Physics of Failure (PoF) and its use in Practice

PLOT Showcase – FHI Leusden

12 October 2023

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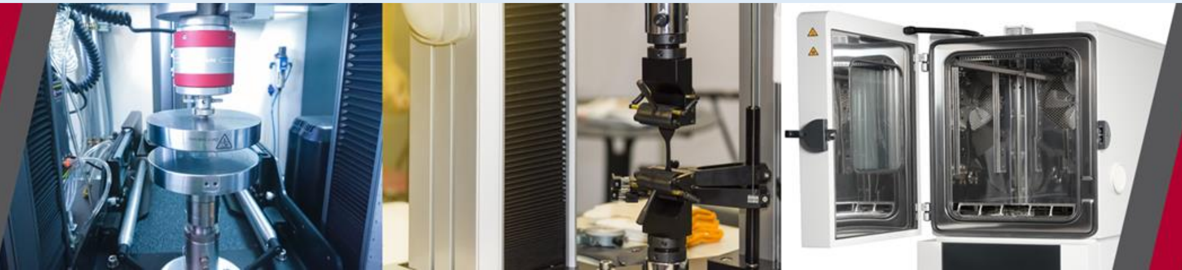
V2i *Vors* to Innovate

PLOT SHOWCASE

12 OKTOBER 2023 – FHI LEUSDEN



Contents

- Introduction V2i
- Physics of Failure (PoF)
    - What is PoF?
    - History of PoF
    - PoF Approach
        - Failure Mechanisms
        - Inventory of potential Failure Mechanisms
        - Stress & Strain Analysis using FEM and DOE
        - Robust Design Optimization
        - Creep Strain and Lifetime Modelling
        - PoF based Accelerated Lifetime Testing (ALT)
        - Root Cause Analysis within PoF
- PLOT Reliability Workgroup

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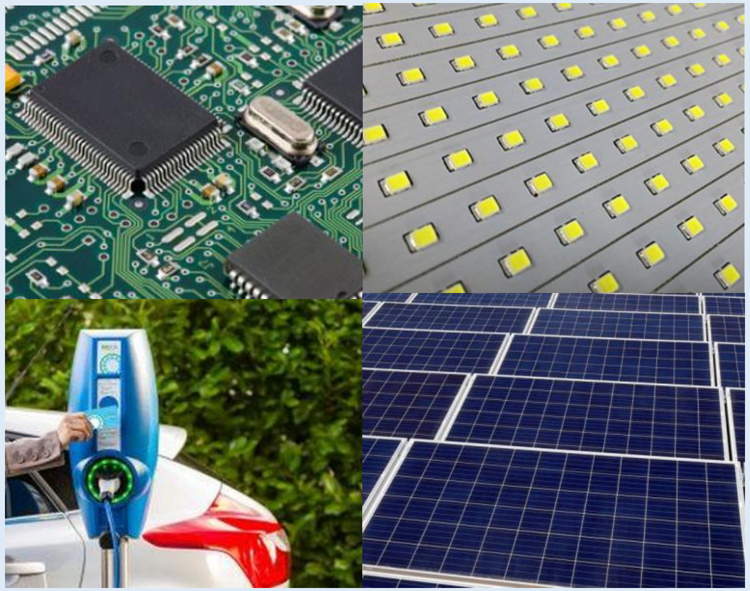
- Innovation, reliability and improvement services



<u>Process Improvement</u>
- Process capability studies
- Yield improvement
- Product and process audits

<u>Product Reliability</u>
- DfR: Transition to built-in reliability
- RCA: Solving long lasting / complicated failures
- Designing Accelerated Lifetime Tests and reliability programs

<u>Systematic Innovation</u>
- TRIZ: Making innovation tangible and predictable
- NPI Optimisation: Accelerating TTM (Time to Market)

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V2i (*Vors* to Innovate)

- Erik Veninga
  - Consultant and owner at V2i (*Vors* to Innovate): consulting and services on Systematic Innovation, Materials Performance, Product Reliability and Process Improvement
  - CTO at CATI: A start up company which develops new packaging and interconnection technologies for the LED industry
  - Board member PLOT-FHI and chairman Reliability work group (theme: Physics of Failure)
  - Background: Mechanical Eng., Industrial Eng., Electronics Industry (10 yrs.) and Applied Research (18 yrs.)
  - ASQ Certified Reliability Engineer (CRE), Quality Engineer (CQE) and Six Sigma Black Belt (CSSBB)

V2i

CATI

FHI PLATFORM OMGEVINGSTECHNOLOGIE

ASQ

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What is Physics of Failure (PoF)?

