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SURFACE VEHICLE RECOMMENDED PRACTICE

SAE J1211 APR2009

Issued 1978-06
Revised 2009-04

Superseding J1211 NOV1978

(R) Handbook for Robustness Validation of Automotive Electrical/Electronic Modules

RATIONALE

In late 2006 Members of the SAE International Automotive Electronic Systems Reliability Standards Committee and ZVEI (German Electrical and Electronic Manufacturers' Association) formed a joint task force to update SAE Recommended Practice J1211 NOV1978 "Recommended Environmental Practices for Electronic Equipment Design." The 1978 of version of SAE J1211[1] was written in an era when electronics were first being introduced to the automobile. There was a high level of concern that the harsh environmental conditions experienced in locations in the vehicle could have a serious negative affect on the reliability of electronic components and systems. Some early engine control modules (ECMs) had failure rates in the 350 failures per million hours (f/10^6 h) range, or expressed in the customer's terms, a 25% probability of failure in the first 12 months of vehicle ownership. At that time, warranty data was presented in R/100 (repairs per 100 vehicles) units, for example, 25 R/100 at 12 months.

In these early years, when the automotive electronics industry was in it's infancy, a large percentage of these were "hard" catastrophic and intermittent failures exacerbated by exposure to environmental extremes of temperature (–40 °C to +85 °C); high mechanical loads from rough road vibration and rail shipment; mechanical shocks of up to 100 g from handling and crash impact; severe electrical transients, electrostatic discharge and electromagnetic interference; large swings in electrical supply voltage; reverse electrical supply voltage; and exposure to highly corrosive chemicals (e.g., road salt and battery acid). The focus of the 1978 version of SAE J1211 was on characterizing these harsh vehicle environment for areas of the vehicle (engine compartment, instrument panel, passenger compartment, truck, under body, etc.) and suggesting lab test methods which design engineers could use to evaluate the performance of their components and systems at or near the worst-case conditions expected in the area of the vehicle where their electrical/electronic components would be mounted. By testing their prototypes at the worst case conditions (i.e., at the product's specification limits) described in the 1978 version of SAE J1211 designers were able to detect and design out weaknesses and thereby reduce the likelihood of failure due to environmental factors.

By the mid-1980s, it became common practice to specify "test-to-pass" (zero failures allowed) environmental conditions-based reliability demonstration life tests with acceptance levels in the 90% to 95% reliability range (with confidence levels of 70% to 90%). This translates to approximately 5 to 20 f/10^6 h. The sample size for these tests was determined using binomial distribution statistical tables and this would result in a requirement to test 6 to 24 test units without experiencing a failure. If a failure occurred, the sample size would have to be increased and the testing continued without another failure till the "bogie" was reached. The environmental conditions during the test were typically defined such that the units under test were operated at specification limits based on SAE J1211 recommended practices (e.g., –40 °C and +85 °C) for at least some portion of the total test time. The "goal" of passing such a demonstration test was often very challenging and the "test-analyze-fix" programs that resulted, although very time-consuming and expensive, produced much-needed reliability growth. Reliability improved significantly in the late 1980s and early 1990s and vehicle manufactures and their suppliers began expressing warranty data in R/1000 units instead of R/100 units.

[1] Relevant information and data from SAE J1211 NOV1978 is preserved in SAE J2837 "Environmental Conditions and Design Practices for Automotive Electronic Equipment: Reference Data from SAE J1211 NOV1978"

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By the turn of the century automobile warranty periods had increased from 12 months to 3, 4, 5 (and even 10 years for some systems) and most manufacturers had started specifying life expectancies for vehicle components of 10, 15 and sometimes 20 years. And by this time several vehicle manufacturers and their best electrical/electronic component suppliers had improved reliability to the point where warranty data was being expressed in parts-per-million (ppm) in the triple, double and even single-digit range. This translates to failure rates in the 0.05 $f/10^6$ h range and better! The achievement of such high reliability is not the result of test-to-pass reliability demonstration testing based on binomial distribution statistical tables. With this method, reliability demonstration in the 99.99% to 99.9999% range would require thousands of test units! On the contrary, the methods and techniques used by engineering teams achieving such reliability excellence did not require increasingly large sample sizes, more expensive and lengthy testing, or more engineers. It is about working smarter, not harder; and about systems-level robust design and robustness validation thinking rather than component-level “test-to-pass” thinking.

The task force leaders and members were of the strong opinion that the 2008 version of SAE J1211 should document the state-of-the-art methods and techniques being used by leading companies and engineering teams to achieve ultra-high reliability while at the same time reducing overall cost life-cycle and shortening time-to-market. The SAE International Automotive Electronic Systems Reliability Standards Committee and ZVEI (German Electrical and Electronic Manufacturers’ Association) are hopeful that this Handbook for Robustness Validation of Automotive Electrical/Electronic Modules will help many companies and engineering teams make the transition from the 1980s “cookbook” reliability demonstration approach to a more effective, economically feasible knowledge-based Robustness Validation approach.

FOREWORD

The quality and reliability of the vehicles a manufacturer produces has become a deciding factor in determining competitiveness in the automotive industry. Achieving quality and reliability goals effectively and economically depends on fundamental knowledge of how to select and integrate materials, technologies and components into functionally capable and dependable vehicle systems and being able to assess whether acceptable levels of quality and reliability have been achieved as the design comes together, matures and transitions into a mass production environment.

Evaluation methods, whether physical or analytical, must produce useful and accurate data on a timely basis in order to provide added value. Increasingly, manufacturers of automotive electrical and electronic (E/E) equipment must be able to show that they are producing a product which performs reliably in applications having defined mission profiles.

Reliability is a measure of conditional probability that a product will perform in accordance with expectations for a predetermined period of time in a given environment under defined usage conditions. To efficiently meet any reliability objective requires comprehensive knowledge of the relationships between failure modes, failure mechanisms and mission profile. Gradual reliability growth by repeated test-analyze-fix cycles is no longer sufficient or competitive (see Rationale).

Ten years ago the prevailing philosophy was: “Qualification tests of production validation units must ensure that quality and reliability targets have been reached.” This approach is no longer sufficient to guarantee robust electronic products and a failure free ownership experience for the life of the car, i.e., a philosophy of the Zero-Defect-Strategy. The emphasis has now shifted from the detection of failures at the end of the development process to prevention of failures throughout the full life cycle, beginning with concept development and requirements specification.

In the past, screening methods were still required after the product had been manufactured and after the product had successfully passed a qualification program. In recent years the emphasis has shifted to reliability-by-design methodologies applied during development. The philosophy of Robust Design has been widely accepted and the number methods, tools and techniques to support the approach have been increasing steadily.

The fundamental philosophy of product qualification is also changing from the detection of defects based on predefined sample sizes to the generation and reuse of knowledge gained by studying specific data regarding the product’s failure modes and mechanisms combined with existing knowledge in the field. Using these methods, known as “physics of failure” or “reliability physics” it is possible to generate highly useful knowledge on the robustness of products.

This handbook is intended to give guidance to engineers on how to apply a robustness validation process during development and qualification of automotive electrical/electronic modules. It was made possible because many companies, including electronic/equipment manufacturers and vehicle manufacturers worked together in a joint working group to bring in the knowledge of the complete supply chain.

This handbook is synchronized with its European counterpart document “Handbook for Robustness Validation of Automotive Electrical/Electronic Modules” published by the German Electrical and Electronic Manufacturers’ Association (ZVEI) www.zvei.org/ecs, Frankfurt, 2008.

Software Robustness is not specifically addressed in this document. However some degree of software evaluation is addressed by the test methods. Some examples are:

- Testing the module in a sub-system configuration if possible.
- Testing the module with realistic loads.
- Exercising the module in various modes during a test.

Also, although this handbook is directed primarily at electrical/electronic “modules” it may certainly be applied to other equipment such as sensors, actuators and mechatronics.

INTRODUCTION

This Robustness Validation Handbook provides the international automotive electronics community with a common knowledge-based qualification methodology based on the philosophy of robust design. Robustness Validation activities begin in the product conceptualization phase and continue throughout the full life cycle of the product. By integrating robust design and robustness validation with systems engineering practices, project teams are able to design-in and demonstrate product reliability for the user’s intended application(s).

This handbook defines a methodology to assess the Robustness Margin of an electrical/electronic module. Robustness Margin is defined as the margin between the outer limits of the modules specification and the actual performance capability of the mass-produced product considering all significant source of variation. The task of determining Robustness Margin is started during the design and development process and continues throughout the production life using monitoring mechanisms. It is in this manner that reliability is assured throughout the life cycle of the product.

This Robustness Validation Handbook defines a Robustness Validation process in which the user and the supplier of the electrical/electronic module establish requirements and acceptance criteria based on a defined Mission Profile and reliability performance requirements for the vehicle application(s). The objective of Robustness Validation process is to design-out susceptibility to failure mechanisms, assess whether the Robustness Margin is sufficient for the intended application(s), and develop inherently robust manufacturing and assembly processes capable of producing zero-defect product.

Robustness Validation relies first on knowledge-based modeling simulation and analysis methods to develop a highly capable design prior to building and testing physical parts; and then on test-to-failure (or acceptable degradation) and failure/defect susceptibility testing to confirm or identify Robustness Margins, to enable failure prediction and verify that manufacturing processes produce defect free parts. These techniques represent advancement beyond “test-to-pass” qualification plans which usually provide very little useful engineering information about failure modes, failure mechanisms and failure points.

Robust design concepts provide an efficient way to optimize a product in light of the “real world” operating conditions it will experience. Validation is a process for evaluating a product’s suitability for use in its intended use environment. Thus it is natural that robustness and validation go hand-in-hand. To achieve efficiency, robustness relies on up front use of “physics-of-failure” knowledge and tools, fundamental principles of statistical experimentation, and techniques and tools like FMEA, P-Diagrams, orthogonal arrays and Response Surface Methodology. However, the objective of robustness is not merely to complete a design of experiments (DOE), but to understand how the product or process performs its intended function within, and at the limits of, the user specifications.

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1. SCOPE

This document addresses robustness of electrical/electronic modules for use in automotive applications. Where practical, methods of extrinsic reliability detection and prevention will also be addressed. This document primarily deals with electrical/electronic modules (EEMs), but can easily be adapted for use on mechatronics, sensors, actuators and switches. EEM qualification is the main scope of this document. Other procedures addressing random failures are specifically addressed in the CPI (Component Process Interaction) section 10. This document is to be used within the context of the Zero Defect concept for component manufacturing and product use.

It is recommended that the robustness of semiconductor devices and other components used in the EEM be assured using SAE J1879 OCT2007, Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications.

The emphasis of this document is on hardware and manufacturing failure mechanisms, however, other contemporary issues as shown in Figure 1 need to be addressed for a thorough Robustness Validation. A Pareto of contemporary issues is shown in Figure 1. Although this document addresses many of the issues shown, however some are outside the scope of this document and will need to be addressed for a thorough RV process application. Examples of issues outside the scope of this document are system interactions, interfaces, functionality, HMI (Human-Machine Interface) and software. At the time of publication of this handbook, a system level Robustness Validation handbook, which addresses these issues, had been initiated.

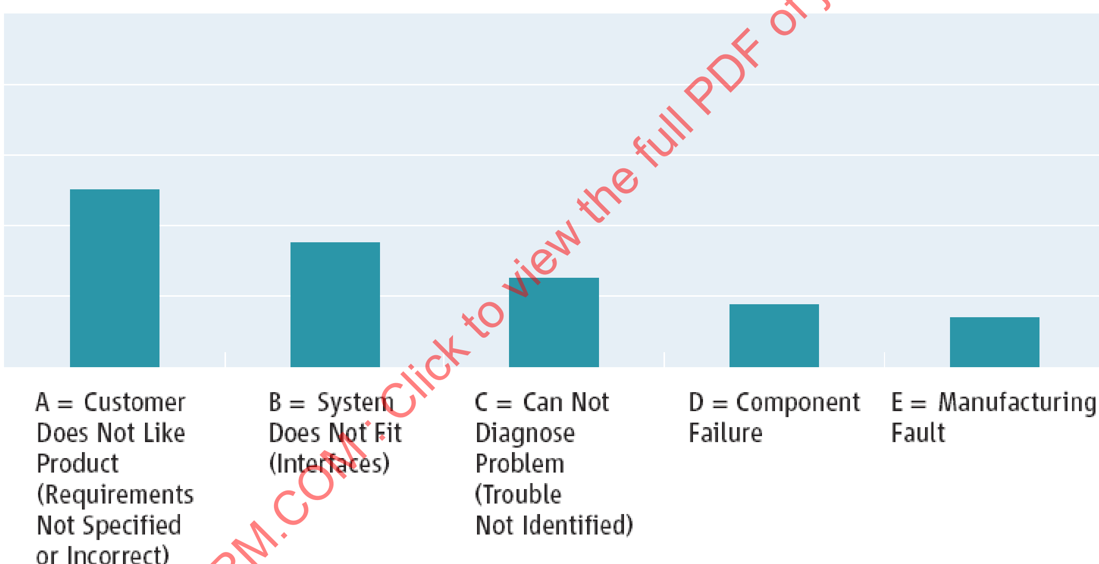


FIGURE 1 - RELATIVE CONTRIBUTIONS OF ISSUES WITH E/E SYSTEMS AT VEHICLE LEVEL [9]

1.1 Purpose

This Robustness Validation Handbook provides the automotive electrical/electronics community with a common qualification methodology to demonstrate robustness levels necessary to achieve a desired reliability.

The Robustness Validation approach emphasizes knowledge based engineering analysis and testing a product to failure, or a predefined degradation level, without introducing invalid failure mechanisms. The approach focuses on the evaluation of the Robustness Margin between the outer limits of the customer specification and the actual performance of the component These practices integrate robustness design methods (e.g., test-to-failure in lieu of test-to-pass) into the automotive electronics design and development process. With successful implementation of robustness validation practices, the producer and consumer can realize the objectives of improved quality, cost, and time-to-market.

The purpose of this Robustness Validation Handbook is to establish globally accepted concepts, processes, methods, techniques and tools for implementing the Robustness Validation qualification methodology for automotive electrical/electronic modules (EEM) and systems.

2. REFERENCES

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of SAE publications shall apply.

[1] Porter, Alex, Accelerated Testing and Validation: Testing, Engineering, and Management Tools for Lean Development, Elsevier Science & Technology Inc., Burlington, MA 1984.

[2] Nelson, W., Applied Life Data Analysis, Wiley 1982.

[3] ISO 16750 Road vehicles - Environmental conditions and testing for electrical and electronic equipment

[4] SAE 2006-01-0729 Vibration Test Specification for Automotive Products Based On Measured Vehicle Load Data, Hong Su

[5] ISO21747 Statistical Methods - Process Performance and Capability Statistics for Measured Quality Characteristics

[6] Pan, N., Henshall, Greg, et-al Hewlett-Packard, "An Acceleration Model for Sn-Ag-Cu Solder Joint Reliability under Various Thermal Cycle Conditions", SMTA International Conference, Chicago, Il. Sept. 25-29, 2005, 2)

[7] Di Giacomo, G., Ahmad, U., "CBCA and C4 Dependence on Thermal Cycle Frequency", 2000 International Symposium on Advanced Packaging Materials, Pages 261-264

[8] Unger, Becker, Goroll, Automotive Application Questionnaire for Electronic control units and sensors, ZVEI, German Electrical and Electronic Manufacturers Association, Electronic Components and system division, Frankfurt www.zvei.org/ecs

[9] Taylor, John, Thesis Report, University of Detroit Mercy. 1995

[10] SAE G-11 Reliability, Maintainability, and Supportability Guidebook, 3rd Edition, SAE Inc., Warrendale, PA, 1995.

[11] IEC 60300-3-1 Dependability management – Part 3-1: Application guide – Analysis techniques for dependability – Guide on methodology; International Electrotechnical Commission (IEC), January 2003.

[12] IEC 60300-3-9 Dependability management – Part 3: Application Guide – Section 9: Risk analysis of technological systems; International Electrotechnical Commission (IEC).

[13] Godoy, S. G. et al, Sneak Analysis and Software Sneak Analysis, J. Aircraft Vo. 15, No. 8, 1978.

[14] Ireson, W.G. et al, Handbook for Reliability Engineering and Management, McGraw-Hill 1996

[15] IEC 60812 Analysis technique for system reliability – Procedures for failure mode and effects analysis (FMEA)

[16] IEC 61025 Fault tree analysis (FTA)

[17] SAE 2006-01-0591, "Method for Automated Worst Case Circuit Design and Analysis," Henry Davis Jr , February 2006

[18] NASA Preferred Reliability Practice No. PD-ED-1212, Design and Analysis of Electronic Circuits for Worst Case Environments and Part Variations, 1990.

[19] Jet Propulsion Lab (JPL) Reliability Analyses Handbook, JPL D-5703, July 1990.

[20] SAE G-11 Reliability, Maintainability, and Supportability Guidebook, 3rd Edition, pg. 261-264, 1995, Warrendale, PA, SAE, Inc.

[21] Zero Defect Strategy – ZVEI Revision 1 January 2007

[22] SAE J2837 – Environmental Conditions and Design Practices for Automotive Electronic Equipment: Reference Data from SAE J1211 NOV1978.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J1213-2 Glossary of Reliability Terminology Associated with Automotive Electronics

SAE J1739 Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA)

SAE J1879 Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications

SAE J2628 Characterization, Conducted Immunity

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this document.

2.2.1 Other Publications

Madhav S. Phadke, iSixSigma LLC: "Introduction to Robust Design-Robustness Strategy"

Dr. Ing. Werner Kuitsch: "Umweltsimulation von Schwingungs- und Stoßbelastungen", lecture at Technische Akademie Esslingen, 2004

Microelectronic Reliability, Volume II: Integrity Assessment and Assurance, edited by E. Pollino, Artech House Publishers, ISBN 0-890-06350-8, 1989

JEDEC-020D Handling of Moisture Sensitive Devices

The Design Analysis Handbook, Edward Walker, ISBN 0-7506-9088-7

Noise Reduction Techniques in Electronic Systems, Henry Ott, ISBN 0-471-85068-3

Williams et al, An Investigation of “Cannot Duplicate” Failures. Quality and Reliability Engineering Journal Vol. 14, Issue 5, pp. 331-337 John Wiley & Sons, 24 Dec 1998

IEC 60300-1 Dependability management – Part 1: Dependability management systems, International Electrotechnical Commission, June 2003”

MIL-STD-810, Environmental Engineering Considerations and Laboratory Tests

3. DEFINITIONS

3.1 Definition of Terms

3.1.1 Accelerated Test

A test designed to identify failures or produce degradation in a shortened period or time.

3.1.2 Acceleration Factor

The ratio between the times necessary to produce the same degradation or failure mechanism in an accelerated test compared to the use conditions.

3.1.3 Component

Parts required for the function of an electrical/electronic module. Example: Capacitors, resistors, ASICs, power-MOSFET, connectors, fasteners, mechatronic assemblies, etc.

3.1.4 Defect

A deviation in an item from some ideal state. The ideal state is usually given in a formal specification.

3.1.5 Degradation

A gradual deterioration in performance as a function of time.

3.1.6 Derating

The intentional reduction of stress/strength ratio in the application of an item, usually for the purpose of reducing the occurrence of stress related failures.

3.1.7 Design Validation

Tests or analyses performed to demonstrate that a component or systems is suitable for its intended use and meets known customer/application validation requirements.

3.1.8 Design Verification

Tests or analyses performed to demonstrate that a component or system has the potential to meet its specified design requirements

3.1.9 ECU (Electronic Control Unit)

Electrical stand alone modules with electrical and/or optical interface. The ECU typically consists of housing, connector, conductor boards and electrical components. Typical example: Motor management systems.

3.1.10 Electrical/Electronic Module

EEM: Electrical stand alone modules with electrical and/or optical interface. The EEM typically consists of housing, connector, conductor boards and electrical components. Typical example: Motor management systems. Mechatronics integrate mechanical and electrical functions into one unit. The mission profile of this solution has to respect both parts. In vehicle applications typical mechatronic products cannot be exchanged independently from electronics. Typical examples: ABS, EPS (Anti Lock Braking System, Electrical Power Steering).

3.1.11 Failure

The loss of ability of an EEM to meet the electrical or physical performance specifications that it was intended to meet

3.1.12 Failure Mechanism

The process or sequence of processes (mechanical, chemical, electrical, thermal, etc.) that produces a condition that results in a failure or fault.

3.1.13 Failure Mode

The manner in which a failure, or fault condition is perceived or detected. (check definition in FMEA standards)

3.1.14 FMEA, (Failure Mode and Effects Analysis)

A disciplined analysis of possible failure modes on the basis of seriousness, probability of occurrence and likelihood of detection.

3.1.15 Load

An externally applied and internally generated force that acts on a system or device. The application of loads results in stress and strain responses within the structures and materials of the system or device. Loads may by mechanical, thermal, electrical, radiation or chemical in nature or any other form of physicality.

3.1.16 Load Distribution

Statistical distribution of load levels over e.g. time, cycles, temperature, voltage, climatic conditions, and other load types. It should represent different use cases.

3.1.17 Mechatronic Module

A module in which mechanical and electrical/electronic functions are integrated.

3.1.18 Mission Profile

A simplified representation of all of the relevant conditions to which the EEM production population will be exposed in all of their intended application throughout the full life cycle of the component.

3.1.19 Model

a simplified representation of a system or phenomenon, as in the sciences, where a hypothesis (often mathematical in nature) is used to describe the system or explains the phenomenon.

3.1.20 Operating Conditions

Conditions of environmental parameters, voltage bias, and other electrical parameters whose limits are defined in the datasheet and within which the device is expected to operate reliably.

3.1.21 Product Life Cycle

The time period from the beginning of the manufacturing process of the electrical/electronic module to the end of life of the vehicle.

3.1.22 Qualification

A defined process by which a product or production technology is examined and tested, and then identified as qualified.

3.1.23 Random Failure

A failure or fault which occurs in a random fashion often but not always fitting a normal probability distribution.

3.1.24 Reliability

The ability of a system or component to perform its required functions under stated conditions for a specified period of time [IEEE 90]

3.1.25 Robustness

Insensitivity to noise (i.e., variation in operating environment, manufacture, distribution, etc., and all factors and stresses in the product life cycle).

3.1.26 Robustness Validation

A process which demonstrates that a product performs its intended function(s) with sufficient margin under a defined mission profile for its specified lifetime. It requires specification of requirements based on a mission profile, FMEA to determine the risks associated with significant failure mechanisms, and testing to failure, "end-of-life" or acceptable degradation to determine robustness margins. The process of measuring and maximizing the difference between known application requirements and product capability within timing and economic constraints. It encompasses the activities of verification, legal validation, and producer risk margin validation.

3.1.27 Simulation

The representation of the behavior or characteristics of one system through the use of another system, especially with a computer program designed for the purpose of simulating an event or phenomenon. The technique of representing the real world by a computer program; such that the internal processes of a system are emulated as accurately as is possible or practical and not merely mimicking the results of the thing being simulated.

3.1.28 Stress Factor

A stress or combination of stresses which triggers a failure mechanism.

3.1.29 System

A set/combination of several EEMs / Mechatronics or sensors / actuators, connected to perform a distributed functionality as shown in Figure 2.

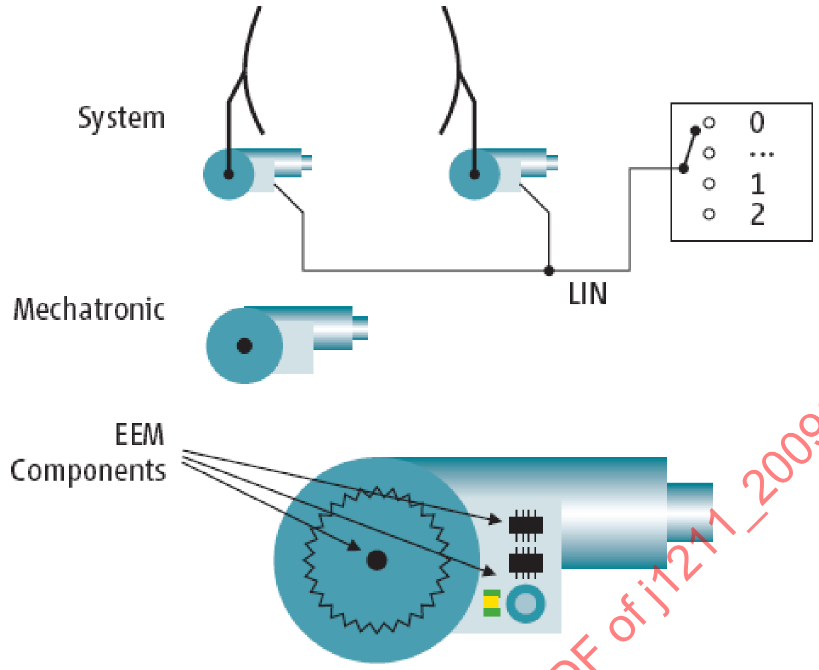


FIGURE 2 - EXAMPLE OF SYSTEM, MECHATRONIC AND COMPONENTS

3.1.30 Systemic Failure

A non random failure caused by an error in any activity which, under some particular combination of inputs or environmental conditions will permit a failure. For example an incorrectly rated resistor.

3.1.31 Temperatures

To describe the thermal conditions in the EEM / mechatronic and the semiconductor components inside the EEM the temperatures at the points defined in Figure 3 can be used. The definitions of the temperatures are:

- $T_{Vehicle}$ Mounting Location Ambient: Temperature at 1 cm distance from the EEM package.
- T_{EEM} Package: Temperature at the EEM package.
- T_{EEM} internal: Temperature of the free air inside the EEM.
- $T_{Comp.package}$: Temperature at the component package.
- $T_{Comp.Pins}$: Temperature at the component pins.
- $T_{Junction}$: Junction temperature of the component chip (or substrate).

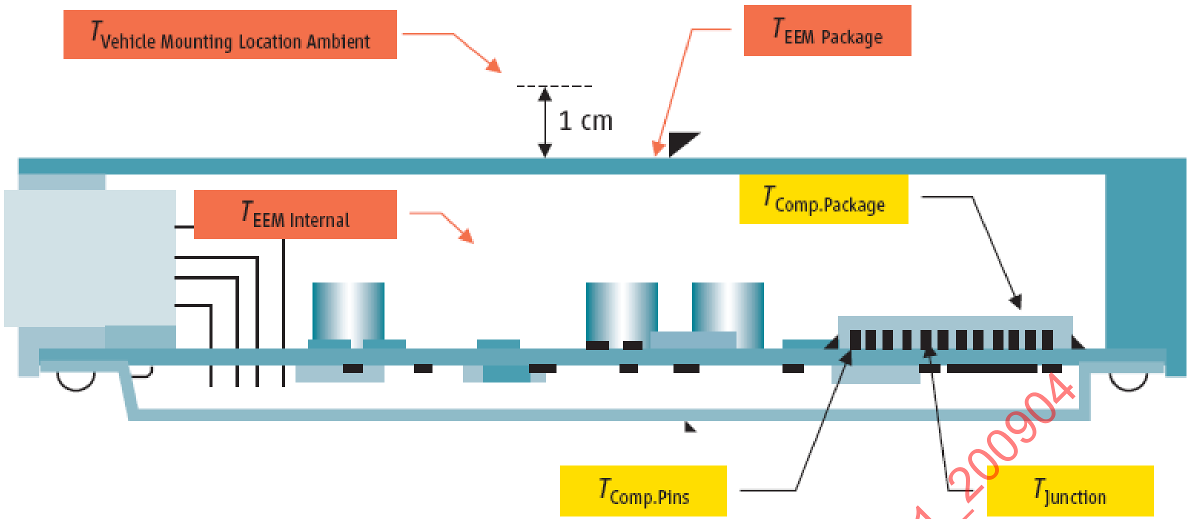


FIGURE 3 - EEM TEMPERATURE MEASUREMENT POINTS

The OEM relevant temperature for mission profiling is: $T_{\text{vehicle mounting location Ambient}}$

In mechatronic systems additional heat sources or sinks have to be considered (e.g. coolant, engine block…)

3.1.32 Trouble Not Identified (TNI)

The Customer Declared Failure could not be duplicated or identified.

3.1.33 Vehicle

The automobile.

3.1.34 Vehicle System

A system on a vehicle.

3.1.35 Verification

The conclusion of the primary product development learning process supporting progress to the legal validation phase that the product has a high probability for meeting all known application requirements. There are no legal ramifications in verification. Learning may occur with test to failure for capability measurement beyond the established requirements and reliability demonstration

3.1.36 Validation

The process of accumulating evidence to support a declaration with legal force that a system/module/component meets the known application requirements. Validation culminates in producing a formal declaration with legal weight that a product has been confirmed supported by objective evidence that the requirement for a specific intended use have been fulfilled. Tests have a defined success point that becomes the base measurement for the “Robust Validation” phase.

3.1.37 Virtual Entity

An item that is not physically real, but displays the qualities of reality or exists in a potential state that could become realized.

3.1.38 Wear Out Failure

Failure caused by accumulation of damage due to loads (stresses) applied over an extended period of time.

3.1.39 Zero Defect Strategy

Is a philosophy mindset and culture, which does not mean zero defects in a literal of statistical sense, but rather, is a whole value chain activity which makes every attempt in its approach and methods to achieve Zero Defects with the Goal to design manufacture a product with the minimum defects possible. See ZVEI Zero Defect Strategy Rev1: Jan2007

3.2 Acronyms

3.2.1	A/D/V	Analysis/Development/ Validation
3.2.2	AMS	Analysis Modeling and Simulation
3.2.3	CAD	Computer Aided Design
3.2.4	CAE	Computer Aided Engineering
3.2.5	CALCE	Computer Aided Life Cycle Engineering
3.2.6	CD	Continuous Duty
3.2.7	CTS	Component Technical Specification
3.2.8	CPI	Component-Process Interaction
3.2.9	Cpk	Process Capability Index
3.2.10	Cmk	Machine Capability Index
3.2.11	DBTF	Design - Build - Test - Fix
3.2.12	DEV/VAL	Development / Validation
3.2.13	DPMO	Defects Per Million Operations
3.2.14	D-SMC	Discrete Surface Mounted Component
3.2.15	DUT	Device Under Test
3.2.16	DV	Design Validation
3.2.17	D & V	Development and Validation
3.2.18	DVP&R	Design Verification Plan and Report.
3.2.19	ECU	Electronic Control Unit
3.2.20	E/E	Electrical/Electronic
3.2.21	EEM	Electrical/electronic module
3.2.22	ESD	Electrostatic
3.2.23	EMC	Electro Magnetic Compatibility

3.2.24 HALT Highly Accelerated Life Test

3.2.25 HASS Highly Accelerated Stress Screen

3.2.26 HAST Highly Accelerated Stress Test

3.2.27 IEC International Electro technical Commission

3.2.28 IP International Protection

3.2.29 I/O Input / Output

3.2.30 IR Infrared

3.2.31 M&S Modeling and Simulation

3.2.32 NAO North American Operations

3.2.33 PCB Printed Circuit Board

3.2.34 PDT Product Development Team

3.2.35 PoF Physics of Failure

3.2.36 PTC Power Temperature Cycles

3.2.37 PV Production Validation

3.2.38 PWA Printed Wiring Assembly (Printed Circuit Board as assembled with all components)

3.2.39 QRD Quality/Reliability/Durability

3.2.40 R Reliability

3.2.41 RIF Robustness Indication Figure

3.2.42 RFA Remote Function Actuation

3.2.43 RKE Remote Keyless Entry

3.2.44 RV Robustness Validation

3.2.45 SAT Simulation Aided Testing

3.2.46 SGT Simulation Guided Testing

3.2.47 SD Short Duration

3.2.48 SOR Statement of Requirements

3.2.49 SPC Statistical Process Control

3.2.50 SS Steady State

3.2.51 TNI Trouble Not Identified

3.2.52 T_g Glass Transition Temperature

3.2.53 T_{max} Temperature Maximum

3.2.54 T_{min} Temperature Minimum.

3.2.55 V_{low} Low Voltage

3.2.56 $V_{nominal}$ Nominal Voltage

3.2.57 V_{high} High Voltage

4. DEFINITION AND DESCRIPTION OF ROBUSTNESS VALIDATION

4.1 Definition of Robustness Validation

Robustness Validation is a process to demonstrate that a product performs its intended function(s) with sufficient robustness margin under a defined mission profile for its specified lifetime. It should be used to communicate, analyze, design, simulate, produce and to test an EEM in such a manner, that the influence of noise (or an unforeseeable event) on an EEM is minimized.

