translated from German, page 5
[72] Compare https://product.tdk.com/info/en/technicalsupport/tvcl/general/mlcc.html accessed 18.09.2016

The "Monte Carlo method usually works with statistical uniform distributions, this means the respective next sampling is done independent of the previous results with equal probabilities." [73] The Monte Carlo algorithm is also one of the stochastic optimization methods.

[73] [Klüver_2012] translated from German, page 71

3 Problem description

3.1 Target

Circuits in the automotive industry must be designed in a way that they remain functional in all conditions despite physical stress over lifetime. To ensure this, in the automotive industry, an environmental validation with real sample parts in the development phase serves as state of the art (see ISO 16750-4). The validation is normally executed in a late design phase, when stable samples are available.

As the standard ISO26262:2011 for Functional Safety in the automotive sector was published in 2011, the qualification processes have been originated in a time when Functional Safety has not been a big issue in the public debate.

This thesis is concerned with the introduction of a simulation-based design and analysis methodology, which focuses on the aging influence, aligned at an early stage of development with focus on safety goals of Functional Safety.

The idea of this work is to develop a simulation-assisted method, by means of which a threat to the safety goal can be detected or ruled out. Especially, the change of electrical properties is considered via aging, and it is investigated whether mechanism of diagnosis can be bypassed or give a false failure.

The simulation-based approach is designed to reduce the uncertainties related to the environmental validation. Based on the results of the simulations a circuit adjustment can be carried out even at an early stage.

In the design process the balance between creativity and structured approach is needed to find technical solutions. Especially in safety relevant developments it is necessary to follow a structured approach. The developed methodology in this work should contribute to the structured approach of using simulation in a design phase to reach certain safety goals.

3.2 Hypothesis

Especially in the automotive field, the components must be designed for more than 15 years of durability and be exposed to stresses and strains such as vibration, temperature variations or humidity changes.

During the product development process an environmental validation is carried out as part of the validation. Here, the temperature range is dependent on the defined design space and an inspection plan is created. As part of this real testing for example 25 modules are exposed to the environmental conditions, and evaluated in terms of the function.

In the context of this test no conscious testing of electronic components on their tolerance limit is carried out, so that from the results of these tests a 100% conclusion cannot be provided on the function over all. The statement is also supported by the studies on the subject of analog EMI. "EMI-related aspects of Functional Safety cannot be verified of solely by the traditional approach to EMI"[74]

[74] [Armstrong_2006] page 472

The idea relies on the hypothesis that environmental validation is carried out with OK samples, although derived originally from a series production, but do not constitute limiting positions. To avoid negative validation results a methodology is proposed to use simulation in an early development phase to evaluate the limiting parameters. Limiting parameters can be caused by tolerances and physical effects, like temperature or aging mechanism. Tolerances are specified by the data sheet. Some models exist for temperature simulation, but there is a lack of models which describe aging effects.

As part of this work an attempt is made to proof that through an aging simulation, a contribution can be made to reduce the uncertainty with respect to the aging loads and Functional Safety in an early development phase.

3.3 Usage and relevance

As more and more electronics are applied in automobiles enhanced in safety-related functions, sufficient means of compliance with the safety requirements of the overall product life cycle is needed. The method of combining electrical simulations with aging simulations represents a further aspect of the product lifecycle in the simulation.

Due to the increased possibilities of computer technology and the development of VHDL-AMS simulators, it is possible also to indicate this combination.

An aspect for 100% virtual experiments is that it can be used at an early development phase.

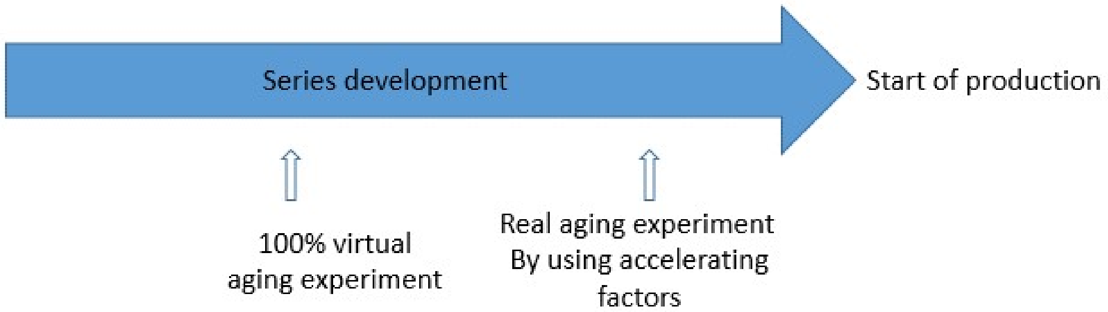

Figure 13 Comparison between time of simulation and real experiment

Since the simulation can be used at an early stage of the project, necessary hardware corrections can be applied easier and less expensive. The benefit is difficult to quantify in monetary terms, however, but is considerable due to the “rule of ten”. This study indicates that the later an error is detected, the higher the costs, concretely the cost of a development stage to the next increasing by the factor of 10. [75] The next figure shows the principle of the rule of ten.

[75] Compare http://www.sixsigmablackbelt.de/fehlerkosten-10er-regel-zehnerregel-rule-of-ten/ accessed on 15.08.2016

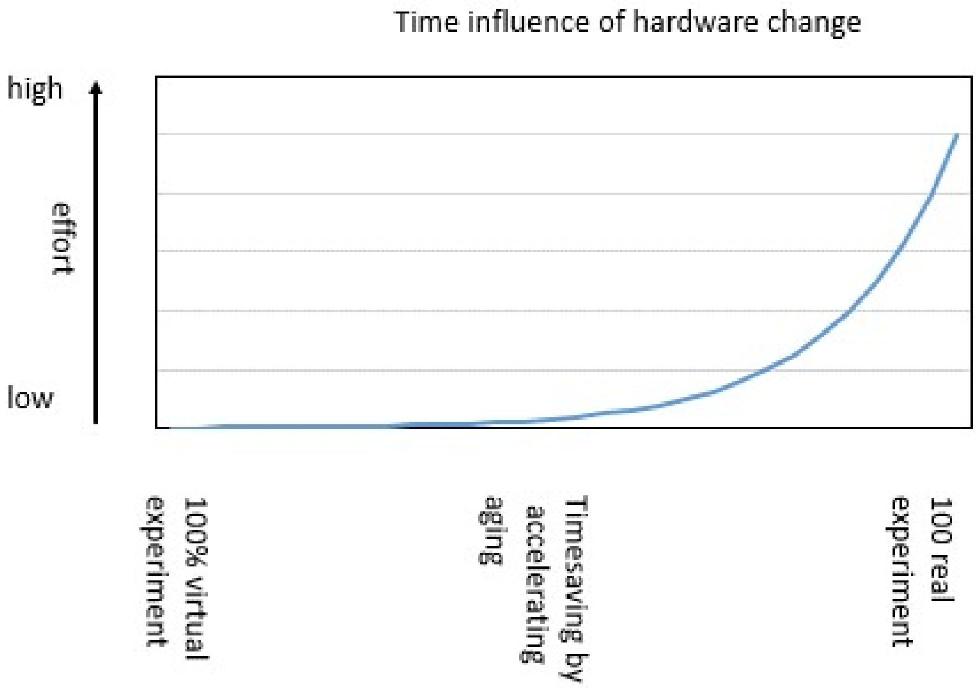

Figure 14 Time influence to effort of hardware change

Additionally the usage of a simulation can be used as documentation that all efforts have been made to avoid failures.

The relevance is not only to avoid critical situations due to malfunctions, but also to avoid false failure which can lead to switch in a safe state and reduce the system availability if not needed.

So using 100% virtual aging experiments causes time and cost benefits.

4 Methodology of work

As part of this work a methodology using VHDL-AMS models to evaluate aging effects of electronics in the automotive industry for safety relevant failures is developed and examined. The goal of the method is to find threats for safety goals and to prove or optimize diagnostics mechanisms.

In particular in this work only aging-dependent hardware events are considered. In contrary redundant architectures or software circumstances are not inside the scope of these investigations, this may be a consequence if the methodology shows a risk.

Out of the theoretical considerations of the requirements of the standards VDI 2221 “methodology for development and construction of technical systems and products”, VDI 2206 “design methodology for mechatronic systems” and the ISO 26262 “road vehicles - Functional Safety processes of Functional Safety” the new methodology is developed. The development and discussion of the proposed methodology is introduced in chapter 5.

According to the normative standards of the ISO 26262 “road vehicle- Functional Safety” a hazard and risk analysis for the under investigation functions is performed. This includes the establishment of safety goals and deriving the functional and technical safety concept. The chosen technical concept leads to a solution according to the risk level. This solution meets the minimum requirement for the individual first errors in combination with the accepted residual failure probability. This is discussed on an example in chapter 6.2.

As prioritization a failure mode and effect analysis (FMEA) focused on aging is used. An example is shown in chapter 6.3.

A core element of the new methodology is using VHDL-AMS models to design hardware circuits in the automotive industry for safety relevant functions in combination with aging effects. As breakthrough milestone for this methodology, is the implementation of a VHDL-AMS model with aging effects required. Here the challenge is to program the simulator to deal with the duration to be simulated.

To prove the methodology a simple passive component like resistor is used. The physics behind aging is not in the scope of this research. Measurements are performed to find suitable equation about aging behavior. The focus in this work is in transferring the available results in VHDL-AMS models. The current state of a resistor model is included in the chapter 6.4. This model is only the basis to show that the proposed methodology can be applied on a simple test circuit. To enable simulations for an industrial purpose additional aging models have to be created in VHDL-AMS previously which simulate the lifetime behavior, but this is not content of this thesis.

To confirm and refine the developed methodology a bottom-up approach is chosen. In the context of this bottom-up approach, a selected throttle valve sensor out of the E-Gas concept is examined by a hardware simulation to the effects of a relevant aging range. The foundations for the E-Gas functionality including the considerations for safety goal of Functional Safety are presented in chapter 6.5.

This work is no basic research for aging and simulating – the focus is on developing and proving a new methodology.

5 Proposed methodology

This chapter is about the idea of the proposed design methodology using VHDL-AMS to consider aging effects in automotive mechatronic circuits for safety relevant functions. In this chapter it is shown how the new methodology is derived and composed from existing standards. Finally the new method is introduced and explained.

5.1 Deriving new design methodology

General development methodology according to VDI 2221 and VDI 2222 Bl1

The methodology of the VDI 2221 is based on the general problem solving process. Further the the methodology is applicable to all phases in the life cycle.[76]

One basic principle of the VDI 2221 is to structure in single problems and solutions, which can be solved in parallel.[77] In the context of this work the aging aspect is a special area which can be considered separately.

Further the problem solving process should be divided in phases, the proposal of the VDI standard is "from the abstract or general to the detailed and special one."[78] In the context of aging it means that a technical concept should be done in general – and when the components are decided it should be proven, that the safety requirements are still fulfilled. In case it is not fulfilled an improvement process is required.

[76] Compare [VDI2221_1993] page 3
[77] Compare [VDI2221_1993] page 4
[78] Translated form [VDI2221_1993] page 5

Also the standard states that the choice of the methods is dependent on the task and preferences of the personal[79] - in other words it gives the developer freedom in the choice of methods.

A general methodology is described. For this reason the process of the 4 phases is further detailed in 7 steps (see figure below):

1. Clarification and definition of the problem
Objective of this step is to clarify the requirements and add missing aspects, like production or after sales. The working product is a requirement list from the designers view.

2. Determination of functions and their structures
In the second step the functions have to be described and how they can be structured. The result is a formal (meta language) or informal (normal language) functional description.

3. Search for solution principles and their structures
In the next step the physical or chemical approach for a solution has to be determined. The result is a principle solution.

4. Dividing into realizable modules
Further the principle solutions get structured in submodules. The working products of this phase are realizable modules and clear interfaces.

5. Form design of the most important modules
The following step is a concretion of the modules – where the material and dimension are determined. The results are preliminary design.

6. Form design of the entire product
In this step the final determination for the design is made. The result is the overall design for the product.

7. Compilation of design and utility data
The final step serves for the product documentation. The output of this step is a complete documentation, which include for example a bill of material or a drawing.[80]

In dependency of the complexity and results the steps may be done more often and the steps can be grouped according to the subject in four phases. These four phases can be:

a) Planning phase

b) Conceptual phase

c) Design phase

d) Elaboration phase[81]

[79] Compare [VDI2221_1993] page 5
[80] Compare [VDI2221_1993] page 9ff
[81] Compare [VDI2221_1993] page 9

The VDI 2221 describes the general procedure. The VDI 2222[82] is a supplement and goes in details from step 1 to 3 and the VDI 2223[83] goes in details from step 4 to 7.[84]

In the following figure the general procedure and the relationship of the three VDI standards are visualized.

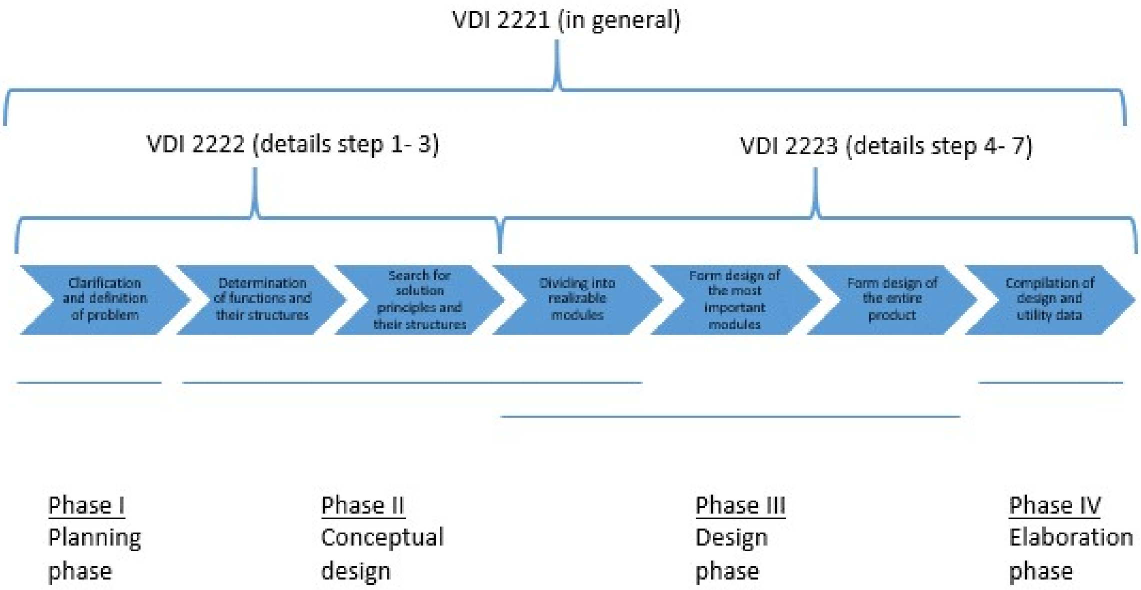

Figure 15 General procedure of systematic development and design according VDI 2221[85]

One chapter in the VDI 2221 deals with computer supported development. Here the requirement is to have an integrated system for all steps and no island solution. This helps to provide consistent data- and workflow.[86] To fulfill this requirement VHDL-AMS is a good choice, because you can start with a general description of the entity and detail it more and more in the project. Further the tool Simplorer from Ansys does not support only VHDL-AMS. It also combines the interfaces to different physical domains.

In the VDI 2222 is mentioned that design catalogues are an appropriate method to find the right solution.[87] Concerning this work the conclusion is to develop an aging library for electronics as an adequate method for approaching the aging problem in electronics.

Development guideline according to VDI 2206

“Innovative products require an interdisciplinary combination of mechanical engineering, electrical engineering and information technology. The term ”mechatronics“ is the expression of this. In view

[82] [VDI2222_1997]
[83] [VDI2223_2004]
[84] Compare [VDI2222_1997] page 2
[85] Compare [VDI2221_1993] page 9
[86] Compare [VDI2221_1993] page 13
[87] Compare[VDI2222_Bl1_1997] page 22

of this situation, a practical guideline for the systematic development of such products is necessary. The present guideline, VDI 2206, is intended to meet this requirement“[88]

The VDI 2206 is supplementing the VDI2221.[89] That is the reason why the VDI2221 series and the VDI 2206 are considered together with the ISO26262 to derive a new design methodology for mechatronic control units with the special focus on aging. The VDI 2206 mentions kinematics, dynamics and strength as additional physical dimensions which are considered in the virtual prototype phase.[90] No aging is mentioned there so that it is new to combine the aging aspect with a virtual method like simulation.

The three main principles proposed by the standard are:

“• general problem-solving cycle on the micro-level
• V model (…)
• predefined process modules for handling recurrent working steps in the development of mechatronic systems“[91]

The general problem solving cycle on the micro level is shown in the figure below on the left side[92]. In the figure it is tried to map the different steps to the general cluster of the VDI 2221.

[88] [VDI2206_2004] page 2
[89] Compare [VDI2206_2004] page 2
[90] Compare [VDI2206_2004] page 24
[91] [VDI2206_2004] page 26
[92] left side of the figure [VDI2206_2004] page 28

Problem solving cycle as a micro cycle according to VDI 2206 → **Phases according to VDI 2221**

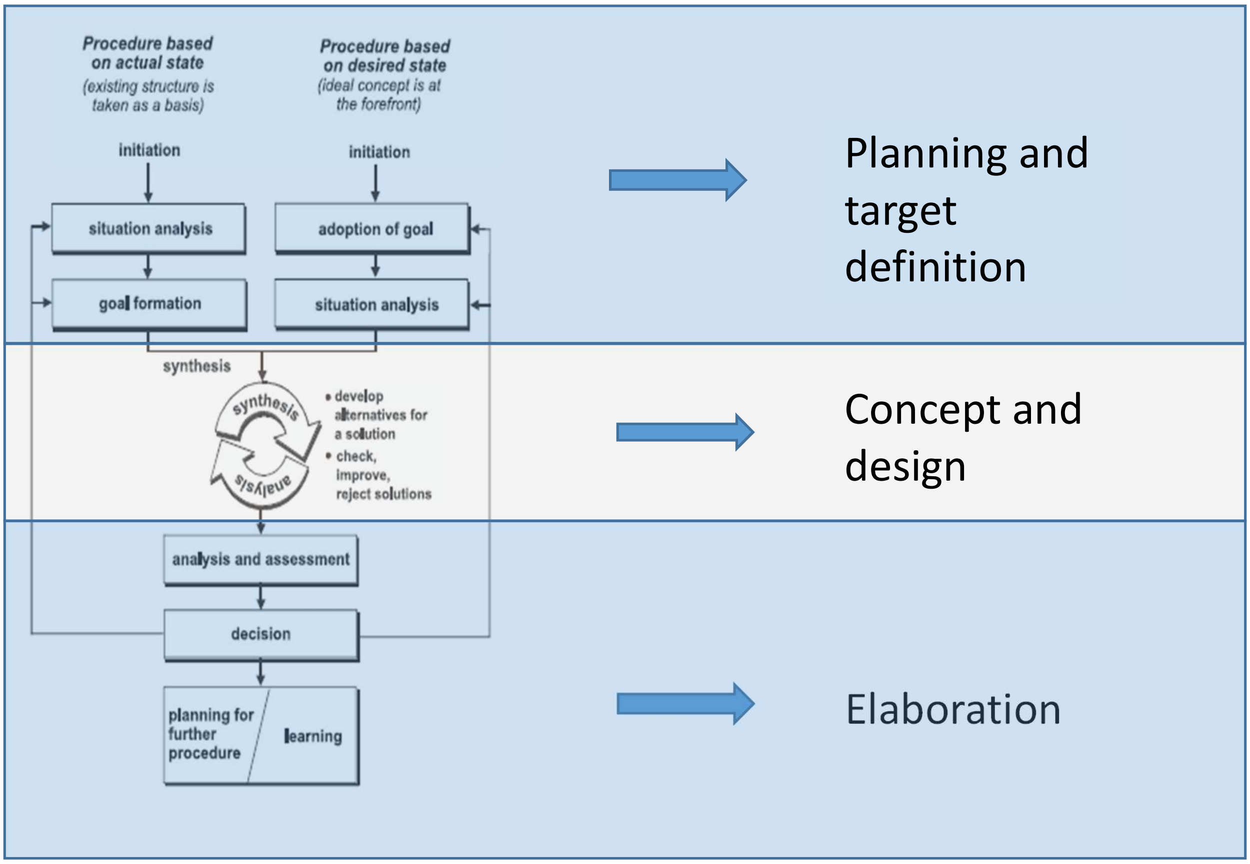

Figure 16 Mapping of problem solving from VDI 2206 to VDI 2221[93].

The second principle is the V-Model at a macro cycle. The V-Model is known from software development and is also combined with the different mechatronic disciplines.[94] It uses modeling techniques from the system design over the domain specific engineering to system integration.

