



Sensor Integrating Machine Elements Congress

15 – 16 September, 2026 in Darmstadt, Germany

Development of Modular Sensor-Integrating Bolts with Self-Sufficient Energy Supply – Interim Results

MiMoSe II (SPP2305) – The Microelectronic Modular System For Sensor-integrating Machine Elements

Matthias Hüls, Ibrahim Parvez Thamimul Ansari, Luca Häfner, Hoc Khiem Trieu, Eckhard Kirchner, Dieter Krause

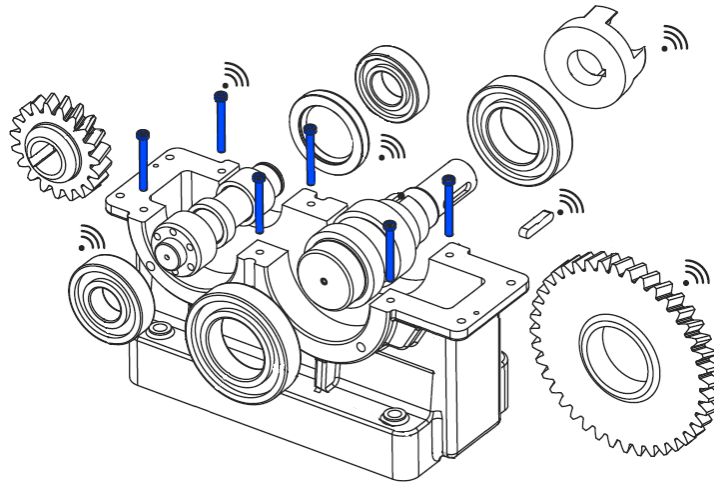
Sensor-integrating Bolts and Methodological Approach

Optimization of Energy Consumption

Derivation of Test Procedures from Requirements

Implementation in the Configuration Process

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Developing the Microelectronic Sensor Systems

Derivation of requirements and compatibility conditions for the modular sensor system, followed by component selection for a sensor-integrating bolt, interface specification, and system integration.

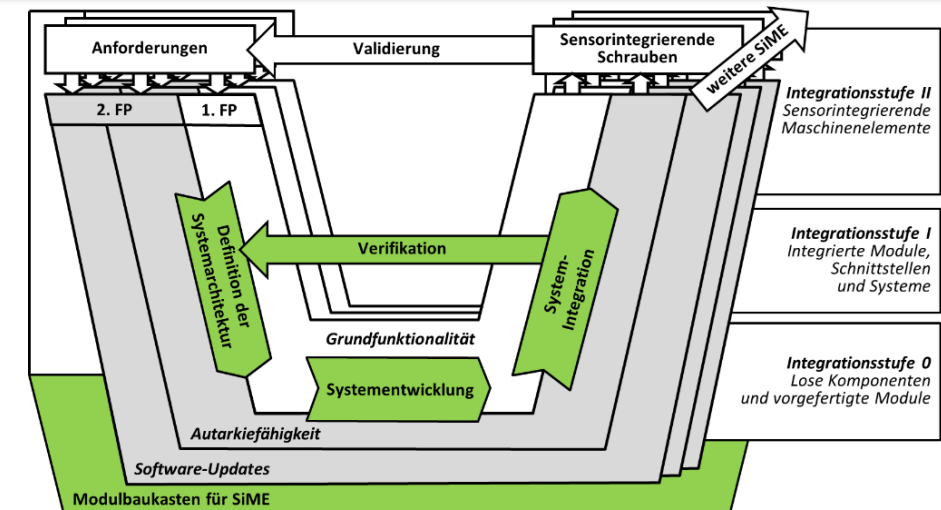
Operation and Verification of SiME

Analysis of requirements, followed by integration and testing of the sensor-integrating bolt. The resulting test procedures and findings are generalized for SiME.

Methodological Approach



Research into a modular system (modular kit) for sensor systems and development configurator, initially demonstrated using sensor-integrating bolts and subsequently generalized to other SiME. The modular system is represented in a system model using SysML and serves as the source of truth. The configurator is linked to the system model and provides solutions based on various optimization strategies.