Robustness Validation can and should be applied for developments of different types, completely new, incremental change or modifications when evaluating the different types of development projects account should be taken of previous knowledge and lessons learned.

4.2 Robustness Validation Process

A robust product is one that is sufficiently capable of functioning correctly and not failing under varying application and production conditions. The Robustness Validation process defined in this handbook relies heavily on team expertise and knowledge, and therefore requires detailed explanation and intensive communication between the user and supplier.

The Robustness Validation flow shown in Figure 4 is an essential part across the development process. This method is based on three key components:

- Knowledge of the conditions of use (mission profile).
- Knowledge of the failure mechanisms and failure modes and the possible interactions between different failure mechanisms.
- Knowledge of acceleration models for the failure mechanisms needed to define and assess accelerated tests.

Robustness validation is a knowledge-based approach [1, 2] that uses analytical methods and stress tests that are defined to address specific failure mechanisms using suitable models, test and stress conditions. This approach results in a product being qualified as “fit for use”, not “fit for standard”.

It is important to note, that as Robustness Validation is a knowledge based approach it must not be applied blindly, or in a standardized default manner as current Verification approaches, but with appropriate experience and training of the people applying the process and of the failure mechanisms. The RV users own knowledge matrix (see Section 7) must be a central part of the RV process within an organization.

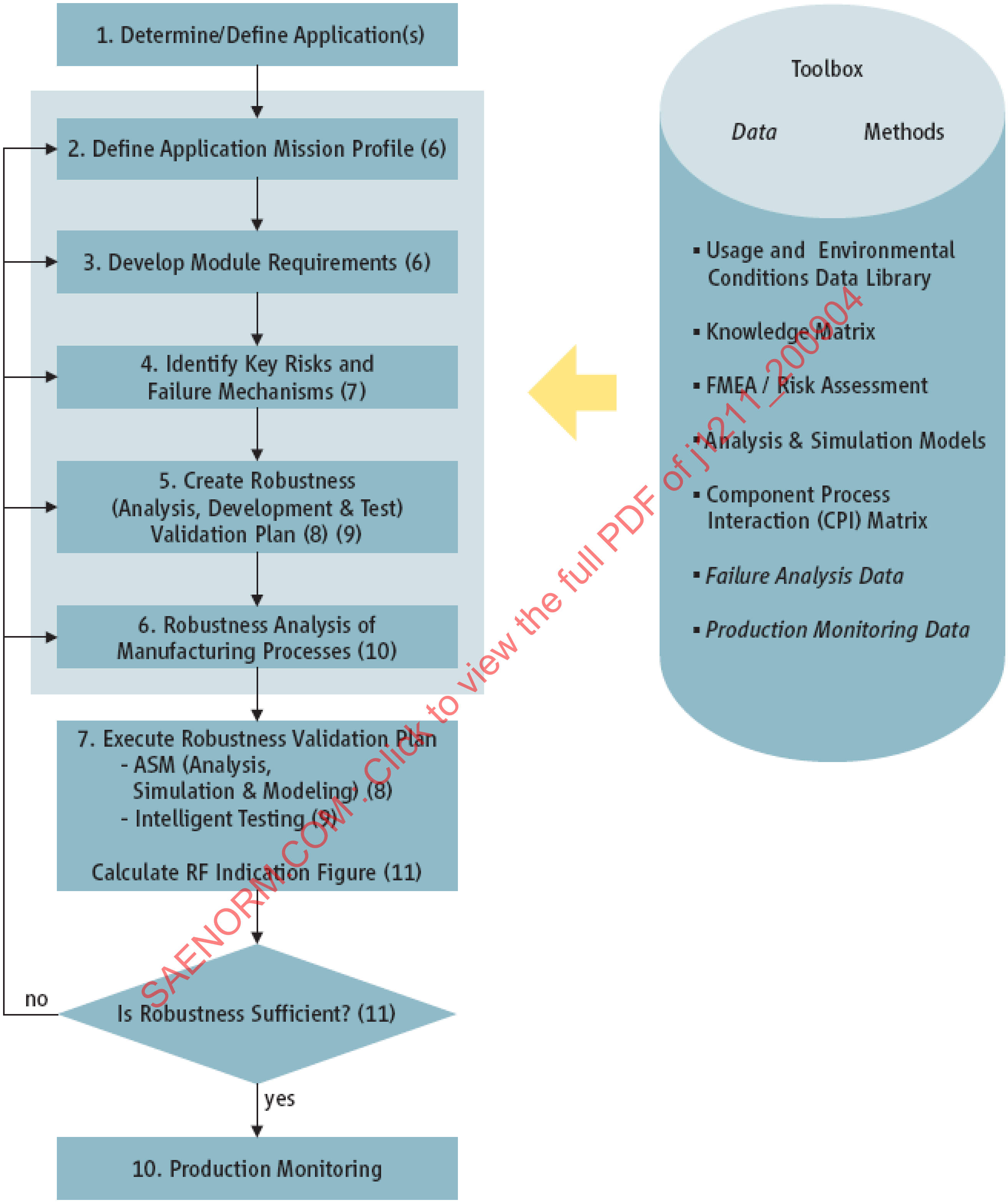


FIGURE 4 - THE ROBUSTNESS VALIDATION PROCESS FLOW

When considering the RV process the standard V model concept should be applied at each level/stage of the RV process from the top (System) level to the bottom (Component) and back up again with repeated iterations and feedback up and down the process chain.

The V-model in Figure 5 shows the concept of requirement flowing from the customer, to the vehicle, to the system, to the module, and to components. The sources of requirements should be documented. Module design concepts need verification which involves sharing and documenting information between the OEM and suppliers at all levels. Once a requirement is accepted, it needs validation to determine if the requirement is satisfied.

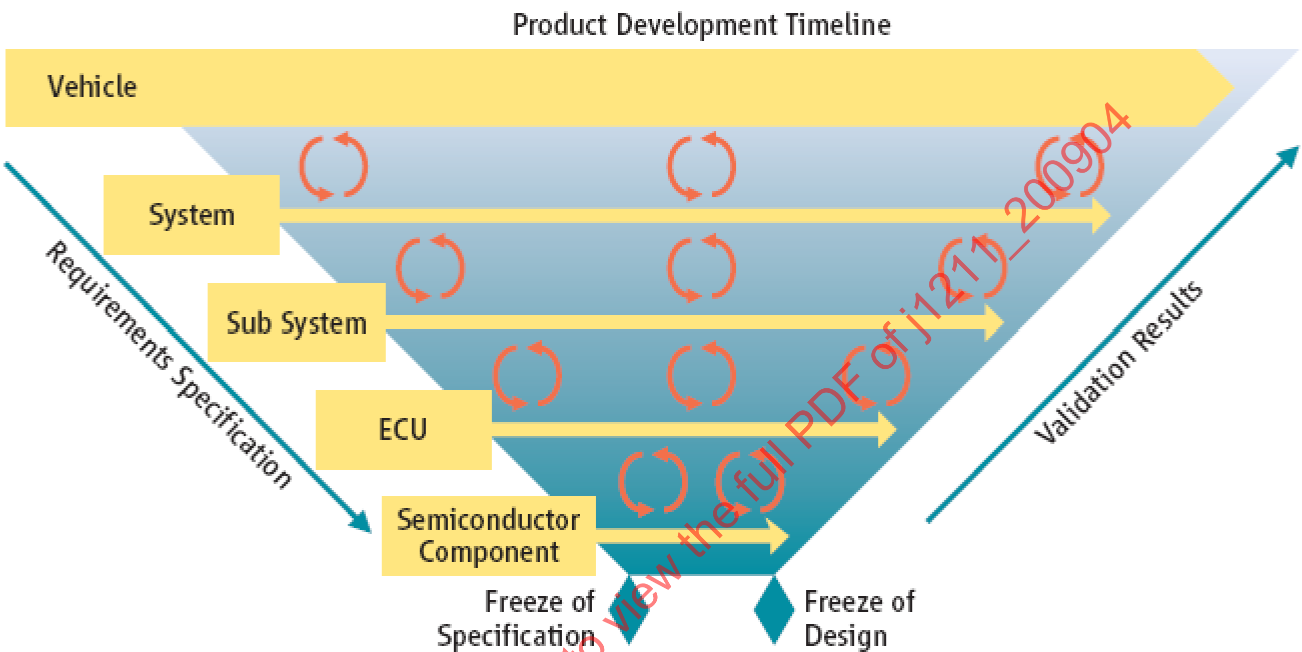


FIGURE 5 - THE AGILE PRODUCT DEVELOPMENT PROCESS

5. INFORMATION AND COMUNICATION FLOW

The efficiency and effectiveness of Robustness Validation largely depends on communication of previous and ongoing learning that takes place between the individuals, teams and organizations involved in the module's design, development, validation, production and use. As seen in Figure 6

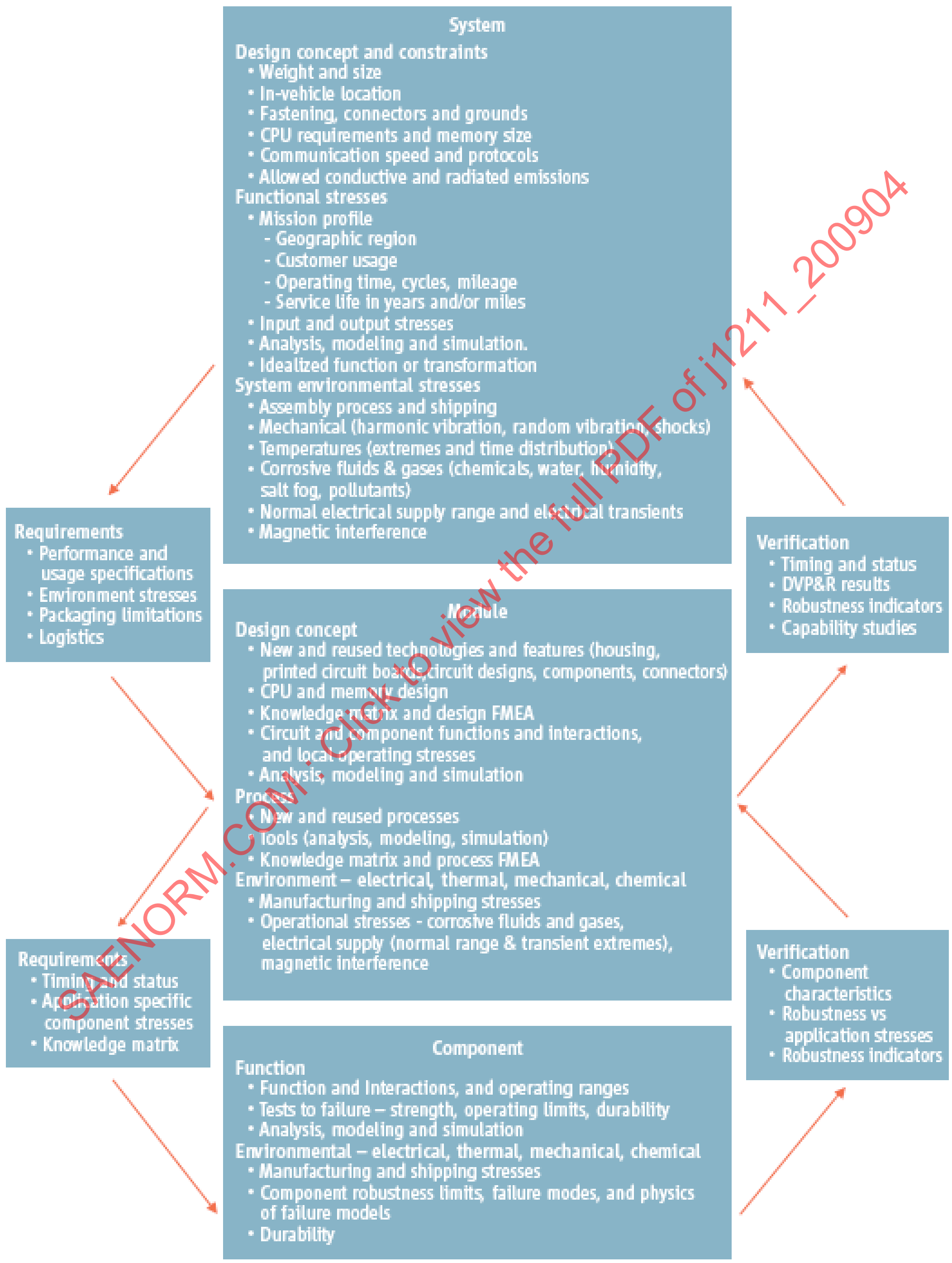


FIGURE 6 - ROBUSTNESS VALIDATION INFORMATION FLOW

5.1 Product Requirements

Modules need to support requirements that are developed from the mission profile which considers different aspects of the module's intended function, environments, and service life targets. There are different sources of these requirements, i.e., the vehicle user, regulatory agencies, market consideration, local environments, dealer service, vehicle and parts shipping and storage, vehicle assembly, mounting location in the vehicle, and other OEM requirements. The requirements flow from these sources to the vehicle, to the system, and finally to the module.

A boundary diagram shows as inputs to the module customer, regulatory, and assembly requirements plus "involved" modules that interface to the device. Some requirements are subjective and difficult to capture as a measurement parameter. The boundary diagram in Figure 7 is a useful tool to assure these requirements are captured.

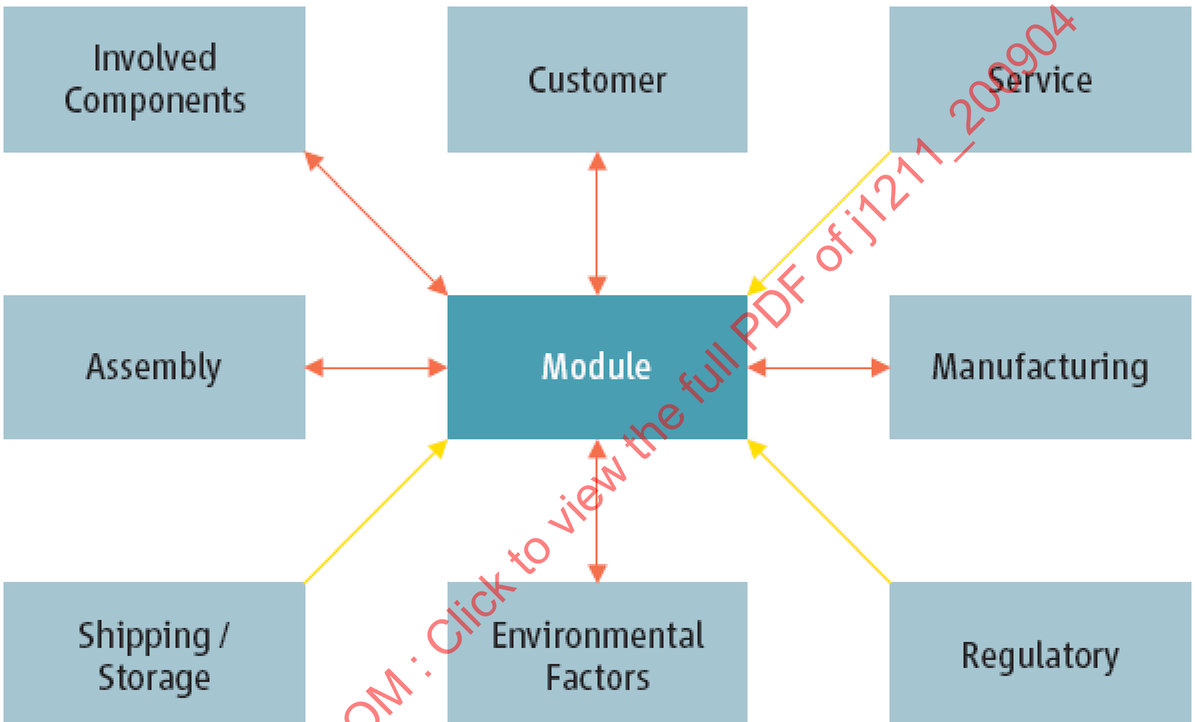


FIGURE 7 - BOUNDARY DIAGRAM

The Parameter Diagram (P-diagram) in Figure 8 captures and summarizes inputs, outputs, environmental stresses, and design constraints for products. A device, represented by a box at the center of the diagram, may be a component, module, system, or vehicle. By convention, inputs are listed on the left with arrows leading into the box; outputs, on the right with arrows leading from the box; environmental stresses, on the bottom with arrows leading to the box; and design constraints, above the box with arrows leading to the box.

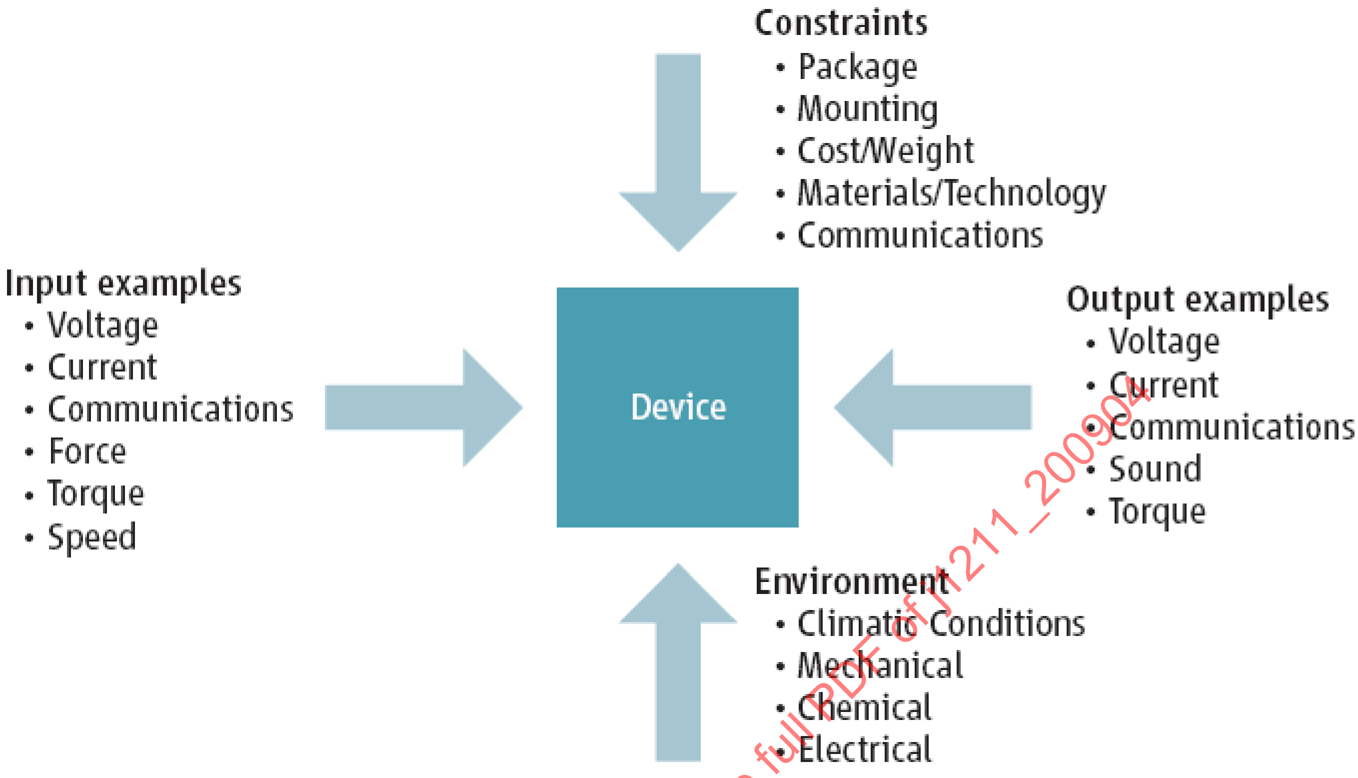


FIGURE 8 - MODULE PARAMETER DIAGRAM (P-DIAGRAM)

5.2 Use of Available Knowledge

Most electronic modules are evolutionary development of past modules and use similar design and manufacturing concepts. There is a high level of reuse of individual components, circuit designs, connectors and housing concepts. In vehicles, the modules perform similar functions and share similar locations. Around 90% of a new module design is similar to some predecessor module. However, the changes that occur may include the addition of functions to a module, some new circuits, new board layouts to accommodate the new circuits, and technology changes of components. Also, the vehicle environment may become more severe.

Traditionally, module verification and validation focused on repeating a standard suite of tests with the addition or deletion of functional tests. Similarly, environmental stress tests were repeated with every new module. As electronic modules become more complex, the potential number of combinations and permutations of operating modes and associated functional tests becomes very large with associated very expensive long duration tests. A more efficient process is required that focuses verification and validation on **changes** and **potential interactions of the changes** with other module functions.

How does one manage this process? The design and process reviews are appropriate forums. The first topic should be the predecessor design. What were the problems and lessons learned? Are their symptomatic warranty, vehicle assembly, manufacturing, and shipping/storage issues? The new design should include changes to correct these issues, i.e., support continuous improvement. The new features need to be reviewed. The new features, old module improvements, and technology changes constitute the scope of the change verification. The risk associated with these changes should be addressed in Design and Process FMEAs. High risk items and functional validation need to be included in a test plan. The Robustness Validation plan should be integrated in the DVP&R.

6. MISSION PROFILE

The Mission Profile is a representation of all relevant conditions an electrical/electronic module will be exposed to in all of its intended applications throughout its entire life cycle. It is therefore important that the Mission Profile for each individual electrical/electronic module be developed and communicated to the engineers designing the module as soon as possible. With a good description of the Mission Profile, engineers can begin to estimate reliability and quality levels and start to work toward achieving 'zero defects' and robust design at all levels of the supply chain.

This section provides an overview of the various conditions and stress factors (loads) an electrical/electronic module may experience during its life cycle. This information is intended to be used as a starting point in developing Mission Profiles for individual electrical/electronic modules. Stress factors may be mechanical, climatic, chemical and electrical loads during manufacturing, operation, stand by operation, transport and car assembly. As shown in Figure 9, the stress factors may be due to environmental loads, functional loads or both simultaneously.

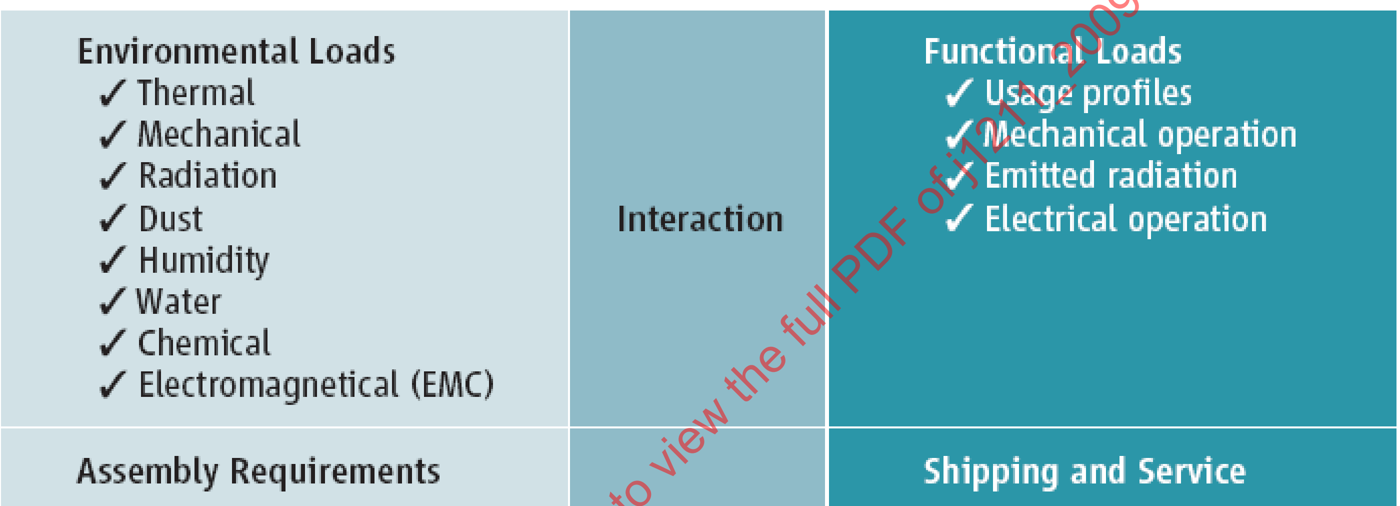


FIGURE 9 - ENVIRONMENTAL AND FUNCTIONAL LOAD STRESS FACTORS

As the product development process progresses, mission profiles and functional loads will be defined more precisely. Therefore changes and revisions to loads or load distributions shall be agreed upon between the parties.

The mission profile is not a test description. It is the basis for material selection, design, test engineering, parameterization, analysis, modeling and simulation, and robustness evaluation.

6.1 Process to Derive a Mission Profile

When developing a mission profile, using the process flow defined in Figure 10 it is likely that multiple sources of data will be utilized. In most cases a combination of publicly available [3, 22], private historical data and freshly generated data will be used. Knowledge of the conditions of use in the vehicle application(s) and the possible effects on the module and components is required. Because some factors may have little effect while other may have a strong effect, it is also necessary to judge the relevance of each factor.

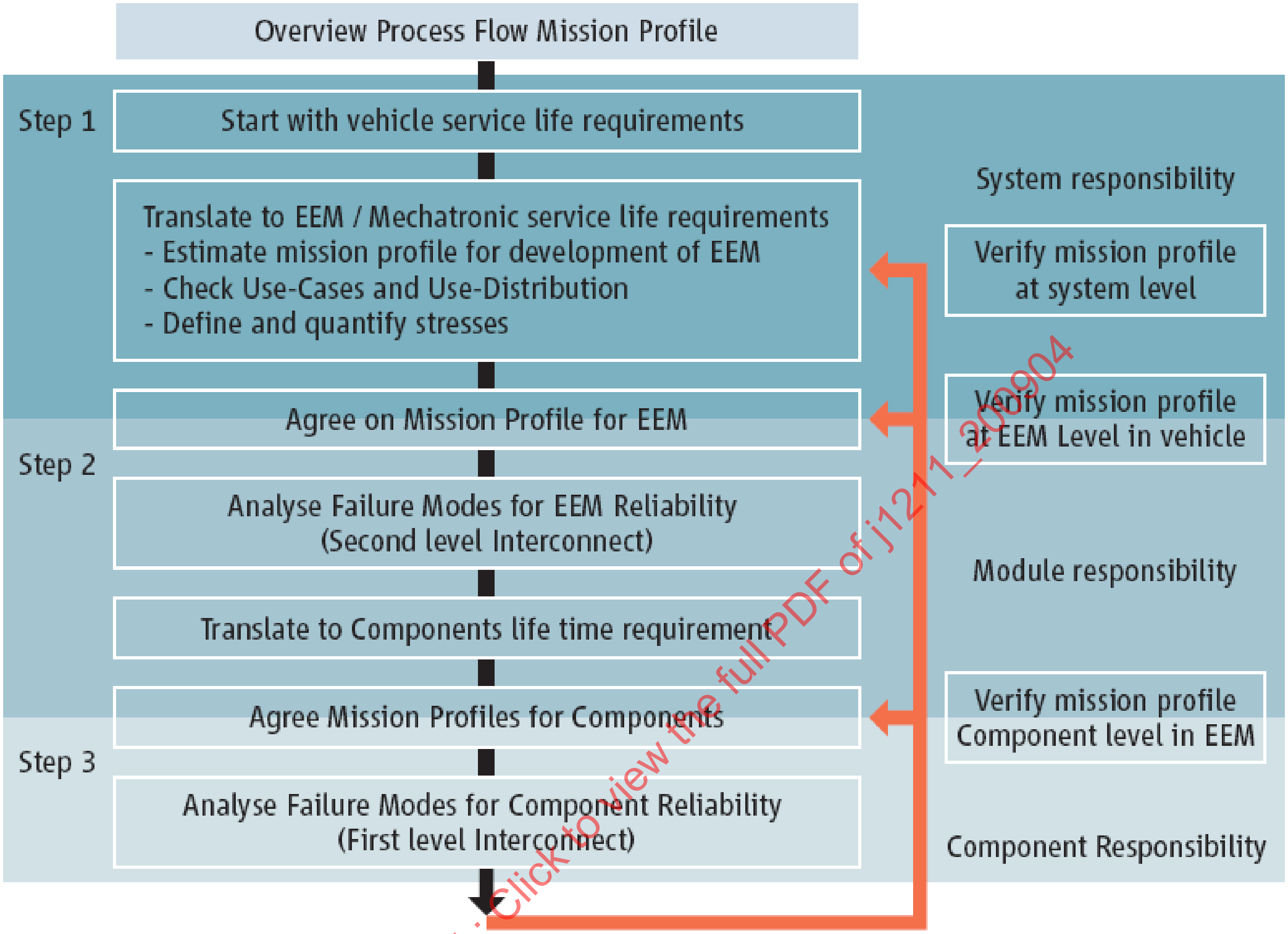


FIGURE 10 - OVERVIEW OF A PROCESS FLOW FOR GENERATING A MISSION PROFILE

STEP 1: Start with vehicle service life requirements. The most general data concern is the required vehicle service life. This comprises information for example:

- Service lifetime: The total lifetime of the car.
- Mileage: The total amount of miles/kilometers that the car is assumed to drive during its service life.
- Engine on time: The amount of time that the engine is switched on (key-on time) and operational during the service lifetime (if product is active during this time).

An example of this kind of data is given in Table 1 below.

TABLE 1 - EXAMPLE OF VEHICLE MISSION PROFILE PARAMETERS AT THE VEHICLE LEVEL

Service lifetime	15 years (= 131.400 h)	
Mileage	600.000 km	High level high mileage request for stand alone EEM (not for mechatronics)
Engine on time	12.000 h	Engine on time is directly proportional to mileage. Operating time of single component may be different than engine on time.
Engine on/off cycles	54.000	Without additional start/stop functions

STEP 2: Translate to EEM / Mechatronic life time requirements (OEM)

The above definitions are valid for the whole vehicle. However, depending on the functionality required, the active and passive periods may be very different for the vehicle versus the EEM. Their different service life requirements are exemplified in Table 2 below.

TABLE 2 - DIFFERENT SERVICE LIFE REQUIREMENTS FOR VEHICLE AND EEM

Vehicle	EEM
Engine on time	EEM on time (operating, active)
Engine off (non-operating time)	EEM off time (non-operating) EEM standby time
Engine on/off cycles	EEM on/off cycles

Furthermore, for the mission profile of the EEM, the mounting location and specific use cases have to be considered. Therefore, for each EEM / Mechatronics, the active, stand-by, sleep and non-operating time must be determined individually.

Step 2.1: Collect possible operating modes (active, stand-by, special loads, sleep, power supply interrupted, cyclically reoccurring operation, and operating mode changes)
Each relevant function must be completely covered.

Step 2.2: Assign operating modes to the defined vehicle lifetime requirements.

Step 2.3: Describe mounting locations, conditions and related loads:

- Temperature (Distribution)
- Temperature cycling (Distribution)
- Vibration (Distribution)
- Water, salt, dust, humidity, chemical agents
- Detail load profiles (e.g. electrical/thermal/mechanical loads) of the EEM/Mechatronic (experience from present projects).

Result: Basis for mission profile for EEM/mechatronic

Consider: Misuse, safety requirements, transport, storage, service (EOS/ESD), processing/assembly, testing.

An example of this kind of data for EEM level is given in Table 3 below.

TABLE 3 - EXAMPLE OF OEM EEM OPERATING LIFE TIME REQUIREMENTS

	Operating on Time (active) (h)	Non Operating Time (h)	EEM Active On/Off Cycles	EEM Specific Operating Load Cycles
Motor-management	12.000 + 3.000 Standby time	116.400	54.000 Without additional start/ stop functions	Engine on/off...
Transmission control module	6.000	125.400		Gear shift...
Door Module	8.000	79.800	36.000 + operating cycles Operating cycles: + window + mirror activation	Window lift...