[93] left side of the figure [VDI2206_2004] page 28
[94] Compare [VDI2206_2004] page 26

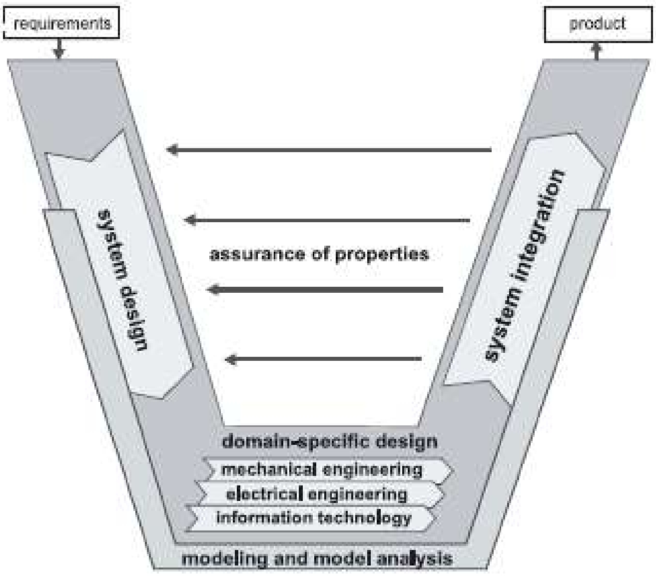

Figure 17 V model as a macro cycle[95]

The third principle requests “predefined process modules for handling recurrent working steps in the development of mechatronic systems”[96]. This requirement is another strong hint to use simulation in mechatronic design. Combined with the multi domain approach and the model requirement one core element for the new methodology has to be simulation with VHDL-AMS.

Hardware design and verification process requirements according to ISO 26262

The general content of the ISO 26262 is described in the chapter 2.5 – so in the following only some details for hardware design and verification/qualification processes are described.

5.1.1.1 Hardware design methodology

In the chapter hardware design the objective is to design and to verify “the hardware in accordance with the system design specification and the hardware design specification”[97] The norm specifies that hardware design includes architectural and detailed design down to a schematic level.[98]

Non-functional causes for failure like temperature or vibrations are explicitly named to consider during the hardware design (architectural and detailed), but no aging is mentioned there explicitly.[99]

[95] [VDI2206_2004] page 29
[96] [VDI2206_2004] page 26
[97] [ISO 26262_2011] part 5 page 8
[98] Compare [ISO 26262_2011] part 5 page 8
[99] Compare [ISO 26262_2011] part 5 page 10

The hardware design begins with the derivation and the verification of the hardware safety requirements within the technical safety concept.[100] As a result of the initial phase a “hardware safety requirements specification (including test and qualification criteria)”[101] is requested. In case there is also software involved a hardware interface specification (HIS) is required. Finally all specification verification has to be documented in a hardware safety requirement safety report.[102] The following figure gives an overview of the content for product development at the hardware level.

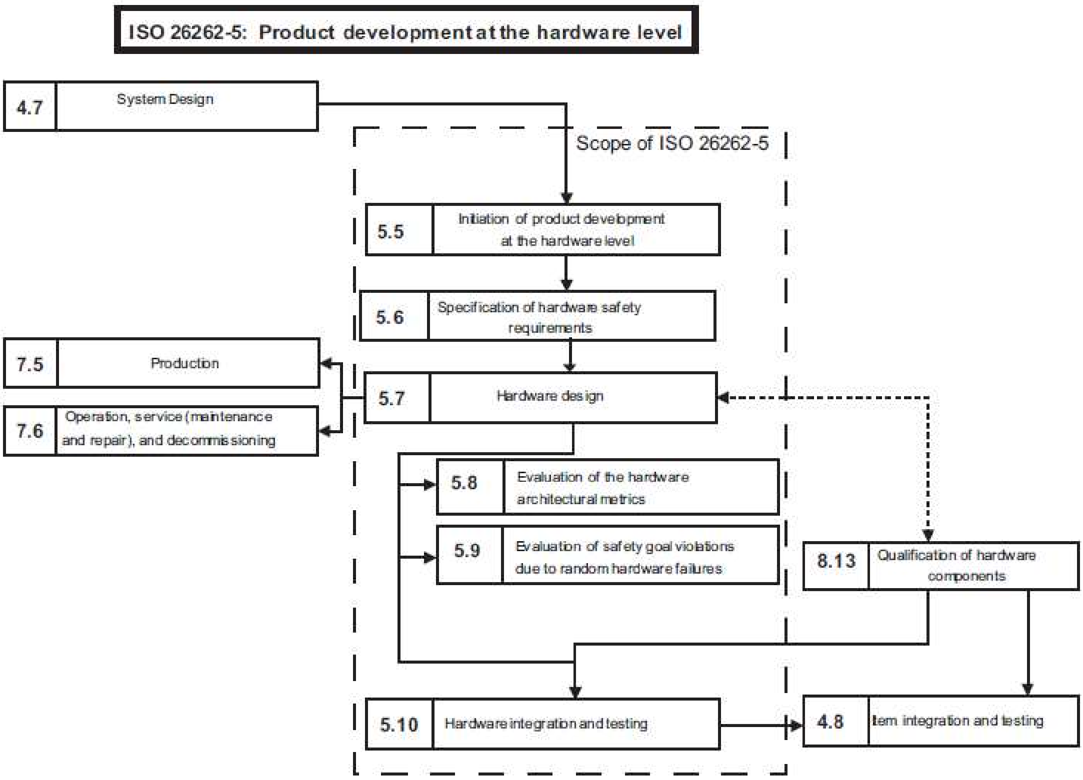

Figure 18 Product development at the hardware level[103]

Also a safety analysis is required to support or to verify the hardware design.[104] Highly recommended for all ASIL levels for an inductive analysis is the failure mode and effect analysis (FMEA)[105] The safety analysis is required for ASIL C and D safety goals and recommend for ASIL B ranking.[106] The target of the safety analysis is to identify:
“a) safe faults
b) single-points or residual faults; and
c) multiple-point faults.”[107]

[100] Compare [ISO 26262_2011] part 5 page 5
[101] [ISO 26262_2011] part 5 page 8
[102] Compare [ISO 26262_2011] part 5 page 8
[103] [ISO 26262_2011] part 5 page 4
[104] Compare [ISO 26262_2011] part 5 page 10
[105] Compare [ISO 26262_2011] part 5 page 11
[106] Compare [ISO 26262_2011] part 5 page 11
[107] [ISO 26262_2011] part 5 page 11

In a note is stated that in most cases the multiple point faults can be limited to dual point failures.[108]
After identifying the different types of faults the norm requires
“a) evidence of the ability of the safety mechanisms to maintain a safe state, or to switch into a safe state … and
b) diagnostic coverage”[109]

As a principle it is stated that “the reuse of hardware components, or the use of qualified hardware components or parts, shall be identified”[110] This principle is a strong argument to use verified VHDL –AMS models to simulate the hardware circuits.

In clause “Verification of hardware design” the below listed methods are mentioned:

Table 3 Hardware design verification[111]

Methods		ASIL			
		A	B	C	D
1a	Hardware design walk-through[a]	++	++	o	o
1b	Hardware design inspection[a]	+	+	++	++
2	Safety analyses	In accordance with 7.4.3			
3a	Simulation[b]	o	+	+	+
3b	Development by hardware prototyping[b]	o	+	+	+

NOTE The scope of this verification review is technical correctness of the hardware design.

[a] Methods 1a and 1b serve as a check of the complete and correct implementation of the hardware safety requirements in the hardware design.

[b] Methods 3a and 3b serve as a check of particular points of the hardware design (e.g. as a fault injection technique) for which analytical methods 1 and 2 are not considered to be sufficient.

In actual development process aging validation takes places with samples testing. For ASIL B simulation is recommended as a verification method. So it makes sense to add in the proposed method a simulation.

The chapter 8 and 9 deal with random hardware failures – although this is not the main scope of the new methodology, because the focus is on systematic failures due to aging influences.

Chapter 10 focuses on hardware integration and testing. “The objective of this clause is to ensure, by testing, the compliance of the developed hardware with the hardware safety requirements.”[112] In order to prove the completeness and correctness of the safety mechanism the methods in the following table are proposed.

108 Compare [ISO 26262_2011] part 5 page 11
109 [ISO 26262_2011] part 5 page 11
110 [ISO 26262_2011] part 5 page 5
111 [ISO 26262_2011] part 5 page 12
112 [ISO 26262_2011] part 5 page 26

Table 4 Hardware integration methods to verify completeness and correctness of the safety mechanisms implementation[113]

Methods		ASIL			
		A	B	C	D
1	Functional testing[a]	++	++	++	++
2	Fault injection testing[b]	+	+	++	++
3	Electrical testing[c]	++	++	++	++

[a] Functional testing aims at verifying that the specified characteristics of the item have been achieved. The item is given input data, which adequately characterises the expected normal operation. The outputs are observed and their response is compared with that given by the specification. Anomalies with respect to the specification and indications of an incomplete specification are analysed.

[b] Fault injection testing aims at introducing faults in the hardware product and analysing the response. This testing is appropriate whenever a safety mechanism is defined. Model-based fault injection (e.g. fault injection done at the gate-level netlist level) is also applicable, especially when fault injection testing is very difficult to do at the hardware product level. For example, showing the response of safety mechanisms to transient faults inside hardware parts, such as a microcontroller, is very difficult to do with fault insertion at the hardware product level since it would require irradiation tests.

[c] Electrical testing aims at verifying compliance with hardware safety requirements within the specified (static and dynamic) voltage range.

All of the methods can be performed on prototypes or per simulation. Especially the fault injection testing is a proper function for simulation – which can be a future usage for the aging models.

Further methods are listed for testing robustness and operation under external stress – more details are shown in the table below.

[113] [ISO 26262_2011] part 5 page 28

Table 5 Hardware tests to verify robustness and operation under external stresses[114]

Methods		ASIL A	ASIL B	ASIL C	ASIL D
1a	Environmental testing with basic functional verification[a]	++	++	++	++
1b	Expanded functional test[b]	o	+	+	++
1c	Statistical test[c]	o	o	+	++
1d	Worst case test[d]	o	o	o	+
1e	Over limit test[e]	+	+	+	+
1f	Mechanical test[f]	++	++	++	++
1g	Accelerated life test[g]	+	+	++	++
1h	Mechanical Endurance test[h]	++	++	++	++
1i	EMC and ESD test[i]	++	++	++	++
1j	Chemical test [j]	++	++	++	++

[a] During environmental testing with basic functional verification the hardware is put under various environmental conditions during which the hardware requirements are assessed. ISO 16750-4 can be applied.

[b] Expanded functional testing checks the functional behaviour of the item in response to input conditions that are expected to occur only rarely (for instance extreme mission profile values), or that are outside the specification of the hardware (for instance, an incorrect command). In these situations, the observed behaviour of the hardware element is compared with the specified requirements.

[c] Statistical tests aim at testing the hardware element with input data selected in accordance with the expected statistical distribution of the real mission profile. The acceptance criteria are defined so that the statistical distribution of the results confirms the required failure rate.

[d] Worst-case testing aims at testing cases found during worst-case analysis. In such a test, environmental conditions are changed to their highest permissible marginal values defined by the specification. The related responses of the hardware are inspected and compared with the specified requirements.

[e] In over limit testing, the hardware elements are submitted to environmental or functional constraints increasing progressively to values more severe than specified until they stop working or they are destroyed. The purpose of this test is to determine the margin of robustness of the elements under test with respect to the required performance.

[f] Mechanical test applies to mechanical properties such as tensile strength.

[g] Accelerated life test aims at predicting the behaviour evolution of a product in its normal operational conditions by submitting it to stresses higher than those expected during its operational lifetime. Accelerated testing is based on an analytical model of failure mode acceleration.

[h] The aim of these tests is to study the mean time to failure or the maximum number of cycles that the element can withstand. Test can be performed up to failure or by damage evaluation.

[i] ISO 7637-2, ISO 7637-3, ISO 10605, ISO 11452-2 and ISO 11452-4 can be applied for EMC tests; ISO 16750-2 can be applied for ESD tests.

[j] For chemical tests, ISO 16750-5 can be applied.

5.1.1.2 Supporting Process Verification and Qualification in the ISO 26262

Part 8 of the ISO 26262 chapter 9 deals with verification. “The objective of verification is to ensure that the work products comply with their requirements” [115] The norm distinguishes between verification in the design, test and production phase. In this work the focus is on the design phase. Further on for this phase the norm names in a general way, that the “evaluation can be performed by review, simulation or analysis techniques. The evaluation is planned, specified, executed and documented in a systematic manner.”[116] The verification should be planned. This should include the content which should be verified by which methods, e.g. simulation. It should also cover the pass and failed criteria and under which environment it should be verified. Additionally it should

[114] [ISO 26262_2011] part 5 page 29
[115] [ISO 26262_2011] part 8 page 16
[116] [ISO 26262_2011] part 8 page 16

also specify the tools used for verification and the consequences if an anomaly is detected. Finally it should mentioned what has to be done if changes have been made.[117]

In this chapter there is no special requirement for aging but only a general description.

Chapter 13 is named “qualification of hardware components” and has two objectives:

- prove that the hardware components fulfill the functional behavior according to the safety concepts
- provide information for the failure modes, their distribution and the capability of diagnostics concerning the safety requirements[118]

In this context it is mentioned that “environmental endurance and robustness”[119]has to be passed according to the standards, e.g. ISO 16750. It is also listed that for “safety related basic hardware parts (e.g. resistors, transistors)” only standard qualification is enough and no special qualification like in part 8 –chapter 8.[120]

In chapter 5 “Interfaces within distributed developments” are mentioned and that the requirements for supplier selections are not applicable if “off-the shelf hardware parts are qualified according to well-established procedures based on worldwide quality standards (e.g. AEC standards for electronic components)”[121]

The ISO standard describes two ways for hardware qualification. One is testing the components by exposing to real environmental conditions, the other one are analytical methods. But the predictions of analytical methods is limited, so that it has to be supplemented by environmental test (like in the ISO 16750)[122].

As an example for analytical methods mathematical models are mentioned. This is one approach for modelling the aging effect – later in the proposed methods. Furthermore the environmental conditions should be considered in the analysis which can be interpreted as a justification for performing an aging simulation. [123]

[117] Compare [ISO 26262_2011] part 8 page 17
[118] Compare [ISO 26262_2011] part 8 page 31
[119] [ISO 26262_2011] part 8 page 31
[120] Compare [ISO 26262_2011] part 8 page 32
[121] [ISO 26262_2011] part 8 page 4
[122] Compare [ISO 26262_2011] part 8 page 32
[123] Compare [ISO 26262_2011] part 8 page 34

5.2 Development of new methodology

Out of the general requirement of the different standards a combination with a special focus on aging is done. The method should be applicable during the design phase. In order to avoid design error which appear with aging. On the other hand it can also help to design failure detection algorithm to control failures. In the figure below of the bathtub diagram the focus of the new methodology is visualized.

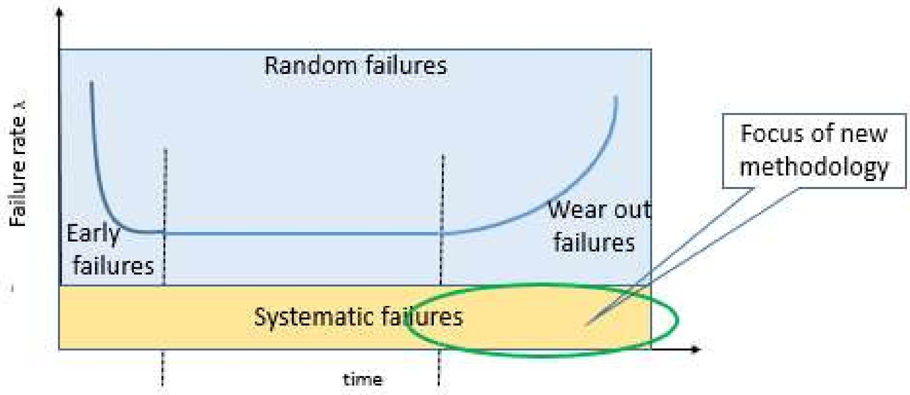

Figure 19 Focus of new methodology during life cycle[124]

[124] Compare [Eberlein_2014] page 12

The main idea of the new methodology is to look on the interface between wear out failures and systematic failures (see figure above). The approach is to apply the method of wear out qualification and transfer it via simulation in an earlier design phase by combing the requirements of the VDI 2221ff, ISO 2206 and the ISO 26262.

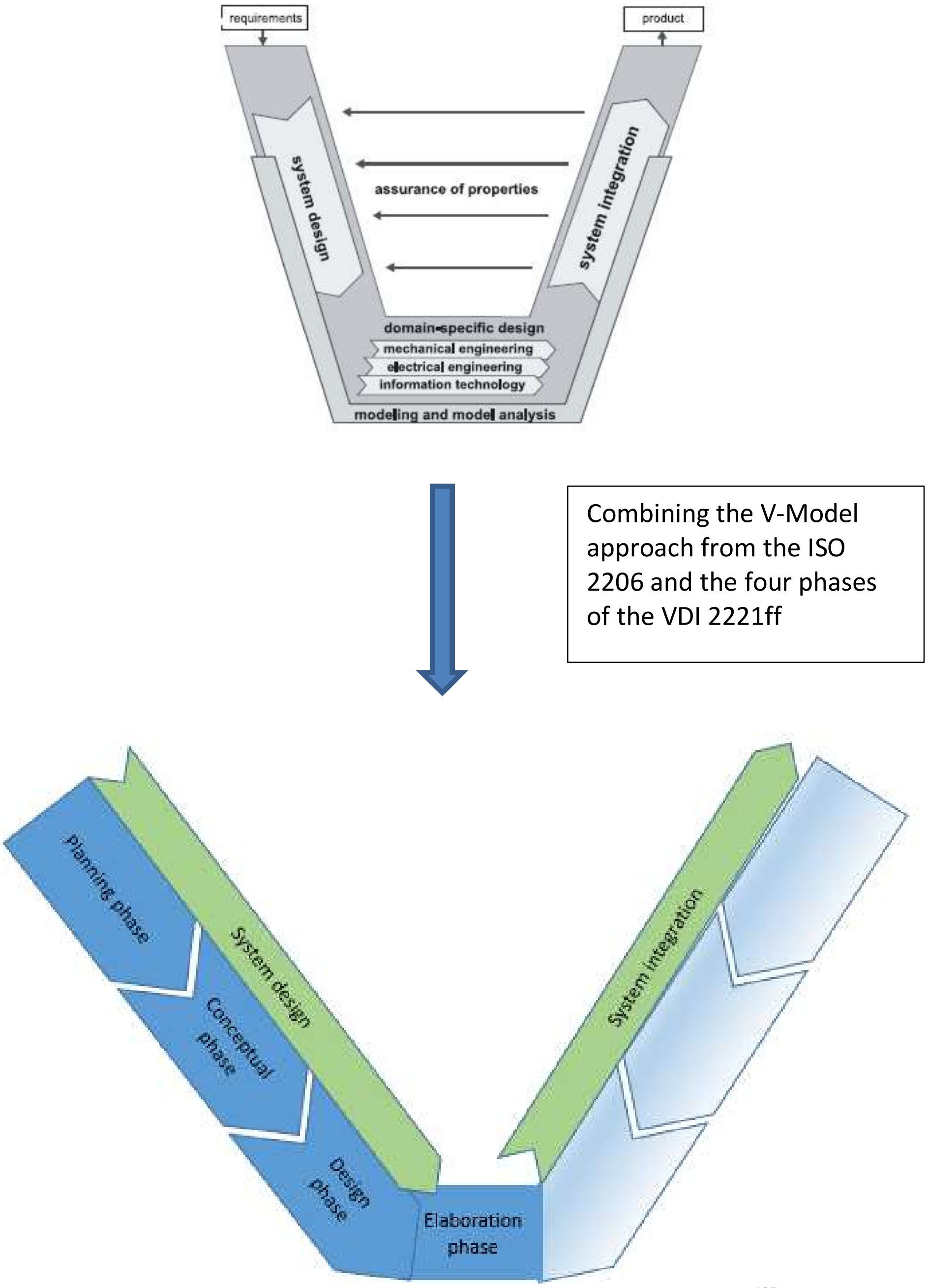

Figure 20 Combining V-Model (ISO 2206) and four phases (VDI 2221)[125]

[125] Compare [VDI 2206_2004] page 26

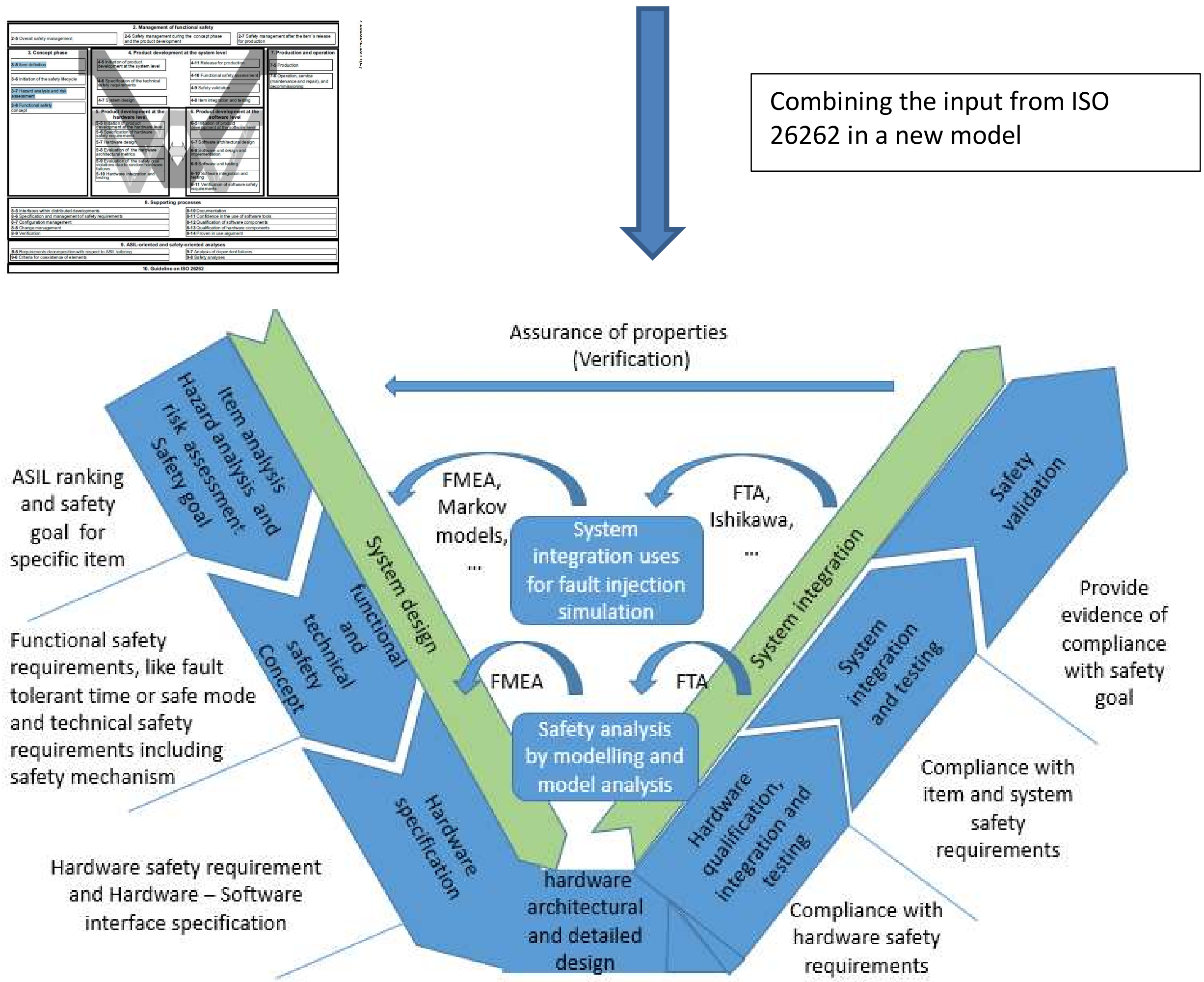

Figure 21 Adding the input from the ISO26262 in a new model[126]

As the focus of this work is a design methodology – only the left branch of the V-Model is considered. Based on the methodology of the ISO 26262 a hazard and risk analysis should be performed to identify and prioritize the risky item. Then based on the safety goal a functional and technical safety concept is developed. Additionally a FMEA is done as a proactive supplement to identify critical components. This method is also widely known in the automotive industry. In principle there are proactive (e.g. simulation) and reactive (e.g. testing) ways to ensure reliability. As the method should be applied in a design phase only the proactive methods are relevant.