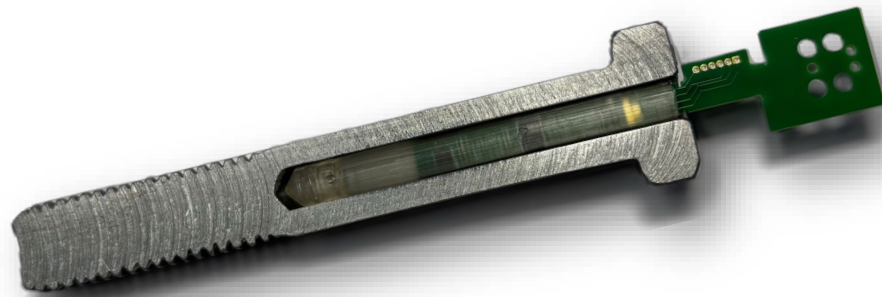


Kirchner et al. 2024; Küchenhof et al. 2024

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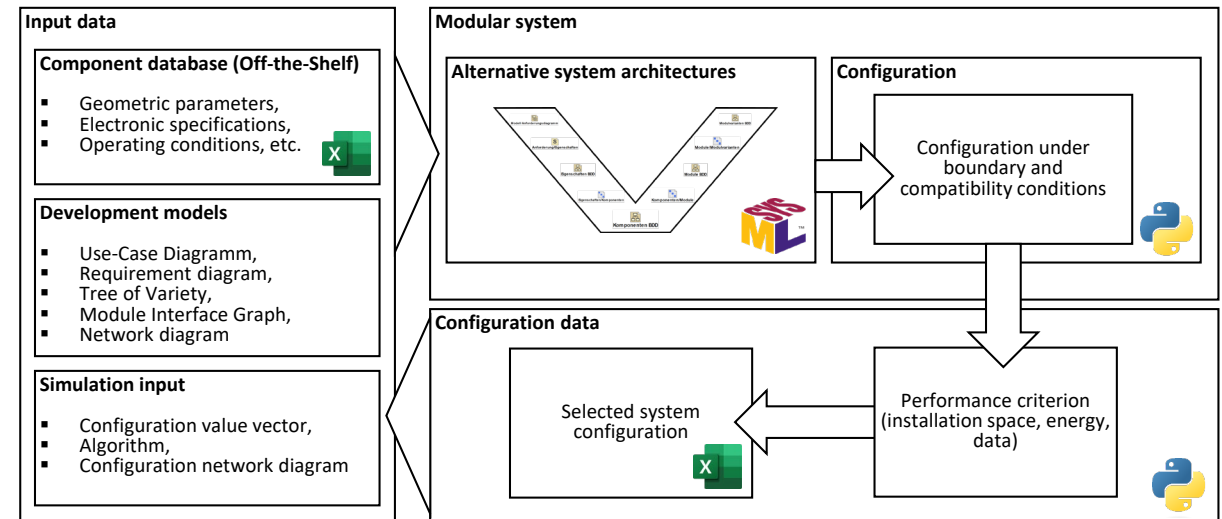
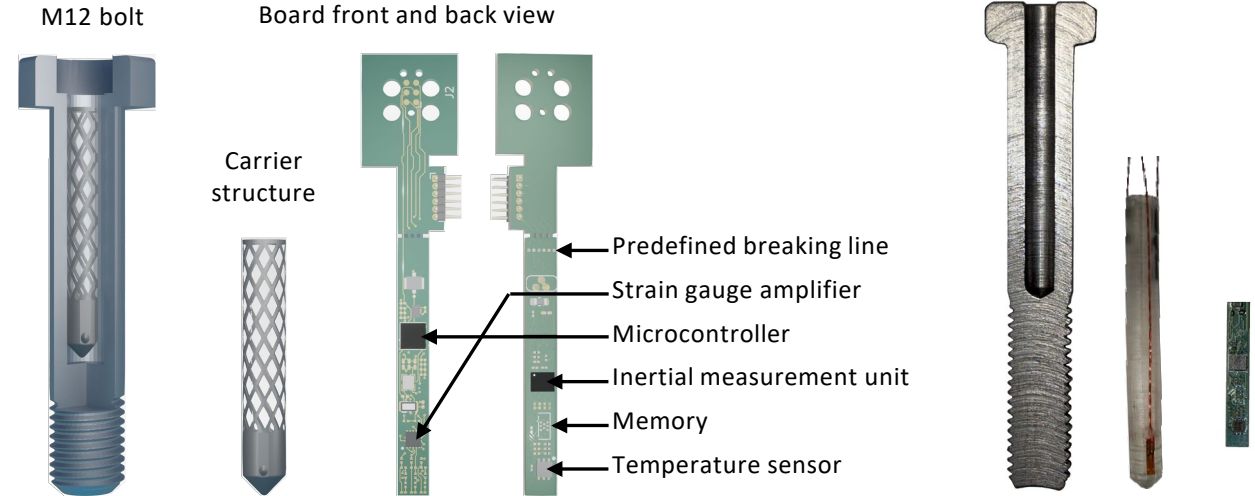
Sensor System and Physical Architecture

A sensor system derived from the modular system was validated. The physical architecture of the SiME bolt was developed and also validated.