6.1.1 Estimation of Mission Profile for Development of EEM

A first set of mission profiles is necessary to derive requirements for use in the development process (temperature limits for component selection, etc.). It is likely that there is little or no data available at that time. However, an approximation can be given by:

- Use standard mission profiles for defined mounting location.
- Use measurements from previous developments.
- Use measurements from similar applications / vehicles.
- Estimate usage, generated by thinking possible use-cases through.

To make sure that all parameters of any adopted mission profile cover the requirement for the specific mounting location, a validation of the chosen mission profile for the specific application is necessary.

These estimates should be verified by actual measurements as parts / installations become available during the development process.

6.1.2 Check Use-Cases and Use-Distribution (Refinement and Validation)

Define Use-Cases – Use-cases can help identify sources of loads and provide operation parameters. By thinking through several use-cases, choices of descriptive parameters, their distribution of values and severity of effect of failure can be outlined. Usually several relevant use-cases can be combined into one enveloping mission profile thus enabling validation with the same plan.

Analyze Use-Distribution – Often EEM/Component stress is significantly higher when operated close to the design limits (e.g. max. load). Also there are use-cases that may result in unusually high load cycle numbers (e.g. taxi driver).

Due to this, considering only possible limits/extremes may not be sufficient, additionally a use distribution is necessary. It shall describe the occurrence likelihood of loads with regard to the operation parameter range.

However, in the case that extreme distributions are ruled out from design considerations or test coverage, failures that may result there from these extreme distributions must still be evaluated for safety and customer satisfaction consequences. Furthermore it should be checked by thinking through use cases, if a combination of different loads can occur simultaneously or sequentially. For certain parts or materials these combinations may provoke different failure modes or accelerate others. Therefore a definition of combined loads may be necessary.

Example – Use-Case Brake application
Stop and Go in the city, breaking every 200 m (high number of cycles, low load)
Highway singular power braking from 200 to 80 km/h (low number of cycles, high load)

6.2 Agree Mission Profile for EEM (System Level with Module Level)

First, possible uses must be collected and be evaluated for relevance. An OEM should supply typical vehicle-oriented descriptions for use scenarios and operating conditions.

- Generate environmental mission profile (e.g. complete ZVEI Application Questionnaire [8]).

- Describe electrical/functional loads (e.g. fill in functional requirements in specification).

6.3 Analyze Failure Modes for Reliability of EEM

With knowledge of the planned design of the EEM, the 1st (… nth) Tier must check the given mission profile (ZVEI Application Questionnaire) and the resulting loads for completeness with regard to failure modes:

- All potential failure modes have to be traced from component level to module up to system level.

- Critical components have to be identified from system down to component level, which in turn can generate need for an additional / different mission profile.

The collected information on source/effect interaction then should be used for a qualitative analysis to identify parameters of the mission profile which do affect reliability of the system and rank them by assumed impact. This clarifies the significance of each parameter and helps in choosing an appropriate precision in its specification (e.g. requiring use-studies, measurements, a fine-grained distribution or allowing rough estimation).

6.4 Translate to Components Life Time Requirements

The translation to the component level must contain applicable environmental electrical and mechanical loads of the EEM design, especially power losses and active pulse loadings. The loads have to be analyzed for each critical component. The Steps are similar to Section 6.1.

Step 1: Collect possible operating modes (active, stand-by, special loads, sleep, power supply interrupted, cyclically reoccurring operation, operating mode changes).
Each relevant functionality must be completely covered.

Step 2: Assign operating modes to the defined vehicle lifetime requirements.

Step 3: Describe related loads for each critical component:

- Temperature (distribution, including power loss)
- Temperature cycling (distribution, including active pulse loading)
- Vibration (of the component in the EEM)
- Humidity in the EEM
- Service (ESD)
- Testing
- Processing Assembly
- Electrical

Result: Basis for mission profiles for critical components

Consider: Misuse, safety requirements, transport, and storage

6.5 Agree on Mission Profile for Components (Module Level with Component Level)

An 'application questionnaire' by the module level supplier shifts the focus to components and technologies intended for implementation and their critical conditions. The Module level supplier provides typical component oriented descriptions for environmental and operating conditions.

- Generate the electrical/mechanical loads as a function of the environmental condition.
- Discuss mission profiles for all critical components with suppliers.

6.6 Analyze Failure Modes for Reliability of Component

All potential failure modes have to be traced from component level to module up to system level. Critical loads have to be identified at the component level.

Result: Sensitivity of system availability to parameters of mission profiles is evaluated, which gives indications on parameter significance and need for dimensioning precision.

6.7 Verify Mission Profile at Component Level in EEM (Module Level to Component Level)

Assumptions used in choosing mission profiles should be verified by measurements in the actual application as the EEM becomes available (e.g. temperatures in EEM package areas, temperatures of component in EEMs, load distributions, software driving behavior).

Deviations can be assessed using results from analyzing failure modes for reliability of components. In case of significant deviation there may arise the need for additional testing or even changes in construction.

6.8 Verify Mission Profile at EEM level in Vehicle (Module level and System Level)

A similar procedure to section 6.7, but in vehicle.

6.9 Verify Mission Profile at System Level

A similar procedure to section 6.7, but with emphasis on distributed or combined functionalities of EEM / sensors in systems.

6.10 Stress Factors and Loads for EEMs / Mechatronics

Stress Factors and loads during vehicle service life include environmental and functional loads as illustrated in Figure 11 and detailed in sections 6.12 and 6.13

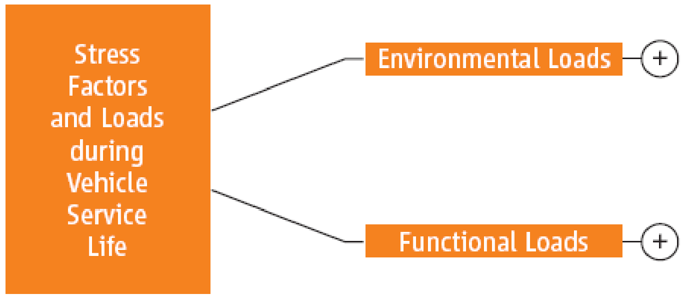


FIGURE 11 - STRESS FACTORS AND LOADS DURING SERVICE LIFE OVERVIEW

6.11 Vehicle Service Life

Service Life of the vehicle can be for example:

- Expected life time (e.g. 10 years, 15 years)
- Expected mileage (200.000 km to 600.000 km)
- Expected operating hours (4000 h to 12 000 h)

As defined in section 6.1 and considering vehicle type (passenger or commercial vehicle).

6.12 Environmental Loads in Vehicle

The EEM reliability can be influenced by the environmental loads as shown in tree analysis of Figure 12. Environmental Loads are external stress factors caused by certain environmental conditions, such as temperature, humidity. Etc

Environmental loads have to be selected from the tree and/or added when necessary for a specific mounting location. Describe and quantify conditions of the relevant loads.

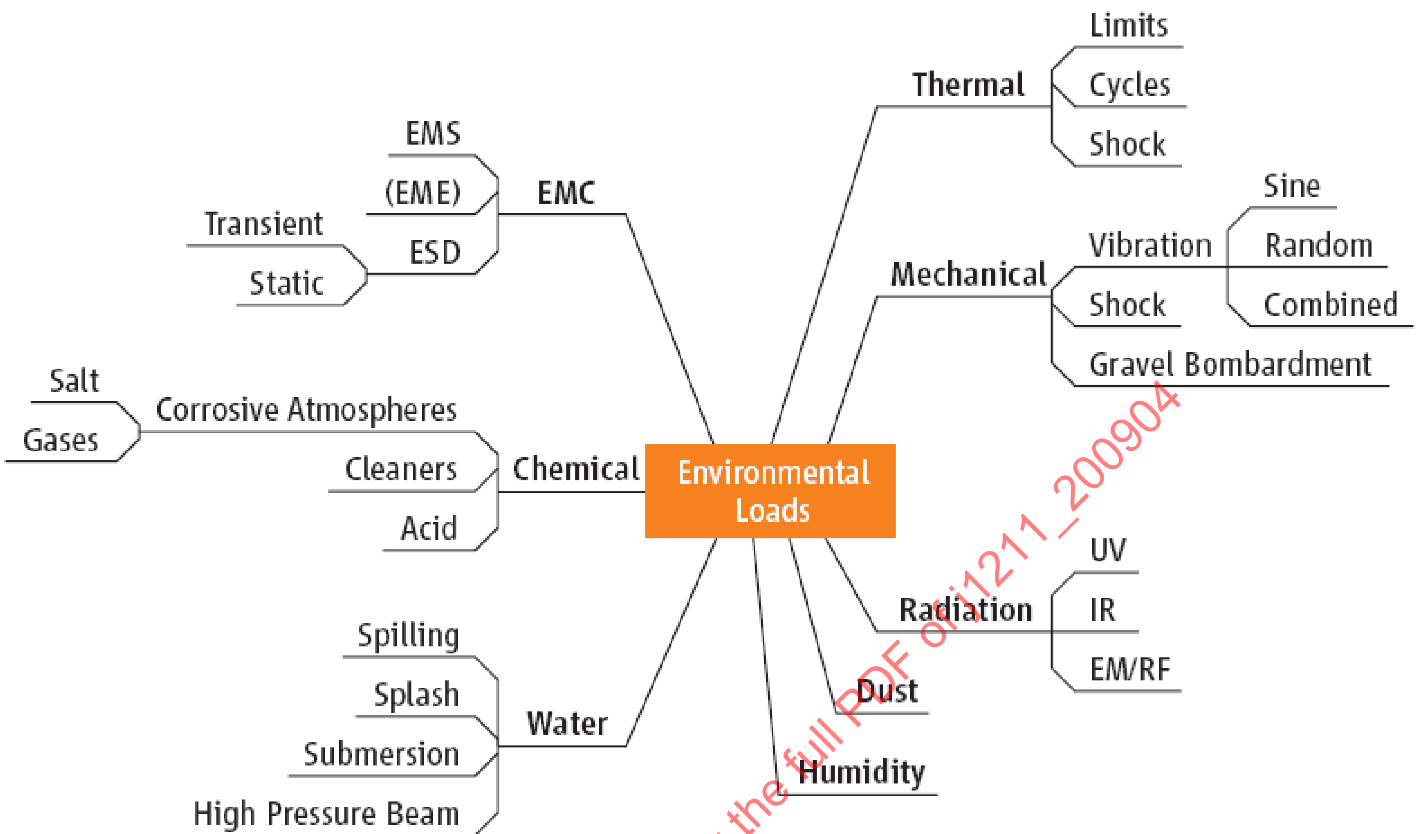


FIGURE 12 - TREE ANALYSIS OF ENVIRONMENTAL LOADS

6.13 Functional Loads in Vehicle

The EEM reliability can be influenced by the functional loads as shown in tree analysis of Figure 13. Functional loads are stress factors caused by EEM operation, usage profiles etc.

Functional Loads for a specific EEM have to be selected from the tree and/or added when necessary. Describe and quantify conditions of the relevant loads.

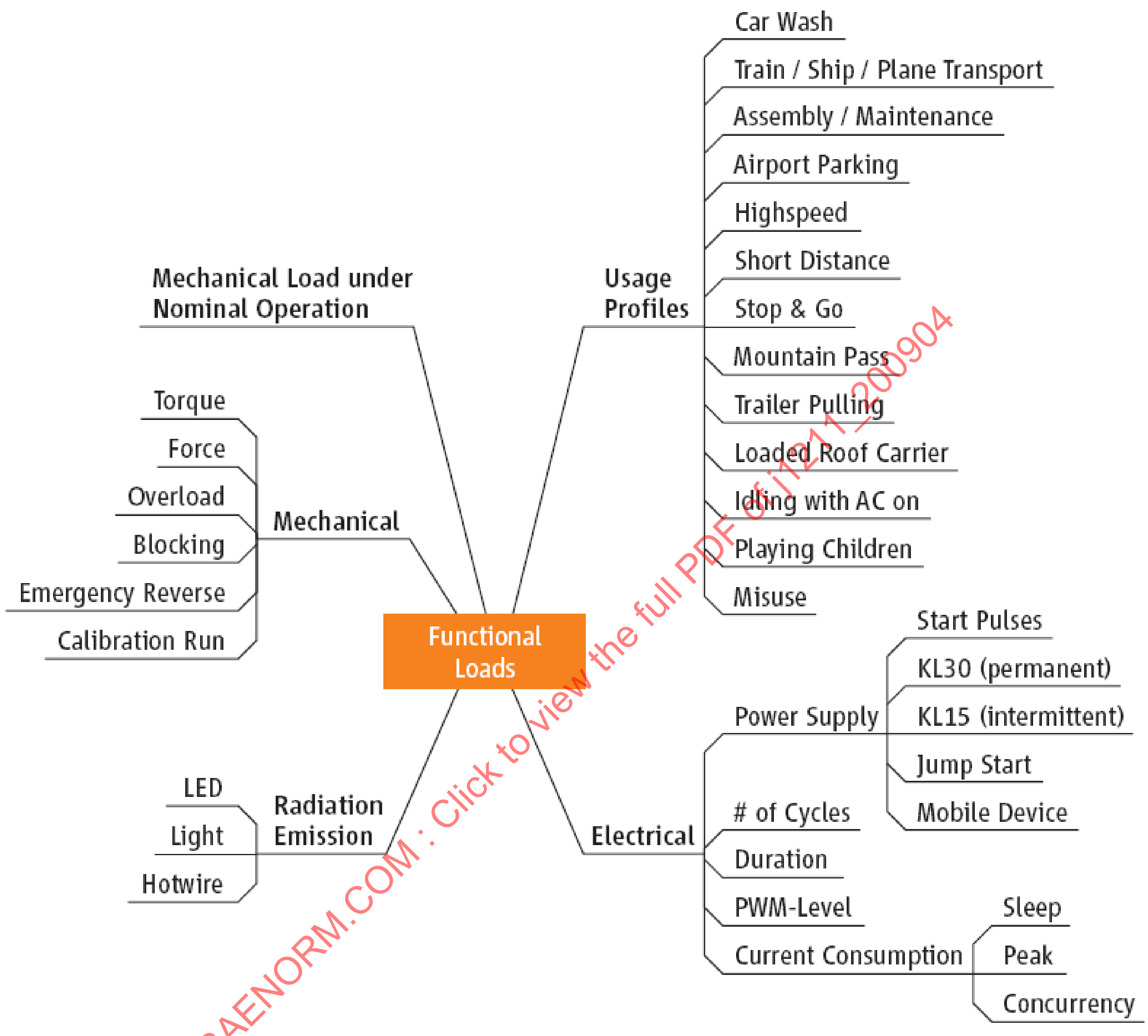


FIGURE 13 - TREE ANALYSIS OF FUNCTIONAL LOADS

6.14 Examples for Mission Profiles / Loads

The Mission Profiles in this section are simplified 'typical' loads for different mounting locations. Note: that these profiles are estimations, which represents typical operational profiles of different drivers in a passenger cars and have to be validated.

However, for several kinds of loads, such as vibration, corrosion, and water intrusion, parameters for lab tests rather than typical values are given.

If the translation of field load to test load is too difficult or the acceleration between field and test conditions (e.g. for some chemical loads) is unknown today, the use of proven standards is encouraged

See Appendix A.1 and A.2 for Examples of Typical Missions profiles.

7. KNOWLEDGE MATRIX FOR SYSTEMIC FAILURES

7.1 Knowledge Matrix Definition

A Knowledge Matrix is a repository for systematic failures, i.e., failures that are systemic or inherent in the product by design or technology. The Knowledge Matrix is a collection of the lessons learned by the organization using the Robustness Validation process. Extrinsic failures, i.e. failures that are random in nature and predominantly generated by manufacturing processes, are covered in Section 10.

In order to apply and interpret the results of the Robustness Validation process, knowledge of the basic failure mechanisms of the electrical/electronic module is required. The root causes of the failure mechanisms and the effects on the module must be known in order to relate the failure mechanisms to the product's performance and the conditions of use. A Knowledge Matrix can be very useful in identifying potential failure mechanisms and their causes.

To make the development and use of the Knowledge Matrix easier to understand the Knowledge Matrix is divided into several logical groups with the first level being the Component Group. An example of this process is illustrated in Figure 14.

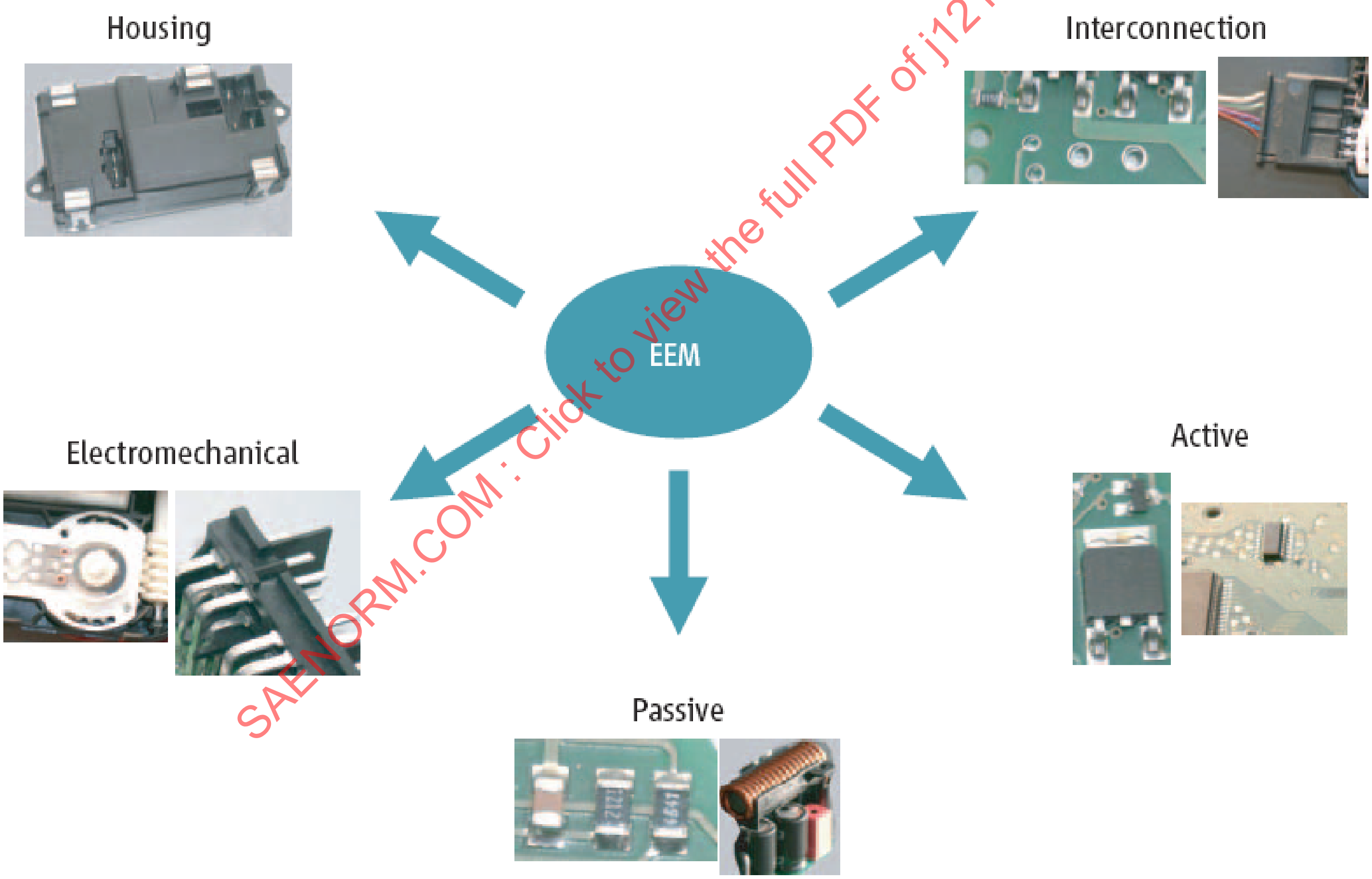


FIGURE 14 - DECOMPOSITION OF AN ELECTRONIC CONTROL UNIT (EEM)

7.2 Knowledge Matrix Structure

The following example Knowledge Matrix shown in Table 4 is defined with the a structure to enable easy navigation of the possible failure modes and causes by taking a module in combination with the intended customer use and breaking it down to the components and technology used to assemble a module.

TABLE 4 - KNOWLEDGE MATRIX STRUCTURE

Field No	Field/Column Name	Field/Column Required	Field/Column Description	Field/Column Content /Example
1a	Main Component Group	Mandatory	Top Level Main Component group	Housing Interconnection Passive Active Electromechanical
1b	Component Sub Group	Mandatory	Components broken down to the next level	Resistor Diode PCB IC Inductor Capacitor Crystal Etc.
2	Product Life Phase	Mandatory	The Product life phase that impacts on the Robustness Characteristics	**Design/Development Phase** Robustness aspects that are determined during the Initial Design & Development phase of a product life. (e.g. wrong material chosen) **Manufacturing Phase** Robustness aspects that are determined during the serial production phase of a product life (e.g. too high process temperature) **OEM Assembly Phase** Robustness aspects that are determined during the assembly of the product into the vehicle. (e.g. mounting force too high) **Customer Use Phase** Robustness aspects that are determined at 0 km & Field (e.g. incorrect specified operation conditions; misuse)
3	Robustness Aspect	Mandatory	The Characteristic that defines the robustness of the product	Cleanliness (e.g. production process), Resistance , Mechanical stability, Material; operational conditions etc.

TABLE 4 - KNOWLEDGE MATRIX STRUCTURE (CONTINUED)

4a	Failure Mode	Mandatory	The effect by which a failure is observed to occur.	EEM-level: incorrect function Component-Level: Open circuit PCB Track
4b	Failure Cause	Mandatory	The specific process, design and/or environmental condition that initiated the failure, and whose removal will eliminate the failure.	i.e. Excessive Current in PCB track
4c	Failure Mechanism	Mandatory	The specific process, by which physical, electrical, chemical and mechanical stresses act on materials to induce a failure.	i.e. Track overheating from excessive current to point of failure.
4d	Failure Type	Mandatory	Systemic or Random	
5	Failure Stressor	Mandatory	The Type of Stress or combination of stress's required to trigger the Failure mechanism	Temperature Cycle + Vibration, Temperature + Humidity + Vibration
6a	Test Methodology	Optional	If available the test methodology to be used to trigger the failure	This field is intended as a reference guide to assist the user in finding an appropriate test methodology and does not constitute a specific test definition. The RV User has the responsibility to understand the failure mechanism and to determine the appropriate test methodology.
6b	Test Reference	Optional	If available the standard reference used to trigger the failure	This field is intended as a reference guide to assist the user in finding an appropriate test methodology and does not constitute a specific test definition. The RV User has the responsibility to understand the failure mechanism and to determine the appropriate test methodology.

7.3 Knowledge Matrix Use

There are two distinct versions of the Knowledge Matrix – the publicly available example version defined in this document and a company-specific version.

The failure data in the publicly available Knowledge Matrix should be considered a starting point and guide for any user of the robustness validation process as it contains only the generic state of current knowledge information.

Users of the Robustness Validation Process should generate their own Knowledge Matrix based on their own specific product types, and their own personal experience and lessons learned. A format and structure similar to the example Knowledge Matrix illustrated here is suggested. The data contained in the sample publicly available knowledge matrix can be used as a guide and a starting point.

There are many ways to use the matrix, and the way to use it depends on what information is already known and what information is needed. The matrix can be used in a reactive manner when there is a failure mode requiring root cause analysis, and an acceleration model. Likewise, the matrix may be used in a proactive preventative manner to identify potential failure modes in a design during the design phase of a product development, particularly as part of an FMEA.

7.3.1 Knowledge Matrix Use in Failure Prevention (Proactive)

As part of the Robustness Validation Process there should be a review of the user's existing matrix against the Mission Profile and product-specific requirements. The user should also be able to demonstrate the completeness of the review during discussions with the customer.

The user should be able to demonstrate lessons learned that are in the Knowledge matrix and are included in the product design, for example a design review report.

One of the outputs of the review might be the FMEA, which includes the lessons learned.

See Appendix A for examples of using the Knowledge matrix.

7.3.2 Knowledge Matrix Use in Failure Analysis (Reactive)

During a failure incident and as part of the user's failure analysis process the Knowledge Matrix can be used to identify the potential root cause of the failure. When a new failure mode and causes are identified during the analysis, processes that are not currently in the user's Knowledge Matrix should be updated to add the new failure mode.

One use of the matrix is when a failure mode has been observed and there is a need to identify the potential failure causes and/or stress factors (stressors). This may be done as follows:

Step 1 – Filter on the component group (column 1a) and component sub group (column 1b) involved
Step 2 – Find the potential Failure modes in Column 4a
Step 3 – Find the potential failure cause in column 4b.

NOTE: It is possible that the specific failure cause does not exist in the matrix. Therefore a new entry would be required to describe the failure.

Step 4 – Find the failure mechanism in column 4c
Step 5 – Review the potential stressors in column 4d

The list of potential failure modes, causes and stressors may then be used to plan an investigation to confirm which one is the correct one for the particular failure.

See Appendix A for Examples of using the Knowledge Matrix.

7.4 Knowledge Matrix Change Control

The users Knowledge matrix must be a controlled document within the users organization subject to change control and regularly updated with lessons learned from each product life cycle.

7.5 Lessons Learned

The Knowledge Matrix is intended to be the main repository for all lessons learned within the organization so users of RV must have in place a process to collect and review lessons learned from their RV activities and update their own Knowledge matrix from all sources of experience with EEM failures.

7.6 Knowledge Matrix Availability

The example Knowledge matrix is freely available from the SAE/ZVEI website and will be updated on a regular basis by a team of experts.

Suggestions to update or modify the example Knowledge Matrix are actively encouraged and such suggestions should be sent to CustomerService@sae.org.

The users' company specific version of the knowledge matrix should be available for review by the customer, but is not required to be given to the Customer.

8. ANALYSIS, MODELING AND SIMULATION (AMS)

8.1 Introduction to the Use of Analysis, Modeling and Simulation

Analysis is the process of studying the nature or operation of an issue, item or substance by sorting out and investigating the component parts so that the relationships of how something is made and why it functions the way it does can be understood. Engineering analysis can focus on either of two objectives: 1) Learning how and why things work or do not work in order to resolve an issue or 2) Using the knowledge and lessons learned from past endeavors to predict how new designs or processes will perform. Many different types of analysis techniques have been developed to deal with different technologies, materials and issues, and which are essentially either a physical, intellectual or mathematical and sometimes statistical process.

It is not the intent of this handbook to go into detail regarding the many established and emerging analysis techniques available today. Engineers not familiar with such techniques are encouraged to seek out, study and apply them as needed. Internationally accepted standards and guides which provide an overview of proven techniques are readily available [10, 11, 12]. Detailed information, whether basic or state-of-the-art, on specific techniques, such as Sneak Circuit Analysis [13], FMEA and Fault Tree Analysis [14, 15, 16], and Worst Case Circuit Design and Analysis [17, 18, 19, 20] are also easily obtained through SAE International, Inc., national and international standards organizations, professional societies and journals, and bookstores.

Modeling is the creation of a representation of a process, device or system, used in predictive analysis to evaluate the behavior of new systems. Engineering models are typically math based and are often incorporated into computer programs. The models can be either empirical (i.e. based on observation of a results or an outcome) or phenomenal (i.e. a model of the actual phenomenon and processes that produce the outcome). Phenomenal models are typically more detailed and therefore more complicated to use. However this results in greater accuracy and makes them more applicable to a wider range of circumstances than empirical models. Care must be applied when using empirical models since they are typically accurate only under a limit range of conditions. These models give birth to the term cook book equations and the common modeler saying that "all models are wrong, however some models are useful if you know how and when to use them". Therefore it is essential that modeling activities first require diligent development and validation of the foundation mode that includes understanding the limitations and ranges of linearity or nonlinearity of the model and how accurately it represents real world conditions.

Simulation refers to the use of one system or media to represent the behavior or characteristics of a real world system. Sophisticated engineering computer program are increasingly required and used to bring life to engineering models by simulating complex events and functions. True simulations attempt to emulate the sequence of deterministic (i.e. cause and effect) internal processes that produce a result by using phenomenal models and not merely predict an outcome or results of an item being simulated. Simulations may also provide a visual representation of the fundamental processes and the results in addition to mathematical and graphical results.

Advancements in computing power, simulation software and modeling algorithms are fuelling rapid progress in automotive **Analysis, Modeling and Simulation (AMS)** methods especially when performed in an integrated Computer Aided Design (CAD), and Computer Aided Engineering (CAE) environment. The skilled, up-front use of CAE analysis improves the optimization of product performance, quality and reliability while reducing the overall time and costs of design, development and validation.

In a modeling and simulation environment, design and analytical Development and Validation (D&V) become essentially one task. The role of AMS in a product development process starts as virtual prototyping tasks for evaluating and (when needed) optimizing features and functions of a new design. The design evolves under this analyze and revise process until the designer and analyst (or designer/analyst) develops and demonstrates a design that can operate in accordance with the requirements and under expected variation and noise factors. The virtual D&V process is completed when it can be demonstrated analytically with accepted and proven models and validation assumptions that the virtual (paper or CAD) design's theoretical capabilities are acceptable to the projects requirements.

Sometimes, the opposite may be proven, i.e. that a specific design approach is not capable of meeting requirements. In this case an organization may save a significant amount of time and resources by not pursuing a design path that is incapable of acceptable performance. However, generally the objective of AMS activities is to grow the capabilities of the design to the point where it is found to be theoretically capable of consistently achieving its requirements and goals while operating in its intended environment. The pre-optimized design can then advance to physical build and test evaluations. The benefits of AMS virtual development and validation processes are:

- Performance, durability and reliability robustness issues can be developed and optimized without the time and cost of physically building and testing prototype parts.
- Designs move in to physical testing pre-optimized by analysis activities that have already screened out many defects and discrepancies.
- Physical testing can be smoother and faster without as many interruptions for fault detection, root cause trouble shooting and corrective action events.
- Physical testing can be optimized. [4]
- Physical testing then does not need to be totally comprehensive, it can be reduced to a series of spot checks of critical features and refocused to criteria that can not be evaluated by analysis.

This rapid combined virtual D&V approach is possible in an integrated CAD-CAE environment because the results of an evaluation can be used to immediately make informed, feedback guided revisions of design features as needed. The virtually revised design can then be rapidly re-evaluated in the AMS environment in order to gauge the degree of improvement until acceptable performance is achieved. The analyst then moves on to the next design criteria until all aspects of the design have achieved the desired level of robust performance, durability and reliability.

In the physical world the pace of D&V activities are limited by the time and cost required to physically Design, Build, Test and Fix (DBTF) successive generations of prototype parts. These real world limitations require the creation and coordination of a series of sophisticated, complete build and test cycles that must cover all aspects of the new design in each round of testing. Formal product validation is intended to be the final physical test series in this process. However, rarely does physical testing identify and resolve all discrepancies to result in a final robust product. Usually the rounds of physical DBTF activities conclude with the design being deemed "good enough" to advance into production launch activities where reliability and capability growth continues via warranty events and customer dissatisfaction feedback.

8.1.1 AMS Scope

This section provides an introduction to Computer Aided Engineering (CAE) Analysis, Modeling and Simulation evaluations and how they can be applied to evaluate, optimize and ensure robustness of Automotive Electrical/ Electronic (E/E) devices and defines recommended practices on how to integrate AMS procedures into development and validation procedures for E/E devices but it does not define the detailed requirements of each modeling or simulation method which are covered in SAE J2820.

This section is a summary of general-purpose math based evaluation techniques and CAE analysis tools that can be applied to calculate a wide range of product characteristics and capabilities common to many E/E devices. These methods can be applied individually or in groups during any product phase to:

1. Calculate capabilities of early design concepts.

2. Perform robustness optimization and virtual validation of a CAD or paper design of a product.

3. Perform test planning, test optimization and extrapolation of test results to field conditions.

4. Investigate and resolve discrepancies.

Four categories of proven AMS tools and modeling methods are defined that can be applied to assess a wide range of E/E product requirements during early product development. These are:

1. E/E Circuit and systems analysis for evaluating performance, power issues and how performance is affected by variation.

2. Electromagnetic Compatibility (EMC) and signal integrity analysis.

3. Stress analysis for determining thermal and mechanical loads, peak stresses, stress distribution and stress transmission paths and evaluating if the design is strong enough to support the stresses.