Finally the procedure is extended by the simulation with aging models. The requirements of simulation and analytic methods in the ISO 26262 are considered by using VHDL models, where the aging aspect is represented by a mathematic equation. The time of the simulation is calculated by the Arrhenius equation similar to design reliability tests or by the experience of the usage time of the device. Based on the result of the simulation it can be continued or additional iteration will be needed.

[126] Compare [ISO26262_2011] all parts

5.3 Description of proposed methodology

Now following is the proposed methodology for considering aging effects during a hardware development to reduce the consequences of late hardware failures or leading to false failure detection by diagnosis.

1. Selection of a suitable safety-related function in the automotive sector
Not each function can be selected. It has to be a function, whose safety dependence is carried out purely by hardware. Safety functions which are performed by software are of course hardware-based, but not concerned within the focus of this work.

2. Performing the Functional Safety activities in accordance with ISO 26262
According to the ISO 26262 each Functional Safety analysis has to be started with the following steps:
- Item analysis
- Hazard and risk analysis
- Risk Classification
- Deriving the safety goals
- Setting up a functional and technical safety concept[127]

3. Using an aging failure mode and effect analysis (FMEA) to find aging relevant hardware components
Implementation of an "aging" FMEA is subjected with the aim of detecting aging dependent critical hardware components that can cause a potential hazard to the safety goal or false failure diagnosis.

4. Development of a VHDL-AMS model with the capability to simulate aging behaviors
Development of aging component models, for the simulation of the aging behavior of the technical safety concept.

The data source for the aging input can be from
a) data sheets or scientific papers
b) field data (proven in use)[128]
c) experiments

5. Simulation
The simulation is applied over the range of evidence. The aim is that safety goals are not violated and the diagnosis intervals are correct. Simulation is performed over the lifetime, with the aim to determine the robustness of the chosen concept.

6. Evaluation of the results
The advantage of a simulation is also to look on certain values to see how big or how small the safety margin is.

[127] Compare [ISO26262_2011] part 3
[128] Compare [ISO26262_2011] part 8 page 35

5.4 Benefit of the methodology

The main benefit of the new methodology is to prove the current design and diagnostic in an early design phase.

In case a hardware risk is identified by using the described methodology, there are architectural approaches in safety-related systems possible, like

- principally avoid a dangerous failure effect, or
- perform a safety-related reaction:
  - safety shutdown or
  - reducing the risk potential by reducing the available power (limp home the automobile)

There are three different architectures approaches to avoidance of hardware failures for safety-related systems:

a) Redundancies (Composite Fail Safety), which are either carried out in a homogeneous or diverse structure and which are independent from each other.

b) The absence of errors (Inherent Fail Safety), the captive nature of properties to be provided. Applications for this are, for example, the forced operation of the contacts of electromechanical relays. Through technical measures the probability of occurrence of a fault can be ruled out.

c) Rapid response to random hardware failures (Reactive Fail Safety) - here the critical factors are the reaction rate or the error reaction. The reaction has to be carried out prior to entering a dangerous impact.[129]

5.5 Limitations of the new methodology

A distinction is made in Functional Safety between systematic and random hardware failures. Systematic errors arise due to shortcomings in the development or in the concept, such as too little tolerance, or lack of protection against EMI. It must be ensured through appropriate measures and methods that systematic errors are avoided. The new methodology contributes in this direction to evaluate also aging effects, because they do not occur on each component, but they are considered under systematic failures.

A worst case circuit analysis is generally performed to evaluate the product development of the hardware design. Thereby ageing effects with limit values are statically considered. The presented method provides a deeper understanding of ageing effects over time. With the availability of the aging models for the safety-relevant components, the presented method additionally offers the possibility to redefine the worst case limit value. The redefinition of the limit values can advantageously facilitate the solvability of a problematic design and lead to an improvement of the circuit tolerances.

Random hardware failures relate exclusively to the hardware level and usually occur sporadically. Random errors are unavoidable, they occur randomly, therefore unpredictable.

[129] Compare [Scharfenberg_2010]

6 Application of new methodology on the E-Gas Function

6.1 Selection of a suitable hardware safety related function

In general a car has a lot of function. It is impossible to consider all of them. So in a first step a suitable safety related function has to be identified. All functions which have no safety relevance can be neglected. So it is mainly the powertrain and safety area which are interesting. Concerning the evaluation of the new methodology the electronic gas (E-Gas)-function was chosen. Other possible functions could be the anti-lock braking system (ABS) or steer by wire Systems. The E-Gas function was chosen because a public hazard- and risk analysis from a working group of the automotive industry already exists.

The E-Gas is the function inside a direct injection gasoline engine which converts the wish of the driver into a torque at the tires, by controlling the air – gasoline mixture at the intake of the cylinder. By the proportion of the air gasoline mixture the optimum between power output and best combustion is influenced. The wish of the driver is measured with the accelerator pedal module, which measures the angle of the pedal. This can be done by potentiometer or by hall-sensors. This input signal together with the other sensors (e.g. knock sensor) is the basis for the engine control unit to control the electronic throttle valve. The position of the throttle valve is read back by a potentiometer and a voltage divider.

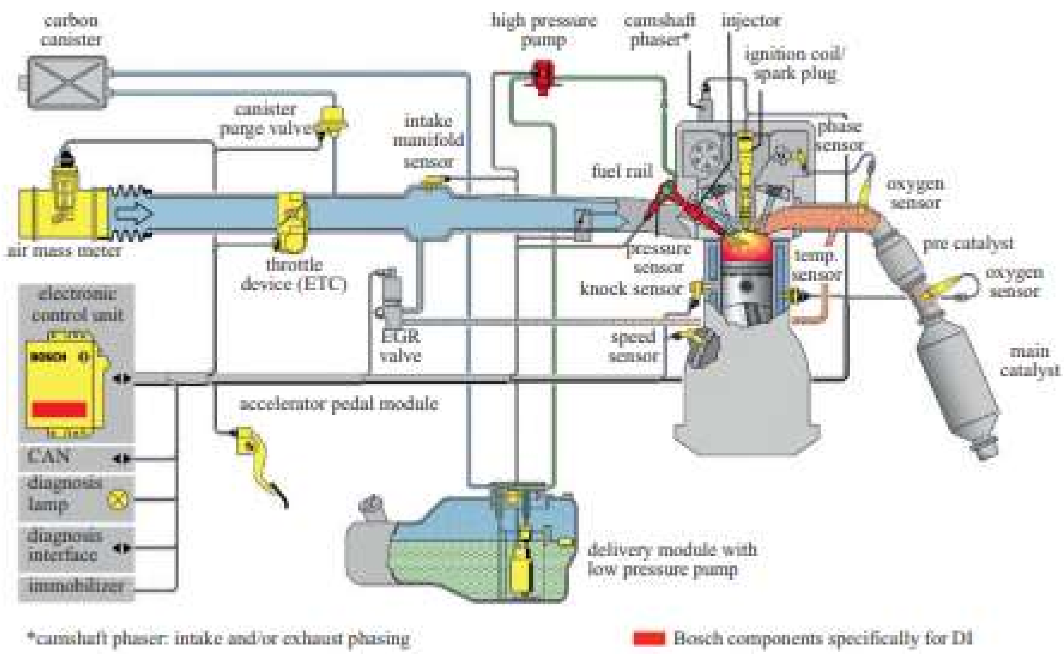

Figure 22 Elements of a direct injection gasoline engine[130]

Due to simplification in following the three main components of the E-Gas-function are briefly explained.

The **accelerator pedal module** signals the driver's wish how to drive. As the torque of the engine is controlled by the ECU the position of the acceleration pedal needs to be converted into an electronic signal. For this purpose potentiometers or hall sensors are used and as this is a safety

130 [Isermann_2014] page 14

relevant information there are two sensors used. The main difference is that they are not supplied with the same voltage, so a plausibility check and an error detection is possible. The two different characteristic curves are shown in the figure below.

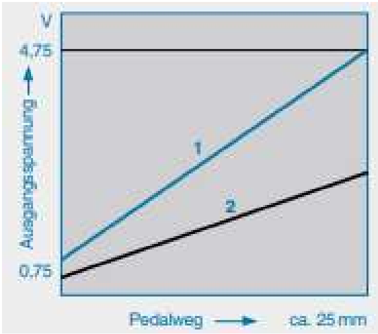

Figure 23 Characteristic curves of the 2 potentiometers in an accelerator pedal module[131]

The **electric control unit (ECU**) uses engine characteristic maps to translate the wish of the driver in a torque. Further the ECU controls the throttle valve, the fuel injection valve and the ignition and evaluates different sensors. “All the open-loop and closed-loop algorithms of the electronic system run inside the control unit. The heart of the control unit is a microcontroller with the program memory (flash EPROM) in which is stored the program code for all functions that the control unit is designed to execute.”[132]

The **throttle valve** is powered by an electrical DC-engine. The position is read back by two potentiometers. Two potentiometers are used to enable a plausibility check of the signal. An example of the throttle valve is shown in the figure below. The resistor track of the potentiometer is visible in the open plastic housing.

As the complexity of E-Gas should be reduced in the further investigations, it is focused only on potentiometers in the throttle valve. A potentiometer is a special form of resistors that is simulated as two resistors in a fixed position.

1. Throttle valve
2. DC engine
3. wiper
4. resistive element path 1
5. resistive element path 2

[131] [Reif_2011] page 350

[132] [Reif_2014] page 160

Figure 24Throttle valve[133]

The electrical equivalent circuit for the positioning can be drawn like in the following picture

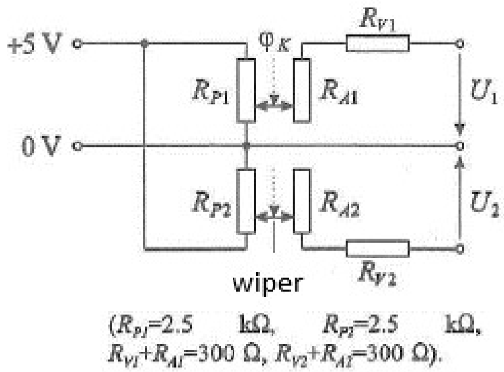

Figure 25 Electrical equivalent circuit of a throttle valve position sensor[134]

As the value for R_p is typically 2,5kΩ, for the practical test of resistor aging the value 2,4kΩ was chosen.

The potentiometers are in the opposite direction and provide an analog voltage. The signals are a function of the angle. A principle diagram is shown in the figure below. Due to the two opposite directions of the two signals a diagnosis of failure is possible (plausibility check).

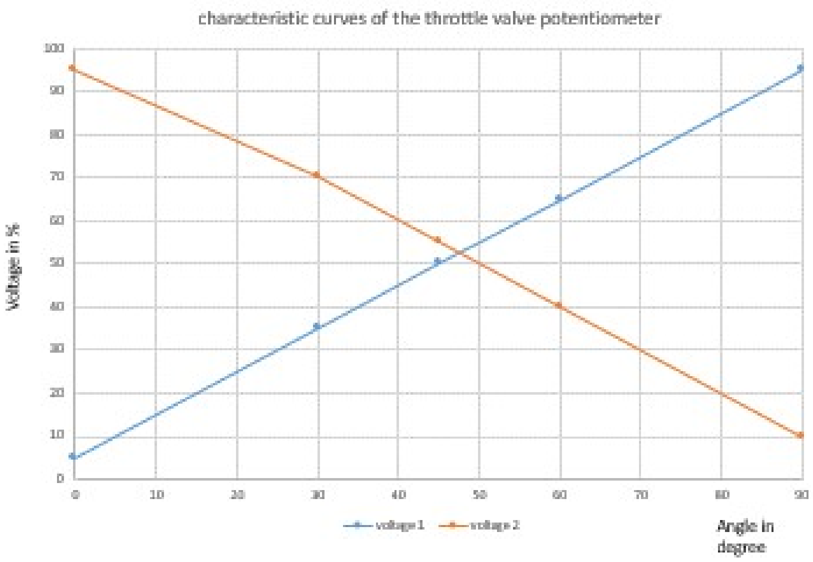

Figure 26 Characteristic curves of a throttle valve potentiometer[135]

133 [Reif_2011] page 15
134 [Pfeufer_1999] page 15
135 [Pfeufer_1999] page 16

6.2 Safety goals, safety concept and safety requirements E-GAS-Project[136]

A working group consisting of the automotive industry with representatives from Audi AG, BMW AG, Daimler AG, Porsche AG and VW AG published together their common requirements for a “standardized E-GAS Monitoring concept for gasoline and diesel engine control units”, because with the introduction of E-Gas a drive by wire function is introduced in the automotive and Functional Safety is therefore more and more important. “The available documentation describes the principles of the concept that shall be used.”[137] Under the developing guidelines is explicitly mentioned “the technical safety concept shall be implemented in accordance with the requirements of ISO 26262”[138]

Item specification

The ISO 26262 requires at the beginning of the activities in the concept phase, that an item definition has to be carried out. Under this item definition arise "the requirements and recommendations for establishing the definition of the item with regard to its functionality, interfaces, environmental conditions, legal requirements, hazards, etc."[139] The E-Gas monitoring concept describes that the functions of providing a driving torque or a braking torque of the combustion engine operates in a passenger car and consists of three components[140] (see next Figure 27 overview of the E-gas with interfaces):

- “Accelerator pedal
- Engine control unit
- Throttle-Valve”[141]

[136] Compare [EGAS_2013]
[137] [EGAS_2013] page 4.EGAS_e-10
[138] [EGAS_2013] page 7 EGAS_e_56
[139] [ISO26262_2011] part 3 page 3
[140] Compare [EGAS_2013] page 8
[141] [EGAS_2013] page 8

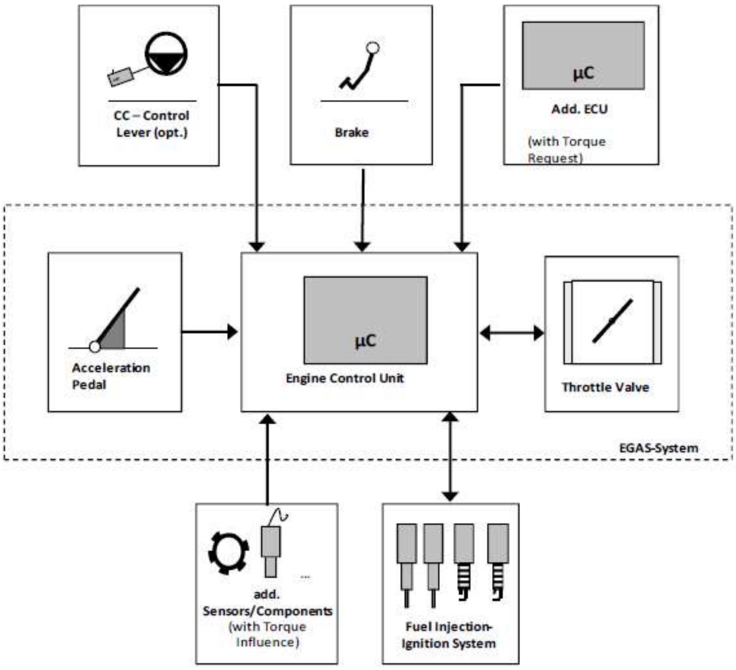

Figure 27 Overview of the E-Gas with interfaces[142]

Hazard Analysis and Risk assessment

“The objective of the hazard analysis and risk assessment is to identify and to categorize the hazards that malfunctions in the item can trigger and to formulate the safety goals related to the prevention or mitigation of the hazardous events, in order to avoid unreasonable risk.”[143] According to the classification in the categories severity, probability of exposure regarding operational situations and controllability the hazard of unintended acceleration is ranked as an ASIL B.[144]

Safety goal

The safety goal is a functional description that should be reached by the functional and technical concept and in the example of the E-GAS one safety goal is defined as “prevention of unintended acceleration”[145]

Functional Safety concept and safety requirements

“The objective of the Functional Safety concept is to derive the Functional Safety requirements, from the safety goals, and to allocate them to the preliminary architectural elements of the item, or to external measures.”[146] In the context of Functional Safety concept safety requirements are

[142] [EGAS_2013] page 9
[143] [ISO26262_2011] part 3 page 6
[144] Compare [EGAS_2013] page 9, EGAS_e-83
[145] [EGAS_2013] page 9
[146] [ISO26262_2011] part 3 page 12

developed and allocated to a subsystem and safety goal. Part of the safety concept is e.g. fault detection and failure mitigation.[147]

The E-Gas monitoring concept specifies for the sensors in the throttle valve "a plausibility check can be applied to the actuator signals (e.g. throttle position) after capturing the signals."[148]

A methodological approach to find more safety requirements can be a FMEA.

Simple technical safety concept of E-GAS

The overall technical concept bases on the 3-level monitoring concept (see Figure 28 Three-level monitoring concept), where 3 levels exist.

The 1st level is the so called functional level, which generates out of the input signals the output signal. This function includes also fault diagnostics and their corresponding reaction.

The 2nd level is called the function monitoring level and runs on the same hardware as level 1, but controls the diagnostic process and triggers an appropriate reaction.

The 3rd level is called the controller monitoring level, that has to run on an independent hardware and checks for example by a question and answer procedure the correct function of function controller.[149]

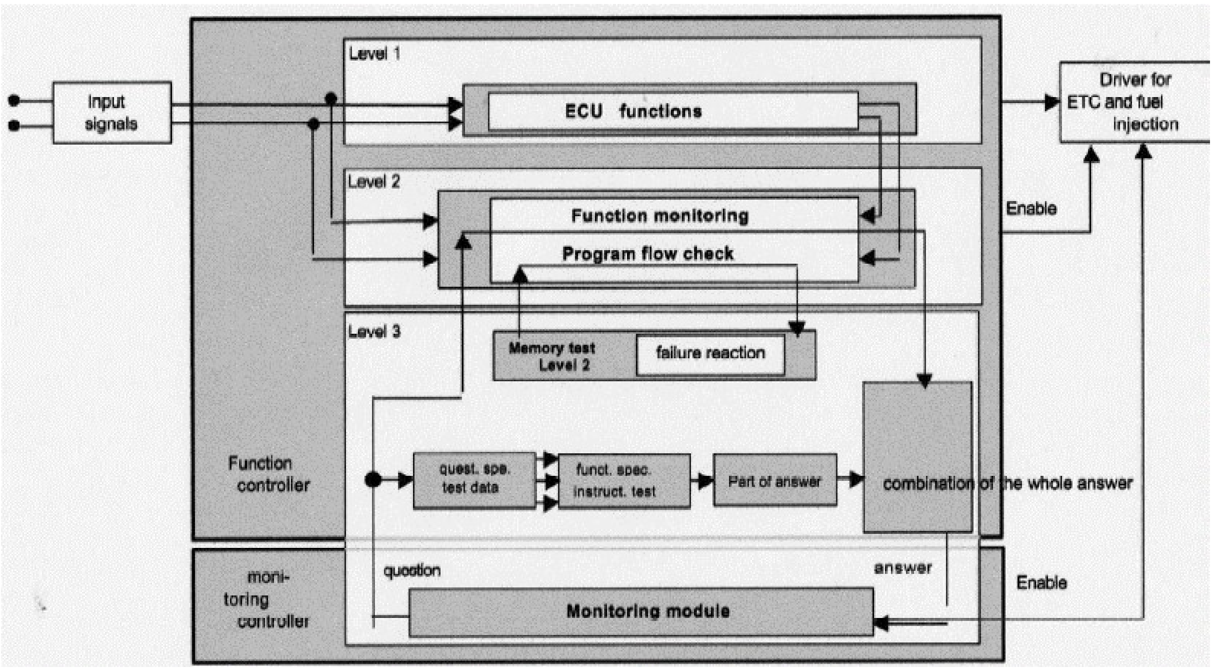

Figure 28 Three-level monitoring concept[150]

[147] Compare [ISO26262_2011] part 3 page 12
[148] [EGAS_2013] page 10
[149] Compare [EGAS_2013] page 13
[150] [EGAS_2013] page 13

The design and fault detection characteristics are specified in the E-Gas monitoring concept. For the throttle valve sensor the redundant concept is proven in use and therefore subject of the further investigation.