- A reliability engineering approach that uses the <u>knowledge of how things fail</u> to improve designs and predict how long these will last in the field.
    - Design for Reliability (DfR) based on a fundamental and up front understanding of failure mechanisms and variation effects.
    - Modelling failure behaviour and lifetime for dominant failure mechanisms by using Finite Element Method (FEM) and reliability models.

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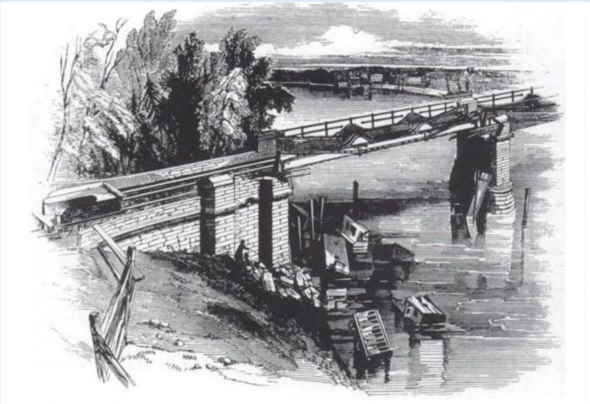
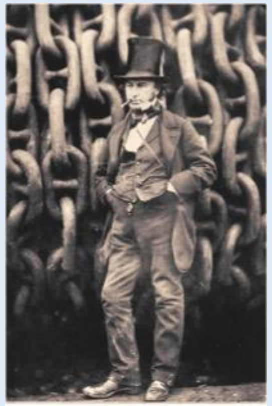
History of PoF: We’ve come from far

- Reliability in the Victorian era: much is still unknown
  - Common practice: designing with safety factors based on for instance the breaking weight of structures
  - Explanation of metal fatigue: “Some mysterious vibratory mechanism that transformed the metal's granular structure”



The Dee Bridge disaster (Chester, 1847): the failure mechanism was not understood by designer Stephenson.



Brunel afterwards: “With the proper care in eliminating inhomogeneities and other imperfections, reliable iron castings of almost any form and of twenty or thirty tons weight could be ensured”.

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History of PoF: Briefly

- World War II: Reliability became an engineering discipline
- The first Physics of Failure in Electronics Symposium in 1962
    - “Reliability and Physics of Failure Program at RADC” paper of Joseph Vaccaro
- The impact of “Predicting the Reliability of Electronic Equipment” paper of IIT Research Institute / Honeywell SSED and the Westinghouse / University of Maryland in 1994
- MIL-HDBK-217 standard becoming obsolete in 1994
- Broader application: from academia to industry from 2000
- Developments in material analysis techniques and software tools!

“Highly driven by the need for reliable electronics”

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History of PoF: Current Situation

- Limited availability of data on fundamental **material properties**
  - Modelling heavily depends on the input of correct material properties, the smallest deviations in composition and processing can strongly influence the materials properties and therefore the accuracy and relevance of modelling results
- In-dept **materials knowledge** is not often available within product designing companies
  - Advanced materials analysis techniques required for characterization
- The number of companies **using modelling techniques** is increasing, but it is not yet common practice across the industry
  - Stress analysis and modelling functions in CAD are often applied

Still, every product designing company can benefit from an PoF approach!

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Failure Mechanisms

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- The fundamental processes that lead to material / interface degradation and failure

- <u>Examples of failure mechanisms</u>:
  - Corrosion
  - (Electro) Migration
  - Diffusion
  - Dendritic growth
  - Fatigue
  - Creep
  - Embrittlement
  - ……

<u>Categorized*</u>:
1) Forced processes
2) Activation driven processes
3) Diffusion driven processes
4) Combinations of the processes, yielding complex aging processes (might include interactions)