4. Physics of Failure based failure mechanism susceptibility analysis for evaluating the durability and reliability capabilities of a design.

When properly applied AMS methods are capable of determining the theoretical performance and durability of a proposed new design. However, modeling and simulation methods are unable to predict what kind of manufacturing errors or variation issues could be inflicted on a design and what their outcome might be.

8.1.2 AMS Mission

It is the mission of this section to foster the development and use of efficiency enhancing E/E AMS CAE techniques by providing a reference resource of Models, CAE tools, methods and a structure for integrating CAE techniques into E/E product development processes and A/D/V plans.

It is the responsibility of the product engineer or team to determine which AMS objectives and procedures are relevant for a specific device, technology or application and how to interpret the results and define application specific acceptance (pass/fail) criteria when appropriate. However, general guidelines for interpretation and acceptance criteria are provided. It is up to product teams to balance the selection of analysis objectives and tasks for mitigating design risk factors against constraints factors such as: availability of CAE resources, component models, expertise of analysts, manpower, and budget etc.

The techniques defined in this document are not all-inclusive due to the dynamic rate of development of new AMS techniques and CAE tools; teams are encouraged to consider the use of other applicable analytical methods as they become available

8.2 Integration of Design Analysis into the Product Development Process

8.2.1 Analysis Template for Automotive Electrical/Electronic Modules

A template of analysis objectives for supporting the development of highly reliable automotive electrical and electronic (E/E) devices is provided in Figure 15. The template is based upon analytical techniques that can be performed with currently available (CAE) software. The following four evaluation areas are:

1. E/E Circuit and Systems Analysis for Evaluating Performance and Power Issues

2. Electromagnetic Compatibility and Signal Integrity

3. Stress Analysis for Thermal and Mechanical Stress Distribution and Transmission

4. Durability and Reliability.

Some of the analytical objectives are independent which enables scheduling flexibility, others are related and may be combined into a single model or simulation to maximize efficiency. Others are dependent as denoted by the dotted arrows where the results of one analysis is used to as an input to another evaluation. Dependent analysis sequences may require scheduling to ensure a timely flow of data especially when analysts from different technical disciplines or departments are involved.

The template is not all-inclusive, due to the dynamic rate of development of new analytical techniques and CAE tools; teams are encouraged to consider the use of other applicable analytical objective or methods not included in the template. The template in not intended to be a mandatory list of tasks to be routinely applied to every program. Nor is it intended to mandate sophisticated high-end CAE simulations for situations when more basic calculation techniques will suffice.

The template Figure 15 is intended to be used as a planning tool to guide a product team through existing analytical methods for evaluating design objectives for automotive E/E devices. The objectives are then combined to determine the specific AMS tasks appropriated to a project to be performed as part of the component's D&V) plan. It is up to the team to balance the selection of analysis objectives and tasks for mitigating design risk factors such as: complexity, new technology, aggressive schedules ... etc., against constraints factors such as: availability of CAE Resources, component models, analyst expertise, manpower, budget, etc.

When CAE analysis identifies potential design deficiencies, there may be a need for additional physical tests for further evaluation of the concern. Discussions on the four analysis objective categories start at section 8.3.

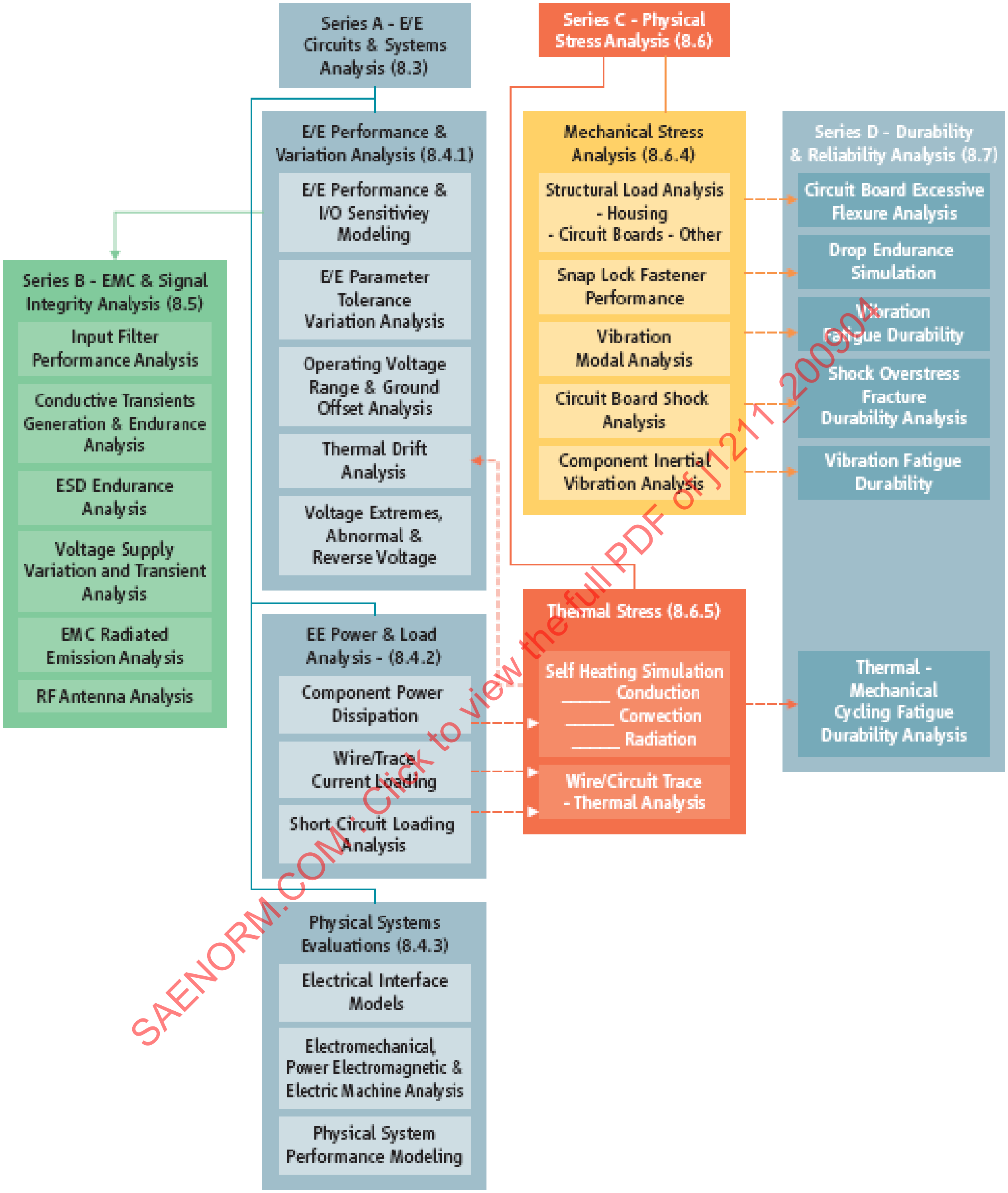
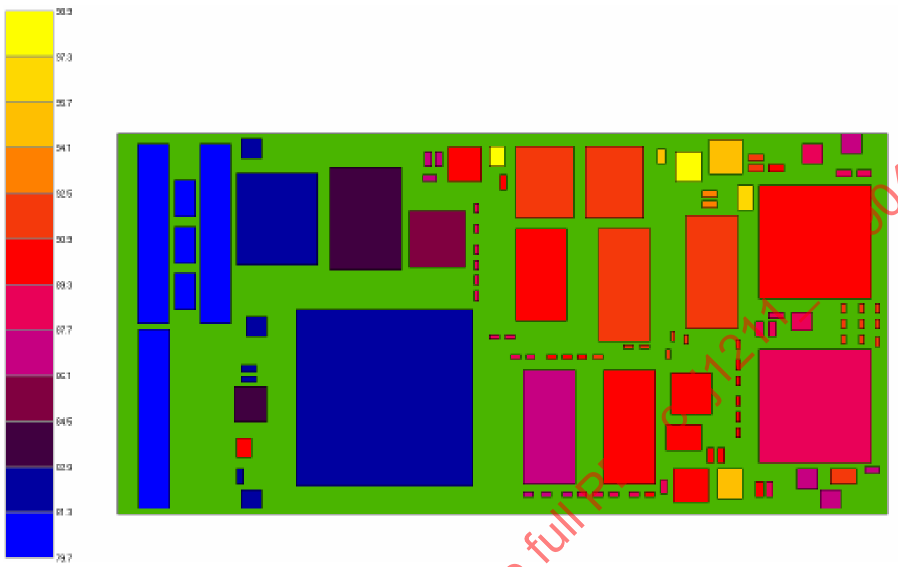


FIGURE 15 - ANALYSIS, MODELING AND SIMULATION OBJECTIVES TEMPLATE

The template combines multiple technical disciplines into an overall virtual engineering prototyping process. Each column contains objectives, which require similar analytical skills and tools that are the primary interest of different members of the product team. The dotted arrows indicate when an analytical object requires the results of another.

EXAMPLE: The results of the electrical power dissipation analysis is required to perform a thermal analysis to determine the local heating characteristics and thermal gradients across a circuit board under various power loading and climate conditions (see Figure 16 below). The thermal results are then supplied back to the circuit analyst and used to evaluate the effects of thermal and electrical drift on critical circuits as the device heats up. Thermal performance results are also used for thermal-mechanical (heating expansion-cooling contraction) fatigue durability analysis.



Above – CAE simulation of component power dissipation to determine case temperatures at a 60 °C ambient.
Below – CAE simulation of circuit board radiated heat temperature gradients for the same situation.

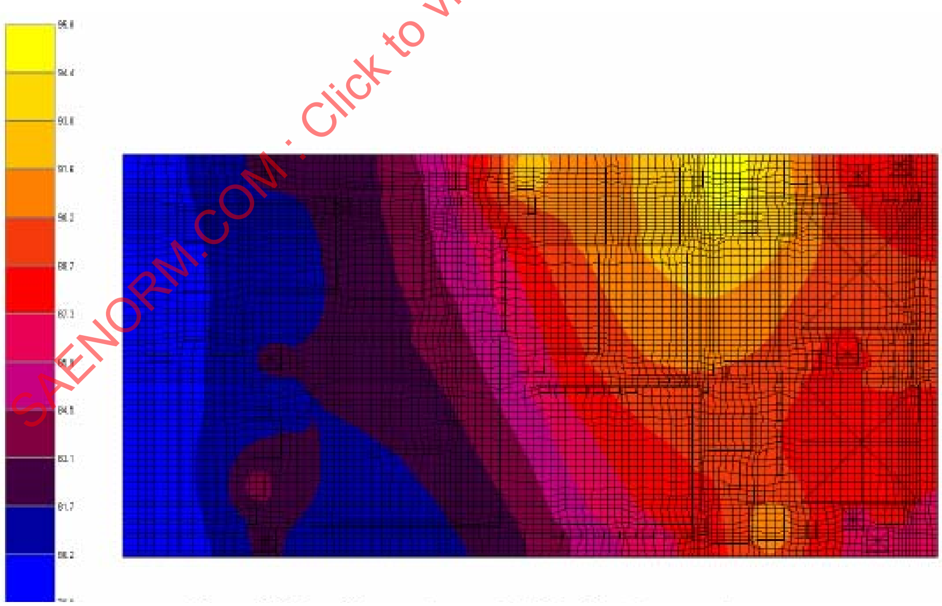


FIGURE 16 - EXAMPLE SIMULATION PCB RADIATED HEAT GRADIENTS

8.2.2 CAE Analysis Reports and Documentation

As AMS analysis shares the burden or replaces physical tests in product development and validation, it is essential that analysis results, conclusions and recommendations be formally documented and archived. The need for analysis records is driven by requirements for product development communication, corrective action tracking and documentation of engineering due diligence.

8.2.2.1 Evaluation Report

All AMS evaluation results and conclusions should be documented in Analytical Evaluation Reports. These reports should document the evaluation objectives and procedures that were selected by the product team and performed on the device. The product engineer should present a summary of the report to the product team. A complete copy of the report should be delivered to the lead product engineer and a copy should be included and maintained as part of the products documentation.

8.2.2.2 Corrective Action Documentation

Issues and design features that did not meet the acceptance criteria shall be documented in a close loop tracking system. When appropriate the analysis should include corrective action recommendations in these analytical evaluation reports.

8.2.2.3 Simulation Aided Testing and the Integration of Simulation and Tests

CAE Analysis is not envisioned to totally replace physical testing. However it is expected to greatly reduce the need for testing and enable a switch to more effective and focused testing that compliments CAE capability.

When requirements can be confirmed by means of CAE virtual validation techniques, physical testing portions of the Development and Validation plan may be reduced to cover:

- Only the requirements that cannot be evaluated by analysis.
- Simplified tests to confirm that CAE models were accurate and based upon valid assumptions.
- Tests to confirm that parts were correctly manufactured and assembled in accordance with design expectations.

When CAE analysis identifies potential design deficiencies, there may be a need for additional physical tests for further evaluation of the concern.

8.3 Circuit and Systems Analysis

The circuits and systems analysis series is related to the operating performance objectives of E/E modules. The objectives are organized into three groupings for

- E/E Circuit Performance and Variation Optimization
- Power and Loading Analysis
- Physical System Performance Modeling

8.3.1 Purpose

Circuit and systems analysis is performed to evaluate the static and dynamic electrical performance of a proposed circuit design in order to identify and resolve performance, tolerance and stability discrepancies during the initial early design stage. When an E/E device is part of a physical system comprised of mechanical, hydraulic, pneumatic or other elements, system level mutli-physics modeling can be used to identify and resolve overall performance and interaction discrepancies.

8.3.2 Recommended Coverage

Challenge/Risk Related Circuits as identified by the product team, Examples Include:

- Circuits with new or complex designs, or new components.
- Circuits that require a high degree of accuracy, stability or timing synchronization.
- Circuits that perform essential vehicle control or safety related functions.
- Other Circuits Identified by the product development team as challenge/risk related.

8.3.3 General Analysis Information Input Requirements

- Circuit or system schematics: Device(s) internal and vehicle level as appropriate to analysis goals.
- Library of circuit element models or ability to create element models for the analysis.
- Definition of excitation signals or interface inputs to the circuit or system.
- Definition of power, grounding and circuit protection conditions for the circuit or system.

8.4 Categories of E/E Circuits and Systems Modeling and Simulations

8.4.1 E/E Performance and Variation Modeling

This category of AMS objectives are used to determine electrical performance objectives for a proposed circuit design such as static and dynamic voltage, current frequency responses, impedance characteristics, etc. The evaluations are performed under the expected excitation, interface, loading, power and ground conditions of the intended application. The method may be applied to analogue, digital and mixed electrical signals.

These AMS objectives are intended to involve and promote communication for effective designs among product engineers, circuit designers and circuit analysts. This effort supports early design optimization and verification that the selected circuit configurations and component values perform stably throughout the range of tolerance stack-up, I/O loading, environmental variation and other noise conditions in accordance with design intent and product requirements. Design deficiencies identified by the analysis are to be resolved or flagged and tracked for further evaluation by the product team until corrective actions can be implemented.

The maximum analysis benefits are typically achieved by focusing on higher risk circuits. The types of typical models and simulations tasks that can be performed for E/E Circuit Performance and Variation Optimization are:

- Performance Simulations and Input/ Output (I/O) Sensitivity Analysis
- E/E Property Tolerance, Variation Analysis
- Operating Voltage Range and Ground Offset Drift Analysis
- Circuit Electrical Performance Thermal Drift Analysis
- Voltage Extremes, Abnormal and Reverse Voltage Analysis

8.4.2 E/E Power and Load Analysis

Power and load analysis is used on the high power circuits of a device to determine the amounts of electrical current and power that must be carried by individual components and circuit connections. This information is used to properly size components and circuit connections for their loads. The results are also used by the self-heating thermal analysis task.

The maximum benefits are typically achieved by focusing power analysis resources to identify surge, and sustained maximum electrical current conditions and to quantify the power dissipation conditions for circuits and components that are expected to self-heat which will raise the overall internal temperature of the device. Typically, components expected to dissipate more that 0.25 watt or expected to self-heat by more than 10 °C under sustained duration conditions (i.e. continuous on or active for more than 5 minutes) should be considered for power analysis. Power analysis is typically applied to high power and heavily loaded input, output, power feed, voltage regulation and ground return circuits.

The power analysis tasks are related to the electrical performance analysis since electrical engineering skills and analysis tools are needed to determine electrical power and current flow. Packaging engineers and thermal analysts use the power analysis results to evaluate and optimize the device's thermal design. The tasks in this series are organized to involve and promote effective design communication among product engineers, circuit designers, circuit analysts packaging engineers and thermal analysts.

The types of AMS tasks that can be used to perform power and load analysis are:

- Component Power Dissipation Analysis
- Wire / Trace Current Loading Analysis
- Short Circuit Loading Analysis

8.4.3 Physical System Evaluations

This category contains AMS techniques for analysis of how an E/E module interfaces with other E/E components and systems in the vehicle as well as with electro-mechanical and mechanical systems.

8.4.3.1 Electrical Interface Models

Electrical interface circuit models of devices are used in vehicle and subsystem level modeling tasks. Unless otherwise specified the models are to be created in the customers modeling language in order to be compatible with the customer's internal EE modeling capabilities. This should be dynamic and account for the effects of vehicle supply and ground voltage variation conditions and support electrical parameter variation modeling across the full range of temperature conditions the circuit is expected to be exposed to (i.e. operating environment temperature plus power dissipation self-heating effects). Interface models shall also support modeling of component parameter tolerances to support variation effects modeling.

Interface models should include documentation of the model's relative accuracy, limitations and any modeling assumptions used in their creation. Detailed requirements for the interface model or required procedures shall be defined by a design team of design responsible engineers.

Examples of the typical types of interface models are:

- Power/Voltage Supply Loading - Models for typical, worst case and parasitic load conditions for battery, ignition and other power feeds for use in vehicle energy management analysis and wiring system design. Typically, load models are required to represent the device's electrical loading characteristics or equivalent resistance and should be accurate over the device's specified voltage and temperature ranges.
- Signal Interface Models - Models of input and output characteristics.
- Transfer Function - Use in evaluating control system performance and system interactions.

8.4.3.2 Electromechanical, Power Electromagnetic and Electric Machine Analysis

There are two categories of Electromagnetic (EM) modeling and simulation tools. One deals with High Frequency EM (HF-EM) waves and radiation issues for wireless radio frequency signals and Electromagnetic Compatibility (EMC). HF-EM will be discussed in the EMC CAE section. This section will deal with CAE tools for Low Frequency Electromagnetic (LF-EM) issues involving power induction for electric machines.

The magnetic and electromagnetic aspects of electric machines cannot be modeled E/E analysis techniques (i.e. theories and equations of Coulombs, Ohm's, Kirchhoff's .etc,). At best E/E analysis can only estimate E/E circuit performance of EM elements by using equivalent circuit approximations to account for some of the electrical aspects of electric motors, generators, relays, solenoids, transformers, inductive sensors .etc. These estimates are usually sufficient for general E/E circuit interface calculations, but they are inadequate for design evaluation and optimization of electric machines and any precision control circuits to the electric machine.

For example, a simple linear solenoid actuator is modeled electrically as a pure resistive-inductive (RL) circuit. But an electrical model cannot account for variations in the actuation force and response time due to voltage changes and the circuit analysis cannot respond to the change in inductance related to the motion of the solenoid's armature. Another example is that electric circuit analysis cannot model the electromagnetic fields, transients and noise characteristics of electric machines. This is a frequent source of electromagnetic interference (EMI) noise problems in vehicle programs.

Highly effective electromagnetic (EM-CAE) AMS programs for performing multi-domain (electrical – magnetic) modeling exists. They are based upon Maxwell's equations of electromagnetic induction. EM-CAE tools are more challenging to use since they require expertise in magnetic and electromagnetic circuit physics in addition to E/E circuit and electric machine skills. Furthermore, magnetic and EM circuit modeling requires physical layout, geometries and magnetic material property parameters in additions to electrical components and connection schematics. Despite the added complexities, the design improvement and time to market value added by these tools is resulting in the increased use of EM-CAE modeling techniques.

8.4.3.2.1 Purpose

This analysis is meant to evaluate the performance of electromechanical devices and their interfaces and interactions with EE module in order to identify and resolve performance, control, stability and EMI discrepancies during the initial early design stages. M&S tasks may include evaluation of magnetic, electromagnetic, mechanical and thermal performance criteria for electric machines such as motors, generators, transformers, inductors, solenoids, relays, inductive and reluctive sensors.

8.4.3.2.2 Recommended Coverage

Coverage is recommended for design, performance and control analysis of all electromagnetic and electro-mechanical mechanics.

8.4.3.2.3 General Analysis Information Input Requirements

- Circuit Schematics of the device and the as appropriate to the analysis objectives.
- Library of circuit element models and magnetic material properties.
- Definition of power, grounding, and excitation signals and circuit interfaces.
- Definition and geometries of mechanical layout and interfaces.
- Definition of required output characteristics and/or output loading conditions.
- Definition of the environment temperature range where device is required to operate.

8.4.3.3 Physical System Performance Modeling

These AMS tasks included multi-physics modeling techniques which are used when systems are comprised of element from different engineering disciplines or electrical energy is required to be transfer across physics domains or transformed into different physical forms. These modeling techniques allow the E/E modules interactions with various automotive mechanical elements to be analyzed in order to perform analysis of complete, sometimes complex systems that are comprised of E/E, electro-mechanical and mechanical elements.

8.5 EMC and Signal Integrity (SI) Analysis:

The Electromagnetic Compatibility (EMC) and SI M&S objectives are to evaluate and optimize the ability of an E/E component or system to correctly function in its environment, without responding to or generating electromagnetic interference (EMI) i.e. stray or misdirected electromagnetic energy.

Signal Integrity (SI) analysis relates to the propensity of higher frequency signals to be degraded by EM wave propagation effects, signal reflections and line impendence mismatch conditions. Evaluating these criteria requires transmission line analysis techniques.

When the functions of a system includes receiving or transmitting signals for radio frequency communication, telemetrics and wireless remote control, EMC analysis should also include antenna performance evaluation.

EMI energy can take the form of radiated waves that can be coupled into signal and power lines or conducted transients superimposed onto signal and power lines. Sometimes, both conditions are involved as a radiated wave is converted into a conducted transient or vice versa.

Every form of EMI requires a configuration or system consisting of:

- A noise generating interference source,
- An energy coupling mechanism,
- A susceptible receiver.

EMI can be prevented by the use of proven, well-documented design features and practices that:

- Suppress or contain noise at the source
- Disrupt or degrade the effectiveness of energy coupling mechanism,
- Protect or reducing the sensitivity of receivers.

Electromagnetic compatibility is essential for safety and reliability in today's high tech vehicles and society.

EXAMPLES: Vehicles cannot afford engine stalls or brake malfunctions because a controller was disrupted by the ringing of a passenger's cell phone. Likewise, the heart pacemaker in a driver can not be allowed to malfunction by activating a car's horn or air conditioning system.

For these reasons automotive OEM's, the SAE, Governments and other industries all have requirements for ensuring EMC by specifying maximum emission and minimum susceptibility levels for products and systems.

Despite these regulations and requirements, designers typically employ only minimal level of EMI control features into initial designs. This practice is based on valid “Over Design” concerns of incurring size, weight and cost penalties due to unnecessary components. Therefore, EMC features and components are often not used until a need is absolutely proven usually by means of EMC testing. Automotive EMC testing is typically comprised of 10-15 different evaluation procedures. These EMC tests require expensive, room size test cells and sophisticated monitoring equipment. EMC optimization usually requires several rounds of building, testing and fixing prototype parts, first on the component level then at the vehicle level. This process needs to be performed on dozens of E/E components and systems on every vehicle. This makes EMC testing the highest cost and most time-consuming activities in automotive E/E product development and validation.

To address this situation, many automotive OEM’s have instituted a detailed EMC design review process which includes a design review checklist and EMC design guidelines based on the lesson learned experiences of the OEM’s technical staff. This manual, labor-intensive review of component schematics and layout is used to ensure that an adequate level of EMC capability has been designed in prior to EMC testing, so that test resources, time and money are not wasted on basic easily prevented issues. The use of EMC-CAE AMS analysis methods during the initial design phase to optimize and verify the EMC capability of a design as it is created is the next logical step.

The types of typical AMS tasks that can be performed for EMC and Signal Integrity Analysis are:

- Circuit Input Filter Analysis.
- Conductive Transient Generation and Endurance Analysis.
- ESD Endurance Analysis
- Voltage Supply Variation and Transient Analysis
- EMC Radiated Emission Analysis
- RF Antenna Analysis

8.5.1 CAE Programs for EMC and SI Analysis

There are a number of EMI related analysis evaluations that can be performed with E/E circuit analysis methods. Filter performance and transient suppression are two basic procedures that should be incorporated into the design evaluation of every new circuit. Circuit analysis methods are of course limited to only the electrical components involved in an EMI threat. EMI/EMC multi domain electrical and magnetic analysis is one of the newer categories of CAE techniques to move out of the tools research labs and into the commercial realm. Much of this advancement is due to research efforts that have created math models and tools of EMI transmission and coupling mechanisms by groups such as the Electromagnetic Compatibility Research Consortium at the University of Missouri - Rolla.

EMC-CAE is also one of the most complex CAE areas due to the many different EMI coupling mechanisms that have to be considered and have produced many different specialized modeling tools and approaches. However, some of the newer EMC-CAE tools combine several analysis techniques. This allows them to model a wide range of EMC conditions for specific applications in a suite of interactive analysis tools there are four basic analysis approaches defined in the following list.

1. Analytical Equations Solvers: The easiest tools to use but have limited scope and are applicable only to simple shapes and structures. They have some use as part of specific application evaluation templates. However, they provide little practical value for most real world modeling situations.

2. Numerical Simulations: Perform any type of full field simulation for the full range of Maxwell’s EM equations. Various types of numerical analysis methods are used such as: Finite Element Model (FEM), Method of Moment (MoM), Finite Difference Time Domain (FDTM), Frequency Domain Finite Difference (FDFD) etc. These programs are the most flexible and challenging tools to use. They require highly skilled analysts to set up the problem and interpret the results in term of how design will respond to the field conditions predicted by the program.

3. Design Rules Checkers: CAE programs that rapidly scan designs and layouts to identify violations of rules contained in user-defined libraries. Good for accurate, automated detection of errors and enforcement of best practices guidelines. Usually an EMC expert is required to define and set up the rules.

4. Expert Systems: CAE programs that evaluate or ask questions about the design in order to suggest the type of EMI control features the design requires or to define and run a sequence of virtual evaluations that interpret the results in term of risk severity and recommend possible solutions.

EMC-CAE tools are then further divided into general and application specific sub groupings.

8.5.1.1 Purpose

The modeling and simulation of EMI/EMC characteristics and modeling of electromagnetic waves and fields is performed to determine their effect on EMI/EMC characteristics. The Results are used to evaluate and optimize the ability of E/E components and systems to correctly function in their environment without responding to or generating disruptive levels of stray electromagnetic energy.

8.5.1.2 Recommended Coverage

The Recommended Coverage depends on the type of devices being analyzed and the capabilities of the modeling tool. As a minimum circuit analysis tools should be used to verify filter performance and transient noise suppression capabilities of new, high risk, high performance and critical electronic circuits. When available radiated EM and design rule verification analysis is recommended on all new circuit board assemblies. Signal integrity analysis is recommended to be performed on high frequency circuits operating in and above the gigahertz range. Antenna performance analysis is recommended on wireless communication systems and wireless remote control systems.

8.5.1.3 General Analysis Information Input and Requirements

Circuit Schematics - vehicle and internal device level as appropriate to analysis objectives.

- Library of circuit element models and magnetic material properties.
- Definition of power, grounding, excitation signals and circuit interfaces.
- Definition and geometries of mechanical layout and interfaces.
- Definition of required signal Input / Output characteristics and signal strength loading conditions.
- Definition of the environment temperature range where device is required to operate.

8.6 Physical Stress Analysis

Physical stress analysis can be used to assess the effectiveness of an E/E device's physical packaging to maintain structural and circuit interconnection integrity and a suitable environment for E/E circuits to reliability function. (Note - electrical stress evaluations were previously discussed in the E/E analysis sections). Physical packaging involves the ergonomic, mechanical support, electrical connections, and power, thermal and environmental management features that sustain the E/E components assemble in an E/E device or module.

Analytical evaluations of these physical aspects transform the discipline of electronics packaging from a subjective art into an objective science. The following overview discusses how Reliability Physics and Physics of Failure principles can be used to analytically evaluate a design's ability to reliably endure operating stresses.

Stress is the effect usage and environmental loads place on a device and its materials. Every loading force applied to or generated in a device triggers either a resulting motion and/or a stress distribution built up within a device's materials and structures to balance the applied forces. The amount of strain experienced is a factor of a device's size, shape and material properties that determine strength.

Sources of stress experienced in electronic equipment is displayed in the pie chart in Figure 17.

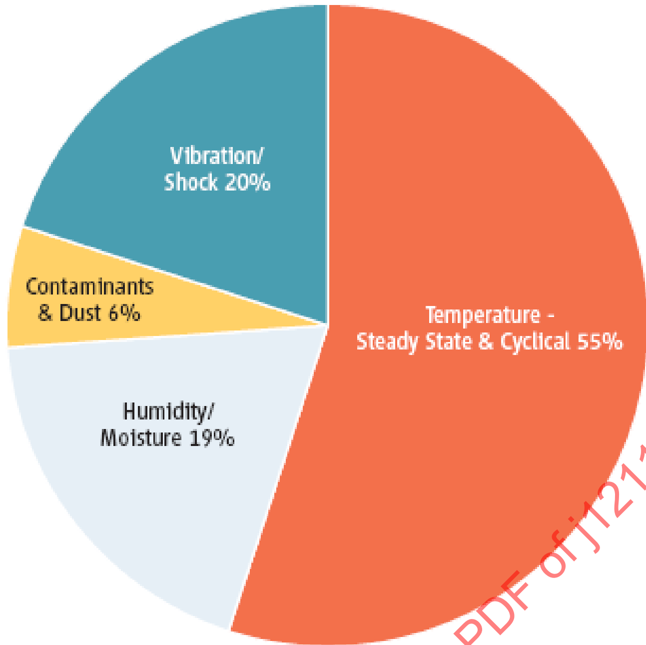


FIGURE 17 - SOURCES OF STRESS FOR ELECTRONIC EQUIPMENT

The percentages vary for different applications and packaging locations.
(ref. "The handbook of electronic package design" section 1.4.2).

Stress can produce four possible outcomes that must be accounted for to achieve a reliable product.

- The strain from an applied stress will be so small as to be inconsequential (i.e. the desired state)
- Electrical properties may shift (i.e. resistance and capacitance drift, piezoelectric effect, etc.) this can alter circuit performance during stress conditions. The amount of drift that can be tolerated without degrading system performance then becomes a key issue.
- The stress may exceed a yield point to trigger an imminent overstress failure mechanism in the materials (i.e. fracture, buckling, excessive deformation, melting or other thermal event, etc.).
- Enduring a steady stress or series of stress cycles, causes incremental damage accumulation in materials. Gradual molecular breakdown eventually produces wear out failures mechanisms" (i.e. fatigue, delamination, creep, corrosion .etc.). Determining the durability time period during which required performance is maintained until wear out failures occur then becomes a key issue which is discussed further in the durability/ reliability modeling section.

Typically, these effects are identified by means of physical performance and life testing that evaluates performance under applied loads over time in a pass/fail format. Such tests do not directly determine stress transfer or strain effects, so information on design margin (i.e. safety factor) that could be used for design optimization is not known. However, M&S methods can also perform stress analysis and optimization as the design is created. The objectives of stress analysis are:

- Identify the loading factors that will stress the device in its intended application.
- Calculate the device strength and the stress - strain relationship transferred throughout the device.

- Verify that the strain doesn't exceed material yield points which could cause imminent failure.

- Identify items that may be highly or frequently stressed. These items are at risk for damage accumulation wear out types of failure mechanisms and will also require long term durability analysis.

A Physics of Failure stress, strain and strength engineering analysis as the initial design is created provides an opportunity to adapt a "Right Design" engineering philosophy. This approach takes a neither takes a minimal or "Under Design" approach, to strength, robustness and reliability features To avoid excess costs, size and mass are minimized unless their need is proven by testing or an over design approach is needed to ensure high quality and reliability.