6.3 Using failure mode and effects analysis (FMEA)

A failure mode and effects analysis is a proactive method to analyze and optimize in a systematic way how a unit, system or a process reacts to failures. Additionally it provides a documentation to prove that a safety analysis has been performed.[151]

A FMEA can be divided in two main parts. The first one is to identify risks and the second one is to define countermeasures including a reevaluation of the risks. For this methodology only the first part is used to identify the risk. If they are identified a simulation is used to find and evaluate countermeasures (see chapter 6.4 and 6.5).

A FMEA is “meant to be a “before-the-event” action, not an “after-the-fact” exercise. To achieve the greatest value, the FMEA must be done before a design or process failure mode has been unknowingly designed into the product.”[152] Nevertheless it has to be mentioned that a FMEA is a living document[153], which should be used also in later development and production phases. It should be corrected also later in order to serve as a knowledge storage for follow-up projects.

To execute an FMEA it is recommend to work in teams with an FMEA moderator to achieve the best results.

There exist different kinds of FMEA, for example design, process, software or logistic FMEA.[154] This means there can be a focus where the FMEA is concentrated on. Following this approach here the proposal is to use the risk evaluation part of the method FMEA with the focus aging – in the following called “aging FMEA”. Here the approach is to look on each component and evaluate it, if there can be a functional impact by an aging behavior of the component.

The general way of performing an FMEA is

a) Defining the scope of the FMEA, which interfaces and content it is and collect all available information
b) Performing a system analysis (structure- and function analysis) for the scope of the FMEA
c) Executing an risk analysis by evaluating all possible failures for the single elements and functions
d) Creating an action plan for all relevant failures[155]

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[151] Compare [DIN60812_2015] page 7
[152] https://www.lehigh.edu/~intribos/Resources/SAE_FMEA.pdf SAE document, page 1 accessed - 22.07.2018
[153] Compare [Werdich_2012] page 9
[154] Compare [Werdich_2012] page 13
[155] Compare [Werdich_2012] page 21

The following figure visualizes the general way

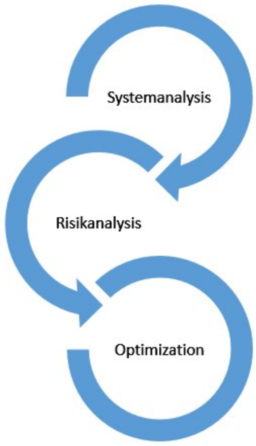


Figure 29 General way of an FMEA

For the system analysis in this case a structural analysis is done on component level.

In the risk analysis aging related potential failures are listed. For each failure a risk priority number (RPN) is calculated. The RPN is the product out of severity, occurrence and detectability. There are several guidelines like in the SAE or VDA how to rate the three criteria.

a) "Severity is an assessment of the seriousness of the effect"[156] of the potential failure. To categorize it a scale from 1 to 10 is used, whereat 1 means none severity and 10 hazardous without warning severity.

[156] https://www.lehigh.edu/~intribos/Resources/SAE_FMEA.pdf SAE Document page 13 – accessed on 22.07.2018

In the following figure only the severity is shown

Effect	Criteria: Severity of Effect	Ranking
Hazardous-without warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.	10
Hazardous-with warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning	9
Very High	Vehicle/item inoperable, with loss of primary function.	8
High	Vehicle/item operable, but at reduced level of performance. Customer dissatisfied.	7
Moderate	Vehicle/item operable, but Comfort/Convenience item(s) inoperable. Customer experiences discomfort.	6
Low	Vehicle/item operable, but Comfort/Convenience item(s) operable at reduced level of performance. Customer experiences some dissatisfaction.	5
Very Low	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by most customers.	4
Minor	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by average customer.	3
Very Minor	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by discriminating customer.	2
None	No Effect.	1

Figure 30 Severity of effects for an FMEA[157]

b) "Occurrence is the likelihood that a specific cause/mechanism … will occur."[158] Also the range goes from 1 to 10, whereat 1 means the occurrence is very unlikely and 10 means it is very high.

c) "Detection is an assessment of the ability of the proposed type (…) current design controls,…, to detect a potential cause/mechanism (design weakness)"[159] Also here 1 means almost certain to catch the failure and 10 means absolutely uncertain to detect the failure.

The RPN is calculated with the following equation

RPN = severity x occurrence x detection

The maximum number for the RPN can be 1000. In order to do a prioritization you sort to the RPN and deal with the 20% (=Pareto principle) highest RPN or which have a RPN higher than 120 or if one criteria has a 10.

For executing the aging FMEA the template from the Tribology Laboratory at Lehigh University[160] was used (see figure 32).

157 https://www.lehigh.edu/~intribos/Resources/SAE_FMEA.pdf SAE Document page 13 – accessed on 22.07.2018
158 https://www.lehigh.edu/~intribos/Resources/SAE_FMEA.pdf SAE Document page 15 – accessed on 22.07.2018
159 https://www.lehigh.edu/~intribos/Resources/SAE_FMEA.pdf SAE Document page 18 – accessed on 22.07.2018
160 Compare https://www.lehigh.edu/~intribos/resources.html accessed on 22.05.2018

The scope of the FMEA are the components of the E-Gas and the aging effects. In the following figure the components are listed. The engine control unit is considered as one block, of course it could be analyzed in more detail as well.

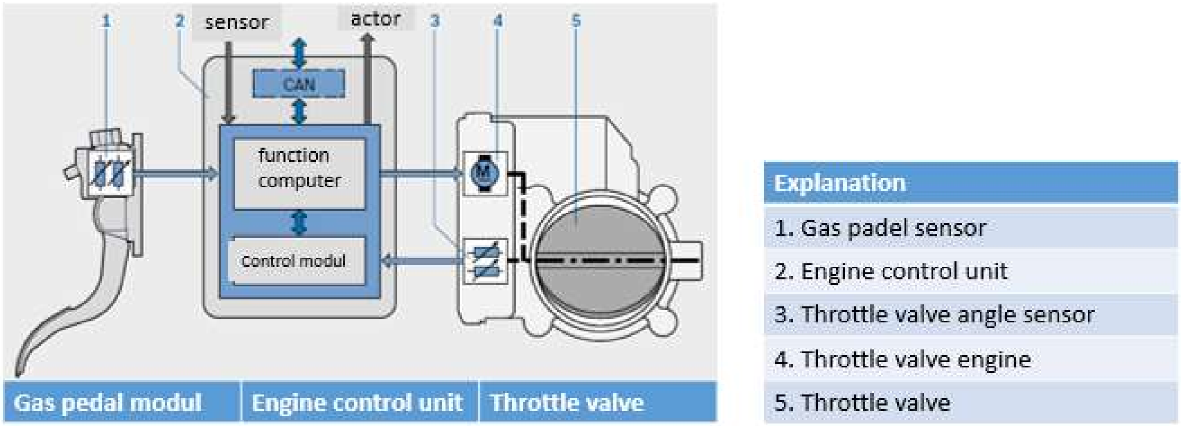


Figure 31 Components of E-Gas[161]

The following figure shows the template and an example of the aging FMEA for the E-Gas.

[161] [Reif_2017] translated from German page 141

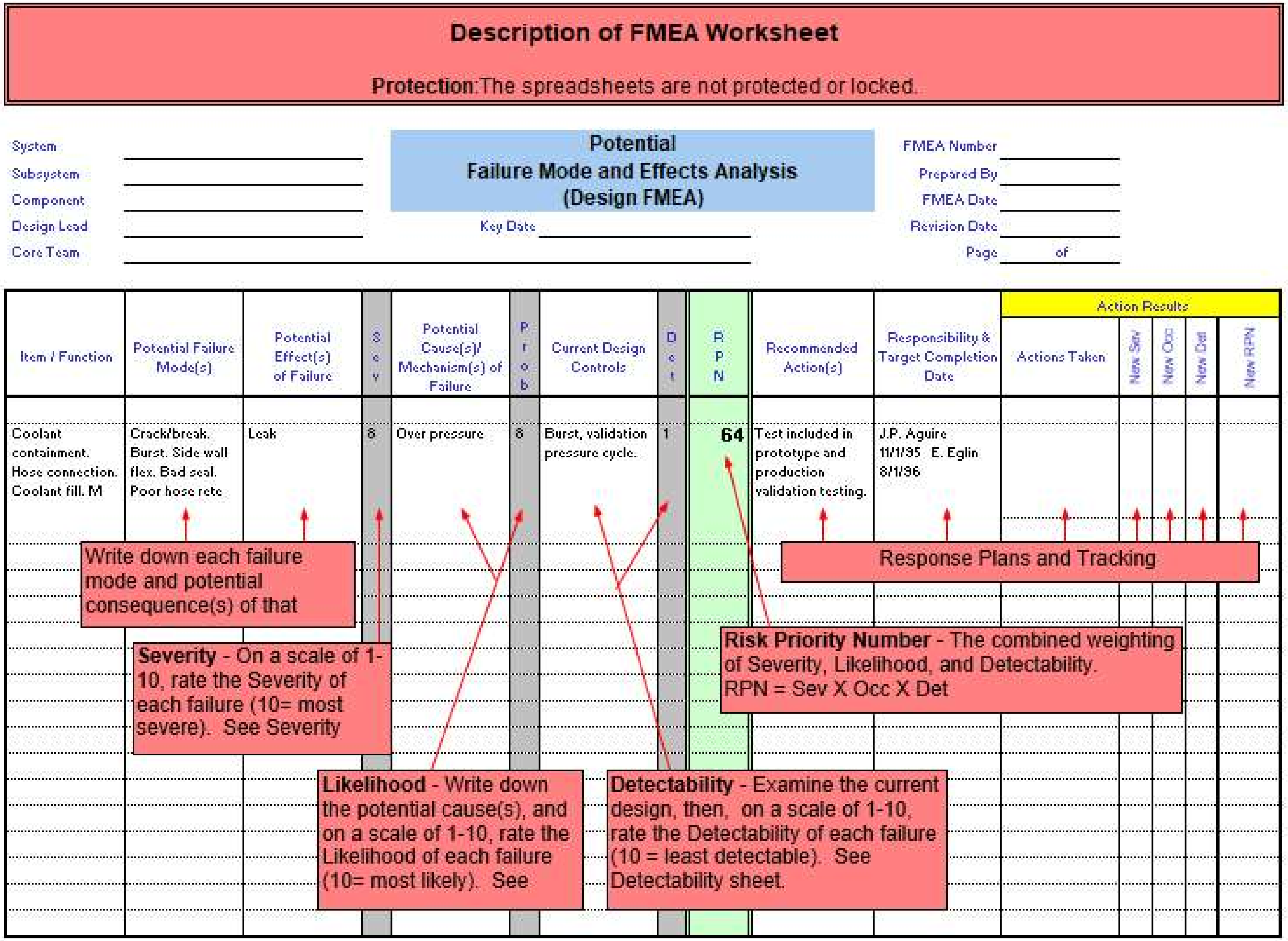
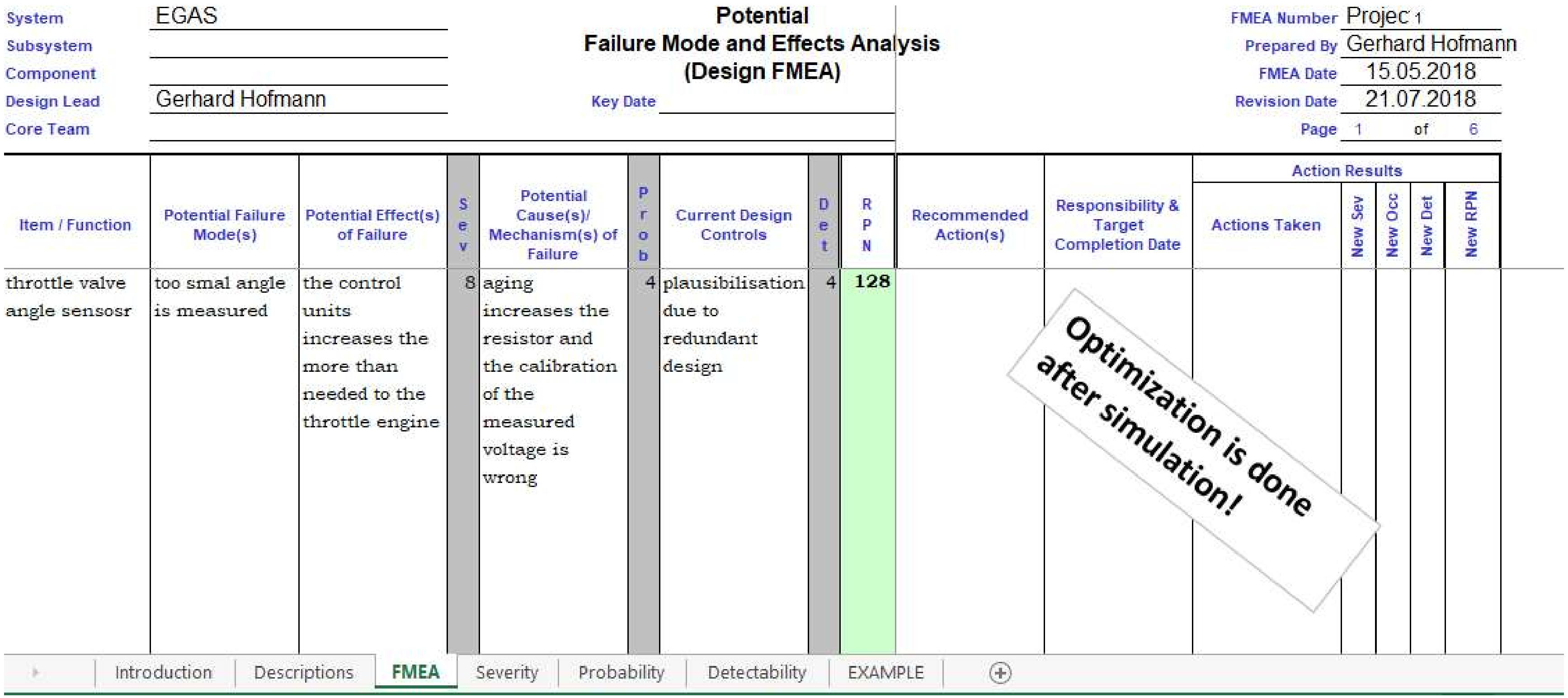


Figure 32 Template with explanation for the FMEA[162]

[162] https://www.lehigh.edu/~intribos/Resources/FMEA-template.xls accessed on 02.07.2018

In the next figure is an example of the aging FMEA for the angle sensor in the potentiometer.



Potential Failure Mode and Effects Analysis (Design FMEA)

System: EGAS
Subsystem:
Component:
Design Lead: Gerhard Hofmann
Core Team:
Key Date:

FMEA Number: Projec 1
Prepared By: Gerhard Hofmann
FMEA Date: 15.05.2018
Revision Date: 21.07.2018
Page 1 of 6

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	New Sev	New Occ	New Det	New RPN
throttle valve angle sensosr	too smal angle is measured	the control units increases the more than needed to the throttle engine	8	aging increases the resistor and the calibration of the measured voltage is wrong	4	plausibilisation due to redundant design	4	128							

Figure 33 Example of aging FMEA

6.4 Development of a VHDL –AMS Model

In order to demonstrate the methodology the scope is a simplification of the potentiometer in the angle sensor of the throttle valve. The Potentiometer are further simplified as a voltage divider with fixed resistors.

Gathering aging information for relevant components

In order to develop a VHDL-AMS Model which includes aging – there has to be a mathematical equation which describes the aging behavior.

The simplest way in scientific papers or data sheets is to describe the aging behavior mathematically. If no such description exists it is needed to perform some experiments. For the aging behavior of resistors both approaches are tried in the next chapters.

The simulation process always starts with the requirements on the model. In the aging case this is the mathematical equation. If this is clear the next step is to translate the requirements in VHDL-AMS. Finally the models need to be validated so that they are conform to the requirements. This principle process is also described in the VDI 2206 in the following figure.

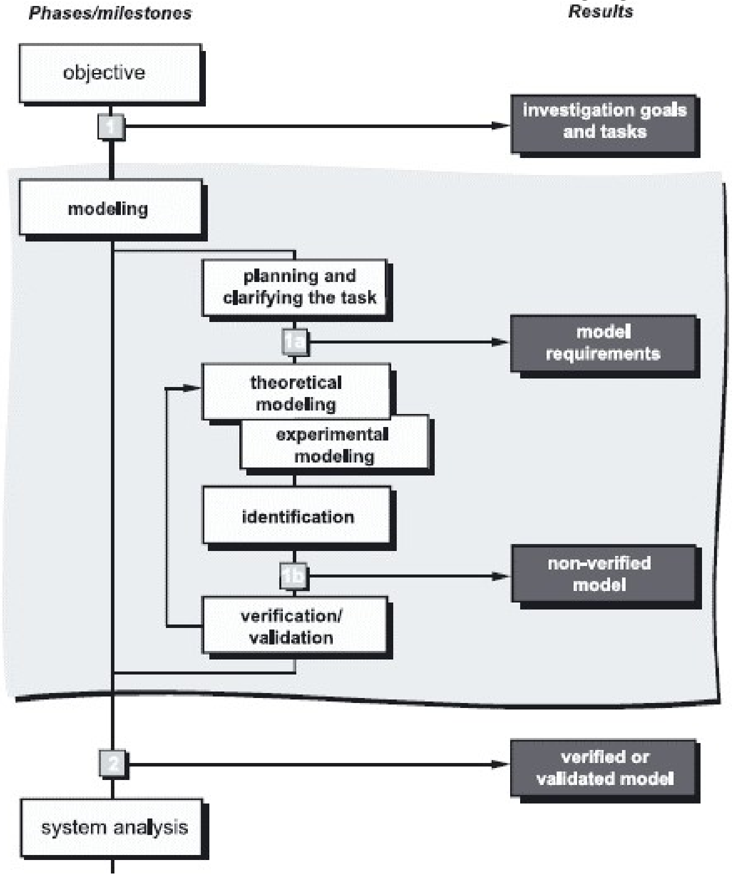


Figure 34 Procedure for modeling[163]

[163] [VDI2206_2004] page 53

Aging behavior of resistor

“An important precondition for this procedure is that the simulated properties coincide adequately with reality.“[164] As the key to apply the proposed methodology it is necessary to find models which can be used for aging simulation. In the following chapter the aging behavior of a resistor is investigated to show that it is possible to simulate aging effects.

Resistors are distinguished between "fixed, mechanically changeable and modifiable by physical quantities resistance values"[165].

Analytic aging models

There is no general equation for resistor aging mechanism, so investigations from earlier papers like “aging behavior of commercial thick-film resistors” are used. The resistor change as a function over time is evaluated. An equation is derived out of the measurements and the diagram in Figure 35 Resistor change over time. This example is chosen to demonstrate that the simulation can be fed out of real measurements.

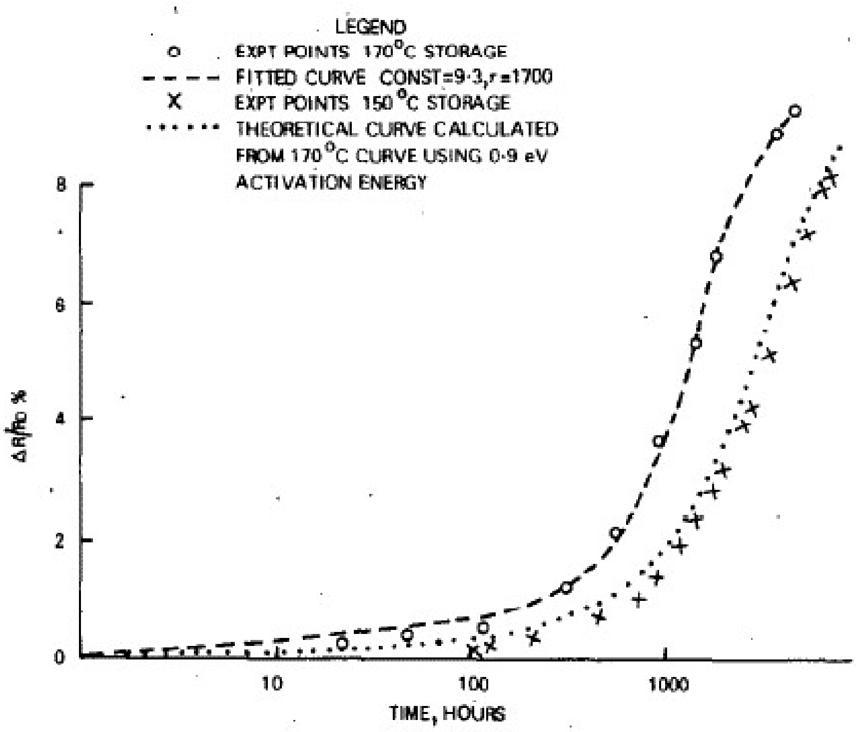


Fig. 18. Comparison of 100 Ω resistor drift with stress relaxation curves fitted to $\Delta R/R_0$ = const × (1 − exp − t/τ) (manufacturer A).