<u>Failure mode</u>: how the failure is observed

<u>Failure mechanism</u>: fundamental process causing the failure

<u>Cause</u>: situation initiating the failure mechanism

** A. Feinberg, "Thermodynamic Degradation Science", 9781119276227 14, 2016.*

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PoF Approach

- General model with essential steps:
  - Identify **potential** failure sites and **failure mechanisms**
  - Expose the product / parts to accelerated stresses to find the dominant **root-cause of failure**
  - Identify and examine the dominant failure mechanism
  - **Model the dominant failure mechanism**, induce variation and optimize the design based on stress analyses
  - Design and conduct a **physical accelerated lifetime test**
  - Combine the data gathered from modelling and testing
  - Develop / apply an equation for the dominant failure mechanism and generate **time-to-failure data**

e.g. FMMEA
↓
AST
↓
FEM
↓
ALT
↓
Lifetime modelling

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Inventory of potential Failure Mechanisms

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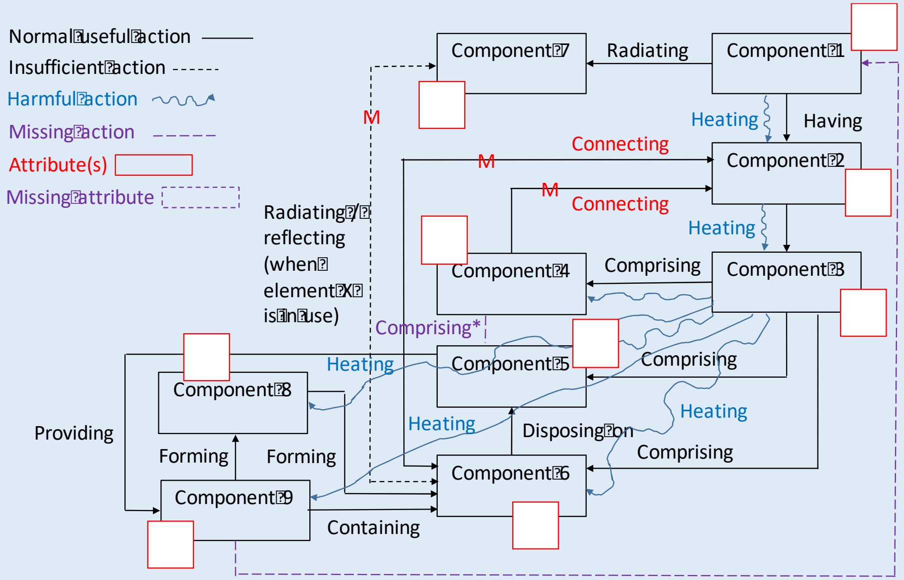
- FMMEA (Failure Mode Mechanism and Effect Analysis)
  - Using: experts, literature, field and failure data, preceding / benchmark products

Part	Function	Pot. Failure Mode	Prob.	Pot. Failure Mechanism	Effect	Severity	Failure Cause	RPN
Solder joint	Electrical interconnect	Cracked joint	1-10	Solder fatigue	Equipment failure	1-10	CTE-mismatch between substrate and component	Kans x Ernst

- FAA (Function Attribute Analysis)
  - Inventory based on coherence in the design