Physics of Failure based M&S stress analysis offers opportunities to 1) improve product Quality, Reliability and Durability (QRD), 2) reduce development-validation cost and time, and 3) perform M&S based design optimization that allows product to be "Right Designed" (i.e. right sized) for the stress load and the intended service life of the application

Electrical, mechanical and thermal stress analyses are the types of stress M&S methods most applicable to automotive E/E modules. Electrical Stress analysis had been previously covered under the Circuit and System analysis sections. The following sections will address mechanical and thermal stress analysis.

8.6.1 Purpose

Physical stress analysis is performed to understand and use the static and dynamic physical, mechanical and thermal stress profiles that the E/E device is required to endure under usage and environmental conditions. It is also performed to evaluate the modules inherent strength, stress transfer mechanisms, stress distribution patterns and stress endurance capabilities in order to optimize and verify that the strength of a design This is needed to show that it can endure the usage stresses that cause "Over Stress" failure mechanisms such as yield, fracture, buckling, thermal melt down, etc. Finally it is used to evaluate structural integrity or circuit interconnection and the suitability of the modules internal environment for E/E circuits to reliably function.

8.6.2 Recommended Coverage

E/E modules with:

- More than 50 components or components larger than 2'' (~5 cm) per side.

- IC components larger the 64 pins or 1" (2.54 cm) per side.

- Discrete surface mount components of EIA package size 2010 or larger.

- Leadless Integrated Circuit component

- Self heat capabilities that are more that 10 °C.

- Mounting locations in an under hood or other high temperature or high vibration environment or integrated into a mechanical component.

8.6.3 General Analysis Information and Input Requirements

- Circuit Schematics: Device(s) internal and vehicle level as appropriate to analysis objectives.

- Circuit Board Component Assembly layout and dimensions.

- Circuit board housing and packaging support dimensions.

- Library of E/E part models of dimension and material or ability to create models for the analysis.

- Library of E/E part materials, their mechanical and thermal stress transfer and strength properties.

- Library of E/E parts Failure Mechanism Models.

- Definition of intended operating and off state - vibration, shock and thermal environmental profiles.

- Definition of operating usage profile and related power dissipation in E/E parts.

8.6.4 Mechanical Stress Analysis

Mechanical stress analysis (also known as structural analysis) calculates the stress-strain conditions that can occur in parts and materials due to the load, shock and vibration conditions a device is expected to endure. The results are evaluated against the material properties and strength capabilities of the device (i.e. yield strength, creep resistance etc.) to determine the loading factors that can overstress the design to cause a failure. After the destructive stress conditions are known, the design can be optimized and analytically validated as able to support the loads. Finite Element AMS tools are used to determine structural stress, strength and behavior. Stress analysis and management is a vital cost, mass and QRD optimization skill as competition and rapidly changing technology results in smaller and lighter parts that must perform at higher stress and power levels.

Mechanical stress analysis is intended to involve and promote communication for effective mechanical packaging design among product engineers, circuit board E-CAD layout designers, packaging engineers/designers and mechanical test engineers and mechanical analysts.

Mechanical stress models and simulations analysis tasks are:

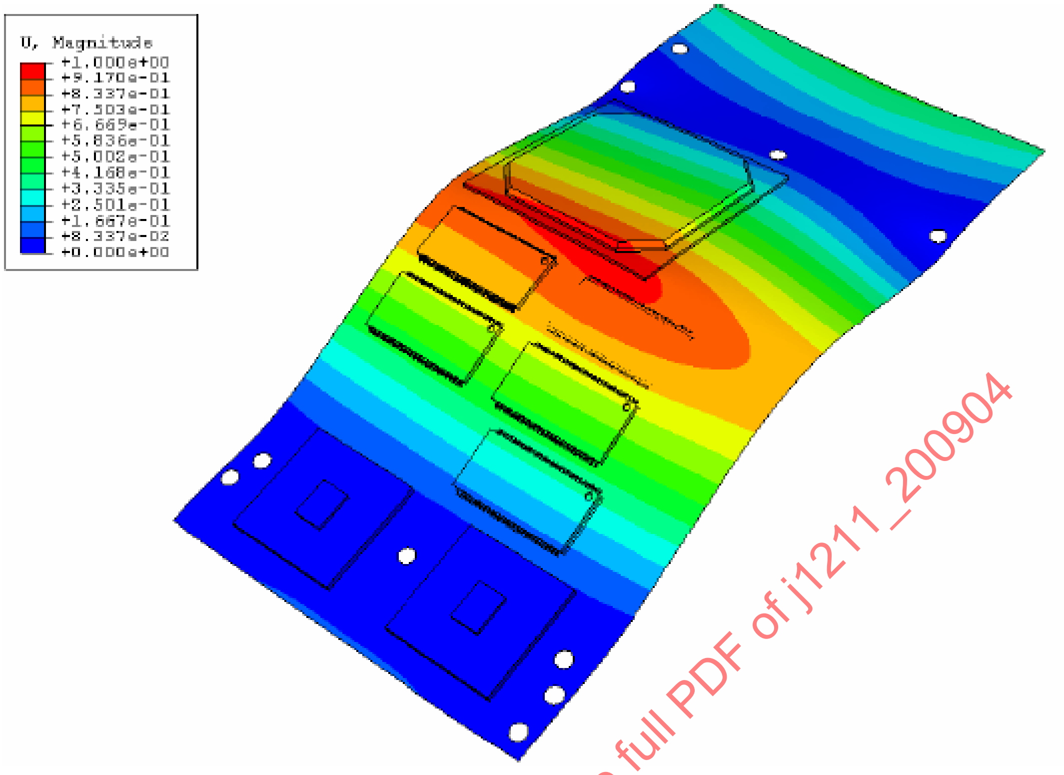
- Structural Load Analysis of Housings, Circuit Board Assemblies (CBAs) and other components.

- Snap Lock Fasteners Performance Analysis

- CBA Vibration Modal Analysis (see example below)

- CBA Shock Response Analysis

- Component Inertial Vibration Analysis.



EXAMPLE OF A CIRCUIT BOARD ASSEMBLY VIBRATION MODAL SIMULATION
Used to determine the first harmonic resonant frequency modal shape to identify the locations of peak bending stress (highlighted in red) and the stresses transmitted to components at those locations.

FIGURE 18 - EXAMPLE PCB ASSEMBLY VIBRATION SIMULATION

8.6.5 Thermal Stress Analysis

The purpose of the thermal analytical stress AMS tasks is to determine the effects of power dissipation self heating on the E/E module. The results of these analyses can then be used as inputs to the durability models and simulations see Figure 15. Combining the results of the durability analyses with experience gives an early indication of the suitability of the initial design to environmental conditions.

Thermal models and simulations are used to predict the maximum temperature of the module and the temperature of its individual components, due to internal heating, when subject to various electrical power and usage loading conditions combined with the external environment heating conditions in the locating where the module is mounted in the vehicle. Thermal AMS is recommended to be performed under the following conditions: Nominal Operation, Heavily Loaded, Worst Case Operation, and Short Circuit. The results of the electrical power modeling can be used as inputs to the thermal stress models.

Thermal stress models and simulations analysis tasks are:

- Power Dissipation Self Heating Simulations.
- Wire / Circuit Trace Thermal Analysis.

8.7 Durability and Reliability Analysis

After the stress conditions are known, the long-term effects of stress endurance that causes gradual degradation or wear out conditions in the materials of a device can be modeled to evaluate the wear out related durability and reliability of the design. Models of wear out failure mechanisms are based on the Physics of Failure concepts of stress driven damage accumulation in materials that continuous or cyclical exposure to stress/ strain cycles causes incremental amounts of damage accumulation in the material that endured these stresses. Gradually molecular breakdown eventually produces wear out failures mechanisms" (such as fatigue, delamination, creep, corrosion etc.).

Determining the durability time period until wear out failures occur becomes a function of calculating the ability of the strength-strain relationship of the materials in design features to resist degradation due to the strength and frequency of exposure to stress loading conditions via the use of Physics of Failure models and simulations. Often stress, strength and durability evaluations may be combined into a single modeling tasks. The primary concern is calculating the time to first failure for the weakest part or material (due to variation effects) that is exposed to the highest or most frequent stress loading conditions. This worst case time to first failure in modeling the failure rate for a theoretical variation profile of a population of parts can be modeled via Monte Carlo simulation to determine reliability performance of the design.

NOTE: Manufacturing and fabrication quality errors can weaken a product, this can degrade the durability and reliability capabilities of even a highly optimized design. Durability and reliability modeling of a proposed virtual design is performed with the assumption that the parts will be correctly built and fabricated in accordance with the expectation of the designer. The PoF Durability Simulation Models are unable to predict what kind of manufacturing errors could be inflicted on a design as it is built and what their outcome might be.

Therefore total product robustness also requires that after a capable, robust design had been developed and validated an equal effort needs to be applied to developing a capable and consistent manufacturing and assembly processes. Issues of manufacturing robustness and quality are covered in Section 10.

The physics of durability / reliability models that can be performed in conjunction with stress modeling tasks are:

- Circuit Board Excessive Flexure Analysis.
- Drop Endurance Simulations
- Circuit board Assembly Vibration Modal Fatigue Analysis.
- Shock Fracture Durability Analysis
- E/E Component Vibration Fatigue
- Thermal-Mechanical of Thermal Shock Cycling Fatigue Durability Analysis.

8.8 Physical Analysis Methods

In additions to math based AMS methods, there are also a number of physical material analysis techniques that can be applied later in the product development process to verify that the physical realization of a new device meet the design expectation for materials and assemblies quality and to verify that the devices are being produced without defects or susceptibilities to certain failure mechanism. These direct quality assessment (DQA) methods can be performed rapidly and without the need for environmental stress testing. They are:

- Metallographic Analysis of Soldering Quality.
- Ion Chromatography of Evaluation of Circuit Board Cleanliness.
- Modal Characterization of Circuit Board Vibration Responses.
- Thermal Evaluation by Infrared Imaging.

9. INTELLIGENT TESTING

9.1 Introduction and Motivation for Intelligent Testing

Intelligent Testing is a new testing approach for EEMs. It is implemented considering the Robustness Validation process philosophy from start of development till the end of production. The aim of Intelligent Testing beyond basic validation of the EEM for automotive suitability is to identify the robustness margin early in the development phase. The results of Intelligent Testing activities are used to calculate the Robustness Indication Figure (RIF) defined in Section 11 of this handbook. In addition, the results of Intelligent Testing may be used for the production ramp up and the control of the production process (control plan, SPC, etc.) and for the definition of any periodic and/or change driven revalidation activities.

The new Intelligent Testing approach is knowledge based and

- Considers the application specific mission profile (see Section 6 Mission Profile).
- considers application, product and process technology specific failure modes (see Section 7 Knowledge Matrix)
- Is implemented by an EEM specific Robustness Validation Plan.
- Uses Test to Failure (accelerated testing potentially exceeding specification limits) with final analysis and assessment of results.

The Intelligent Testing approach requires a change of mindset as well as strong communication throughout the complete value chain. It defines not another “cook book” style test specification, but instead gives a general guideline on how to get comprehensive robustness information about the product. .

Not all information and knowledge related to the application of different acceleration models, or their calculation will be contained in this section. Topics of this complexity are beyond the scope of this handbook. Detailed information on these topics can be found in existing public literature (see Section 2 References).

9.2 Intelligent Testing Temple

In this section a temple as shown in Figure 19 is used as a visual aid to convey the concepts of Intelligent Testing. The three pillars of the Intelligent Testing Temple represent the three basic categories of tests in the Robustness Validation process:

- Capability testing
- Durability testing
- Technology specific testing

In general all three categories of tests are performed during all phases of development:

- Prototype Phase
- Design Validation Phase
- Product Validation Phase

The scope off tests is allocated to the three development phases, depending on the maturity of the product. Testing in the production ramp up and series production phase is an integrated part of Intelligent Testing, since the results of testing during the development phases are used to optimize the production control parameters. On the other hand the statistical information out of this phase is used to confirm Robustness Validation test results which have minimal statistical evidence due to limited samples quantities.

The implementation of the "state of the art" capability testing and durability testing, combined with failure mode and technology-specific testing, at the right time is the key for "Intelligent Testing" in the Robustness Validation process.

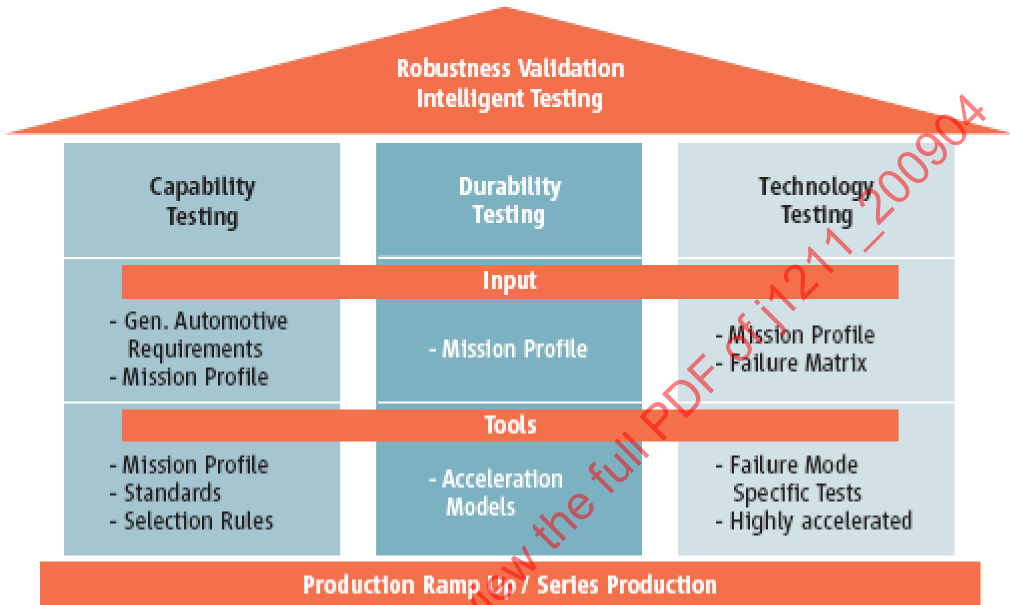


FIGURE 19 - ROBUSTNESS VALIDATION INTELLIGENT TESTING TEMPLE

9.2.1 Capability Testing

Capability Testing confirms the ability of the product to withstand specific stresses, thus verifying that the product is capable for such stress factors which are not related to any life time or durability factors.

These capability tests are typically defined in the vehicle manufacturer's requirements specification (based on mission profile) and should be performed as soon as possible for any new technologies, depending on the availability of test samples and maturity of the product related to this specific stress factor and failure mechanism. Design changes potentially affecting these capabilities may require that some tests be repeated (based on structured risk assessment). The scope of capability testing during any of the three development phases is shown in the temple of Figure 20.

For any well known product and process technologies, these capability tests should be performed with final product configuration during the product Validation phase for final confirmation.

Some examples for capability testing are:

- Flammability testing
- Water/ Dust protection
- Electrical testing (Over voltage, Reverse polarity)
- Drop test

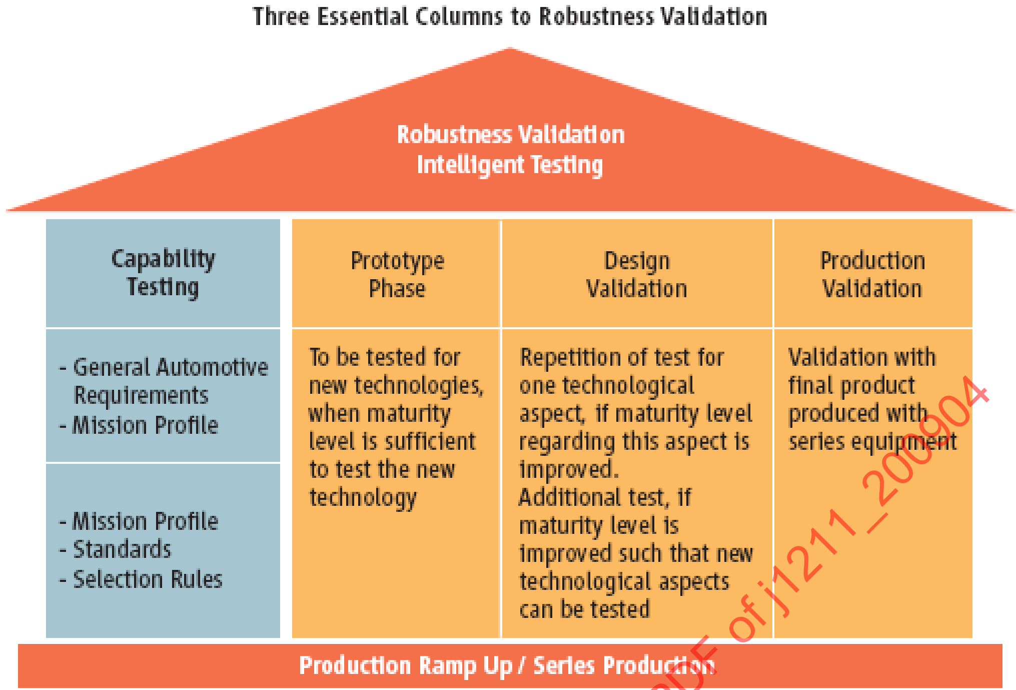


FIGURE 20 - INTELLIGENT TESTING TEMPLE: CAPABILITY TESTING

9.2.2 Durability Testing

Durability testing assesses how long the product is able to perform to specification when subjected to various stress factors. Durability tests can be performed using either a test-to-failure or a "success run" approach against specified end-of-test criteria. To make such Durability tests possible within a reasonable time frame, the stress factors can be set at accelerated stress levels which are based on mathematical models. For the most part, current test standards (definition of stress level and duration) utilize the success run approach, which means the target is to pass the tests without any failure.

The Robustness Validation approach emphasizes obtaining test-to-failure results during Prototype and Design Validation phases to identify the robustness margin of the product compared to the expected life. Despite this the success run test approach is still part of the Intelligent Testing process as final validation of conformance to Mission Profile conditions which is performed during the Production Validation phase to confirm the production (product/process) conformity and produceability and is the success point from which margin is measured. During the Prototype phase the existing acceleration models are enhanced to reduce the time for testing to get earlier and faster results for a robustness assessment. See Ref [2]. The applicability and accuracy of the acceleration models depends on many parameters and may only be valid for a limited stress level range. There is therefore a need for strong communication through the value chain to define test cases with high acceleration while avoiding the generation of failure mechanisms which are caused by the acceleration factors having no relevance to the field. Test results from the Design Validation phase are used for the calculation of the RIF. The scope of durability testing during any of the three development phases is shown in the temple of Figure 21.

Some examples for Durability testing are:

- High temperature Durability testing
- Power thermal cycling testing
- Mechanical Endurance test

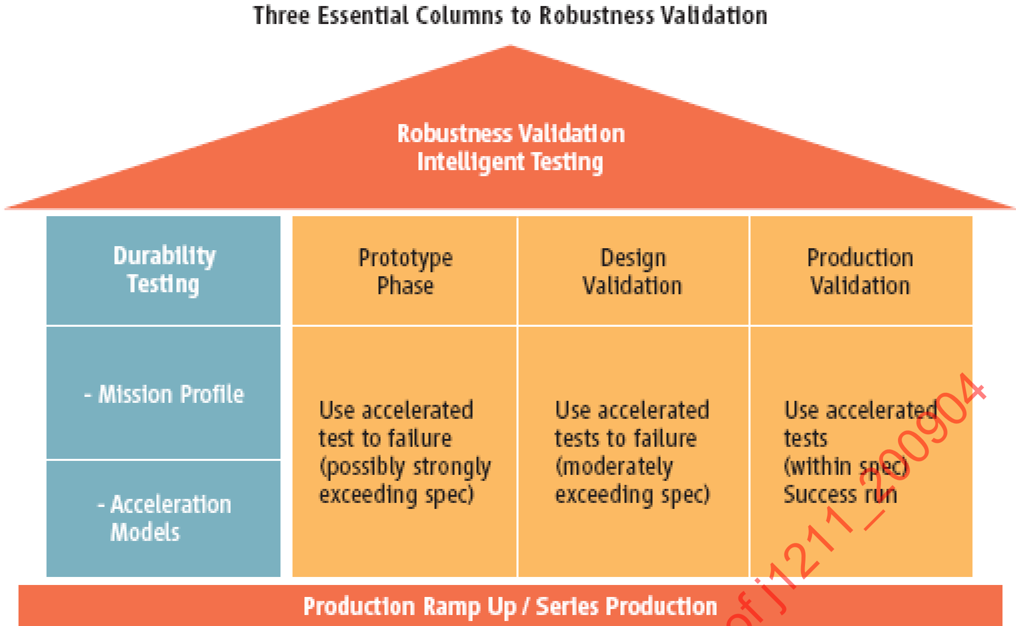


FIGURE 21 - INTELLIGENT TESTING TEMPLE: DURABILITY TESTING

9.2.3 Technology-Specific Testing

The aim of Technology-Specific Testing is to activate specific failure modes by applying specific highly accelerated test conditions. It is quite suitable to assess new product and process technologies regarding these specific failure modes in a short time. The technology specific tests are based on the Mission Profile and the Knowledge Matrix and should be performed as soon as possible in the prototype phase when the maturity of the product is given for the specific technology.

Test-to-failure (TTF), or testing to determine levels of degradation, is necessary to establish the suitability of a product for usage. During the product design phase, engineers rely on published data that identifies material and subcomponent limitations. However, the published data frequently includes undocumented safety margins. A module is a composite of many components and materials, each with their own safety margins. The only way to understand the strength and durability of a module is to increase stresses to determine what levels produce failures or unexpected operating modes. When these events occur, the recommended practice is to perform a root cause analysis to determine if there exists avoidable design or manufacturing issues.

Some stresses that can be used for TTF are:

- High and low steady DC voltage and current levels
- Transient voltages and currents
- High and low steady state temperature operation
- Thermal cycles and shock
- Humidity
- Mechanical random vibration, sine vibration, and shocks
- Exposure to environmental pollutants
- Customer usage cycles

During the Prototype Phase such Technology-Specific Tests are performed with very high acceleration factors in order to generate very fast, technology-specific failure mechanisms which are expected or which are critical based on the Robustness Validation test plan. These tests results show weaknesses of the product for specific technologies and failure mechanisms, with limited correlation to the field due to less accuracy or lack of the models for such acceleration factors. The HALT test method is an adequate test method for such Robustness analysis during prototype phase. During the Design and Production Validation phases such Technology-Specific tests shall be performed if the maturity level of these specific failure modes is changed. The scope of technology-specific testing during any of the three development phases is shown in the temple of Figure 22.

9.2.4 Production Ramp-up and Mass Production

During the production ramp-up phase shown as the base of the temple in Figure 19 through Figure 22 the results and experience gained from the Robustness assessments in the development phase are used to define production control plan parameters. In addition data gathered during ramp-up and Mass production allows the engineering team to validate the development results of robustness assessments with statistical evidence.

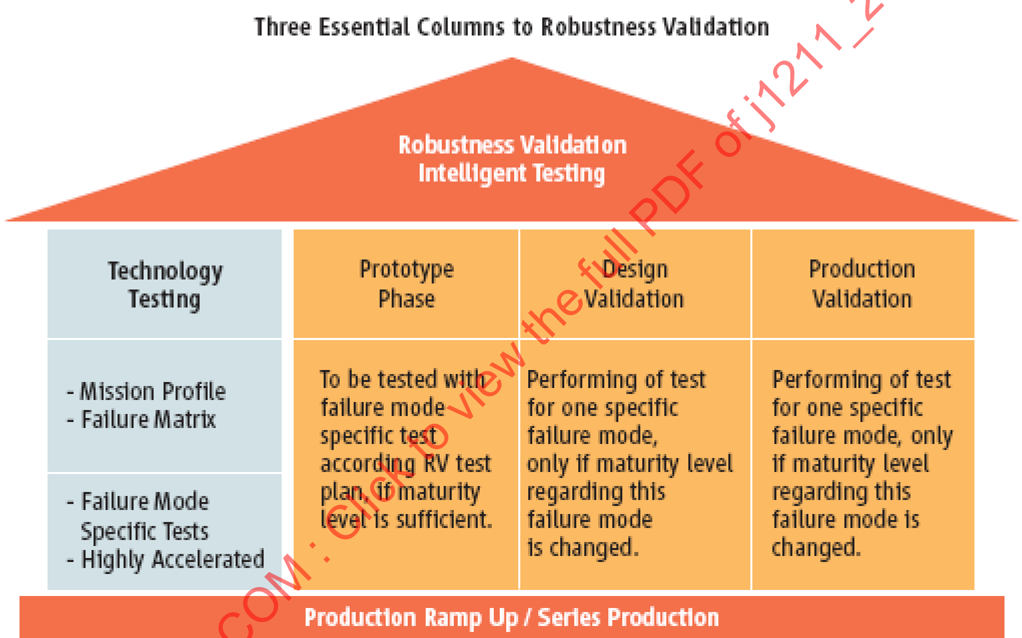


FIGURE 22 - INTELLIGENT TESTING TEMPLE: TECHNOLOGY-SPECIFIC TESTING

9.3 Assessment of Product Robustness in the Development Phase

9.3.1 Robustness Validation Plan Development

The first step during the Robustness Validation process is the creation of the Robustness Validation Plan during the concept phase. The Robustness Validation Plan defines all stress tests necessary to asses the suitability of the robustness of the product during development with respect to the Mission Profile. . An overview of the robustness validation plan development flow is shown in Figure 23.

The requirements are defined in the mission profile, normally described in the specification of the OEM. OEM and 1st tier supplier shall develop the Robustness Validation plan together to find a common understanding of the requirements in detail and to share their experiences.

The following sources of information can be used to help find the potential weaknesses of the product and can therefore be used for the creation of the Robustness Validation plan:

1. Mission Profile (see Section 6).

2. Knowledge Matrix: (see Section 7).

3. Assessment of New Sub Components: Special interest should be given to new (sub) components (e.g. microcontrollers or sensors). Criteria for (sub) components are similar to the above mentioned for the comparison of existing products.

4. Assessment of New Process - For new processes similar criteria apply as for existing products.

5. Comparison with existing products: If a product with a comparable technology in design, process and fused in a comparable mission profile is available, then experiences with this product shall be considered to reduce the effort for testing in the RV test plan. To assess the comparability between two products, the following criteria have to be considered in detail:

    - Product design (Materials, components, solders, adhesives, layout, etc)
    - Production process (location, production line, tooling, handling, process materials, etc
    - Mission profile for the comparable products
    - Quality level (requirements)
    - Load conditions (Thermal, current, mechanical, etc)
    - Test results
    - Maturity and release status

    Such comparison is also applicable on sub systems (e.g. the voltage supply part of a control unit). Comparative tests have to run under identical conditions. The repeatability of test procedures is a fundamental characteristic.

6. FMEA: The identified critical results of the Design, Process and System FMEA also provide input to the Robustness Validation test plan.

7. Analysis, Modeling and Simulation: Results of any simulations shall be considered for the creation of the Robustness Validation test plan.

All assessment results shall be considered to create the Robustness Validation Plan to define the right tests at the suitable point in time.

The Robustness Validation Plan should include amongst others:

- Phase: (Prototype / DV / PV)

- Intention of the tests

- Number of DUT´s

- Description of the tests (including. used acceleration models and factors)

- Assessment and acceptance criteria

The Robustness Validation Plan is intended to be a living document and should therefore be continuously reviewed based on the development progress, the product maturity level reached, and the test results. Strong communication is therefore needed between all involved parties. The DVP&R can be used to document all Robustness Validation activities, necessary for a complete Robustness Validation.

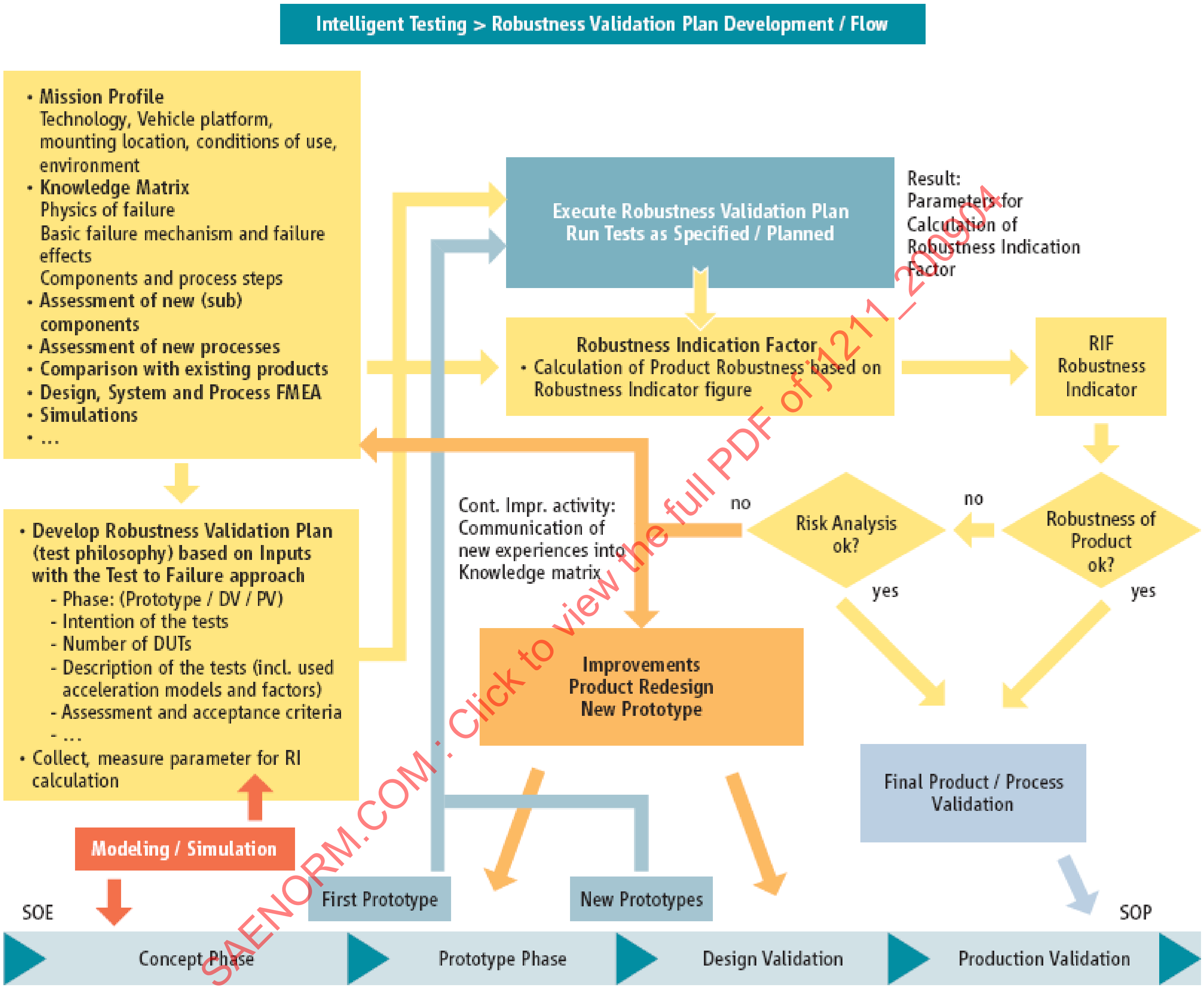


FIGURE 23 - VALIDATION PLAN DEVELOPMENT FLOW

9.3.2 Robustness Validation Testing

The actual stress testing in the Robustness Validation Process extends from the Prototype Phase to the Design Validation Phase and finally to the Production Validation Phase, and is done according to the Robustness Validation Plan created during the concept phase as described in this section.

The important aim of Intelligent Testing is to be able to describe the robustness of the product by means of robustness indicator figures and to verify the basic suitability of the product for use in a vehicle according to the defined mission life profile over the vehicle lifetime.

9.3.2.1 Prototype Phase Testing

To achieve these aims, testing during the Prototype Phase focuses on identifying potential weaknesses and on improving the product maturity rapidly with respect to these potential weaknesses in short development cycles. Especially new technologies, materials and (sub)-components should be tested in this early stage of development to see if these new technologies, materials and parts provide special weaknesses for the complete product.