Figure 35 Resistor change over time[166]

---

[164] [VDI2206_2004] page 47

[165] [Stiny_2015] translated from German, page 19

[166] [Sinnadurai_1982] page 316

The diagram of the resistor change over time is computed with Matlab to find the coefficient for the formula which is found by Sinnadurai

$$\frac{\Delta R}{Ro} = a * (1 - e^{\frac{-t}{b}})$$

With the curve-fitting toolbox (see Figure 36) and customer equation are the coefficient a and b estimated with

a= 409.6
b=2.495e+05.

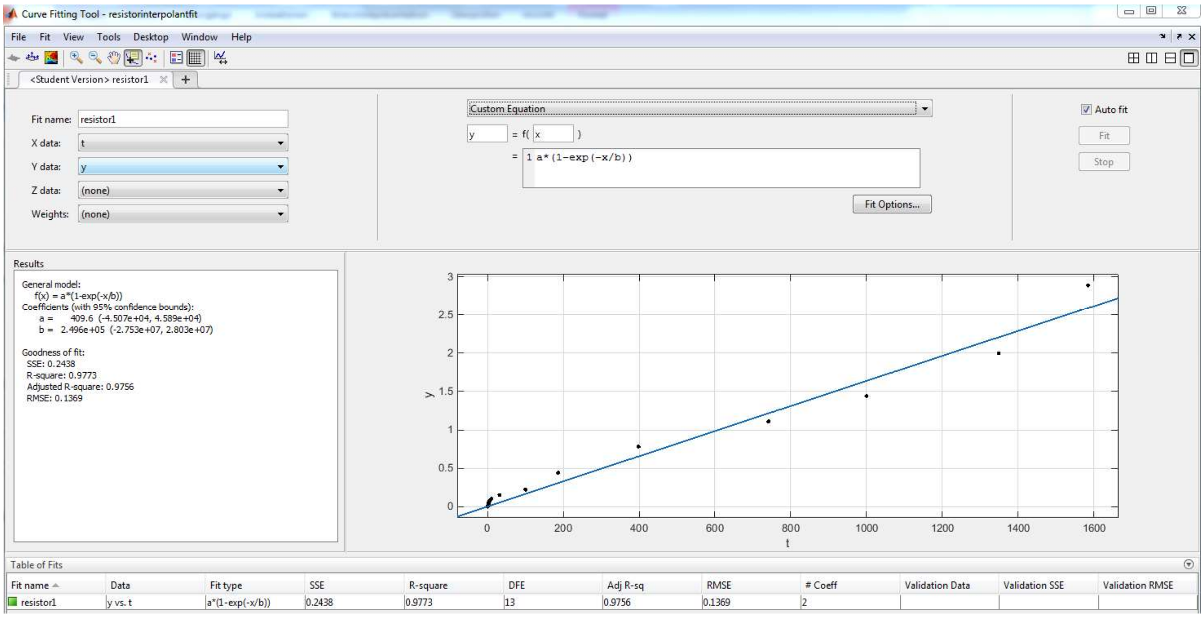


Figure 36 Curve fitting toolbox from Matlab to find the coefficient

To evaluate the parameter on the one hand the diagram (see Figure 37 Matlab diagram calculated) is compared with the original one (see Figure 35 Resistor change over time). The Matlab diagram is generated by a short Matlab code shown in Figure 38 Matlab code to generate diagram

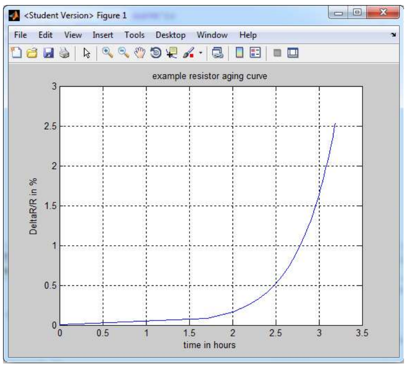


Figure 37 Matlab diagram calculated

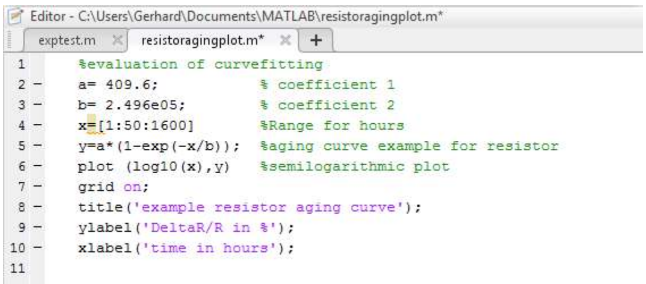


Figure 38 Matlab code to generate diagram

On the other hand an evaluation through the numerical fit results can be done, by using[167]
a) 95% confidence bounds of the fitted coefficients in the toolbox
b) Goodness of fit statistics, here the SSE (sum of squares due to errors) and the adjusted R-square statistic are the best indicator to evaluate the fitting.

A further important parameter in simulation is the simulation time – for this simulation the approach of Sinnadurai is followed, which uses a 500h test duration to simulate a lifetime of 20 years at stress condition of 85°C and 85% of humidity or 2100h at 150°C.[168] So 2000h are chosen, because this fits to the duration of the experiment in chapter 6.4.5.

Aging information in data sheets

The key parameters can be found in data sheets for the simulations, we used the resistance value and the temperature coefficient. There is also manufacturing tolerance which can influence the circuit behavior. The tolerances are specified normally in percent from the nominal value. For variance tests also the tolerance field may be important. For the aging only statically values are given in the data sheet which can be used for worst case calculation. Mathematical equations over time are not available, so an investigation in previous papers of the IEEE database has been performed.

The data sheet of an example resistor shows the temperature coefficient or the worst case tolerances. (see Figure 39 Data sheet excerpt of a resistor)

TECHNICAL SPECIFICATIONS		
DESCRIPTION	VALUE	
	MRS16	MRS25
Resistance range	4.99 Ω to 1 MΩ	1 Ω to 10 MΩ
Resistance tolerance and series	± 1 %; E24/E96 series	
Maximum dissipation at T_{amb} = 70 °C	0.4 W	0.6 W
Thermal resistance (R_{th})	170 K/W	150 K/W
Temperature coefficient	± 50 ppm/K	
Maximum permissible voltage (DC or RMS)	200 V	350 V
Basic specifications	IEC 60115-1 and 60115-2	
Climatic category (IEC 60068)	55/155/56	
Max. resistance change for resistance range,		
load:		
R ≤ 100 kΩ	± (0.5 % + 0.05 Ω)	± (0.5 % + 0.05 Ω)
R > 100 kΩ	± (1 % + 0.05 Ω)	± (0.5 % + 0.05 Ω)
climatic tests:		
R ≤ 100 kΩ	± (0.5 % + 0.05 Ω)	± (0.5 % + 0.05 Ω)
R > 100 kΩ	± (1 % + 0.05 Ω)	± (0.5 % + 0.05 Ω)
soldering:		
R ≤ 100 kΩ	± (0.1 % + 0.05 Ω)	± (0.1 % + 0.05 Ω)
R > 100 kΩ	± (0.25 % + 0.05 Ω)	± (0.1 % + 0.05 Ω)
short time overload	± (0.25 % + 0.05 Ω)	± (0.25 % + 0.05 Ω)

Figure 39 Data sheet excerpt of a resistor[169]

[167] Compare help text from Matlab fits in curve fitting app (Matlab R2014a)
[168] Compare [Sinnadurai_1982] compare page 314, table III
[169] http://www.produktinfo.conrad.com/datenblaetter/400000-424999/418374-da-01-en-WIDERSTAND_METALL_0_6_W_1__10K_BF_0207.pdf accessed on the 16.02.2016

In the data sheet for resistor is no time dependent (= aging) coefficient mentioned. So in a simulation model only a worst case of the tolerances or some combination can be considered with variance simulation. e.g. a monte carlo method.[170]

[170] Compare [Murthy_1983] page 1

Experimental aging models by measurements on resistors

Not much research on aging has been done so far. In a paper over "accelerated aging of thick film resistors" you find observation that "in summary, the most consistent response to all three stress conditions was the progressive increase in resistance with time, the rate of change differing with inks, resistor values and encapsulations, also some resistors remained remarkably stable and one group (in somewhat fragile style of package) occasionally decreased in value."[171] Due to this observation it was decided to perform an own measurement. In a first step a test plan was developed to measure eight different commercial types of resistors. After preparing the test stand the test was executed and the measurement is evaluated.

6.4.1.1 Test plan

The objective of the measurement is to measure the aging influence on the resistor. In Birolini's reliability engineering he states that the dominant parameter influencing the failure rate for resistors is ambient temperature and power stress[172]. Out of this knowledge it is decided to put the devices under test (DUT) in a climber chamber and to use a very low power consumption. The power dissipation is chosen very low – so that there is no internal heating. At the resistor is a total value of $U_{Resistor}$ = 4,9V and $I_{Resistortotal}$ = 0,13A so the power dissipation at the resistor can be calculated as $P_{Resistor}$ = $U_{Resistor}$ * $I_{Resistor}$= $U_{Resistor}^2$ /R= (4,9V)2 /2,4kΩ = 10m W. On one resistor there is an internal power dissipation of 10 mW.

Before the tests were done – a test plan was developed – hereby the following basic principles are considered.

Table 6 Basic principles for a test plan[173]

What	voltage and current of the corresponding resistor
How often	Cyclic time is 30min – for 64 resistors
How Many	64 resistors – 8 of each type
With which equipment	Multiplexer board, Power supply, Clima chamber and PC (details see chapter test stand)
When	For at least 2000h
Who	Ludek Elis and Gerhard Hofmann
Where	KAE Lab University Pilsen
How	According Testplan "aging resistor temperature experiment testplan" v1.0

[171] [Sinnadurai_1980] page 242
[172] Compare [Birolini_2014] page 32
[173] Compare [Pfeifer_2014] page 527

6.4.1.2 Test stand and equipment

The following figure shows the principle block diagram of the test stand. The test stand consists of a climate chamber in which 56 resistors (7 of 8 different families/types) are hooked up via Temp-Flex (Flat-Ribbon Cable, FEP - Fluorinated Ethylene Propylene)-cable with the multiplexer board. The multiplexer board communicates with an analog interface from national instruments and both boards are controlled by a LabVIEW program. With the LabVIEW program the sample rate, and the number of channels can be configured. With a dual power supply the multiplexer board and the resistors are supplied with electrical power. The resistors are grouped on a separate resistor board which contains 8 resistors. In the climate chamber are seven resistors of one family on a resistor board and eight of these boards are put in the climate chamber and one resistor of each family is put on a separate board outside the chamber as a reference.

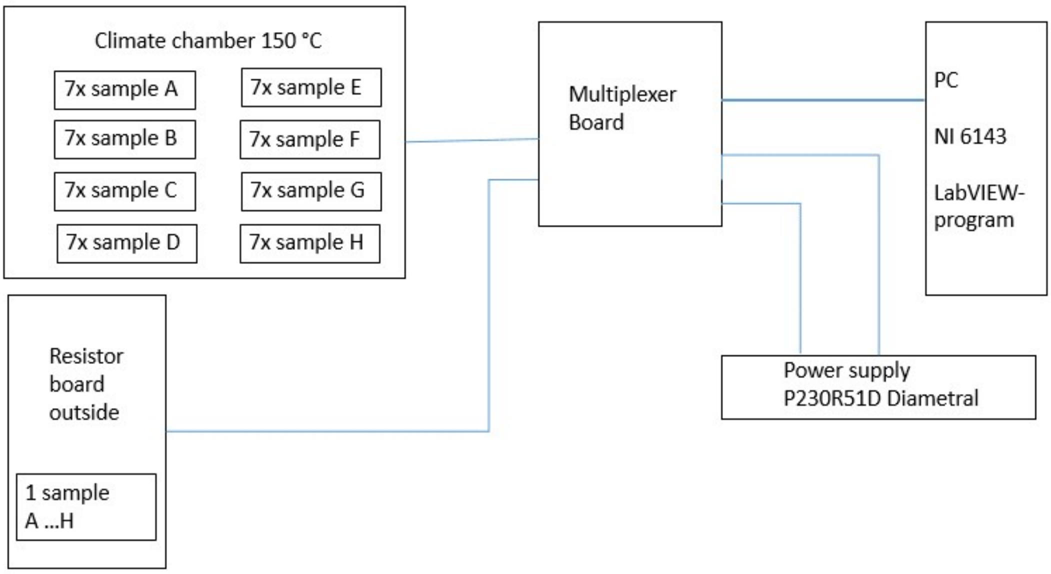


Figure 40 Principle block diagram Test setup

In the following table is the test equipment listed

Table 7 Test equipment

Testequipment type	**details**
Power supply	P230R51D Diametral 2x 0…30V, 4A
Climate chamber	Haraeus T5042 EK
PC- NI-Card	NI 6143 8 AI (16-Bit, 250 kS/s/ch), 8 DIO, PCI Multifunction I/O Device
LabVIEW Program	Measurement.vi (Uses the NI- Interface to collect data)
Muliplexer-voltage-current Measurement board	8 Multiplexer ADG406 with 16 channels (0..4 for current 5..8 for voltage)
Multimeter/Temperature measurement	Metex M-4660A + PT100

The test stand is located under normal laboratory conditions and looks like in the following figure.

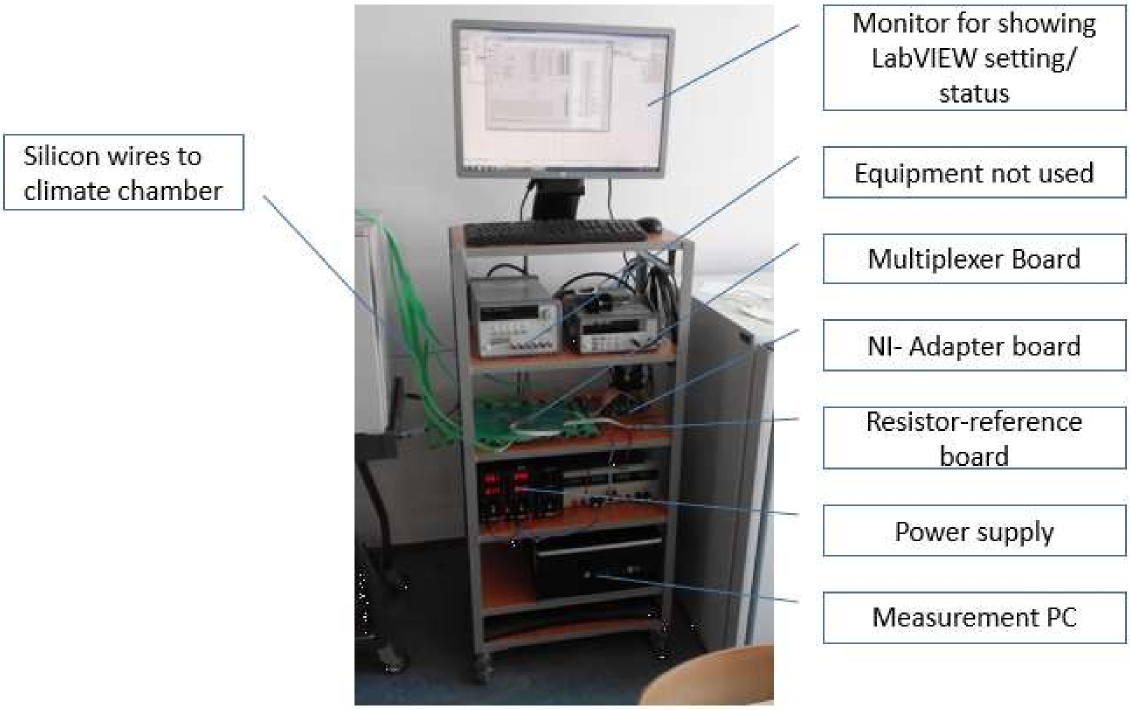


Figure 41 Test stand

A maximum temperature of 150 degree Celsius was chosen. Because this is 5 degrees below the maximum allowed temperature of 155 °C. This temperature required that Temp-Flex wires had to be used to lead the signals outside of the climate chamber. The setting on the climate camber see the following figures.

Figure 42 Climate chamber next to test stand

Figure 43 Loaded climate chamber and setting of climate chamber

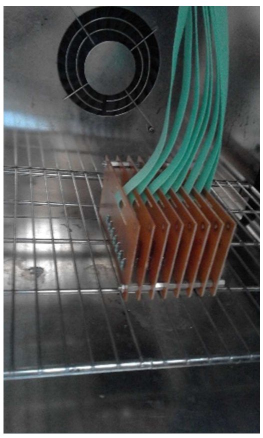


Figure 44 Climate chamber loaded with resistor boards and Temp-Flex wires

The climate chamber is temperature regulated and the initial temperature is double checked with an external thermometer. The climate chamber was reserved for 3 months to fulfill the 2000h.[174] The setup of the test is shown in the following table

Table 8 Test settings

Test Setting	
Temperatur	150°C
Vboard	9,1V
Vresistor	4,9V
Iboard	0,17A
Iresistor	0,13A
Sampling rate	600s

In order to collect the measurement data a multiplexer board is used. The **multiplexer board** is a homemade board of the departement– with mainly consists of 8 multiplexers with 16 channels of the type ADG406 (see the block at the bottom of the schematic in the following figure) and 64 current to voltage converters and signal conditioning circuits INA138 and 64 voltage divider and a connector socket. (see the upper circuits in the figure below)

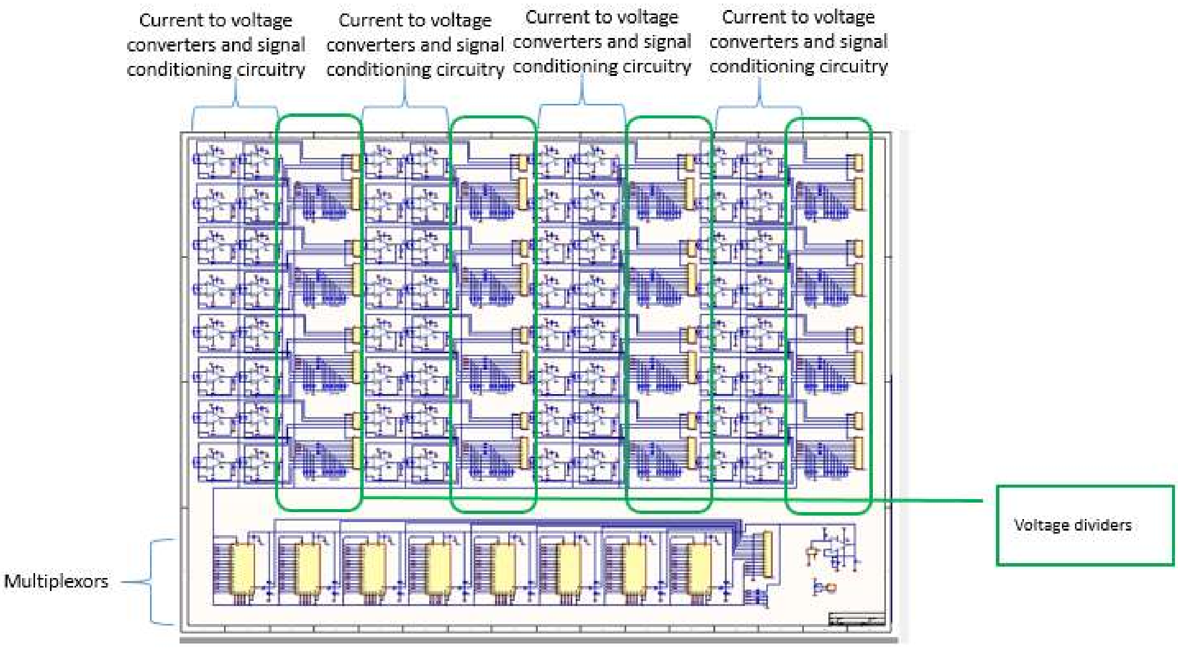


Figure 45 Multiplexer board

174 2000h :24 ≈83,3d ≈2,8 months

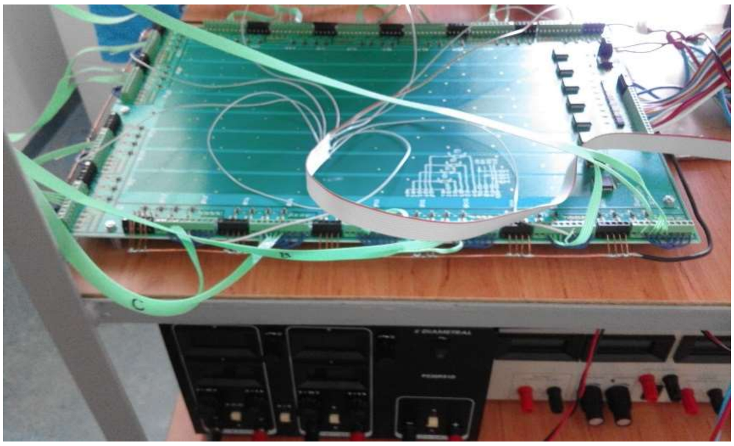


Figure 46 Wired multiplexer board

The current to voltage converters and signal conditioning circuits follows the application recommendation in the data sheet. R_L is chosen with 56 kΩ and R_s with 180Ω. The loads are the resistors (DUT) in the climate chamber with 2,4kΩ.