First Systems Model and Configurator

Along with the first modular system, a corresponding configurator was implemented, and an approach incorporating various artifacts and tools was formulated.



Küchenhof et al. 2024; Häfner et al. 2026
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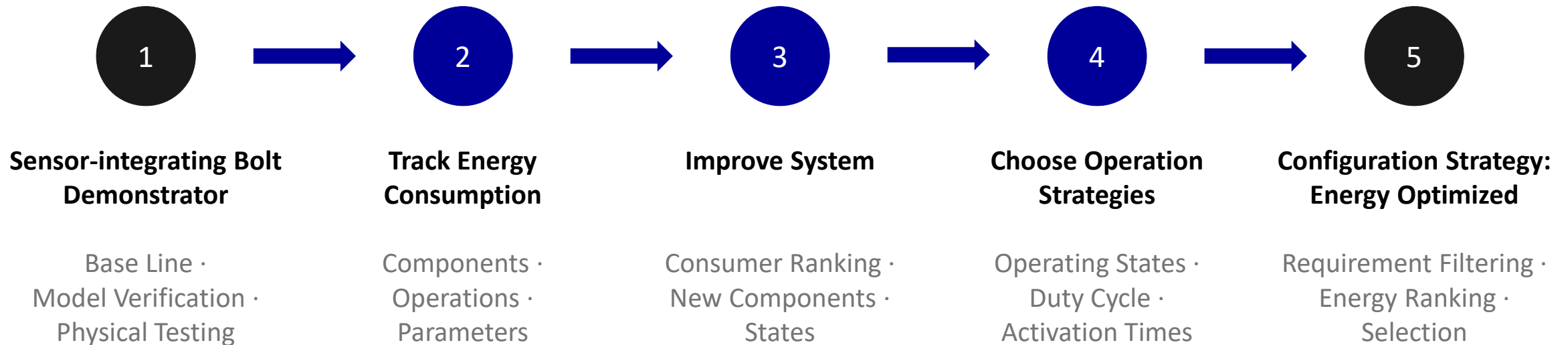
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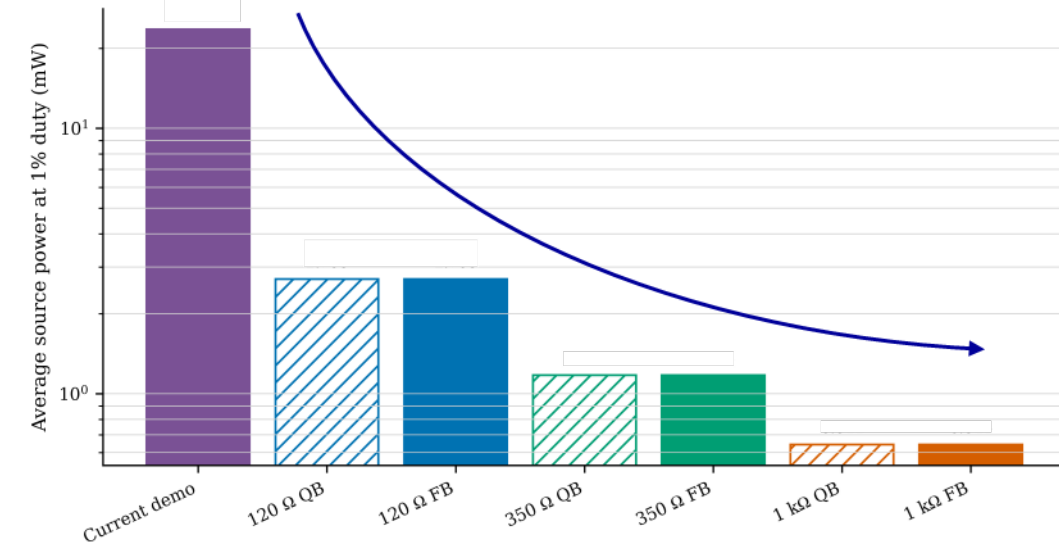
The demonstrator is used to develop a strategy for energy optimized sensor system configurations:



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Averaged power over the duty cycle for the sensor-integrating bolt demonstrator at 3.3V (Version1):