Potential weaknesses can be identified by stressing the product to failure, then analyzing the occurring failures and improving the robustness towards the occurring failures. Since it is very important during the prototype phase to realize fast improvements, the time for stressing the product until it fails is very limited. This is why highly accelerated stress tests are to be used during the Prototype Phase either by strongly increasing the stress level of a test e.g. the temperature delta of a thermal shock test or by using multiple kinds of stress e.g. temperature, humidity and vibration either simultaneously or in sequences.

These highly accelerated tests are especially suitable to simulate one special failure mode e.g. a failure mode being related to a new technology used (failure mode specific testing). The information contained in the knowledge matrix should be the basis for choosing suitable highly accelerated test conditions for special technologies, materials or designs. By increasing the stress on the DUTs, failures could be easily generated on the one hand, but since these highly increased stress levels usually exceed the stresses occurring in real field use by far, special attention must be used on the other hand when analyzing and interpreting the generated failures.

The failure analysis results must be carefully assessed to distinguish between failure modes caused by an exaggerated high test stress level that is exceeding basic physical limits of a DUT, for example, increased temperatures during test causing the used solder materials to melt, or failure modes that show real weaknesses of the product especially deterioration and wear out. A broad range of specialists should therefore be involved in the assessment of the failures.

The reduction of test times by increasing the test stress level provides the ability to repeat tests with modified DUT´s rapidly, thus allowing engineers to judge the effect of any modification quite fast.

The second method for identifying potential weaknesses of a product quickly is the use of comparative test with highly accelerated stress levels. With these comparative tests, newer samples can be tested versus older samples showing the effectiveness of the improvements. Known good products (e.g. from series production) can be tested and compared to new products. This helps to assess the relevance of failures which have occurred. If the new product fails at lower stress levels or earlier than known good parts, improvements are usually necessary, especially if the failure occurs with new technologies or materials. On the other hand, if the new products tend to fail after the known good parts it is likely that the new product is at least as robust as the existing one.

It should be noted that even with successful comparative testing, the correlation between the stresses in field use and the highly increased stresses used for highly accelerated testing is usually very poor. It is therefore usually necessary, in order to make accurate statements regarding the automotive suitability of a product for field use or statements regarding the robustness of a product, that further tests need to be performed.

9.3.2.2 Design Validation Testing

It is desirable to verify conformity to a customer specification on the one side and get end-of-life information within reasonable periods of time on the other side, to achieve this it is a good practice to perform the tests during the Design Validation Phase with stress level only moderately exceeding the DUT's specification stress levels. Exceeding the physical limits of a DUT must be avoided.

Design Validation Testing is generally performed at stress levels at or only very moderately exceeding the specification of a product, so it is possible to find a test-field correlation by the suitable acceleration models. Since the robustness limits of a product can only be determined based on the test time that is necessary to cause the DUT to fail, all tests during the Design Validation Phase shall be performed as test-to-failure tests.

For the Robustness Validation Approach, the tests during the Design Validation Phase are most important, since the results of these tests are the basis for the calculation of the wear related Robustness Indicator Figures (RIF).

9.3.2.3 Production Validation Testing

The aim of the Production Validation Testing is to validate the product produced with series equipment according to the customer specification and the agreed Mission Profile. Since all weaknesses in the design of the product should have been found and resolved during the Prototype Phase and the Design Validation Phase, the Product Validation Tests are expected to be successfully performed on first run.

Successful Production Validation Tests rule out unexpected systemic failures, failures caused by late design changes (that should be avoided anyway) and production related failures. To avoid the risk of generating failures without field relevance, all test conditions should be within the design limit specification of the product. This limits the possibilities to accelerate the necessary test times according to the used acceleration models and may jeopardize the time schedule. If necessary, the vehicle manufacturer and the module supplier could define acceptance criteria for pre-releasing a product (for example after 75% or 85% of the Product Validation Tests has been performed without problems) based on an agreed risk assessment.

After successfully completing the Production Validation Testing the suitability of the product for automotive applications and the desired robustness levels are generally confirmed. Statistical information from production ramp-up and series production can then be used to validate results on a statistically significant basis.

The supplier needs to alert the vehicle manufacturer if the full production validation can not be completed. The PV risks can then be assessed using the robustness validation results.

9.3.2.4 Statistical Validation of Robustness Assessment Results

The increasing number of test samples available during production ramp-up allows a statistical analysis of the critical parameters found during the Robustness Assessments performed during development. This data can be used to validate the Robustness results from all development tests on a statistical basis as the final step of the Intelligent Testing process. For example ICT or EOL Test results. See Section 10.

9.4 Retention of Robustness during the Production Phase

Besides the product-independent process validation results, the results from all product-specific robustness assessments during Design and Product Validation should be considered to ensure that all identified critical parameters will be accounted for in the production control plan and may be monitored by statistical process control (SPC). In addition, 100% monitoring of identified critical parameters of end-of-line data should be analyzed for drifts and anomalies. See Section 10 for further details

In the event that there are product and/or process design changes a re-validation should be defined and performed according to this Robustness Validation process. In addition, a review should be performed annually to determine the necessity for re-validation activities. If a re-validation is found to be necessary, the revalidation should be completed according to the Robustness Validation Process defined in this handbook.

Table 5 summarizes some key attributes of the Intelligent Testing Process versus a Traditional approach. The Intelligent Testing process has the potential in many programs to save validation cost-time while also being more effective at finding real issues in a time frame that allows sufficient reaction time. For example in some cases 50% reduction in test costs has been achieved. However, the most significant savings have been achieved in terms of total lifecycle costs (warranty costs, engineering redesign costs, liability risk etc.) through the use of the intelligent testing process versus the traditional approach in which these future costs are avoided.

TABLE 5 - GOALS COMPARISON OF TRADITIONAL VS. INTELLIGENT TESTING

Item	Description	Traditional Process	Intelligent Testing Process
1	Approach	Cookbook	Tailored test plan utilizing historical data, analysis and development testing to focus on potential product weaknesses and changes.
2	Surrogate Data	Varies	Maximize to reduce non value testing.
3	Cost, Test Time	Expensive, Long	Potential to reduce by 50% or more.
4	Effectiveness	Minimal	More effective. Aimed at contemporary issues Focused on what is unknown.
5	Test for Success	Majority of tests	Some but also generates variable data (test to failure or measuring degradation).
6	Sample Size	Large	Smaller, reduced facilities with the focus on what's needed to verify the unknown.
7	Monitoring	Limited	Continuous monitoring (allowed by smaller sample size)
8	Test Configuration	Artificial loads, minimal interfaces	Sub-system with realistic loads and interfaces (allowed by reduced sample size).
9	Time Compression where Possible	Not applied sufficiently	Example: Reduce dwell times on thermal cycling/ shock. Measure DUT board temp and set dwells to stabilization +5 minutes. Use surrogate data to only run the test required to verify the unknown.
10	EMC Testing	Done separately at room temp.	Supplemented by more realistic Conducted Immunity testing in Development Stage. Reference SAE J2628

10. MANUFACTURING PROCESS ROBUSTNESS AND ITS EVALUATION

10.1 Purpose and Scope

Manufacturing process robustness is needed to ensure that the work done to establish robustness during the design and development phases of a product life cycle is not eroded by the processes used to manufacture the product. It is necessary to have a knowledge and understanding of how, when and the significance of the issues that can occur during manufacturing which will reduce or affect the robustness of a product related to the mission profile or its' intended use.

Outlined in this section is a method to evaluate the degree of robustness or lack of robustness that can exists with a given or estimated manufacturing process. Defined and outlined is a matrix (CPI Matrix) to capture in a systematic manner this evaluation and to generate a Knowledge matrix for manufacturing processes from incoming material transport and handling to finished product shipping and handling.

10.2 EEM Manufacturing Process

There are many combinations of manufacturing processes that can be used for different products. Outlined in Figure 24 is a typical manufacturing process for a typical EEM, for demonstration purposes, the users of RV will need to adapt the examples used here to their own particular product manufacturing processes.

Current typical EEM's are manufactured with a double-sided reflow process, with solder paste printing, component placement and solder reflow followed by some back end processes to complete the product for components that cannot be assembled with standard Surface Mount Technologies (SMT).

The following example shows one possible manufacturing process flow to demonstrate how complex it can get and to give some background for the later discussion. Please note that the implementation and use of the mentioned testers are also just for example.

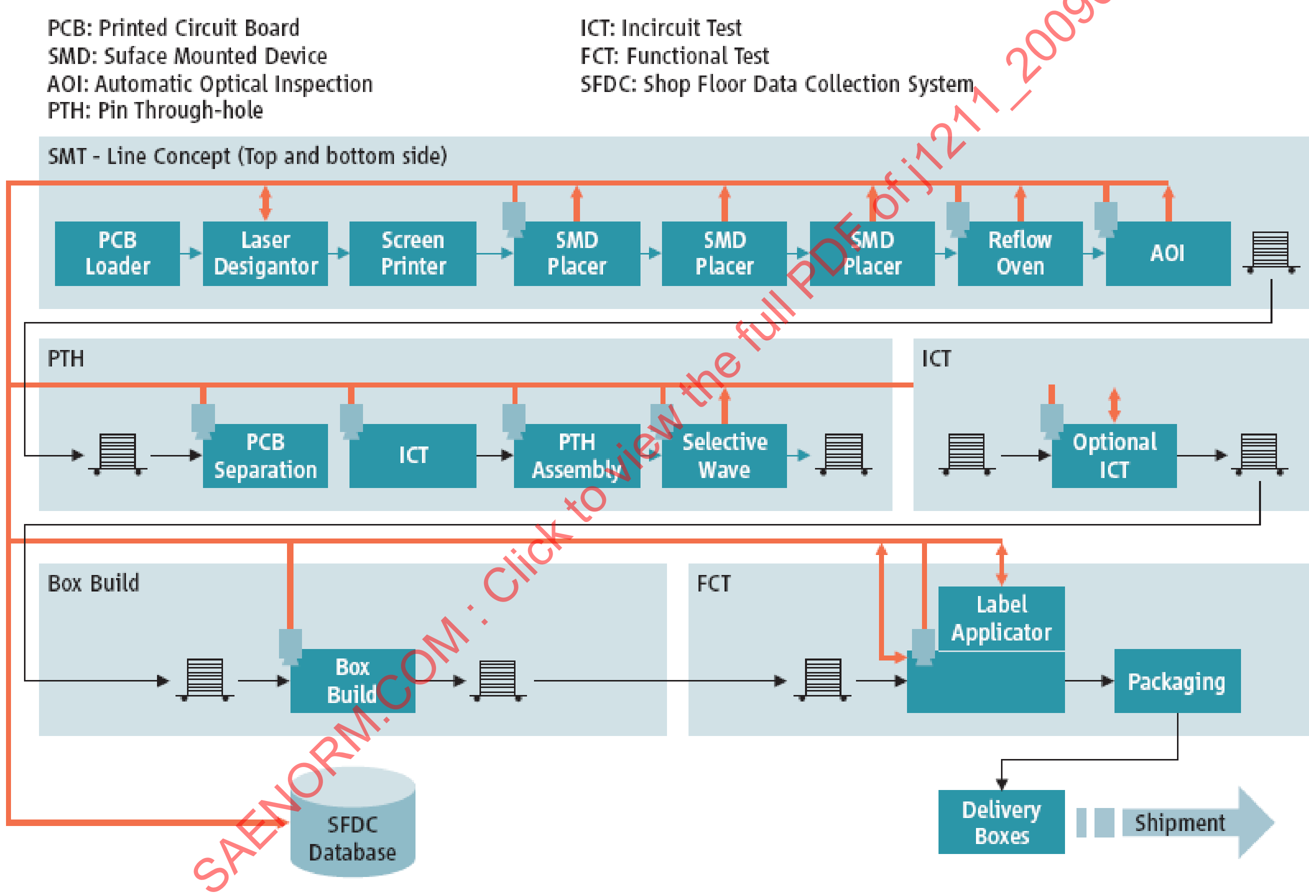


FIGURE 24 - TYPICAL EEM MANUFACTURING PROCESS

Please note that there may be new or additional product or process requirements not included in this example that must be considered, like conformal coating or sealing which may need to have some specific or special attention. Generally, there is no standard process – there is just standard equipment or tools which need to be setup in a manner which supports the Zero Defect Strategy [21].

Please note that special care is needed in the use of the ICT as they can sometimes have a negative impact on the EEM. This means that before a particular tester or equipment is used, all the positive aspects (e.g. test coverage increase) have to be balanced against the negative ones (e.g. electrical overstress, mechanical damage).

As you can imagine there are many possible combinations and interactions between the manufacturing processes used to manufacture a product the product design and the components used in a product. A typical manufacturing process is made up of many sub processes, each with their own variations and interactions. The intent here is to evaluate the interactions and noise variations caused by different material lots, equipment status, etc to ensure that the manufacturing windows can be as wide as possible. This will assure the minimum amount of Robustness erosion by getting the manufacturing process right the first time and to keep it sustainable over the product lifetime.

The following example in Table 7 shows one case where these interactions are demonstrated

EXAMPLE: reflow soldering / component interaction

Demonstrates:

– flux influence
– component influence
– solder joint influence

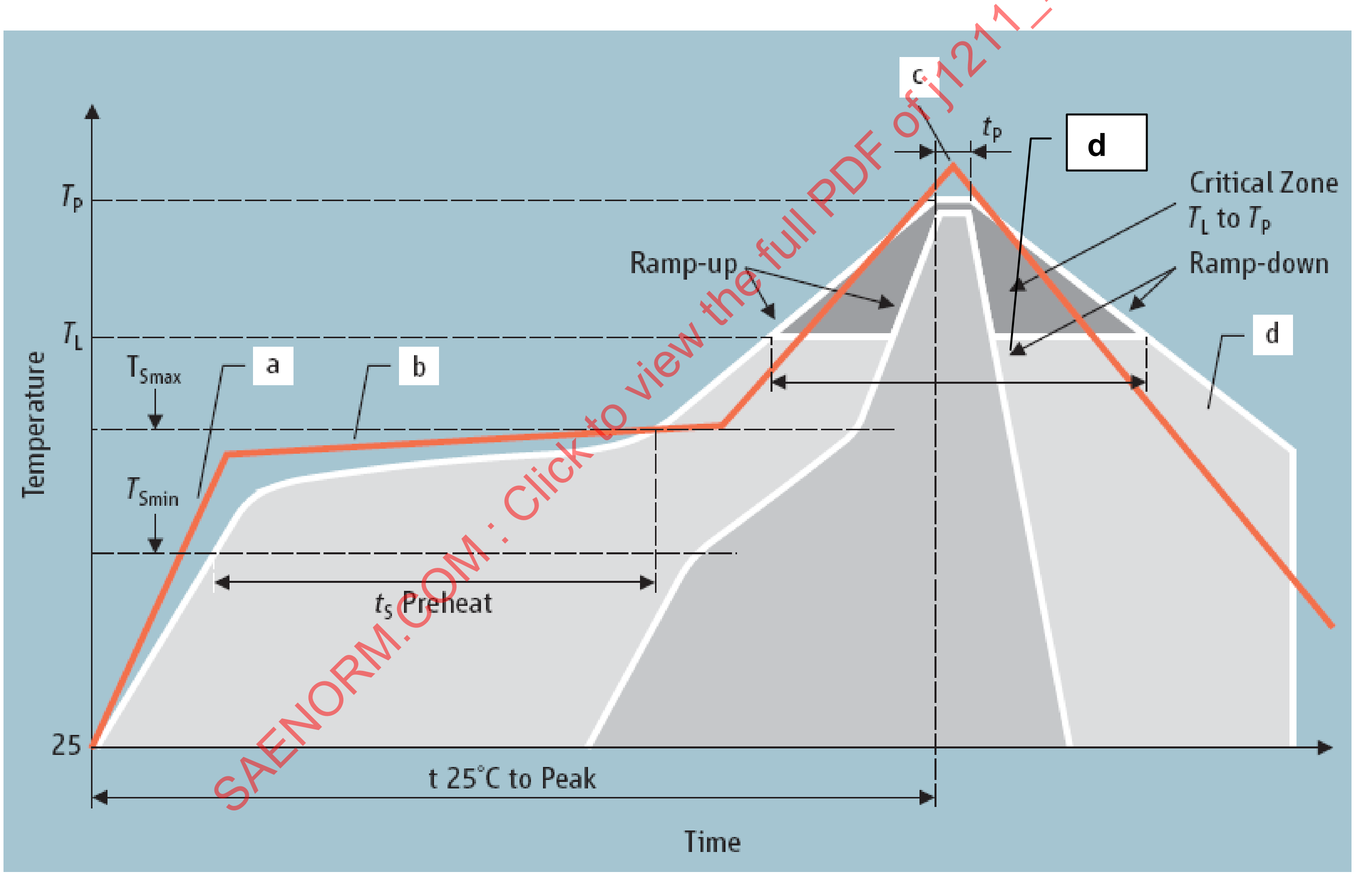


FIGURE 25 - TYPICAL SOLDER REFLOW PROFILE

Figure 25 shows a typical reflow soldering profile and the JEDEC J-STD-020 MSL classification profile which defines the border lines between user application (manufacturing) and qualification at the component manufacturer. The manufacturing process has to stay within the grey border profile as recommended by the component manufacturers or paste providers.

The red line shows an arbitrary profile with the following potential failure modes:

a. Ramp up too fast = Risk for thermal stress cracks in components

b. Ramp up to a too high soak level: =_Risk for premature exhaustion of solder flux = poor solder joint

c. Too high peak temperature / too long time at peak =_Risk for delamination, cracks, pop corning, and other thermal overload damage

d. Ramp down too fast = Risk for solder joint voids or weak solder joints.

In this section we outline a method to systematically evaluate and capture these interactions.

10.3 Robust Process Definition

Process:
A Process is any repeatable activity within an organization with the target of supporting a specified product or service. This may also include internal and external services and locations as well as logistics and packaging. It must havea defined input and output as well as a defined flow.

Robust Process:
A robust process is a process or sub-process which does not negatively affect the parameters of its output or consumes any of the robustness of its inputs. This requires processes which keep their parameters inside the setup limits under all noise factors and varying conditions.

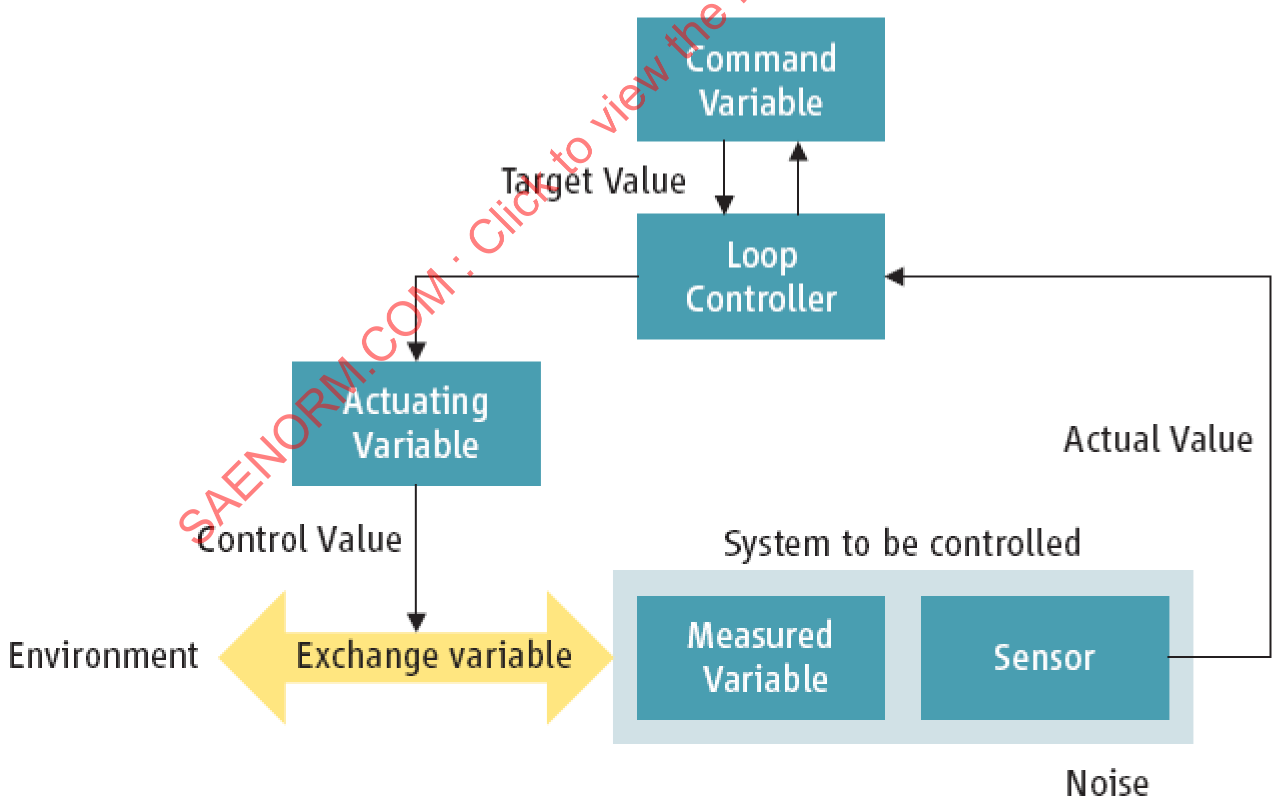


FIGURE 26 - CONTROLLED PROCESS

The Typical EEM manufacturing process in Figure 26 contains many control loops. The target is to optimize for each individual parameter the control deviation and to look always for a negative control.

The next challenge is to look also to all interactions or interrelations between the different process steps to optimize and assure that stable negative feedback loops are in place not only individually for each sub process but for the whole manufacturing system.

To get an understanding of the complexity involved a simple example can explain the case:

- A component is placed on a PCB and should be soldered with a reflow oven. The data sheet of the component specifies the basic soldering conditions, such as maximum temperatures, max temperature ramp up and down rates, maximum time and so on. As long as the reflow profile is within the specified component limits, a process is called robust against this specific material condition. If however the process parameters drift up to the component specification limits or if they exceed the specification, the process may negatively affect the component by damaging it.

It should be easy to stay within the component specification limits. However but taking into consideration that there is not only one component on the board and there are also other influences like solderability or wettability of the component and the recommended profile of the solder paste to comply with respect, the unidirectional picture becomes a multi-dimensional one and as a consequence the process parameters have to respect all of the component specifications of all of the components used.

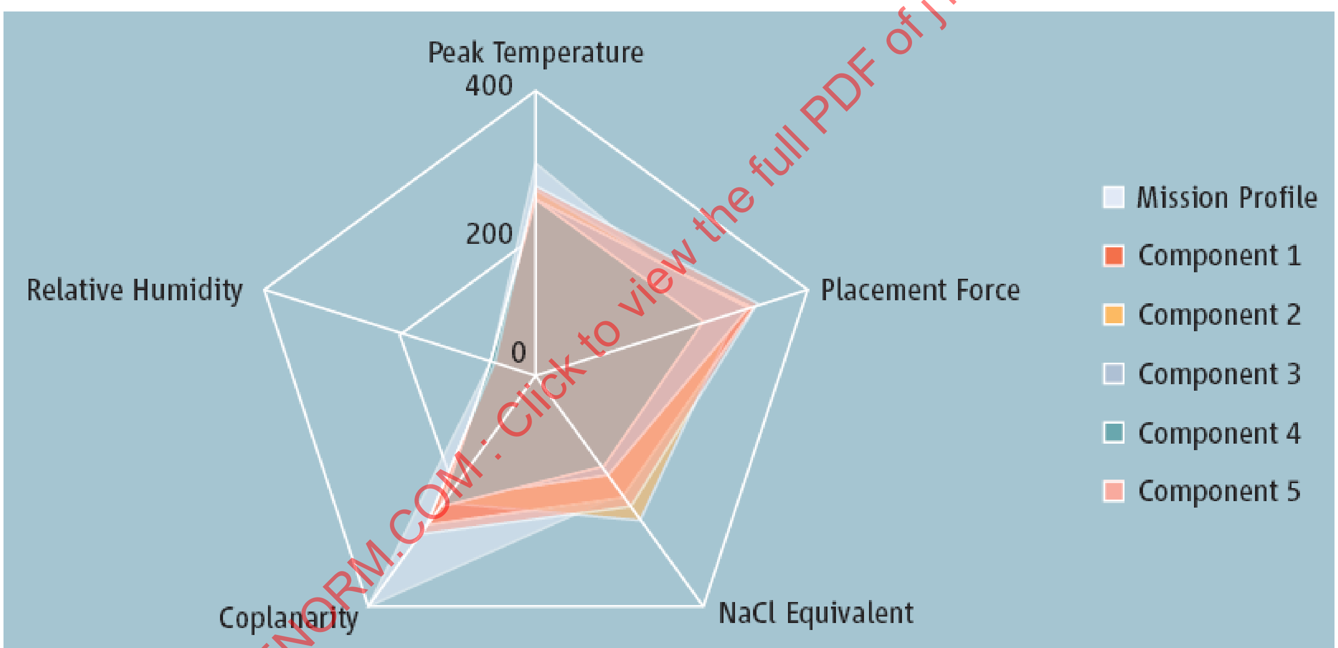


FIGURE 27 - EXAMPLE ROBUSTNESS FOR COMPONENT CHARACTERISTICS

Figure 27 shows the comparison of all mission profiles to the basic mission profile of the EEM. All areas where no blue space is seen are potentially critical.

10.4 Process Interactions

There can be an almost infinite number of interactions between all the variables in a complete manufacturing process. However in this section we consider the main interactions between components and process this can be characterized by a matrix of four quadrants as shown in Figure.

- Materials on Materials Q1-1
- Materials on Process Q2-1
- Process On process Q2-2
- Process on Materials Q1-2

In this section we will focus on the quadrant Process to Material Q2-1 to demonstrate the concept.

Component Process Interaction Matrix			Material	Process
			Subgroups	Subgroups
			Attributes	Attributes
Material	Subgroups	Attributes	Q1-1	Q1-2
Process	Subgroups	Attributes	Q2-1	Q2-2

FIGURE 28 - COMPONENT PROCESS INTERACTION MATRIX

10.5 Component Process Interaction Matrix

The Component Process Interaction Matrix is a tool which allows the evaluation of critical attribute interactions, the CPI – Matrix (Component – Process – Interaction – Matrix).

- CPI Matrix is a four quadrant matrix which shows interactions between Components and Processes in different directions.
- This section shows two directions with the focus on Process ➔ Material
- The basic concept is to combine methods like QFD (Quality Function Deployment), FMEA (Failure Mode and Effects Analysis) and DFM/DFT (Design for Manufacturability and Testability) and to use the results in a direct synergy.

Extended use and scope of the matrix result

- Define and get acknowledged potential random failures as a combination between the matrix factors and characteristics.
- Evaluate potential individual risks which are latent or intermittent restricted to certain failure modes.
- To localize these failure modes and to ultimately transfer them into the knowledge matrix.

The following sections show how to create it and to use it with a general scope and finally how to transfer the structure to individual projects.

a. Matrix Template Structure

The matrix structure is as shown in Figure 28 used in the example CPI Matrix and is derived from the QFD (Quality Function Deployment) matrix.

The matrix design includes 4 quadrants with the basic direction from rows to columns. These are marked in different colors, as shown above. In general it can be used to evaluate relationships in all directions. The focus is from *MATERIAL source to Material and Process* or from *PROCESS source to Material and Process* - but both are also possible together. As a minimum evaluation it is also possible to use just one quadrant of the four by always respecting the row – column directions.

In total the matrix can generate more than 60.000 direct and individual attribute relations which are assigned by ranking numbers. The original file with an example of the working group can be downloaded from the SAE website at http://www.sae.org/standardsdev/robustnessvalidation/km.htm as well as a working file for individual use. The assessment and the mentioned numbers are only examples and can be used as the basis for starting your own Evaluation but are an example evaluation only. It is the responsibility of the user of RV to generate and evaluate their CPI matrix from their product and process experiences.

b. Basic Use

The example CPI matrix must be modified to the RV users needs. It is possible to add individual groups, sub groups or single attributes (the existing file is just a proposal based on the current knowledge and experience). This makes it possible to setup a project or product related scope and to evaluate all the interactions for the EEMs under consideration.

The use and the structure are not directly comparable to the FMEA or similar tools but the output could be used to construct an efficient FMEA. Due to the fact that the CPI Matrix goes down to the detailed attributes it should be evaluated before the FMEA and used also as a living document.

The focus of the matrix is mostly on the random / non systematic failures. The systematic ones are considered in the Knowledge Matrix in Section 7 but the aim is to transfer as much as possible over time from random to systematic once the failure mode and root cause becomes defined. This is strongly supporting a Zero Defect approach.

c. Result Expectations

The final output of the CPI Matrix will show the detailed interactions of the individual parameters in a ranked format. With this Pareto type of presentation the user will see the most significant interactions or relationships according to his ranking of the attributes. This will allow him to assess the relative risk of not meeting the robustness requirements.

For the critical attributes it is recommended to go more into detail and assess further sub attributes not already contained in the matrix. By applying this kind of filter the scope is focusing more and more on the most critical interactions and therefore supporting the elimination of the any remaining random / non systematic failure risks. This learning curve will then allow a transfer of random / non systematic failure modes to the systematic root cause which can then be added to the Knowledge matrix.

10.5.1 CPI Matrix Development

As we are considering Process and material interactions to start the development of the matrix we should consider the main process steps and components which are involved in the EEM under Consideration. A typical but non exhaustive list could be as follows in this section. The RV user must generate their own lists and they form the rows and columns of the matrix.

The process for CPI Matrix creation is

1. Generate a list of process steps
2. Define the significant attributes for each process step
3. Generate a list of Components
4. Define the significant attributes for each Component
5. Assign Attribute Weight Factors for each Attribute defined in steps 2 and 4
6. Assign level of interaction factors for each attribute defined in steps 2 and 4
7. Create pareto of interaction factors and determine actions

10.5.1.1 Typical Main Process Steps (process categories)

1. Component logistics
   - component design qualification
   - specification of the different components
   - component incoming quality
   - component kitting / setup
   - PCB / component handling
2. Front-end Assembly
   - solder paste printing
   - glue printing
   - component placement
   - reflow soldering
3. Backend Assembly
   - manual assembly
   - press fit
   - wave soldering
   - selective soldering
   - depanelisation
   - final assembly
4. Testing
   - Automatic Optical Inspection, Automatic X-ray Inspection, In Circuit Test, Burn in, Run in, Boundary Scan, Flying probe
5. Maintenance
   - Actual and preventive taken together
6. EEM Logistics
   - Packing, Packaging and shipping / transport

10.5.1.2 Process Step Attributes

For each process step identified in 10.5.1.1 above a sub-list of the significant thermal, electrical, chemical and mechanical attributes that impact the robustness of the final product should be generated from the following sources:

1. Field data (product performance)

2. FMEA (design, product, process)

3. Risk analysis

4. Knowledge matrix / data base

5. Process performance data

6. Industry standards

7. Internal monitoring and screening

An example of a process step attribute list relating to the attributes influencing environmental factors for solder paste printing is shown in Table 6:

TABLE 6 - PROCESS STEP ATTRIBUTES - SOLDER PASTE PRINTING

Attribute	Thermal	Chemical	Mechanical	Electrical
Stability of environmental parameters (e.g. humidity, temperature)	x	x		x
Solder paste material		x		
Printing type			x	
Stencil type (Laser cut, Electro Formed,)			x	
Stencil thickness			x	
Cleaning cycle		x	x	
PCB support			x	
Printing shape			x	x
Hole filling (pin in paste)			x	x
Pad overprinting			x	x
Stencil use time			x	
Paste use time		x	x	
Pump cleaning		x	x	

10.5.1.3 Typical Component Contents

a. Main component groups

- Passive
- Active
- Interconnection
- Electro mechanical
- Housing
- Consumables

b. Component sub groups

- Passive
- Active
    - Hermetic
    - Non Hermetic
- Electro mechanical
- Interconnection
    - PCB
    - Cables
    - Connectors
- Housing
    - Plastics
    - Metal

10.5.1.4 Component Attributes

For each component group in section 10.5.1.3 a sub-list of the significant thermal, electrical, chemical and mechanical attributes that impact the robustness of the final product, should be generated from the following sources:

1. Component Data sheet

2. PPAP

3. Component questionnaires

4. FMEA (design, product, process)

5. Risk analysis

6. Knowledge matrix / data base

7. Process performance data

8. Industry standards

9. Monitoring and screening

An example of a process step attribute list relating to the attribute's influencing environmental factor for a printed circuit board (PCB) as a component is shown in Table 7.