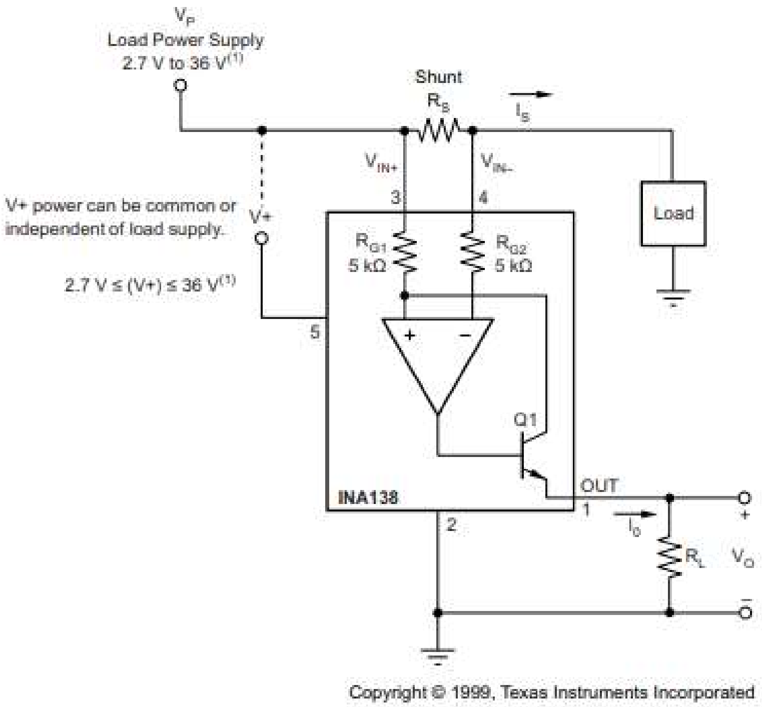


Figure 47 Basic circuit for current to voltage converter[175]

The transfer function for the operational amplifier is

$I_o = g_m (V_{in+} - V_{in-})$ with gm is the transconductance with 200µA/V or $\frac{1\,A}{5000V}$

[175] http://www.ti.com/lit/ds/symlink/ina138.pdf accessed 11.05.2018

The term (V_{in+} - V_{in-}) can be replaced by I_S*R_s

$I_o = g_{m^*} I_S{*}R_s$

The output voltage V_O is the I_O*R_L

$V_O = I_O{*}R_L = g_{m^*} I_S{*}R_{s\,*}\, R_L$ [176]

With this equation the circuit converts the current I_s in a voltage V_O. This voltage is digital sated from an analog input card of national instruments. The values then are processed by a LabVIEW program and stored in a semicolon separated file. Additionally with the LabVIEW file the analog input card can be configured. The following figure shows the LabVIEW configuration panel.

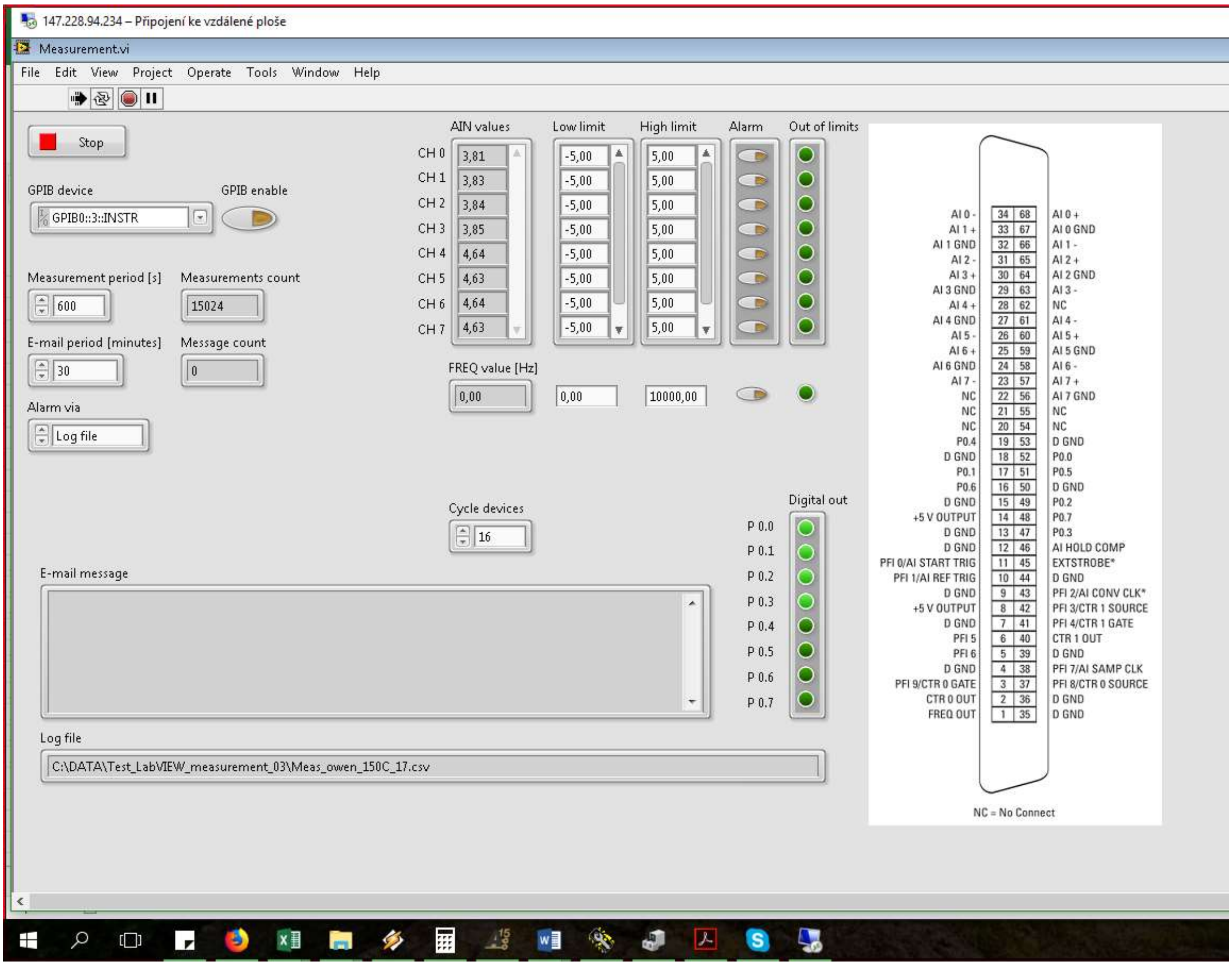


Figure 48 LabVIEW configuration panel

[176] Compare http://www.ti.com/lit/ds/symlink/ina138.pdf accessed 11.05.2018

As devices under test (DUT) the following table shows the chosen resistors. Here the value are chosen of the resistor of a throttle valve and it is tried to get a mixture of different types.

Table 9 Device under test chosen resistors

Number	Type	Value	Description	Type of construction	Tol.	Manufacturer	Part-Number	max Temp in °C	maximum aging Tolerance Δ R/R	Temp. coeffi-cient
R1-R8	A	2,4 kΩ	metal film	THT	1%	WELWYN	MFR4-2K4FI[177]	155	0,5%	50
R9-16	B	2,4 kΩ	metal film	THT	1%	MULTICOMP	MCMF006FF2401A50[178]	155	1,5%	50
R17-R24	C	2,4 kΩ	carbon film	THT	5%	TE CONNECTIVITY	CFR50J2K4[179]	155	5%+0,1Ω	350
R25-R32	D	2,4 kΩ	metal film	THT	1%	VISHAY	MRS25000C2401FCT00[180]	155	0,5%+0,05Ω	50
R33-R40	E	2,4 kΩ	metal film	SMD0805	1%	WALSIN	WR08X2401FTL[181]	155	1%+0,1Ω	100
R41-R48	F	2,4 kΩ	metal film	SMD0805	1%	VISHAY	CRCW08052K40FKEA[182]	155	1%+0,05Ω	100
R49-R56	G	2,4 kΩ	metal film	SMD0805	1%	MULTICOMP	MCMR08X2401FTL[183]	155	1%+0,05Ω	100
R57-R64	H	2,4 kΩ	metal film	SMD0805	1%	Panasonic electronic components	ERJ6ENF2401V[184]	155	N.A	100

177 Compare http://www.farnell.com/datasheets/2331354.pdf?_ga=2.83018130.504599267.1536763498-759771344.1525182251 accessed on 12.09.2018
178 Compare http://www.farnell.com/datasheets/1804148.pdf?_ga=2.137087284.504599267.1536763498-759771344.1525182251 accessed on 12.09.2018
179 Compare http://www.farnell.com/datasheets/1723854.pdf?_ga=2.108840198.504599267.1536763498-759771344.1525182251 accessed on 12.09.2018
180 Compare http://www.farnell.com/datasheets/2046132.pdf?_ga=2.40184102.504599267.1536763498-759771344.1525182251 accessed on 12.09.2018
181 Compare http://www.farnell.com/datasheets/1960319.pdf?_ga=2.107184646.504599267.1536763498-759771344.1525182251 accessed on 12.09.2018
182 Compare http://www.farnell.com/datasheets/2310790.pdf?_ga=2.69848596.504599267.1536763498-759771344.1525182251 accessed on 12.09.2018
183 Compare http://www.farnell.com/datasheets/2549522.pdf?_ga=2.82430354.504599267.1536763498-759771344.1525182251 accessed on 12.09.2018
184 Compare http://www.farnell.com/datasheets/1911175.pdf?_ga=2.70435092.504599267.1536763498-759771344.1525182251 accessed on 12.09.2018

To connect the resistors to the multiplexer board a special resistor board is designed.

The **resistor board** helps to solder more easily the different types of resistors together. A simple resistor board is designed. To get maximum flexibility the board can be used with axial pins (THT) and different SMD grid dimensions. In the following figures the circuit and the layout is shown.

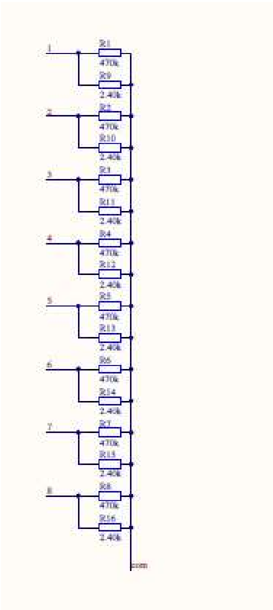


Figure 49 Universal resistor board

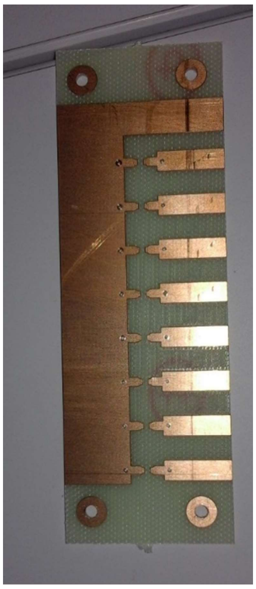


Figure 50 Layout resistor board

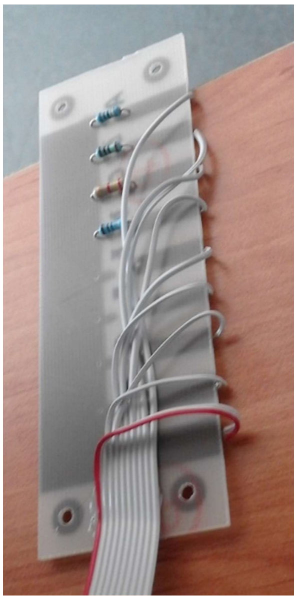


Figure 51 Assembled resistor board

The components are soldered on the resistor board and the board is connected to the multiplexer board. So that all DUT are hooked to the multiplexer board and the multiplexer board sends the data to the analog interface from national instruments and the LabVIEW program stores it in a coma separated file.

6.4.1.3 Test execution

The devices under Test (DUT) are put in a climate chamber under constant temperature of 150 °C. The temperature is self-regulated over time.

The aging experiment are carried out on 8 different resistor types (see table above) Always 7 resistors of one type are measured inside the climate chamber and 1 resistor is measured as a reference outside the chamber. So a total of 64 resistors are tested.

Every two weeks the data is stored in a different file, to avoid that the maximum number of lines in the file are exceeded.

6.4.1.4 Test evaluation/documentation

In a first step soldering influence on the resistors is evaluated. So the resistors are measured before and after soldering. In the next table the example of resistor type B is shown.

Table 10 Example on Type B-Resistor comparison resistor before and after soldering

Sample		14.06.2017		
type	N#	before soldering	after soldering	difference
B	1	2389,283	2390,1	0,817
	2	2389,04	2389,85	0,81
	3	2386,244	2386,77	0,526
	4	2390,382	2390,77	0,388
	5	2390,824	2391,29	0,466
	6	2388,995	2389,73	0,735
	7	2388,371	2389,06	0,689
	8	2390,274	2390,6	0,326
	mean value	2389,176625	2389,77125	0,594625

The measurement shows that there is a small (appr. 0,8Ω or 0,03%) increase in the value. This can be explained by the additional resistance of the solder material and is below the maximum influence in the datasheet. Due to soldering the “resistance change rate is ± (1% + 0.05Ω) Max.with no evidence of mechanical damage”[185]. Important is that there is no big influence due to some relaxation effects.

For the 64 resistors 128 values have been measured. For each resistor two voltages are measured. One voltage is the voltage at the resistor U_R and the other voltage U_I corresponds to the current I_R through the resistor.

$$R = \frac{U_R}{I_R}$$

U_R is directly measured over a voltage divider and I_R can be calculated over the transfer function of the current to voltage circuit (see above).
Starting from the transfer function
$U_I = I_0 * R_L = g_m * I_S * R_s * R_L$ [186]

Where I_S represents the current through the resistor I_R. Transforming to I_R

$$I_R = \frac{U_I}{g_m * R_S * R_L}$$

Using this to calculate the resistor the following equation is used

$$R = \frac{U_R(g_m * R_S * R_L)}{U_I}$$

[185] https://www.farnell.com/datasheets/1804148.pdf accessed on 11.09.2018
[186] Compare http://www.ti.com/lit/ds/symlink/ina138.pdf accessed on 11.05.2018

For evaluating the data excel is used to combine the corresponding values. Finally excel is used to generate a diagram to evaluate the data.

Due to the multiplexer board output consisting of 8 channels 16 measurements are needed to measure the 64 different resistors (128 values). The 8 multiplexer on the board handle the measurements of the 64 current to voltage converter and the 64 voltage divider which is shown in next figure.

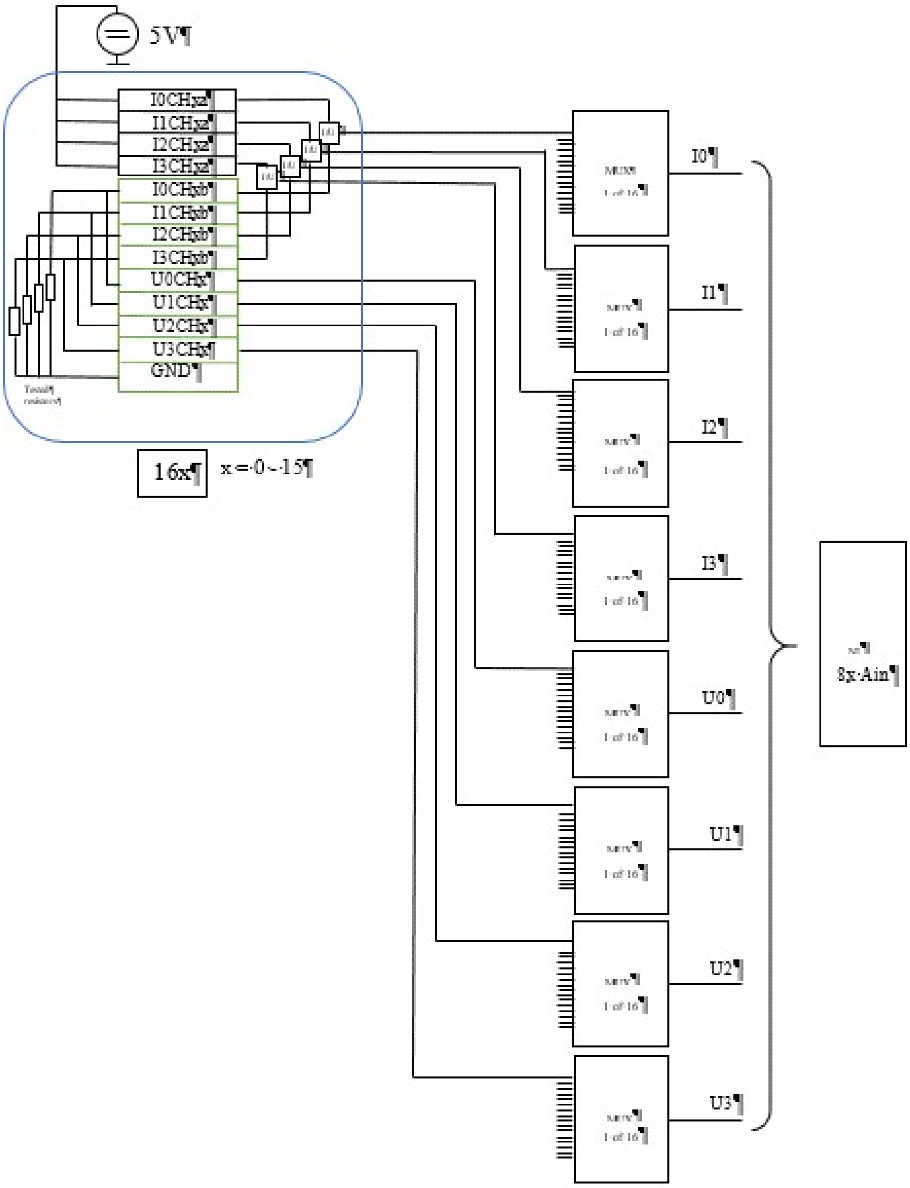


Figure 52 Output of the multiplexer board

An example of the raw data is shown in the following table

Table 11 Raw data example for 16 measurements

Number	Date	Time	Device	AIN0	AIN1	AIN2	AIN3	AIN4	AIN5	AIN6	AIN7
0	03.04.2018	13:44:40	0	3,88107	3,86169	3,89771	3,8768	4,66614	4,66599	4,66736	4,66599
1	03.04.2018	13:44:41	1	3,82462	3,86322	3,87527	3,88809	4,63013	4,62921	4,62997	4,62738
2	03.04.2018	13:44:42	2	3,86597	3,88763	3,89633	3,8858	4,66446	4,66202	4,6637	4,66278
3	03.04.2018	13:44:43	3	3,89282	3,88977	3,92715	3,91068	4,66736	4,66568	4,66751	4,66614
4	03.04.2018	13:44:44	4	4,03534	4,0184	4,06082	4,04175	4,64813	4,64767	4,6489	4,64935
5	03.04.2018	13:44:45	5	3,97827	4,00894	3,98499	3,94333	4,60434	4,60602	4,6048	4,61075
6	03.04.2018	13:44:46	6	3,86932	3,85986	3,89893	3,89328	4,66888	4,66644	4,66797	4,66431
7	03.04.2018	13:44:47	7	3,89374	3,88702	3,91846	4,07791	4,65958	4,65881	4,65942	4,66034
8	03.04.2018	13:44:48	8	3,8829	3,90274	3,93555	3,88412	4,6727	4,66995	4,67255	4,67194
9	03.04.2018	13:44:49	9	3,84094	3,85696	3,86505	3,87787	4,61777	4,62021	4,61884	4,61823
10	03.04.2018	13:44:50	10	3,81042	3,84583	3,82462	3,84186	4,63684	4,63608	4,63684	4,63577
11	03.04.2018	13:44:51	11	3,87741	3,86581	3,88245	3,91098	4,6701	4,66919	4,67072	4,66705
12	03.04.2018	13:44:52	12	3,86841	3,86322	3,86307	3,87634	4,67209	4,67117	4,67422	4,67239
13	03.04.2018	13:44:53	13	3,81424	3,80676	3,82095	4,05472	4,63745	4,63974	4,63821	4,6344
14	03.04.2018	13:44:54	14	3,84369	3,85742	3,86688	3,87054	4,66858	4,66705	4,66827	4,66705
15	03.04.2018	13:44:55	15	3,86276	3,86475	3,89175	3,89435	4,64279	4,64371	4,64386	4,64218

The interpretation of the data is like following. The values in the columns AIN0 to AIN3 represent the voltage of the converted current and the values in the columns AIN4 to AIN7 represent the voltages at the resistor.

The information of the resistors is shown in table 10. The resistors R8, R16, R24, ... R64: were kept out of climatic chamber (the rest of resistors are in groups in the climatic chamber) as a kind of reference.

An excel formula filters the data for the single resistor and does some smoothening of the data, by using the floating mean value of the last 200 values. The advantages of the smoothening is to eliminate single measurement failures, because the aging effect is a steady and slow effect. For the evaluation only the floating mean value is used. In the following figures is one example diagrams for the samples R1 to R8 (=type A) resistor. The resistors from type A are chosen as example only to demonstrate the method.