Components / Operations	Electrical Power at Different Duty Cycles [mW]		
	Continuous	10% duty	1% duty
3x Strain Gauges; no switch	23.2	23.2	23.2
Microcontroller 1	25.0	2.6	0.3
...	...	...	...
CMOS Switch bias/leakage	3.3×10^{-5}	3.9×10^{-5}	4.0×10^{-5}
Total average	58.7	27.3	23.6



Averaged power over the duty cycle for the sensor-integrating bolt demonstrator at 3.3V (Version2):

Components / Operations	Electrical Power at Different Duty Cycles [mW]		
	Continuous	10% duty	1% duty
3x 1 kΩ Strain Gauges Bridged	28.8	2.9	0.3
Microcontroller 2	24.1	2.5	0.3
...	...	...	...
CMOS Switch bias/leakage	3.3×10^{-5}	3.9×10^{-5}	4.0×10^{-5}
Total average	63.2	6.3	0.6

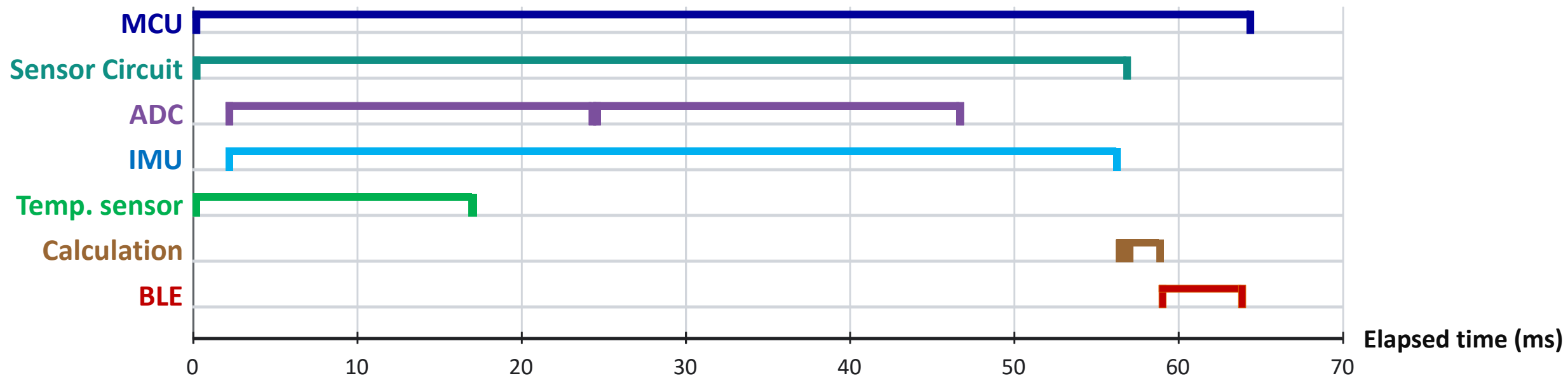
Energy Consumption Behavior

Relative to the duty cycle, different components exhibit varying behavior in terms of energy consumption.

To characterize their behaviour, three different strategies of operation are defined:

- 100 % duty cycle (continuous)
- 10 % duty cycle
- 1 % duty cycle

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Event Train for 20 s:



Out Strategy: 1% Duty Cycle

A 64 ms measurement event repeats every 6.4 s and the node sleeps for about 6.3 s between events ($f=0,16$ Hz).