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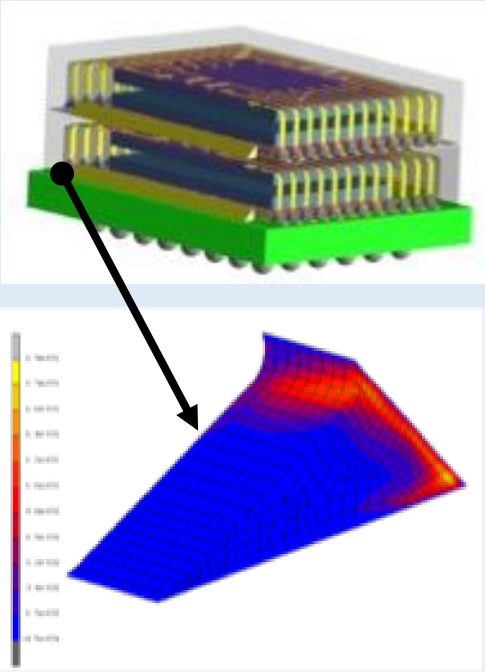
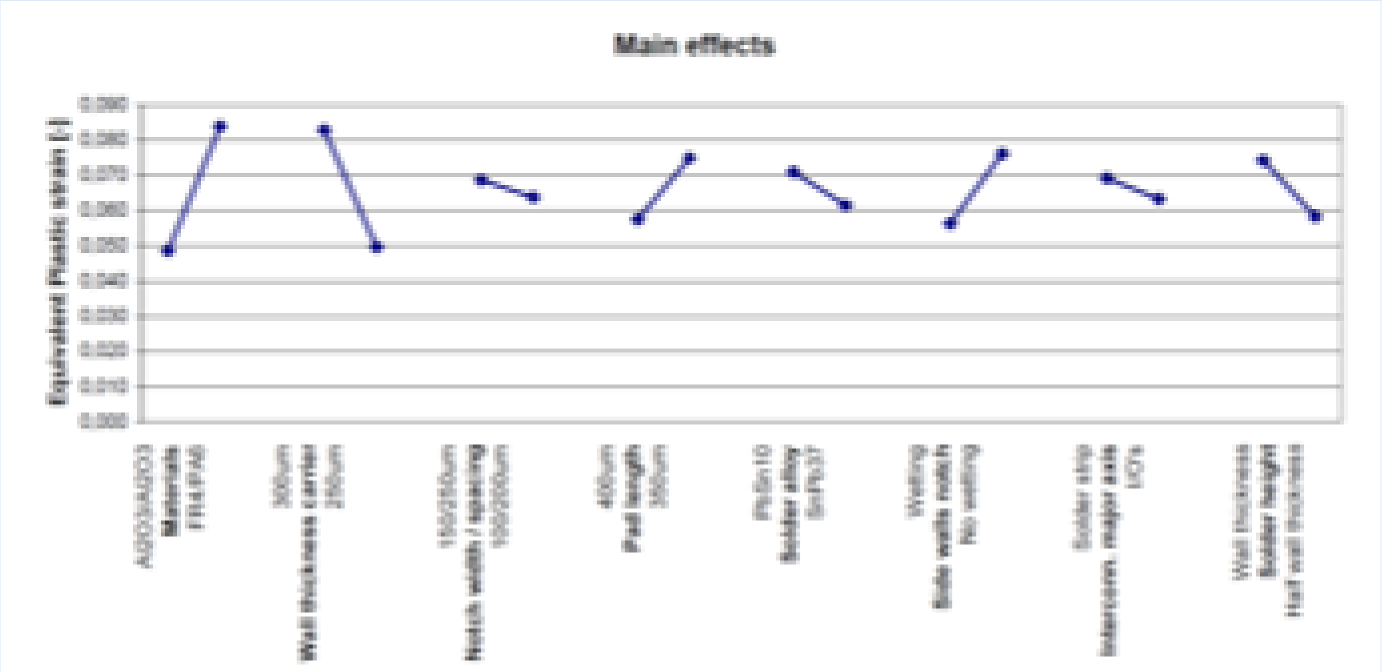
Stress & Strain Analysis using FEM and DOE

- Solder joint design for stacked Chip Scale Package (CSP)
  - Example: Total equivalent plastic strain (Temperature cycle: -40 / +125 °C)





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Robust Design Optimization

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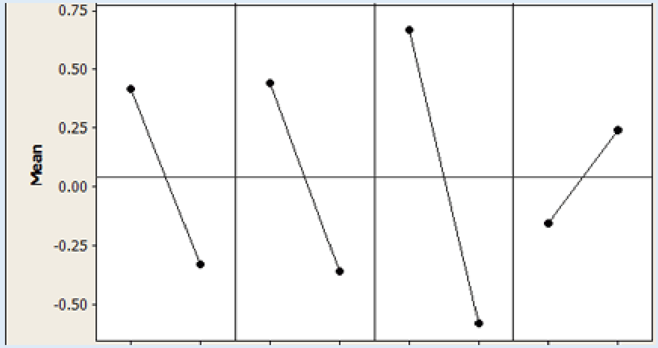
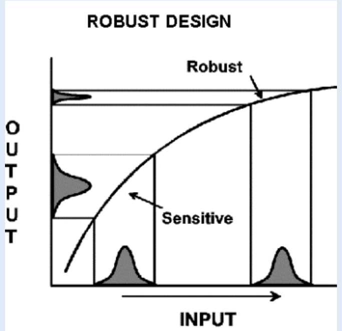
- Following the stress analysis
  - Example of a DOE-based approach:



DOE screening experiment to select significant parameters.