The first diagram is a boxplot diagram – here the variance of the single resistor is visualized. The diagram shows the resistor R8 (under room temperature) has the lowest mean value and the smallest deviations. But it is also seen that the resistors R1 … R7 show a different behavior, but the mean value is inside the 1% tolerance.

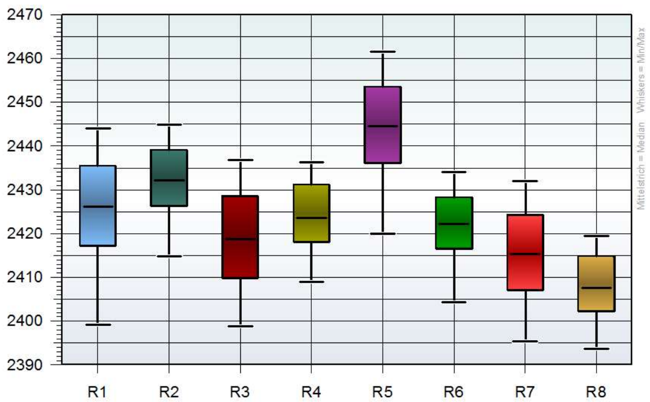


Figure 53 Example boxplot of the R1... R8 (type A)

A statistical analysis of the set of 8 samples of the type A resistors is done and summarized in the following table

Table 12 Sample of statistical evaluation of resistor measurements

Resistor type A	R1	R2	R3	R4	R5	R6	R7	R8
Mean value	2428	2433,7	2421,2	2425,4	2446,4	2423,4	2417,3	2409,5
Standard deviation.	12,254	8,6299	11,751	8,4027	11,712	8,0389	11,176	7,7479
Median	2428	2433,3	2421,2	2425	2446,4	2423,2	2417,2	2409,1
Min	2399,2	2414,9	2398,8	2409	2419,9	2404,4	2395,4	2393,6
Max	2459,2	2454,7	2446,1	2443,8	2477,7	2445,4	2442,7	2426,5
Sample size	16000	16000	16000	16000	16000	16000	16000	16000

The resistors R8 is kept out of climate chamber (the rest of resistors are in the climate chamber) as a kind of reference. It shows that the mean value is very close to the nominal value and the standard deviation is the smallest one. Using the linear temperature coefficient from 50ppm/°C.[187] for this resistor and the equation for temperature dependencies for resistors

$$R_T = R_0 * (1 + \alpha * (T - T_0))$$

T_0 : reference temperature – normally 20°C
T : temperature
R_0 : resistor at reference temperature
R_T : resistor at certain temperature T
A : temperature coefficient of resistance in [ppm/°C]

Assuming a value of 2410Ω at 20 °C, so only due to temperature influence the resistor changes to 2425Ω at 150°C, which explains the difference in the mean value between the resistor outside the climate chamber and inside.

[187] Compare http://www.ttelectronics.com/themes/ttelectronics/datasheets/resistors/MFR.pdf accessed on 11.09.2018

In the following diagrams the change of the floating mean value is shown.

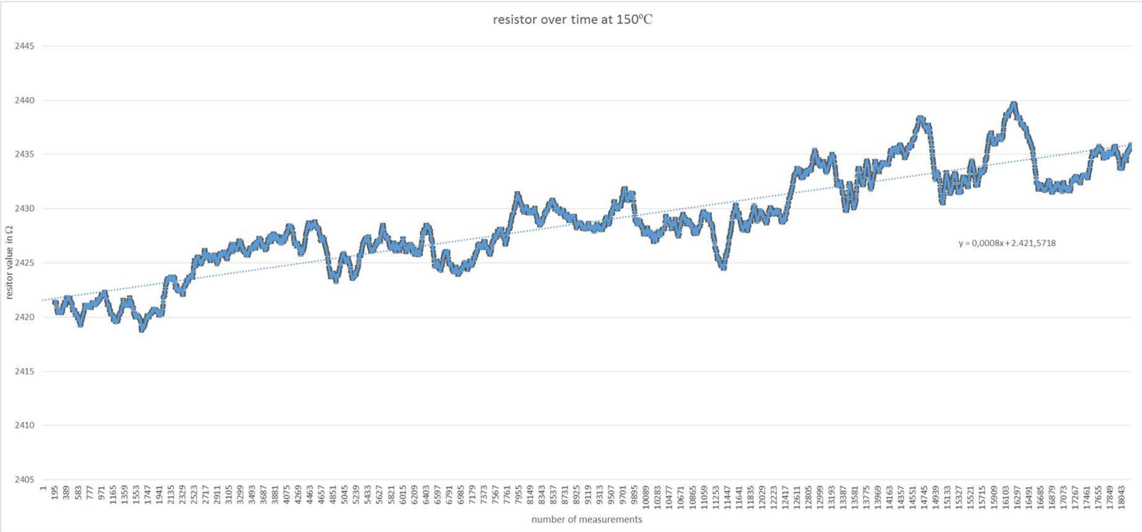


Figure 54 Resistor 1 sample #1 resistor of time at 150 ° C

The linear trend line for this measurement is y=0,0008*x + 2421,6. This formula will be used in one of the scenarios to model the circuit.

The diagram shows a steady increase by 15 Ω. The fluctuation in the measurements is not due to the resistor but induced by the measurement equipment – and is not further investigated, as it is only a demonstration how the method can be used.

In comparison to the resistor stored at 150 °C the following diagram shows the reference resistor at room temperature, because there is no acceleration effect the aging effect is less than with 150 °C.

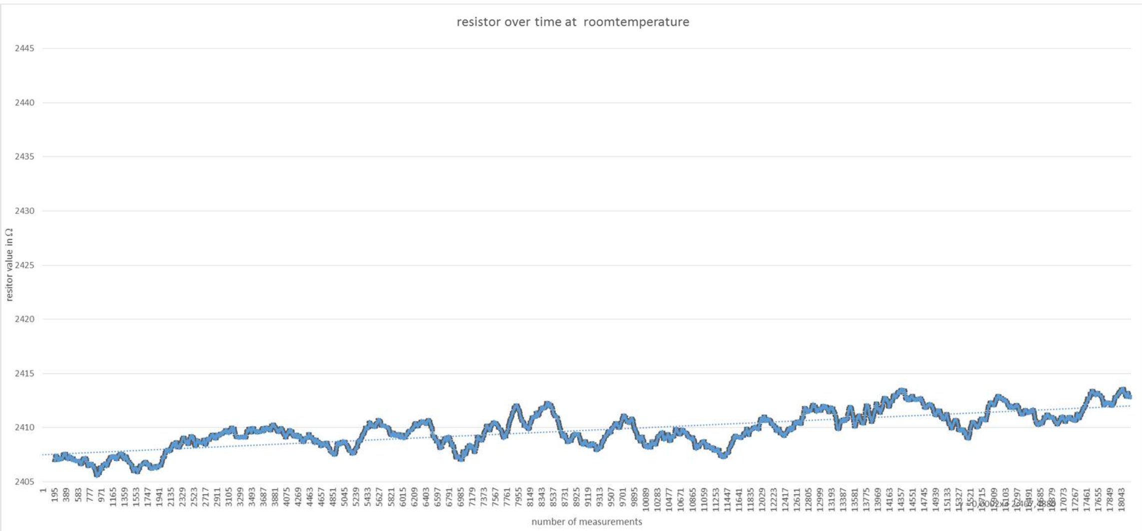


Figure 55 Resistor R8 over time at room temperature

Results show that there is not a big change for aging like described in one of the diagrams in the paper of Sinnadurai over time[188].

Sinnadurai did “some observations on the accelerated aging of thick film resistors” – and summarized that “the most consistent response of all three stress conditions was the progressive increase of resistance with time, the rate of change differing with inks, resistor value and encapsulation, although some resistors remained remarkably stable and one group … occasionally decreased in value.”[189]

6.4.1.5 Conclusion for further modelling

As outcome of the experiment it is seen that one curve in the paper “The Aging Behavior of Commercial Thick-Film Resistors” could not be confirmed.

Further it is seen out of the experiments, that there is not a consistent value and the different components have a big variance.

Keeping these tolerances in mind and that all models are a picture of reality, it is possible to derive a mathematic equation for aging – it can be used in further models.

[188] Compare [Sinnadurai_1982]
[189] [Sinnadurai_1980] page 242

6.5 Simulation with special aging models

Used simulation tool – Simplorer from ANSYS

The company ANSYS was founded 1970 and offers engineering software. Today it has around 3000 employees and its headquarters is located in Canonsburg, Pennsylvania, USA.[190]

The product "Simplorer" is described as „an intuitive, multidomain, multitechnology simulation program used to simulate, analyze, and optimize complex systems, including electromechanical, electromagnetic, power and other mechatronic designs."[191] As modelling techniques can be used circuits, block diagrams, state machines or equations which can be modelled in VHDL-AMS, SML or C/C++[192]

The following figure shows the workbench of the Ansys Simplorer electromagnetic suit 16.2. Here you organize the projects.

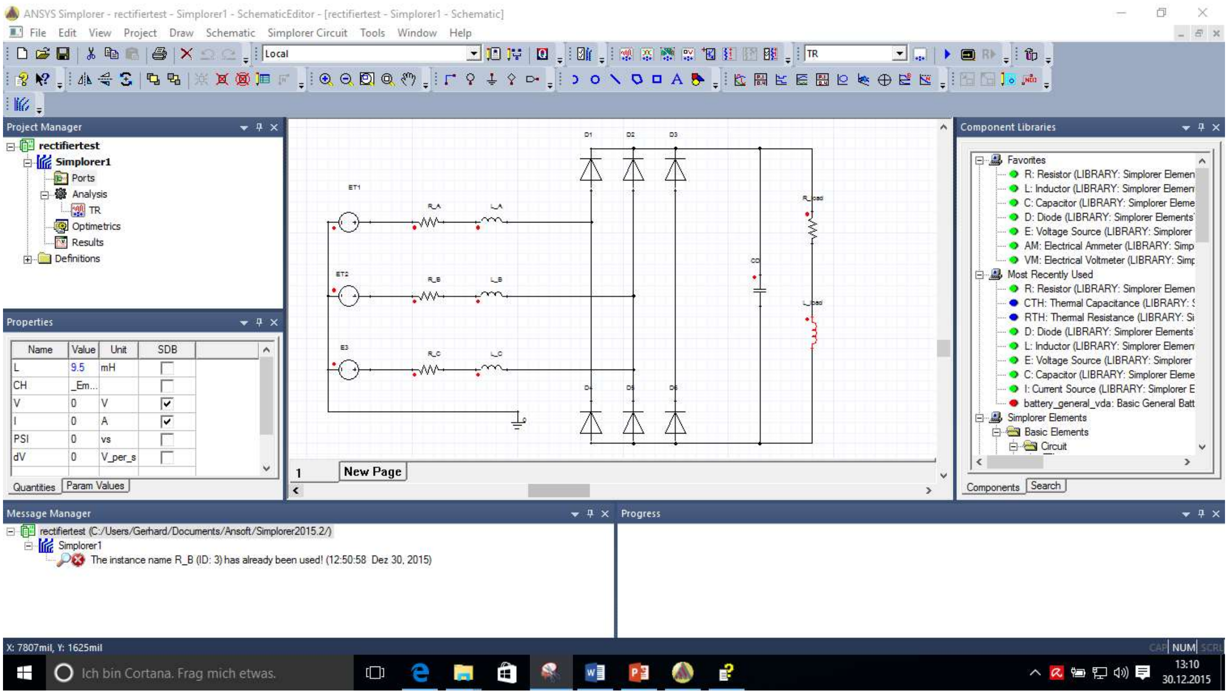


Figure 56 Workbench of Simplorer – electromagnetic suit 16.2 with an example circuit

[190] Compare http://www.ansys.com/About+ANSYS accessed on 31.12.2015

[191] http://www.ansys.com/staticassets/ANSYS/staticassets/resourcelibrary/brochure/ansys-simplorer-brochure-14.0.pdf accessed on 31.12.2015

[192] Compare http://www.ansys.com/staticassets/ANSYS/staticassets/resourcelibrary/brochure/ansys-simplorer-brochure-14.0.pdf accessed on 31.12.2015

Used model for analytic aging resistor

In order to simulate the aging dependencies of a resistor a simple circuit was used (see Figure 57 Simple circuit to simulate resistor). In order to see the behavior of the ideal resistor directly in the results a current source was used and the voltage drop on the resistor was visualized. According to the ohms law R = U/I, if the current is constant, the resistor is proportional to the voltage drop (VM1). Of course the model of resistor with stray capacitance and inductance can be used. For clarification of aging the ideal model is used.

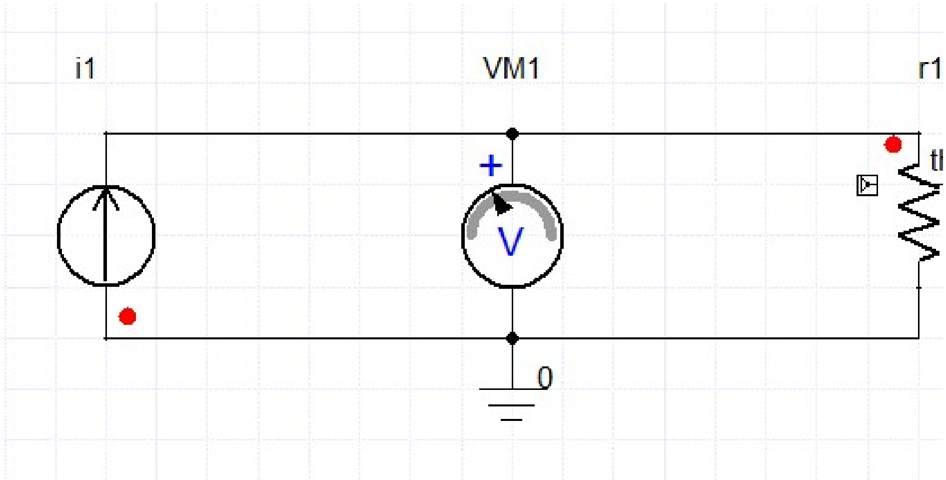


Figure 57 Simple circuit to simulate resistor

To model the aging effect of a resistor in the architecture in VHDL –AMS the following VHDL code is used. The variable Rstart represents the nominal value of the resistor at the beginning – and the Ragingcoeffa and Ragingcoeffb are figured out by approximating the measured values with a mathematic function (see chapter 6.4.3) The x-axis is represented by the time and therefore the term real(zeit) is used.

```
v==i* (Rstart*Ragingcoeffa*(1-exp(-real(zeit)/Ragingcoeffb)));); 
```

Different approaches to model aging function were tested. In the first approach to simulate the time dependency the attribute time'pos (now) was used. As the original unit of time was in ns a correction by dividing with 3600 10E-9 was necessary. By using a simulation time of 1500 hours the simulator could not converge and reported a warning (see Figure 58 Error message with time'pos(now) approach).

Figure 58 Error message with time'pos(now) approach

In a second approach the e-function was approximated by a polynomial function, which would be not so accurate but close to the original function. Here the problem occurred that the accuracy of the solver found its limits, so it responded with not plausible values.

The final solution was simulating the time with one additional counter or in other words digitalized the calculation of the resistor. For this reason a process was included with the "Wait for 1hr" statement. A process was necessary to get a sequential behavior and to use the wait function. The wait function waits to the specified time. As the aging function is a continuous curve it is okay to digitialise it. The accuracy can be increased by lowering the constant “waiting time”. Also the e-function could be modelled with this solution.

Another problem that was observed, was that the used variables could not be transferred to the main architectural behavior, because they are only valid inside the process. To solve this problem a signal “sigRvar” was introduced, because with signals a communication to the rest of the architecture is possible. The process is actually used in the model aging function and it was turned into an entity “aging_func” to be usable not only by one component. The library model of ideal resistor was used as an aging component.

In Figure 59 Simple VHDL AMS Model of a aging resistor. is the VHDL Code for this solution.

```
LIBRARY IEEE;
USE IEEE.ELECTRICAL_SYSTEMS.ALL;
USE IEEE.MATH_REAL.ALL;
ENTITY  aging_func IS
  port
                  (
                   aged_value : out real
                  );
END ENTITY aging_func;

ARCHITECTURE arch_aging_func OF aging_func IS
CONSTANT Ragingcoeffa: real := 409.6;
CONSTANT Ragingcoeffb: real := 2.495e+05;
CONSTANT Rstart: real := 1.0e+03;
SIGNAL    sigRvar: real :=0.0; -- signal which is modifided in process p1

BEGIN
  P1: PROCESS
    VARIABLE B : boolean := false;
    VARIABLE zeit : integer :=0;
          BEGIN
          WAIT for 1 hr;    -- optional time
          zeit := zeit+1;
          sigRvar<=Rstart*Ragingcoeffa*(1-exp(-real(zeit)/Ragingcoeffb));
          Assert B
          report "time ="& integer'image(zeit) & "h " &" sigRvar in process = "&real'image(sigRvar)
          severity note;
          end PROCESS;
aged_value <= sigRvar;
END ARCHITECTURE arch_aging_func;

-- VHDLAMS MODEL aging_res --
LIBRARY IEEE;
USE IEEE.ELECTRICAL_SYSTEMS.ALL;
```

```
USE SIMPLORER_ELEMENTS.ALL;
ENTITY  aging_res IS
PORT(
        TERMINAL P : ELECTRICAL;
        TERMINAL N : ELECTRICAL);
END ENTITY aging_res;

ARCHITECTURE arch_aging_res OF aging_res IS
  signal shared_par : real;

BEGIN
   MODEL_inst : entity R
    PORT MAP
        (
         P => p,
         N => m,
         R => shared_par
         );

  AGING_inst : entity AGING_FUNC
   PORT MAP
        (
        aged_value => shared_par
        );
END ARCHITECTURE arch_aging_res;
-- END VHDLAMS MODEL aging_res -
```

Figure 59 Simple VHDL AMS Model of a aging resistor[193].

To verify that the model is working, an assert command reportet the resistor values and exported it to an excel-file. This data is then compared with the points extracted out of the paper of Sinnadurai. The comparison shows that it is not identical but similar – and for demonstrating the method enough.(Figure 60 Comparison of results of aging resistor simulation – measurement)

[193] [Hofmann_2016]

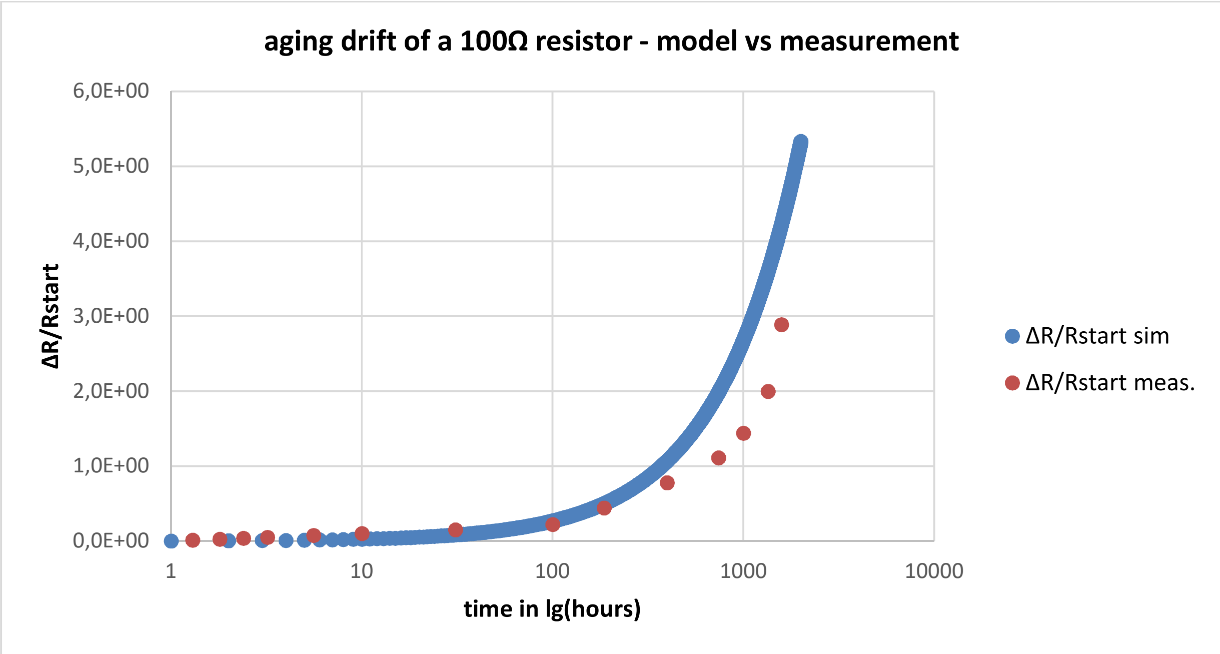


Figure 60 Comparison of results of aging resistor simulation – measurement

Used model for experimental aging resistor

Out of the data of the experiments in chapter 6.4.5 a different aging equation is found. For the model it means, that the formula out of the paper of “The Aging Behavior of Commercial Thick-Film Resistors” is replaced by the equation found in the experiments.

Out of the aging measurements the linear trend line for the resistor R1 is used to demonstrate the procedure.