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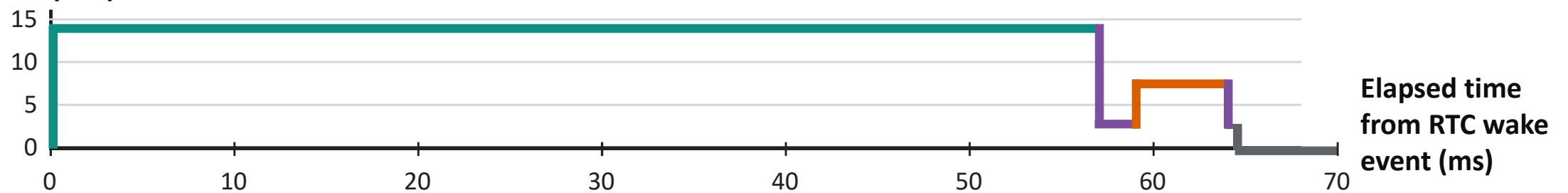
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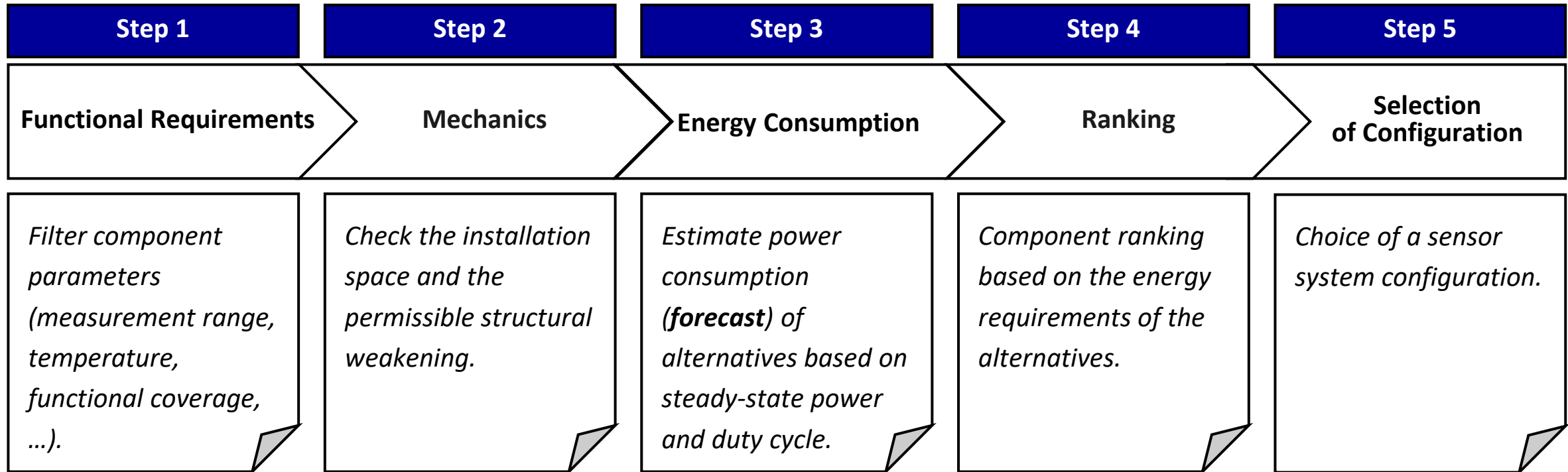
Design Changes:

- Switch the strain path
- Use 1% duty cycle
- Select 1 kΩ full bridges
- Migrate to different Microcontroller

Source Current (mA) at 3.3V



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... but forecast $\neq$ evidence
An energy-optimized alternative is only reliable once the model assumptions and requirements have been tested under realistic conditions.

Sensor-integrating Bolts and Methodological Approach

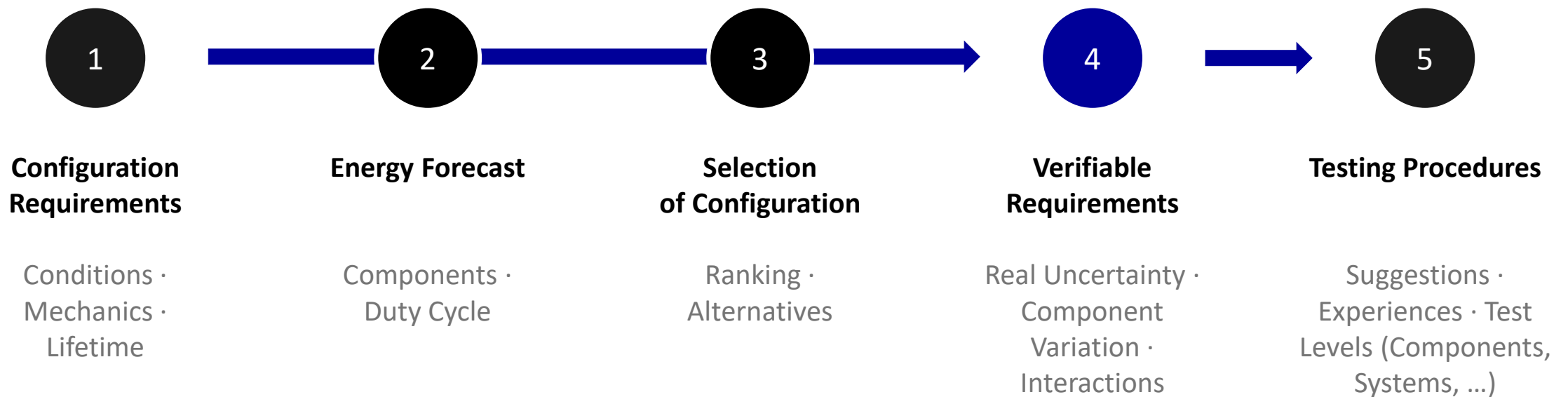
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Sensory Function & Measurement Quality



- **Testing** measurement precision & accuracy in lab
- **Testing** precision & accuracy under real conditions
- **Testing** drift of SGs under thermal load
- ...