TABLE 7 - COMPONENT ATTRIBUTES - PCB

Attribute	Thermal	Chemical	Mechanical	Electrical
PCB surface finish		x	x	x
Substrate material	x		x	
Solder mask		x	x	
Warpage			x	
Pad design			x	x
Through hole plating			x	x
Contamination		x	x	x
Delamination and track open			x	x
Via outgasing	x	x	x	
Wetability	x	x	x	x
Solderability	x	x	x	x
Etc.				

10.5.1.5 Template of Full Matrix (4 quadrants matrix)

Component Process Interaction Matrix			Material	Process
			Subgroups	Subgroups
			Attributes	Attributes
Material	Subgroups	Attributes	x	x
Process	Subgroups	Attributes	x	x

FIGURE 29 - COMPONENT PROCESS INTERACTION MATRIX EXAMPLE

The Component Process Interaction Matrix (CPIM) shows the interaction between each main group (e.g. Process ➔ Material). The target is to see the correlation between each individual attribute and how it impacts the robustness of the product. Emphasis can be put over all or special quadrants or upon request on a specific quadrant(s).

For example, one possible focus may be the process and how the process attributes impacts the material attributes (given BOM – Bill of Material / AVL – Approved Vendor List).Following the "Zero Defect Strategy" and being able to have an early involvement in the design phase, the reverse direction should also be evaluated.

10.5.1.6 Attribute Weight Factors (Importance indicators)

To enable the generation of a pareto a linear weighting of

1 – Low importance
2 – Medium importance
3 – High importance

(Other weighting models are possible) is given to each attribute

The example CPI Matrix has weight factors assigned by experience consensus. This should be modified or adjusted and should be aligned with the individual process of each RV user. The example weightings are intended as guidelines.

10.5.1.7 Level of Attribute Interaction

To enable the generation of a pareto a linear weighted ranking of

0 – No interaction
1 – Low interaction
2 – Medium interaction
3 – High interaction

– A special value to express individual concerns (this should only be used for special cases – not for a regular weighting)

(Other weighting models are possible) is given to each attribute. Special values to express individual concerns (3.1) should only be used for special cases and not for a regular weighting.

In the example CPI matrix, the rating is assigned by experience and consensus of the working group. This should be individually modified or adjusted and should to be aligned with the individual process of each user. The example weightings are intended as guidelines.

This methodology is similar to the FMEA (RPN) procedure.

10.5.2 CPI Matrix Assessment of Interactions

	CPI-Matrix Date: 2007-xx-xx	Tabel summa describes the interdependency between one material factor to all processes -press "copy row" button to copy rows to column -press "sort" button to sort acc. special / attributes -to change assessment from 80/20 use cell D5 Sort copy row		Connectors	Consumables	Consumables	Passive components	Passive components	Passive components	PCB	PCB	PCB	AOI post reflow	AOI post reflow	Component placement (automatic)	Component placement (automatic)
	Requirements	Ranking: 0 to 3		retention force - C	Solder paste - Cons	Flux material - Cons	Substrate (mechanical stability) - PC	Termination - PC	Wetability - PC	surface finish - PCB	substrate material - PCB	pad design - PCB	Camera resolution	Camera angle	placement force	component size / weight
		Weighting factor (1-3)														
Process	AOI post reflow	Camera resolution		0	0	0	0	0	0	0	0	0	0	0	0	0
Process	AOI post reflow	Camera angle		0	0	0	0	0	0	0	0	0	0	0	0	0
Process	Component placement (automatic)	placement force		0	0	0	0	2	0	0	0	0	0	0	0	0
Process	Component placement (automatic)	component size / weight		0	0	0	0	0	0	0	0	0	0	0	0	0
Process	FCT	Contact force		0	0	0	0	0	0	0	0	0	0	0	0	0
Process	FCT	Warpage		0	0	0	3	0	0	0	2	0	0	0	0	0
Process	PCB / Component handling	ESD - comp-hand		0	0	0	0	0	0	0	0	0	0	0	0	0
Process	Reflow soldering (convectional oven)	Temperature profile in general		0	2	2	0	1	0	1	2	0	0	0	0	3
Process	Reflow soldering (convectional oven)	temperature ramp rates		0	1	1	0	2	0	0	0	0	0	0	0	1
Process	Reflow soldering (convectional oven)	solder balls		0	0	0	0	0	0	0	0	0	3	2	0	0
Process	Solder paste printing	cleaning cycle		0	0	0	0	0	0	0	0	0	0	0	0	0
Process	V-scoring	V-score depth		0	0	0	2	0	0	0	2	0	0	0	0	0

FIGURE 30 - LEVEL OF INTERACTION WARPAGE

For each intersection of the matrix the level of interaction needs to be assessed using the criteria defined in 10.5.1.7

For example using Figure 30

Functional Test – Warpage → Substrate (mechanical stability) passive component is evaluated with a 3 (High Interaction) because the bending stress of the Functional Tester has a high impact on the Substrate (mechanical stability) of passive components.

10.6 CPI Matrix Calculations

To enable the sorting and prioritizing of the interactions the weighting and interaction levels are used to create an assessment number similar to the FMEA RPN number

a. Row calculation
   The row sums of all attribute interactions multiplied with the weighting factors show the over all importance of the component or process to all other selected characteristics or attributes.

b. Sorting
   The sorting of the line sums show the importance of the individual process or component importance.

c. Selections
To mark some attributes as specials it is possible to give them the value “3.1”. This ensures that they will be always on the top of the sorted list.

The most important attributes are can be specialized by applying e.g. the 80/20 rule. Individual parameter setting is possible.

d. View direction definition (e.g. effect of process on components)
One quadrant shows always just one direction of interaction. It is important not to mentally switch between the relationship directions during the assessment of the individual values

e. Rule application (e.g. 80/20)
For the application of the Pareto rule the accumulated sums of all line sums will be calculated. The reference value (accumulated sum of line sums) will be multiplied with the rule factor (in this guideline equal to 0.80 = 80%). The relation to the basic sum then shows the Pareto limit.

The file also allows an individual ranking by entering other ratios.

CPI-Matrix

Date: 2007-xx-xx

Tabel summs describes the interdependency between one material factor to all processes
-press "copy row" button to copy rows to columns
-press "sort" button to sort acc. special / attributes
-to change assesment from 80/20 use cell D5

Sort | copy row

					Sub group			Active components (non-hermetic)	Active components (non-hermetic)	Active components (non-hermetic)	Connectors	Connectors	Connectors	Consumables
	Requirements	Ranking: 0 to 3		Weighting factor (1-3)	Attribute	Accumulation of line sums	Special Assessment	coplanarity (package warpage)- Acnh	Solderability- Acnh	Moisture sensitivity- Acnh	termination material (contact resistance) - C	plastic material - C	retention force - C	Solder paste - Cons
	Weighting factor (1-3)			20	371	74.1								
	Sub group	Attribute												
Component	PCB	surface finish - PCB		1	8.1	8	1	0	3	0	1	0	0	3.1
Component	Active components (non-hermetic)	coplanarity (package warpage)- Acnh		3	12.3	0	1	0	3.1	0	0	0	0	0
Process	Reflow soldering (convectional oven)	Temperature profile in general		3	24.0	24	0	0	3	0	3	0	0	2
Component	Consumables	Solder paste - Cons		2	6.0	30	0	0	3	0	0	0	0	0
Component	Active components (non-hermetic)	Solderability- Acnh		3	0.0	30	0	0	0	0	0	0	0	0
Component	Consumables	Flux material - Cons		2	10.0	40	0	0	3	0	0	0	0	2
Component	PCB	pad design - PCB		3	9.0	49	0	0	2	0	0	0	0	1

FIGURE 31 - 80/20 RULE RESULTS

The example includes only selected attribute rankings and is just for demonstration.

The application of the 80 / 20 Pareto rule shows in Figure 31 that 80% of the total impact of attributes is caused by:

- Special: PCB
  - Surface Finish

- Special: Active Components
  - Co planarity

- Reflow soldering
  - Temperature profile

The matrix needs to be read from Row to column.

Sum of scores in horizontal lines:
Is an indication of “How does these row attributes effect column attributes” -> The higher the score, the bigger the effect of the specific attributes.

Sum of scores in columns:
Is an indicator of “How this specific attribute is affected by all row attributes “-> the higher score is, the bigger this attribute will be affected.

This score is basically just for information and not automatically calculated within the matrix.

Examples of high, medium and low impact attributes are shown Figure 32.

a. High Impacts:

	Sub group	Attribute							
Component	PCB	surface finish - PCB		1	4.0	4	0	0	3
Component	Active components (non-hermetic)	coplanarity (package warpage)- Acnh		3	12.3	0	1	0	3.1
Process	Reflow soldering (convectional oven)	Temperature profile in general		3	18.0	18	0	0	3

b. Medium and low Impacts:

Component	Consumables	Solder paste - Cons		2	6.0	24	0	0	3
Component	Active components (non-hermetic)	Solderability- Acnh		3	0.0	24	0	0	0
Component	Consumables	Flux material - Cons		2	6.0	30	0	0	3
Component	PCB	pad design - PCB		3	6.0	36	0	0	2
Process	Reflow soldering (convectional oven)	temperature ramp rates		3	6.0	42	0	0	2
Component	Passive components	Termination - PC		2	0.0	42	0	0	0
Process	Reflow soldering (convectional oven)	solder balls		2	0.0	42	0	0	0
Process	FCT	Warpage		3	0.0	42	0	0	0
Process	V-scoring	V-score depth		2	0.0	42	0	0	0
Process	FCT	Contact force		3	3.0	45	0	0	0
Component	Passive components	Substrate (mechanical stability) -PC		1	0.0	45	0	0	0
Component	Active components (non-hermetic)	Moisture sensitivity- Acnh		3	0.0	45	0	0	0
Component	Passive components	Wetability - PC		2	0.0	45	0	0	0
Process	Component placement (automatic)	placement force		1	0.0	45	0	0	0
Component	PCB	substrate material - PCB		1	0.0	45	0	0	0
Process	Solder paste printing	cleaning cycle		1	0.0	45	0	0	0
Process	AOI post reflow	Camera resolution		1	0.0	45	0	0	0
Process	AOI post reflow	Camera angle		3	0.0	45	0	0	0
Process	Component placement (automatic)	component size / weight		2	0.0	45	0	0	0
Component	Connectors	termination material (contact resistance) - C		2	0.0	45	0	0	0
Component	Connectors	plastic material - C		2	0.0	45	0	0	0
Component	Connectors	retention force - C		1	0.0	45	0	0	0
Process	PCB / Component handling	ESD - comp-hand		1	0.0	45	0	0	0

FIGURE 32 - EXAMPLE ATTRIBUTES LISTED BY DEGRESS OF IMPACT

Note that the examples are just for demonstration. Even the lower impact characteristics may have high impacts if the point of view will be changed or if there are other dependencies.

See more examples on how to use the CPI Matrix in the Examples Section A.7

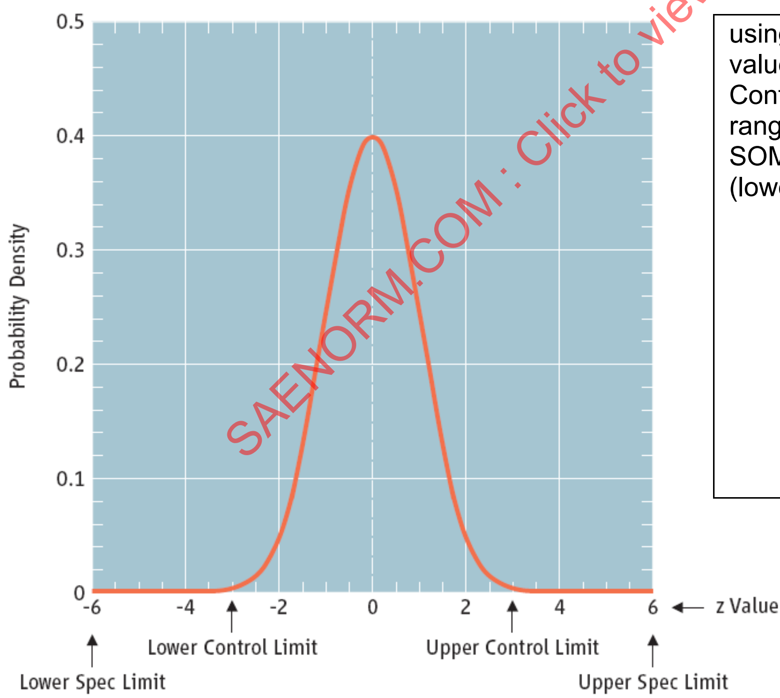
10.7 Robustness Indicator to Describe the Process Robustness

The robustness indicators as described in Section 11 should distinguish between functional and process related factors. The focus of the functional related ones is on the specified function within the required conditions or mission profile. The focus of the process related ones is related to the applied parameters by the processes in combination with the design and the components used to manufacture the product.

In general it is usual to express the process related factors by the general capability of equipment (machines) with the Cm, Cmk factors and the process itself with the Cp, Cpk factors – see ISO 21747 [5] for a more detailed explanation. The relationship of each is dependent on how detailed and specific the analysis is done. One general fact and disadvantage is still that the monitoring of all this is difficult and resource intensive and unfortunately not very often practiced. It is also the case that the data to generate these values are often not precise enough or trimmed to get the required values. A first step is potentially to do tester verification using “Golden Samples” with a smaller characteristic window for defined special values to verify the stability and therefore the capability of the tester. An advanced method would be the use of online monitoring of these characteristics using all tested products. This would increase the statistical basis for the mean stability value and also the standard deviation variation. The result then needs immediate feedback to the manufacturing process to get the best robustness result.

To ensure that all potential risks and robustness erosion possibilities are covered it is also important and required that worst case samples of components are used in certain process capability measurements rather than the normal average component.

A worst case sample is a component which is still within the specified limits but has special significant characteristics at or close to the specification limits (see Figure 33). Potentially these samples have to be especially prepared by the component manufacturer (e.g. co planarity on QFP).



using Average samples it is considered that the values are around the mean value (Between Lower Control and upper control LIMIT. To have the full range it is necessary to get the components WITH SOME special characteristics at the specified limit. (lower and / or upper spec. limit).

FIGURE 33 - WORST CASE SAMPLES

This new approach is a little bit different to the hitherto applied method in that firstly the influencing factor relationships are analyzed individually and secondly the most important factors have to be added to a continuous screening program.

By respecting this new approach it is possible to see the whole chain of tolerances and therefore the relationship of each influencing factor to all others. Beginning with the design related specific characteristics which are mandatory to be observed the next step is the combination of these with the material and the processes. This can be done also by using the CPI-Matrix. Therefore the weighting factors have to be set accordingly as high.

Depending on the influence (negative or positive) the tolerance calculation should then be done for the worst case. If the evaluation still shows robustness against the process on the limits it can be assured to have a higher robustness by during serial production over the full range of values.

These details allow a very accurate analysis of each influencing factor and make it easier to decide which of them have to be added to monitoring or screening.

By doing this screening and applying the standard capability rules it becomes possible to get critical factors under control or show at least per step the individual capabilities.

For some situations the general capability calculation may not be detailed enough. Therefore it is recommended to go one step deeper and start with the DPMO (defects per million opportunities) calculation. This method will give a more accurate picture by looking into individual characteristics and by doing certain benchmarks whether on machine capabilities or on design / component / process combinations.

This monitoring allows the creation of more and long term data and pinpoints the potential optimizations regarding the short and mid term capability studies.

The monitoring can be done with regular tools, such as:

- Xbar R
- Multi Vari chart
- Box plot
- SPC

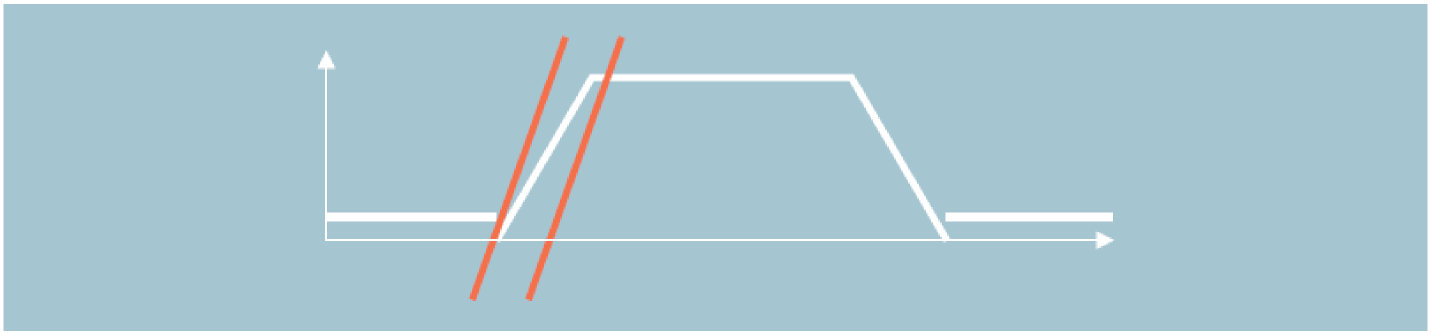
Process Robustness Indicator Example:

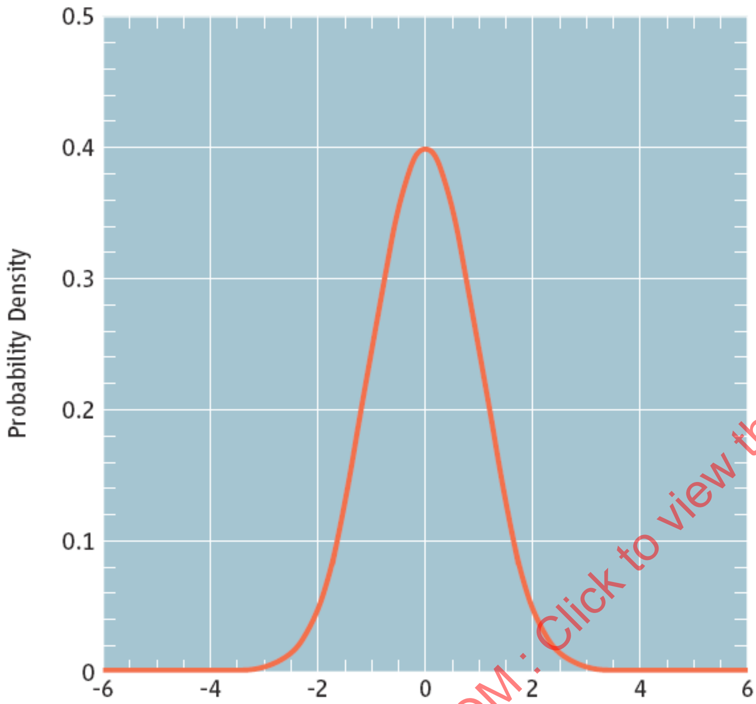
Monitoring of ICT Result for the following Ramp up Characteristics

Sleep current of EEM ➔ Parametric test on module level

Sleep current of one component ➔ Parametric on component level

Switch on / Switch off characteristics ➔ Characterization





Varying values related to the current ramp up rate, could be continuously measured and logged.
By monitoring the individual value, the distribution shows the functional related robustness of the component characteristic.

The picture shows one possible distribution.
A continuous monitoring of the values allows the user to keep this factor under review and to see any potetial influence to the expected life time of the component or finally of the EEM.

FIGURE 34 - EXAMPLE PROCESS INDICATOR

10.8 Extended Use and Scope of the Matrix Result

By using the matrix and having at least statistically relevant data it may become possible that evaluated random / non systematic failures can be transferred to the companies' Knowledge Matrix. This individual knowledge matrix becomes more and more accurate over time and use. By transferring the failure mode / root cause to the systematic knowledge matrix it should become a universal property of the organization to be used in a lessons learned process beginning from design to processing to shipping.

10.9 Preventive Actions and Side Benefits

The previous pages describe how to assess, evaluate and generate data for non systematic failures on EEM level. It includes and focus's mostly on the manufacturing processes by taking into consideration how much robustness is consumed by the manufacturing of the EEM. This focus is the new concept, because in the past the robustness was mainly evaluated on the EEM level or on the components.

By using the CPI matrix in combination with the design phase activities the loop is now closed. This means that now beginning with Design which delivers the special characteristics, to the components which deliver an individual robustness according to the data sheet or specification, to the process which is described in this section the EEM will deliver the requested over all robustness.

The most effective preventive action is to get a design and components which allows the use of standard manufacturing equipment and the application of regular characteristics and equipment parameters. This can only be done if there is a direct relation between mission profile, product design, material, process design and manufacturing.

As side benefits the monitoring in parallel of the defined characteristics and parameters in serial production allows one to see already some small non conformities in advance. This allows a timely feedback to all involved parties whether just for acknowledgement or for reaction.

11. ROBUSTNESS INDICATOR FIGURE (RIF)

11.1 Meaning and Need for a Robustness Indicator

Only if the robustness of an EEM is measured, is it possible to express the robustness in clear figures and to compare different designs or different suppliers. Otherwise, robustness would just be a diffuse definition. In general, robustness can be understood with the P-Diagram in Figure 35.

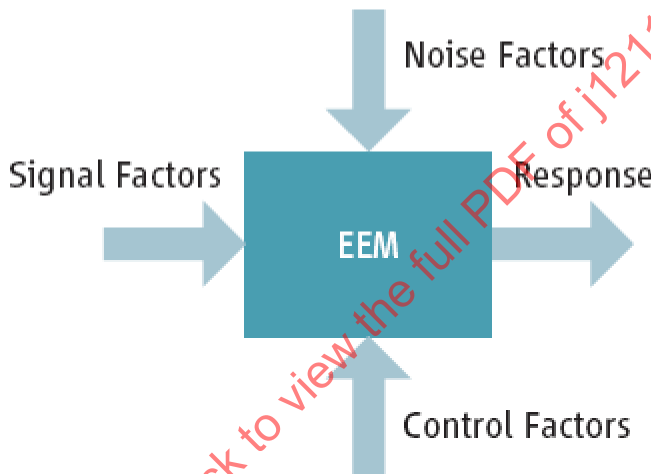


FIGURE 35 - ROBUSTNESS P-DIAGRAM

Noise factors for automotive products are represented by typical (environmental) stress factors like vibration, humidity or temperature. Furthermore, noises during the production (noises in soldering process or testing processes) can be taken into account.

Because Robustness is defined to be the difference between the limits of the design or the product and the mission profile or the specification requirement, this difference shall be used to generate the RIF.

11.2 RIF Diagram

To visualize and report on the Robustness Figures a collection of RIF's can be represented by a Spider diagram with the Parameters being measured on each axis and with the Missions profile and Actual EEM Performance for the parameter plotted on the relevant axis. The points for the mission profiles from each axis can then be joined to represent the mission profile for the parameter set (the Red area) and the EEM measured performance point of the axis' can be joined to visualize the actual EEM performance for the set of parameters (Blue Area) See Figure 36 and Figure 37.

The RIF Diagram uses a Radar, Spider or Kiviat Diagram, This chart is available in MS Excel however MS Excel allows only a single scale for the all the axes, other diagramming tools are available as well as add-ins for Excel which allow difference scales for each axis.

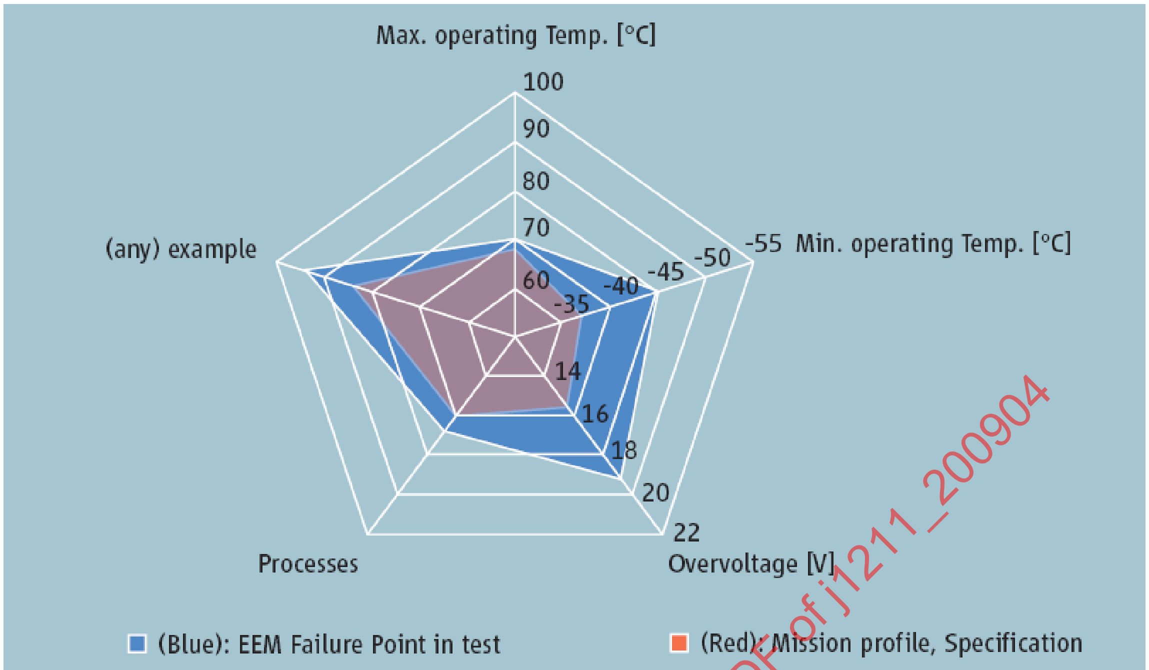


FIGURE 36 - RIF PLOT FOR CAPABILITY TESTS
(Scale Linear, With Dimension e.g.: °C, V)

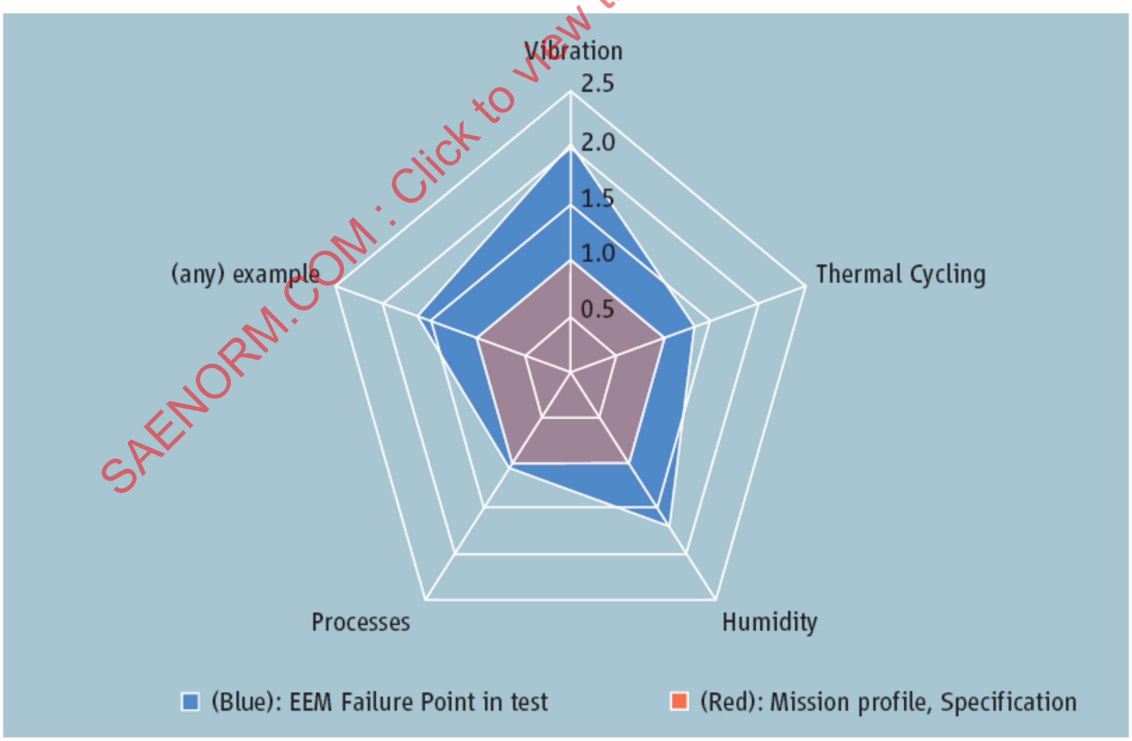


FIGURE 37 - RIF PLOT FOR DURABILITY TEST
(Scale Linear, Related to Specified Test Time of Each Stress Test, Without Dimension,
Calculated According to Acceleration Models)

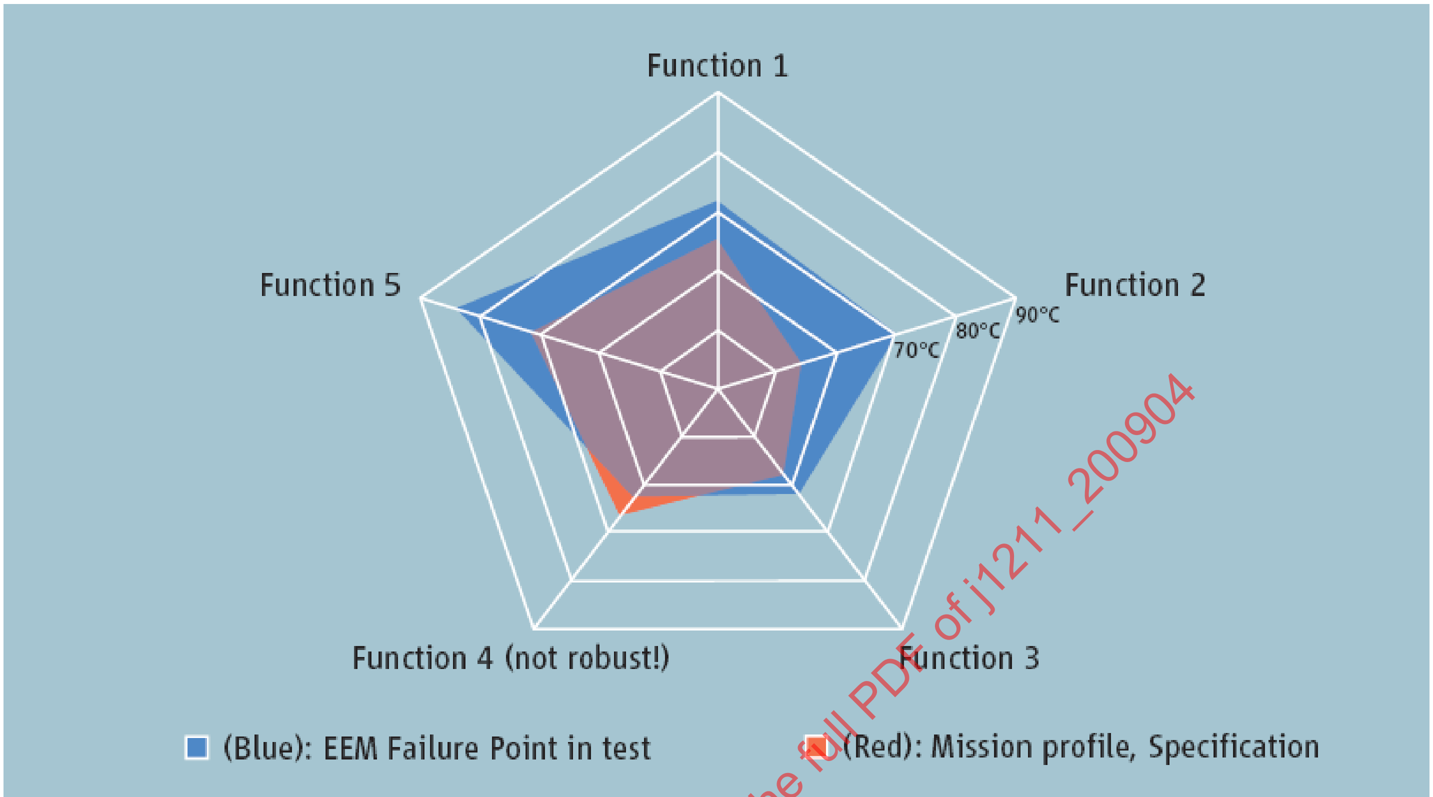


FIGURE 38 - ALTERNATIVE / ADDITIONAL RIF PLOT FOR DIFFERENT FUNCTIONS
A Dut Under One Defined Environmental Stress E.G. Temperature

An example for functions of an Infotainment System radio, phone, CD / DVD, MP3, TV, Bluetooth etc is shown in Figure 38.