	Inner Array			Outer Array			
	Factors			Noise Factor 1: Level 1	Level 2	Level 3	Level 4
Run	*A*	*B*	*C*				
(1)	-1	-1	-1	5.05	6.50	7.00	7.15
a	1	-1	-1	5.05	5.05	5.35	6.15
b	-1	1	-1	5.95	6.85	7.65	7.95
ab	1	1	-1	4.65	4.95	5.35	5.00
c	-1	-1	1	6.35	7.00	7.25	7.00
ac	1	-1	1	4.05	6.55	6.15	6.45
bc	-1	1	1	6.85	7.05	7.00	8.00
abc	1	1	1	4.65	5.55	6.00	6.15

Parametric investigation based on DOE with an outer-array to optimise according to robust design principles.



Make output less sensitive to input variations.

Remark: There are various optimisation techniques and many modelling software packages have optimisation options integrated or tools available.

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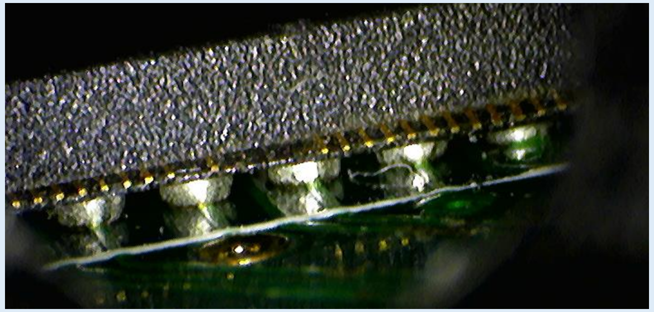
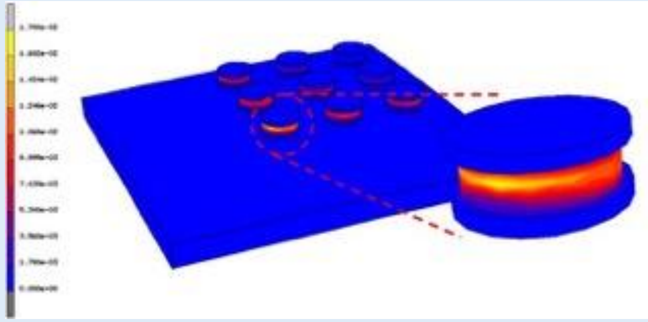
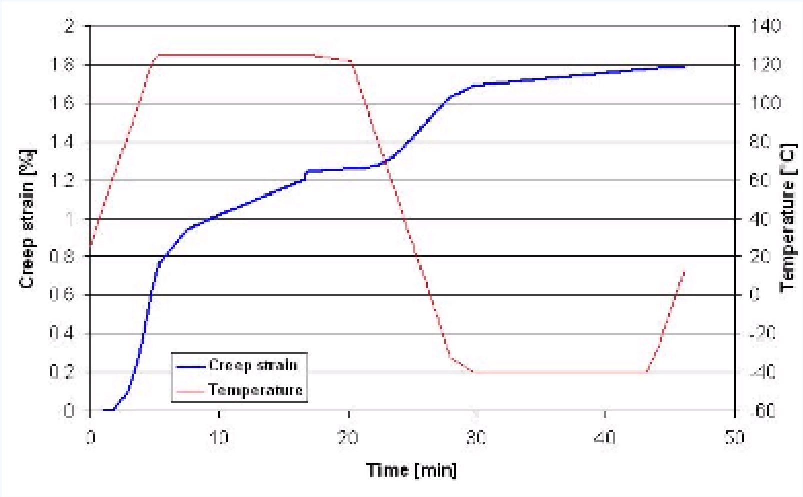
Creep Strain and Lifetime Modelling

- Example: Solder joint in BGA (Ball Grid Array) package
  - Failure mechanism: Thermo-mechanical fatigue of SnAgCu solder (+125 / -40 °C)







Example creep strain in corner joint during temperature cycle.