Mechanical Primary Function



- Load-bearing capacity **calculations** for weakened bolt
- FEM-**Analysis** to check influence of shank bore
- Tensile **test** on bolt to verify theoretical analyses
- ...

Energy Consumption



- **Calculation** of required power and energy
- **Simulation** of EM compatibility & heating
- **Measurement** of energy consumption under thermal load
- ...

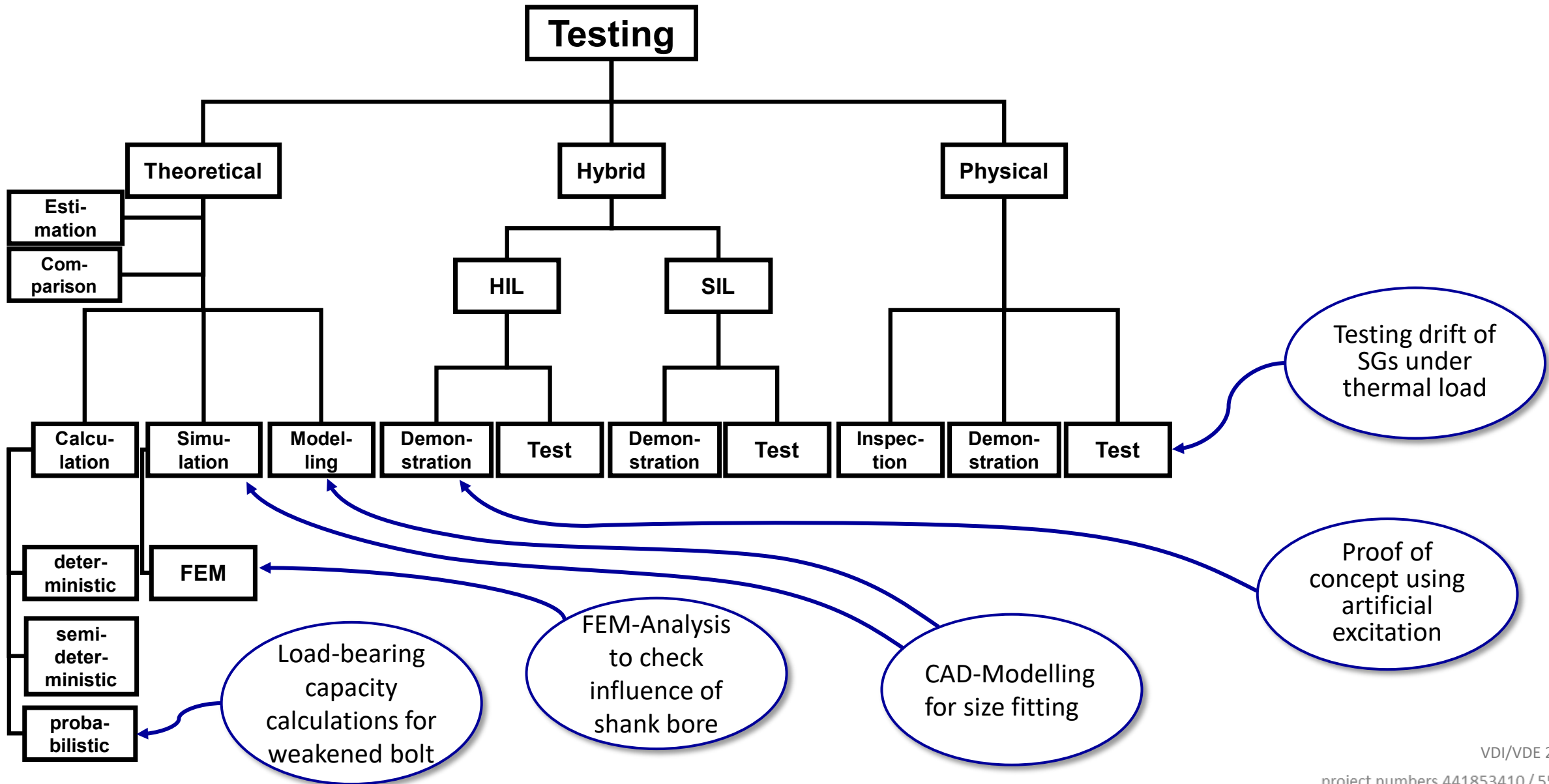
Lifetime and Durability

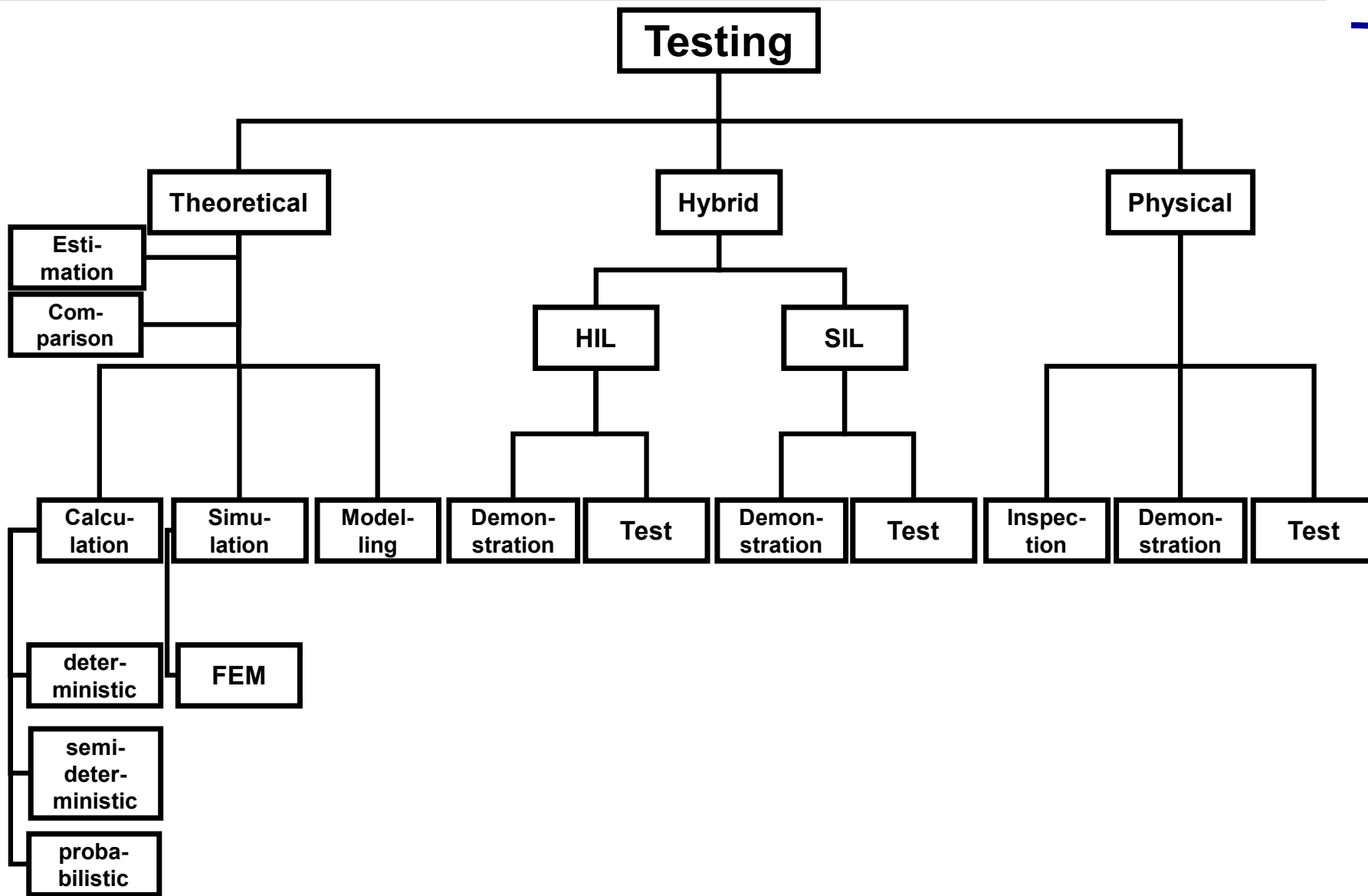


- **Calculation** of damage intervals for mech. structure
- Heat cycling **test** for electronics
- Long term heat exposure **test** under load
- ...

Further Areas

- Proof of concept using artificial excitation
- CAD-Modelling for size fitting
- ...