Note that the Scale is arbitrary, and because Function 4 does not even cover the Mission Profile, the DUT is not robust!

11.3 Instructions for Generating a RIF

The RIF can be calculated for every category / every (reliability) influence factor such as Vibration, Thermal Cycling, Humidity, Processes or Intelligent Testing.

It is not useful to generate a RIF for "soft factors" like "communication".

If test data (e.g. from vibration test) are used to generate a RIF, then the first DUT which fails in the test shall be taken to calculate the RIF

In the determination of RIF, statistical considerations are not included. The DUTs used for testing shall be regarded as to be built with stable and controlled processes. Therefore, it is NOT necessary to test a statistical number of DUTs (e.g. 30) to determine the RIF. If test data (e.g.: Vibration test) are used to generate a RIF, then typically one, two or three DUTs shall be tested.

Some examples of the most important RIFs are shown in this guideline. To add additional, product-specific RIFs, the calculation can be done according to the "General instruction for generating a RIF" as follows:

A RIF shall be determined for

- Capability testing / functional limits
- Durability testing / destruction limit

It is important to note that in some cases, the SW of a DUT protects the HW in severe conditions by shutting off the DUT or parts / functions of the DUT. Therefore, such a SW-Function can influence or affect the determination of the RIF.

RIF-Plot:For better visualization, the single RIFs can be shown in a RIF-Plot or different RIF-Plots (see RIF Figure 36, Figure 37 and Figure 38.

11.4 Generation of RIF

11.4.1 RIF for Durability Testing

Durability testing means the ability of a DUT to meet a defined requirement with consideration of durability items e.g. the capability to meet a requirement during the whole specified lifetime. For example, if a DUT is required to work at maximum temperature for 1500 h but a failure occurs at 1250 h, then the robustness is not sufficient

11.4.1.1 RIF $_{ARR}$ for Durability Testing with the Arrhenius-Model

For situations where the Arrhenius model can be applied (e.g., high temperature tests, lifetime tests with constant temperature, etc.). It is necessary to compare different temperature conditions. The formula is:

$$\pi_B = e^{(EA \cdot TF)} \quad \text{(Eq. 1)}$$

with:

E_A: Activation Energy [eV] (eV: Electron Volt) (example: 0.44 eV)
TF: Temperature Factor
TF = 1 / k · [(1 / T1) – (1 / T2)]

with:

k: Boltzmann Constant
T1: First temperature
T2: Second temperature

EXAMPLE: Calculation of RIF $_{ARR}$

Max. temperature according to the specification: 85 °C (358 K)
Test temperature (moderate accelerated conditions): 95 °C (368 K)
Required Test time (at 85 °C) according to the specification: 1500 h
Failure at accelerated condition (95 °C) occurs: 1963 h
TF = 11604.8 K / eV · [(1 / 358 K) – (1 / 368 K)]
TF = 0.88

then:

$\pi_B = e^{(EA \cdot TF)}$
$\pi_B = e^{(0.44\ eV \cdot 0.88)}$
$\pi_B = 1.47$
$RIF_{ARR} = 1963\ h \cdot \pi_B / 1500\ h = 1.93$

11.4.1.2 RIF CM for Durability Testing with the Coffin-Manson-Model

For situations where the Coffin-Manson model can be applied (e.g.: temperature cycling / temperature shock tests)

$$N_1 / N_2 = (\Delta T_2 / (\Delta T_1)^{k} \qquad \text{(Eq. 2)}$$

with:

N_1: Number of temperature cycles until defect at stress level according to specification
N_2: Number of temperature cycles until defect at stress level in accelerated test
ΔT_1: Temperature stroke at stress level according to specification
ΔT_2: Temperature stroke at stress level in accelerated test
k: Material constant

NOTE: k is dependent on the materials. It shall be determined in fundamental tests depending on the technology, used in the DUT. See Table 8 below for guidelines.

TABLE 8 - LOW CYCLE THERMAL FATIGUE COFFIN-MANSON MODEL EXPONENT k (Eq. 2)

Low Cycle Thermal Fatigue Coffin-Manson Model Exponent			
Component Type	Structural	Complex Electronic with Lead Based Solder	Complex Electronic with Lead Free Solder
k Range	3 - 25[1)]	2 - 3[2)]	2 - 3[2)]
Typical Recommended Value for k	10	2.5	2.65[3)] use Norris Landzberg for temperatures > 100°C

Table Notes:
1) For structural materials based upon fatigue failure distributions from rotating beam specimen data.
2) Based upon time equivalence for observed thermal fatigue related failure modes
3) It is recommended to use Coffin-Manson only up to 100 °C max. temperature on solder joint.

NOTE: There is experimental evidence that the Norris-Landzberg model is more accurate as it includes effect of rate of change and dwell time factors.

It should be applied, if temperature level in the solder joint could achieve temperatures >100 °C.

Norris-Landzberg model:

$$N_f = (\Delta T)^{k_1} \cdot t^{k_2} \cdot \exp[k_3 / T] \qquad \text{(Eq. 3)}$$

with:

t: Duration time at high temperature
T: Upper temperature level
Factors for typical lead free eutectic solder SnAgCu
k1 = 0.6, k2 = 0.4, k3 = 4.8.

Reference: H. Ehrhard, R. Becker, Th. Rupp, J.Wolff: Mission Profile and the reliability of lead free control units, VDI Report No 2000, 2007

EXAMPLE: Calculation of RIF $_{CM}$

Temperature stroke according to the specification: ΔT_1 = –40 °C / +70 °C (110 K)
Temperature stroke according accelerated conditions: ΔT_2 = –40 °C / +90 °C (130 K)
Required number of cycles according to the specification: $N_3 = 200$
Failure at accelerated condition occurs: $N_2 = 325$
K = 2
$N_1 = N_2 (\Delta T_2 / (\Delta T_1)^{k}$
$N_1 = 325 ((130\ K)^2 / (110\ K)^2)$
$N_1 = 454$
$RIF_{CM} = N_1 / N_3$
$RIF_{CM} = 454 / 200$
$RIF_{CM} = 2.27$

11.4.1.3 RIF_{LAW} for Durability Testing

The Lawson Model is used for the humidity enhanced corrosion failure mechanism, Lawson Model defines the acceleration factor due to the combined effects of high temperature and relative humidity. In situations where the Lawson-Model can be applied (e.g.: High-Humidity-High-Temperature (HHHT-Tests), use the following equation:

$$A_{t/RH} = A_t - A_{RH} = e^{\left[-\left(\frac{E_A}{k}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] + b\left[(RH_1)^2 - (RH_2)^2\right]} \quad \text{(Eq. 4)}$$

where:

- $A_{t\,/\,RH}$ Combined acceleration factor of the Lawson Model considering temperature (T) and relative humidity (RH)
- A_t Acceleration factor due to temperature
- A_{RH} Acceleration factor due to relative humidity
- b Constant ($b=5.57 \times 10^{-4}$)
- E_A Activation energy (EA=0.4 eV)
- k Boltzmann constant ($k=8.617 \times 10^{-5}$ eV / K)
- T_I Absolute Kelvin temperature [K]: i=1 for test condition, and i=2 for field conditions
- R_{HI} Relative humidity [%];i=1 for test condition, and i=2 for field condition

NOTE: Generally, the values for the activation energies used in the Lawson Model and the Arrhenius Model are different, since both models describe completely different failure mechanisms.

The total test duration for HHHT test is calculated by:

$$t_{HHHT} = t_{non\ op.time} / A_{T\,/\,RH} \quad \text{(Eq. 5)}$$

where:

- t_{HHHT} Test duration required for HHHT test
- $t_{non\ op.time}$ Non Operating Time during service life in field (see mission profile)
- $A_{T\,/\,RH}$ Combined acceleration factor of the Lawson model according

EXAMPLE: Calculation of RIF_{HHHT}

For an EEM located in the under-hood compartment and having a Service Life in Field of 10 years, the RIF_{HHTH} is calculated as shown below:

- A component is mounted outside the passenger cabin or trunk.
- The average temperature during Non Operating Time is defined in the mission profile to be T2=23 °C / 296 K and the average relative humidity is RH2=65% (example, according to mission profile).
- Test conditions for HHTH-test are T1=85 °C / 358 K and RH1=85%
- Application of Lawson's-equation with these values results in a combined acceleration factor of the Lawson of At / RH = 80.4.
- From the Mission Profile, the components Non-Operating Time during 10 years Service Life in Field is $T_{non\ op.time}$ = 79 600 h.
- The DUT in the accelerated test (T_1=85 °C / 358 K and RH_1=85%) shows a failure after 1200 h.

then:

$$RIF_{LAW} = 1200\ h \cdot A_{t\,/\,RH} \,/\, T_{non\ op\ time} \quad \text{(Eq. 6)}$$
$$RIF_{LAW} = 1200\ h \cdot 80.4 \,/\, 79\ 600\ h$$
$$RIF_{LAW} = 1.21$$

11.4.1.4 RIF for Vibration-Testing

$$(a_0 / a_1) = (T_1 / T_0)^{1/M} \quad \text{(Eq. 7)}$$

with:

a_0 = Power spectral density or sinusoidal acceleration (g peak) until defect at stress level according to specification
a_1 = Power spectral density or sinusoidal acceleration (g peak) until defect at accelerated stress level
$T_{1:}$ = Time until defect at stress level according to specification
$T_{2:}$ = Time until defect at stress level at accelerated test
1 / M: Material constant

For the Value of M please see Table 9 below:

Please note this table shows typical value to be used, the RV users should review their application of RV and determine the best value of M to use in their own circumstances and document the value used.

TABLE 9 - VIBRATION DAMAGE EQUIVALENCE EQUATION EXPONENT M (Eq. 7)

	Vibration Damage Equivalence Equation Exponent					
Vibration Type	Sine	Complex Periodic	Random	Random	Random	Random
Hardware Type	All	All	Simple Structures	Simple Structures	Complex Electronic	Complex Electronic
Units	Peak G	Peak G	RMS G	PSD G^2 / Hz	RMS G	PSD G^2 / Hz
M Range	5 to 20 1)	5 - 20 1)	5 to 20 1)	2.5 to 10 1)	4 to 13 2)	2 to 6.6 2)
Typical Most Conservative Recommended Value for M ⅔	6	8	8	4	4	2

Table Notes see ref [6] and [7]
1) For structural materials based upon fatigue failure distributions from rotating beam specimen data with damping considerations.
2) Based upon time equivalence for observed vibration related failure modes.
3) Stress concentrations and high application stresses reduce the usable range of M.
4) Failure mode correlations should dictate the M value chosen.

EXAMPLE: Calculation of RIF_{VIB}

Acceleration according Specification: $a_0 = 2.79\ G_{RMS}$
Acceleration according accelerated condition: $a_1 = 3.81\ G_{RMS}$
Required Duration according Specification: $T_2 = 24$ h
Failure at accelerated condition occurs: $T_1 = 14$ h
M = 4.0 (Electronic board)
$T_0 = T_1 / (a_0 / a_1)^M$
$T_0 = 14\ h / (2.79\ g / 3.81\ g)^{4.0}$
$T_0 = 48.7$ h
$RIF_{VIB} = T_0 / T_2$
$RIF_{VIB} = 48.7\ h / 24\ h$
$RIF_{VIB} = 2.03$

11.4.1.5 RIF in Case of Step-Stress Testing

11.4.1.5.1 Vibration Step Stress Testing

If a Vibration step-stress test is applied: then to determine the limits of the design / the DUT, the test condition (gRMS-level) is increased in steps (e.g.: one hour each step, 3 dB increase each step) until the first fatigue failure appears. This facilitates reaching the limits of the design in a short test time. In this case, the Miner accumulation rule for fatigue damage can be applied.

Miner accumulation rule for fatigue damage:

Every Damage $D_1 = n_1 / N_1$, $D_2 = n_2 / N_2$ is accumulated to the total stress for the DUT.

with:

n_1: Number of load cycles OR duration of test at stress level 1
N_1: Number of load cycles OR duration of test till fatigue damage
Total Damage $D_{total} = \sum D_i = n_1 / N_1 + n_2 / N_2 + ...+ n_n / N_n$

Therefore, if a vibration step-stress test was performed, the formula in 11.4.1.4 shall be applied in this way:

$T_0 = T_{11} / (a_{01} / a_{11})^M + T_{11} / (a_{02} / a_{12})^M + T_{13} / (a_{03} / a_{13})^M + ... + T_{1n} / (a_{0n} / a_{1n})^M$
a_{01} .... a_{0n} : Acceleration levels at the different steps of the vibration-step test
T_{11} .....T_{1n}: Duration at the different steps of the vibration-step test

then:

RIF = T_0 / T_2 (see 3.1.4)

11.4.1.5.2 Humidity-Step-Stress-Testing

If a humidity step-stress test is applied, then to determine the limits of the design / the DUT, the test condition (temperature) is increased in steps (e.g.: 10 K each step, 12 h each step) until the first failure caused by humidity appears. This facilitates reaching the design limits in a short test time.

In this case, Miner's accumulation rule for damage also can be applied (note: that this is a new approach, not State of the art).

Miner's accumulation rule for damage:

Every Damage $D_1 = n_1 / N_1$, $D_2 = n_2 / N_2$ is accumulated to the total stress for the DUT.

With:

t_1: Duration at humidity level 1
T_1: Duration when humidity-caused failure occurs
Total Damage $D_{total} = \sum D_i = t_1 / T_1 + t_2 / T_2 + ...$

NOTE: further examples of calculations are not given here, because to apply the miner-rule for damage for a step-humidity test is a new approach and not state of the art.

11.4.2 RIF for Capability Testing

Capability testing means the ability / capability of a DUT to meet a defined requirement without consideration of durability items. For example, the capability to meet a requirement concerning over voltage, max. Or min. operating temperature, IP protection. For example: if a DUT is required to work at –40 °C, then the capability of the DUT shall be determined at what min. temperature the operation is according to specification. If a failure occurs at –35 °C, then the robustness is not sufficient.

In capability testing, the durability aspect is not included. The durability / time influence is considered in the section "Durability Testing".

EXAMPLE: Calculation of RIF

Min operating voltage according Specification: $U_{min\,2}$ = 9 V
Failure due to too low voltage in test occurs at: U_{min1} = 8.05 V
RIF = $U_{min\,2} / U_{min1}$
RIF = 9V / 8.05V
RIF = 1.12

11.4.3 RIF for Processes

11.4.3.1 Manufacturing Processes/ Equipment related

A DUT needs a defined number of manufacturing processes (component placing, soldering reflow, soldering SMD, ICT, final test...).

- The required CpK value shall be mutually agreed before.

- For each of the processes, a CpK-value shall be determined according to the methods described in the Section 10.

- The RIF Processes for a single process is the Cpk-value for this process.

EXAMPLE: The required Cpk for an in-circuit test to be robust was mutually agreed to be 2.0.

– The real Cpk was determined to be Cpk = 1.44
– Then the RIF In circuit test = 1.44 / 2.0 = 0.72 (and therefore not sufficient)

Example ranges of RIF figures for other manufacturing processes can be seen in Figure 39.

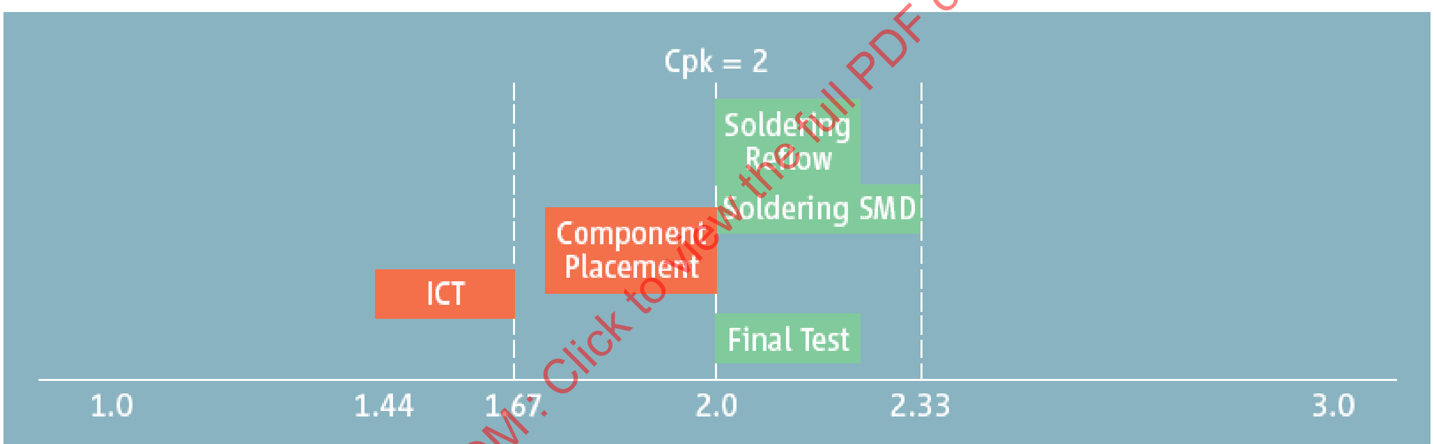


FIGURE 39 - RIF PLOT FOR PROCESSES:
Green, if the CpK is higher than the agreed value.=> robust!
Red, if the CpK is lower than the agreed value. => Not robust!

11.4.3.2 Monitoring Processes, (Function Related)

- A DUT has characteristic functional values (key parameters) which shall be monitored with a monitoring process.

- For each type of DUT, the key parameters shall be determined according to the methods described in Section 10.

- These key parameters shall be monitored in the production line.

- These key parameters shall be shown as additional CpK-value.

- The monitoring parameters shall be visualized in a plot analogous to Figure 39. (Only the variables are different.)

- The monitoring parameters shall be ranked according to the "importance number" of this parameter in the FMEA.

EXAMPLE:

- The key parameter for the monitoring of an EEM was determined to be the slew rate of a signal.

- Because this key parameter has significant influence to the robustness of this product, it shall be evaluated in detail in the FMEA.

- The importance number for this signal in the FMEA was determined to be 6.

- The required CpK for this slew rate was mutually agreed to be 1.67.

- The real CpK for this slew rate was determined to CpK = 1.83.

- Then the RIF_{key} parameter slew rate = 1.83 / 1.67 = 1.10.

- For the comparison of this RIF-number with other RIF-numbers of this product, the "importance value" of the FMEA shall be considered.

12. NOTES

12.1 Marginal Indicia

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

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APPENDIX A - SECTION EXAMPLES

A.1 MISSION PROFILE EXAMPLE 1: DOOR MODULE

This example deals with a Standard EEM that is the controlling part of door systems. It connects to the car's power supply, to CAN-Bus and some actuators and sensors and is not necessarily complete.

Application Profile

The significant mechanical, climatic and chemical influences which impact on the component during its service life are summarized in the following application profile.

A.1.1 Door Module Service Life

Service life in the field	10 years
Mileage over the service life	400.000 km
EEM on time	8.000 hours
EEM off time (non operating time)	79.600 hours

A.1.2 Mounting Location of the Component

Inside the door, assembled on mechanical carrier

A.1.3 Environmental Loads

A.1.3.1 Climatic Stress (Temperature/Humidity)

Operated in the vehicle (EEM on time)	Temperature profile [1] (Ambient temperature of the component at the mounting location) [2]	Temperature	Distribution
		- 40°C	6%
		23°C	65%
		60°C	20%
		80°C	8%
		85°C	1%
	Humidity [3]	Relative humidity up to 100% Condensation and icing	
Installed in the vehicle without operation (EEM non operating time)	Temperature	Minimum temperature: -40°C Maximum temperature: +85°C Typical temperature: +23°C	
	Humidity	Relative humidity up to 100 %; Condensation and icing Mean 60% relative humidity [4] Average temperature: +23°C	
Transportation	Temperature	Minimum temperature: -50°C Maximum temperature: +95°C	
	Transportation time	Max. 24 hrs. Uninterrupted at minimum temperature Max. 48 hrs. Uninterrupted at maximum temperature	
Storage [5]	Temperature	Minimum temperature: -10°C Maximum temperature: +55°C	
	Storage time	5 years	
	Humidity	Max. 85% relative humidity	
Long-term storage for after-series supply [6]	Temperature	Minimum temperature: -10°C Maximum temperature: +40°C	
	Storage time	15 years	
	Humidity	Max. 80% relative humidity	
Temperature changes	Number	7300 temperature cycles over 10 years [7]	
	Temperature delta	Average: 34 K [8]	

Remarks:

1) The temperature profile contains the assumed field load distribution world-wide (arctic- and hot climate). This distribution represents an envelope over typical use-cases.
2) $T_{\text{Vehicle Mounting Location Ambient}}$
3) In door
4) Assumption similar to [1]
5) Necessary storage time in the dealer's garage and additional in the center of distribution
6) Necessary storage time in the dealer's garage and additional in the center of distribution
7) In principle, every little temperature change experienced by the component during its Field Service Life in Years contributes to its total thermo-mechanical stress. Despite this fact, only two large thermal cycles per day (for passenger cars) are usually sufficient to determine cumulative effect of thermo-mechanical stresses experienced by an E/E-component. Based on this assumption, the total Number of Temperature Cycles during Service Life in Field can be calculated by using a simple formula given below:
   Number of Temperature Cycles during Service Life in Field = 2 * 365 * Service Life in Field
8) Typical average temperature deltas based on field studies and engineering experience.

A.1.3.2 Dust / Water

Water	Water drips (15° inclination)
Particles	Dust: small particles, fine powder

A.1.3.3 Chemical Stress/Resistance to Media

Environmental influence	Salt fog atmosphere
Gaseous pollutants	Industrial climate (H_2S, NO_2, Cl_2, SO_2)

A.1.3.4 Mechanical Stress

Vibration	Random excitation	See below
Acceleration	Mechanical shock	Acceleration up to 500 m/s^2
	Mechanical shock endurance	70.000 shocks driver door

A.1.3.5 Random Vibration

Vibration profile Random vibration	Frequency [Hz]	Power spectral density (PSD) [(m/s^2)^2/Hz]
	5	0.884
	10	20.0
	55	6.5
	180	0.25
	300	0.25
	360	0.14
	1000	0.14
	2000	0.14
	RMS acceleration	30.8 m/s^2

Remarks: Accelerated test condition, worst case field scenario envelope curve

A.1.3.6 Transport/Storage/Crash/Assembly

Acceleration (single events)	Mechanical shock
	Drop (free fall 1 m)

A.1.3.7 ESD

OEM-Standards or ISO or IEC (worst case field scenario)	Up to +25 KV...ESD

A.1.4 Relevant Functional Loads

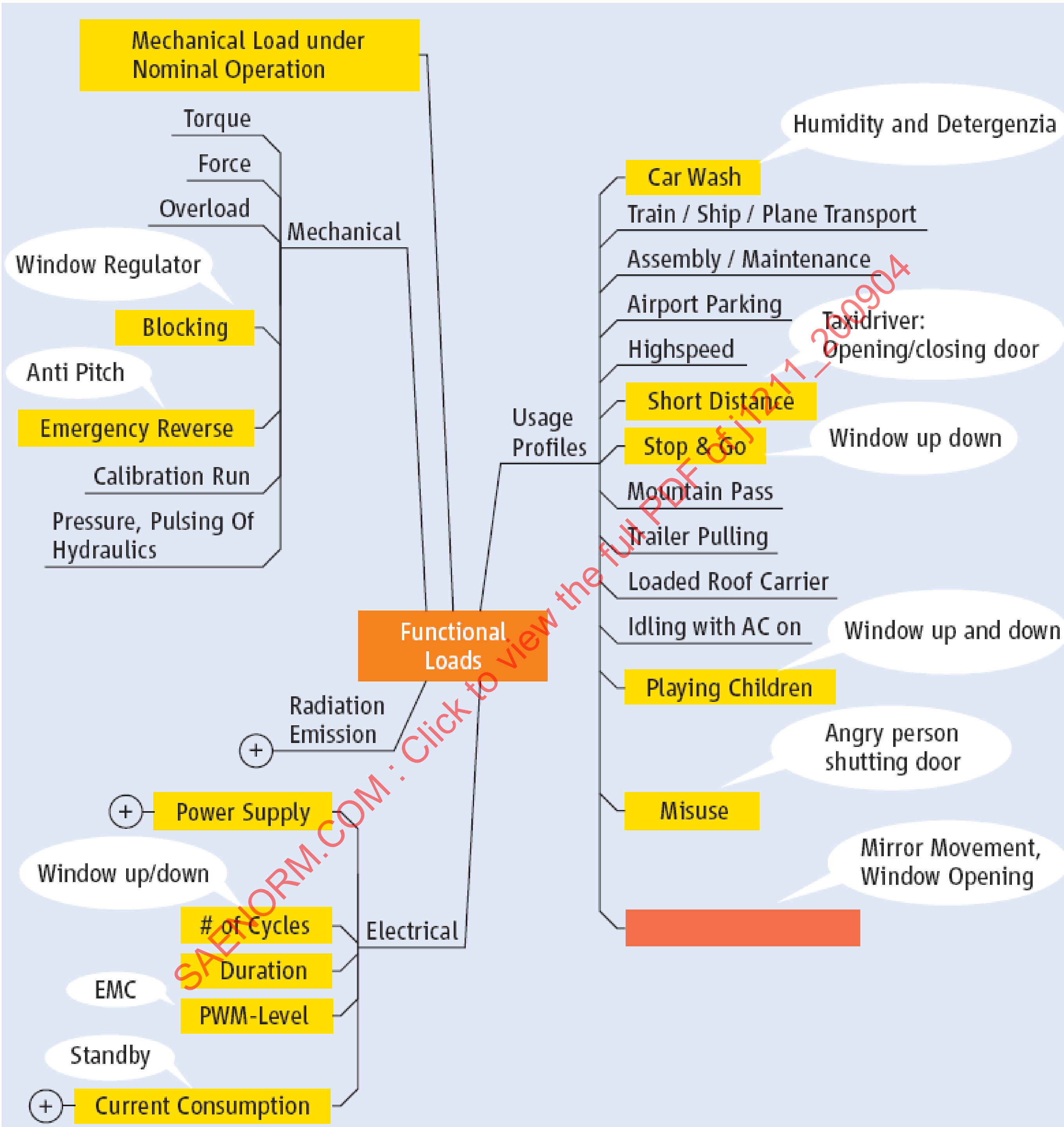

FIGURE A1 - TREE ANALYSIS FUNCTIONAL LOADS DOOR MODULE

Note, that this assessment indicates relevant functional loads for a virtual product. Please check the relevance in detail for your design and application.

- Yellow: relevant load
- Red: additional relevant load
- Grey: load not relevant
- Bubble: Comment

A.2 MISSION PROFILE EXAMPLE 2: MECHATRONIC TRANSMISSION CONTROL MODULE

This example deals with a mechatronic that is the controlling part of an automatic transmission system. It connects only to the car's power supply, to one CAN-Bus and to hydraulic lines of actuators. It contains hydraulic valves and an RPM-sensor.

Application Profile

The significant mechanical, climatic and chemical influences which impact on the component during its service life are summarized in the following application profile.

A.2.1 Transmission Service Life

Service life in the field	15 years
Mileage over the service life	250.000 km [1)]
EEM on time	6.000 hours
EEM off time (non operating time)	125.400 hours

Remarks:
1) The service life time of the mechatronic is given by the mileage of the mechanical gearbox (limited by mechanical wear), which is 250 000 km.

A.2.2 Mounting Location of the Component

Bottom of gearbox, surrounded by oil
The connector is part of the gearbox outline.

Remarks:
The mechatronic module itself is surrounded by oil (=chemical load), but the connector has contact to the medium outside.

A.2.3 Environmental Loads

A.2.3.1 Climatic Stress (Temperature/Humidity)

Operated in the vehicle (EEM on time)	Temperature profile [1] (Ambient temperature of the component at the mounting location) [2]	Temperature	Distribution
		- 40°C	2%
		23°C	18%
		100°C	70%
		130°C	9%
		140°C	1%
	Humidity [3]	Relative humidity up to 100% Condensation and icing	
Installed in the vehicle without operation (EEM non operating time)	Temperature	Minimum temperature: -40°C Maximum temperature: 140°C Typical temperature: +23°C	
	Humidity	Relative humidity up to 100 %; Condensation and icing Mean 65% relative humidity [4]	
Transportation	Temperature	Minimum temperature: -50°C Maximum temperature: +95°C	
	Transportation time	Max. 24 hrs. Uninterrupted at minimum temperature Max. 48 hrs. Uninterrupted at maximum temperature	
Storage [5]	Temperature	Minimum temperature: -10°C Maximum temperature: +55°C	
	Storage time	5 years	
	Humidity	Max. 85% relative humidity	
Long-term storage for after-series supply [6]	Temperature	Minimum temperature: -10°C Maximum temperature: +40°C	
	Storage time	15 years	
	Humidity	Max. 80% relative humidity	
Temperature changes	Number	10950 temperature cycles over 15 years [7]	
	Temperature delta	Average: 70 K [8]	

Remarks:

1) The temperature profile contains the assumed field load distribution world-wide (arctic- and hot climate). This distribution represents an envelope over typical use-cases.
2) $T_{Vehicle\ Mounting\ Location\ Ambient}$: Oil temperature
3) Only connector concerned
4) Assumption similar to [1]
5) Necessary storage time in the dealer's garage and additional in the center of distribution
6) Necessary storage time in the dealer's garage and additional in the center of distribution
7) In principle, every little temperature change experienced by the component during its Field Service Life in Years contributes to its total thermo-mechanical stress. Despite this fact, only two large thermal cycles per day (for passenger cars) are usually sufficient to determine cumulative effect of thermo-mechanical stresses experienced by an E/E-component. Based on this assumption, the total Number of Temperature Cycles during Service Life in Field can be calculated by using a simple formula given below:
   Number of Temperature Cycles during Service Life in Field = 2 * 365 * Service Life in Field
8) Typical average temperature deltas based on field studies and engineering experience.
   Simplified estimation: 23 °C + 70 K = 93 °C; consistent to the temperature distribution maximum near 100 °C.

A.2.3.2 Dust / Water

Water	High-velocity water jet with increased pressure 1)
	Temporary immersion in water 1)
	Continuous submersion in water (e.g. water crossing and boat release maneuver) 1)
	High-pressure steam-jet cleaning 1)
Particles	Dust 1)

Remarks: 1) Load (simplified mission profile)

A.2.3.3 Chemical Stress/Resistance to Media

Environmental influence	Mechatronics	Connector
Media	Gear oil (= permanent 15a)	Salt fog atmosphere
Cleaning agents		Differential lubricants, cold cleaner, car wash soap fluid, windshield washer, engine oil, gasoline, engine coolant, battery acid, engine cleaner
Gaseous pollutants	Atmosphere inside gear	Industrial climate (H_2S, NO_2, Cl_2, SO_2)

A.2.3.4 Mechanical Stress

A.2.3.5 Random and Sinusoidal Vibration

Vibration profile	Frequency [Hz]	Power spectral density (PSD) [(m/s²)²/Hz]
Random vibration	10 100 300 500 2000	10.0 10.0 0.51 5.0 5.0
	RMS acceleration	96.6 m/s²
Vibration profile	Frequency [Hz]	Amplitude of acceleration [m/s²]
Sinusoidal vibration	100	30.0
	200	60.0
	400	60.0

Remarks: Accelerated test condition, worst case field scenario envelope curve

A.2.3.6 Transport/Storage/Crash/Assembly

Acceleration (single events)	Mechanical shock
	Drop (free fall 1 m)

A.2.3.7 ESD

OEM-Standards or ISO or IEC (worst case field scenario)	Up to +25 KV...ESD