Y=0,0008*x + 2421

In VHDL translated it means

```
BEGIN

    WAIT for 1 hr;  -- wait for 1 hour

zeit := zeit+1;
--  sigRvar <= Rstart*Ragingcoeffa*(1-exp(-real(zeit)/Ragingcoeffb));
    sigRvar <= 0.0008*Zeit + Rstart; -- linear expretion due to measurment
```

Figure 61 Modified VHDL Code for linear trend line

The output of the single resistor is

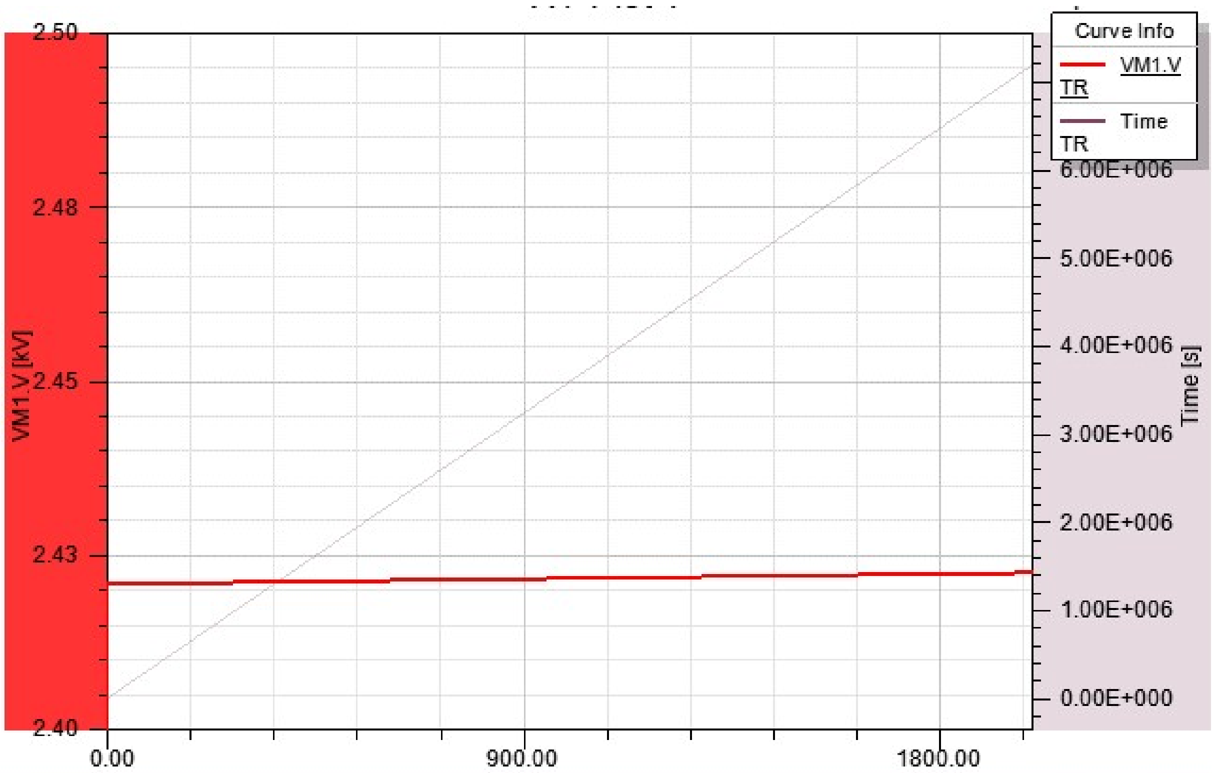


Figure 62 Resistor model behavior out of measurement data

Here the linear trend is seen in VM1.V.

Aging models of the potentiometer of the angle sensor in the throttle valve

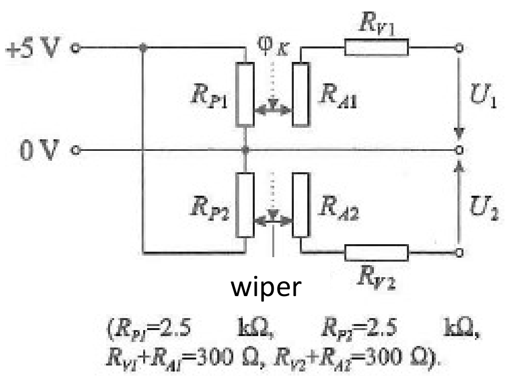
Using the results from the FMEA (see chapter 6.3) the risky components is the resistor in the potentiometer. In order to demonstrate the methodology simplification are done to simulate the potentiometer of the angle sensor in the throttle valve.

In the electronic gas (E-Gas) application there is a double potentiometer as angle meter in the throttle valve and in the gas pedal.

As the angle sensor is an input signal for the motor electronic to control the power, the signal is safety relevant. In order to avoid failures the sensor is redundant and the engine electronics check if the signals are plausible. In case the engine electronic detects a failure the control unit puts the engine in a safe state and informs the driver by an engine control symbol.

A plausibility of the signal could be done by comparing the two signals and if the difference exceeds a defined limit the control unit rates this as failure. The purpose of the simulation can be to prove the diagnostic mechanism or to optimize a reasonable limit. If the limit is set for example to 20% a lifetime prediction can be made.

The circuit for a throttle valve is a simple voltage divider – if you look at the next figure



R_{p1} = 2,5kΩ; $R_{A1} + R_{V1}$ =300 Ω
R_{p2} = 2,5kΩ; $R_{A2} + R_{V2}$ =300 Ω

Figure 63 Equivalent circuit of a sensor in the throttle valve[194]

The current to the sliding contact (R_{A1}, R_{V1}, R_{A2}, R_{V2}) is limited due the analog/digital converter to 15µA. If you compare it with the main branch with approximately 2mA (= 5V/2,5kΩ) it can be neglected. The voltage drops on R_{V1} is 300Ω*15µA=4,5mV so that U_1 is in the range of 4,955 to 0V. So for simulation a simple voltage divider can be used.

Another simplification is that instead of the potentiometer 2 fixed resistor values are used.

Simulating the equivalent circuit as voltage divider with aging effects, did not show any influence. The reason for this is, that the simulation models for the single resistors were completely identically. So extreme scenarios were investigated, where only one single resistor shows an aging behavior.

[194] [Pfeufer_1999] – page 15

All simulations are done over 2000h.

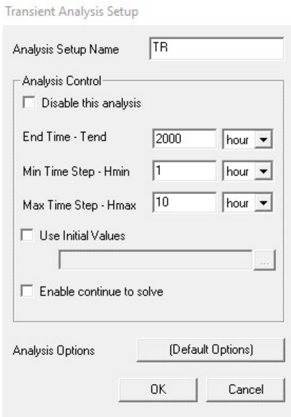


Figure 64 Simulation setup for 2000h

Scenario 1 is the situation, only 1 resistor shows aging effects. Although it is unrealistic that only one resistor would show an aging effect – but it is a worst case assumption, because other aging effects would compensate each other. Here two options are available: the aging from the own measurements (see chapter 6.5.3, scenario 1a) or from other studies (see chapter 6.5.2, scenario 1b).

The model of the simplified equivalent circuit is shown in the following figure.

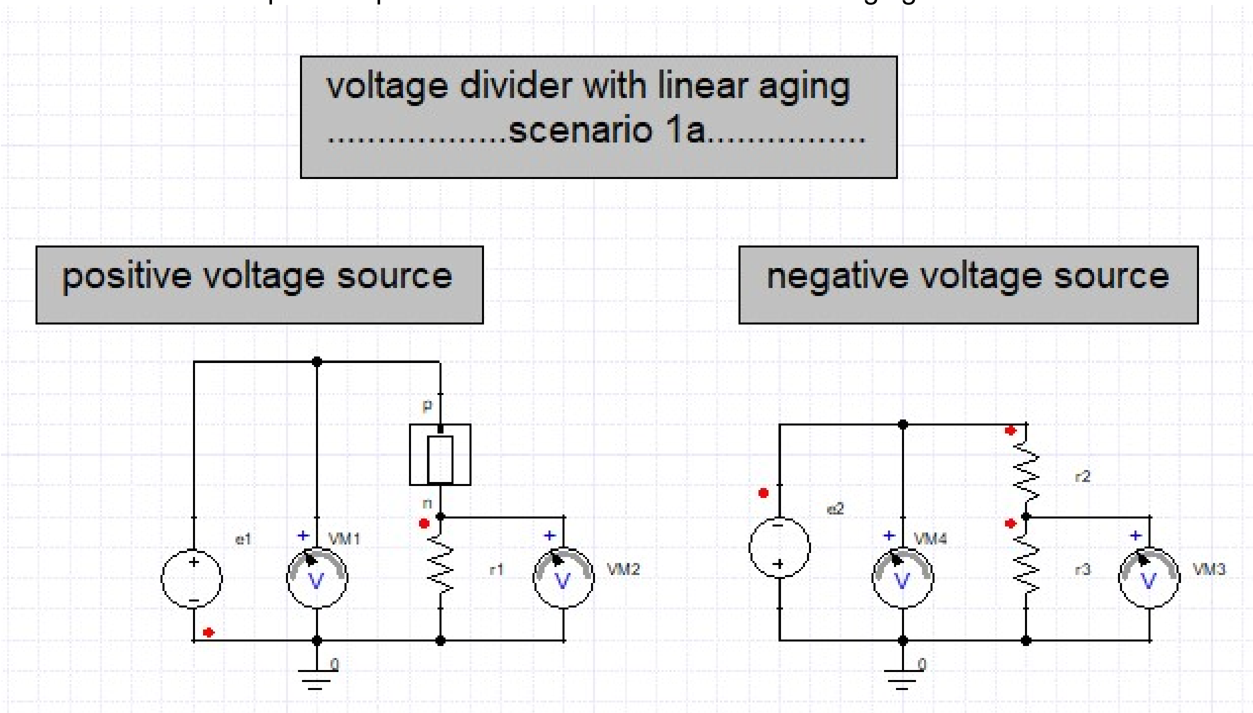


Figure 65 Simplorer model for simulation potentiometer in the throttle valve - one resistor

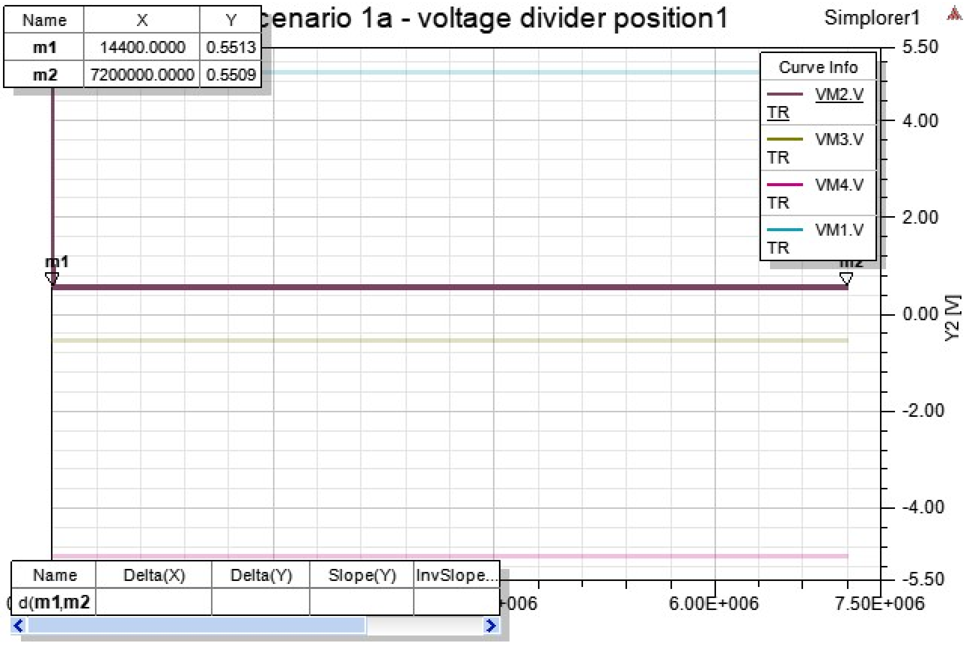


Figure 66 Simulation of linear aging - one resistor

In scenario 1a after the simulation only a small influence is seen on the output voltage VM2.V In this case only a change by 0,7% of the original value of 0,5513V is seen – this change is smaller than 1%. So the failure is also smaller than 1%. This value is much below the limit and therefore the design is ok and shows no problem to use it.

For scenario 1b the e-function out of chapter 6.5.2 is used – the formula is modified to

sigRvar <= Rstart+Rstart*Ragingcoeffa*(1-exp(-real(zeit)/Ragingcoeffb));

The circuit was the same one as in scenario 1a. The following figure shows the result for simulating scenario 1b.

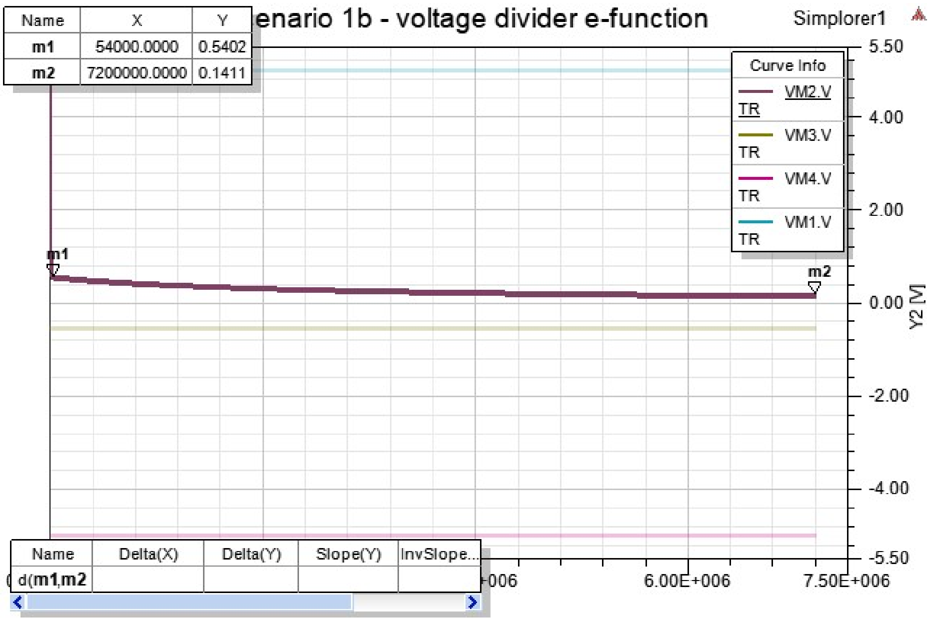


Figure 67 Simulation of e-function aging – one resistor

With the values from the marker (see table in the left top corner) – a change in the voltage is seen from 0,5402V to 0,1411V – which means a change by 73% - This value exceeds the chosen limit (20%) and therefore further design activities are needed. This behavior would be detected by the plausibility check, because only one resistor shows was modified. The other circuit would get a different signal and the engine modul could switch in a safe state.

Scenario2 is the situation when two resistors show aging effects, one in each voltage divider. Here the scenario with the e-function is evaluated because it is considered as the most critical one.

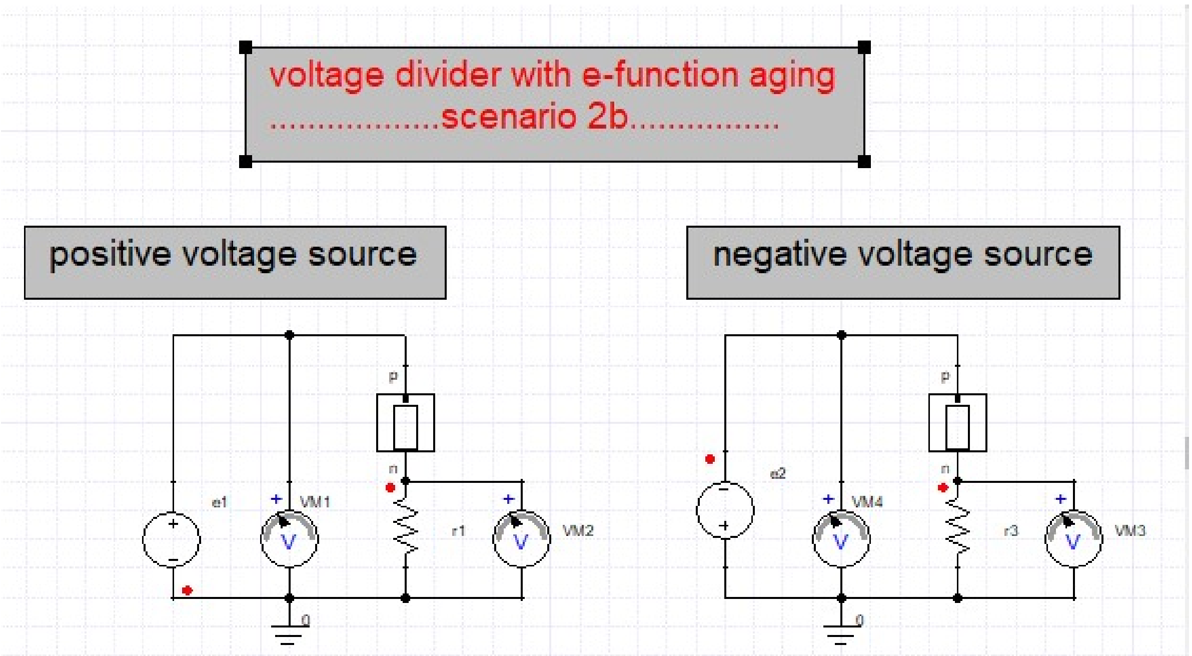


Figure 68 Simplorer model for simulation simplified potentiometer in the throttle valve- two resistor

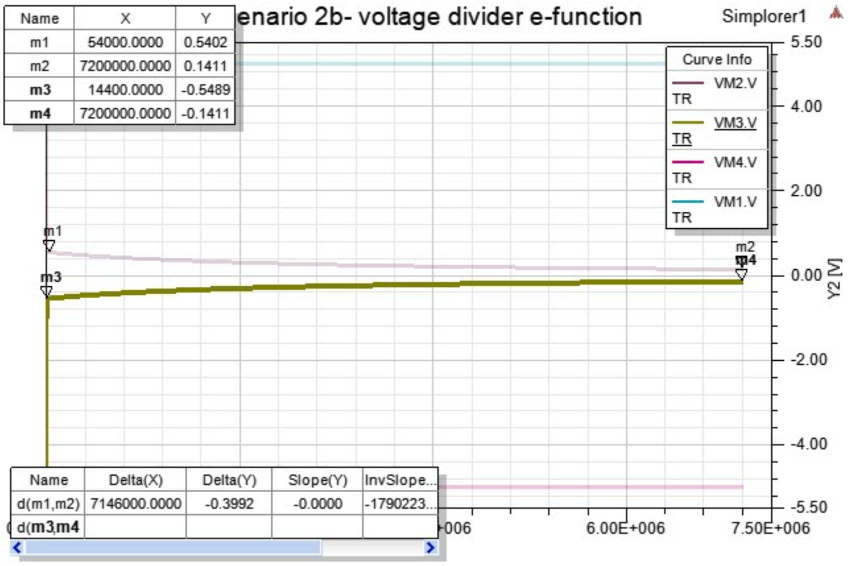


Figure 69 Simulation of e-function aging - two resistors

There is a change in the signal over time – but as there is an effect on both voltage dividers and then the plausibility check fails, because no failure will be detected. So the conclusion is in this case an additional plausibility check against an absolute value is needed. In case this would not be done – a wrong value would be used for calculating in the engine control unit and a too strong engine moment is possible – which could affect the safety goal.

6.6 Evaluation of simulation results

The simulation helps to prove that also aging effects on a circuit can be better understood and improvements in an early development phase can take place, e.g. add an additional plausibility check (see scenario 2b) or to optimize the prove of the diagnostic mechanism (see scenario 1b)

The simulations shows that there is a benefit in using aging simulation in an early phase with the focus on Functional Safety.

7 Summary and conclusion

In the first step, a methodology is presented (see chapter 5), which connects the two areas Functional Safety and simulation with the focus on aging.

The methodology uses as basis the requirements from the ISO26262 for the technical concepts. To prioritize the tasks a FMEA is used to find the critical components, functions or system, which can than be simulated via VHDL-AMS.

A limitation in the system is seen in acquiring aging relevant data. Here different approaches are possible- to get the data from own measurements, other paper or the supplier of the component. Further the benefit is limited in case a worst case design is made and reliable tolerances for aging are available.

In the final step it has been demonstrated by a simple example that by VHDL-AMS model aging effects can be simulated with the ANSYS Simplorer by electrical components (see chapter 6.5). The benefit of using simulation is in an easy and quick possibility to evaluate different scenarios in an early design phase – which are difficult to reproduce with real hardware. Further the presented method provides a deeper understanding of ageing effects over time. It offers the possibility to redefine the worst case limit value. The redefinition of the limit values can advantageously facilitate the solvability of a problematic design and lead to an improvement of the circuit tolerances.

Summarizing it is shown that the described methodology is an additional contribution to a structural approach of improving the design reaching the safety goals and optimizing the diagnostic mechanism in an early design phase by aging simulation. The main limitations are the existing aging information for the single components.

It will be mentioned that this methodology is a supplement to the already existing procedure, like worst case simulation and with the current data base it cannot substitute the actual environmental validation.

As a further research field it is seen how aging mechanism work in electronic components and systems. Also the methodology can be further used to develop or investigate safety reaction, like diagnostics.

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CERTIFICATE

This is to confirm that the paper "Überlegungen zur normativen Anpassung der ISO 26262 aufgrund des autonomen Fahrens"

was presented by

Gerhard Hofmann,
University of West Bohemia in Pilsen

at the Automotive Software Congress
in Landshut on the 23th of September 2015.

Yours Sincerely

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