Time and temperature dependent creep strain modelling (hyperbolic sine equation):

$$\frac{d\varepsilon_p}{dt} = A \cdot [\sinh(\alpha\sigma)]^n \cdot \exp\left(-\frac{Q}{RT}\right)$$

Lifetime modelling based on accumulated creep strain per temperature cycle:

$$N_f = (C'\varepsilon_{acc})^{-1}$$

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PoF based Accelerated Lifetime Testing (ALT)

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- Accelerated Lifetime Testing based on inducing and accelerating the potential (dominant) failure mechanism(s)
  - Requires thorough knowledge of the product, materials, interconnects and interfaces in advance!
  - Testing can support the modelling activities (e.g. model verification, parameter generation) and vice versa (e.g. test design, unravelling the impact of test loads)
  - Can save time and costs and provides more insight compared to classical approaches such as testing according to standards or extensive programs based on operational and field load simulations.

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Root Cause Analysis within PoF

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- Common approach: a structured investigation using quality methods and tools to find underlying causes of problems or events.
  - The root cause is found when evidence is found and the problem can be "turned off and on" (concluded with a confirmation test)
- Within a PoF approach: proceed with a Failure Analysis (FA) to find the underlying failure mechanism at material level
  - A very valuable source of failure knowledge to solve issues durable and make the solutions predictable
  - Establish design rules based on failure mechanisms (fundamental, generic with broader applicability)

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PLOT Reliability Workgroup

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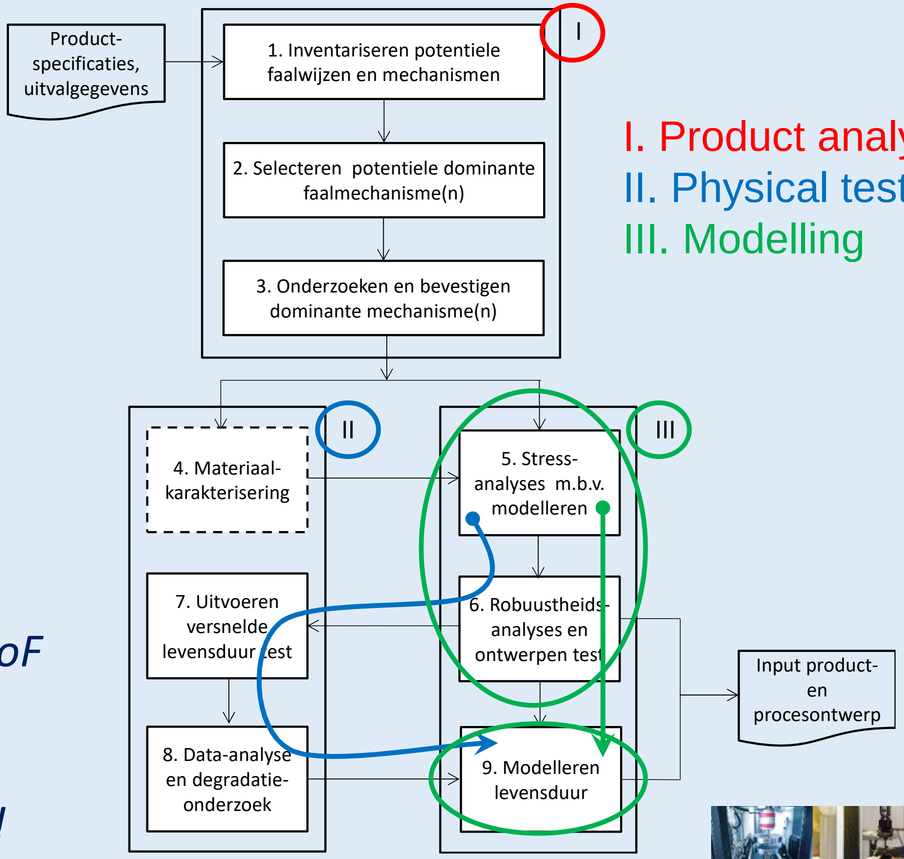
- Focus workgroup on PoF:
  - Work to be done regarding implementation in the industry
  - Theme to which many reliability-related topics can contribute
  - Upcoming topic: Robust design



I. Product analysis
II. Physical testing
III. Modelling

This is an approach to go through the PoF processes within the workgroup, not necessarily the preferred approach for embedding in a product design process!

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