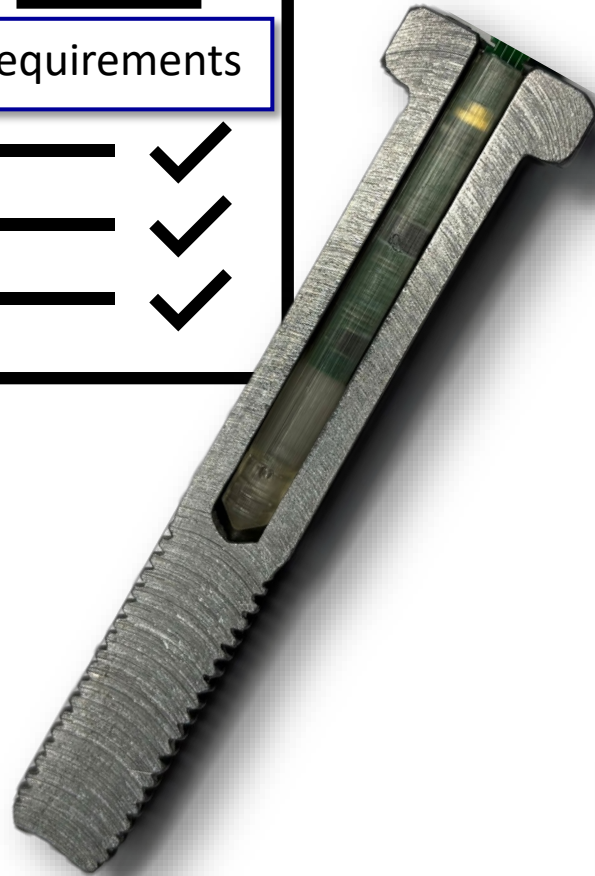
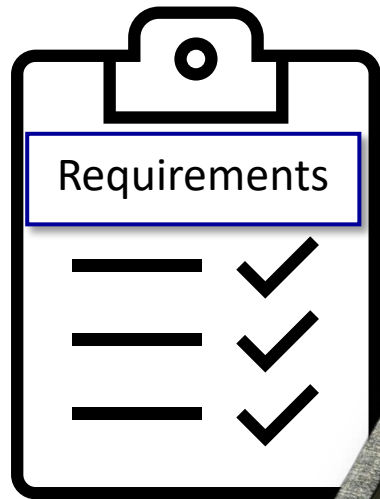




Test Procedures
Estimation
Comparison
Calculation
Simulation
Modelling
Demonstration
Inspection
Test

VDI/VDE 2206:2021

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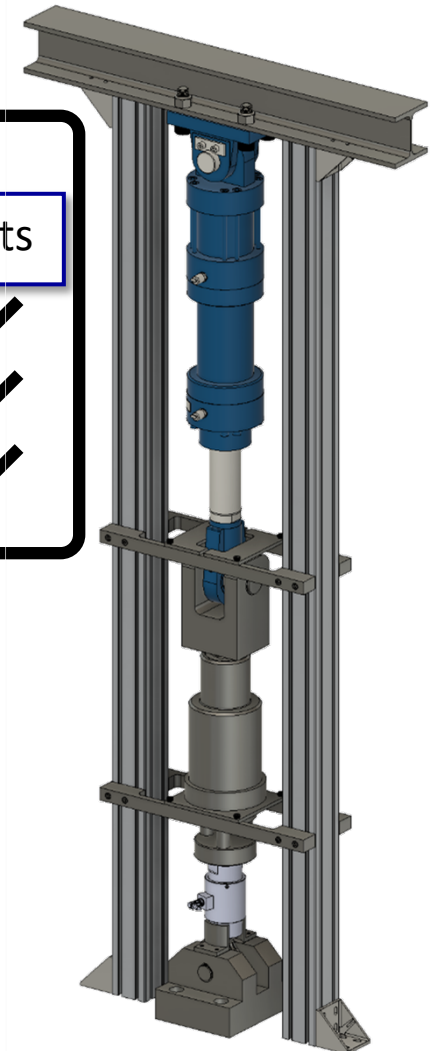
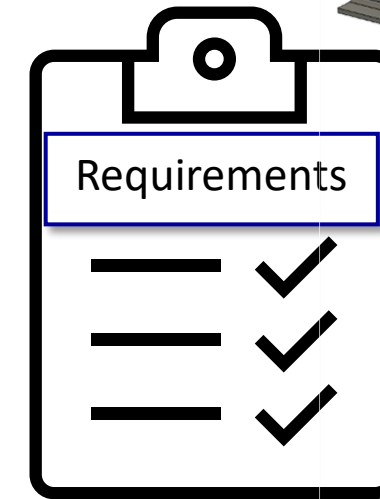


How to Derive Test Procedures and Test Requirements?

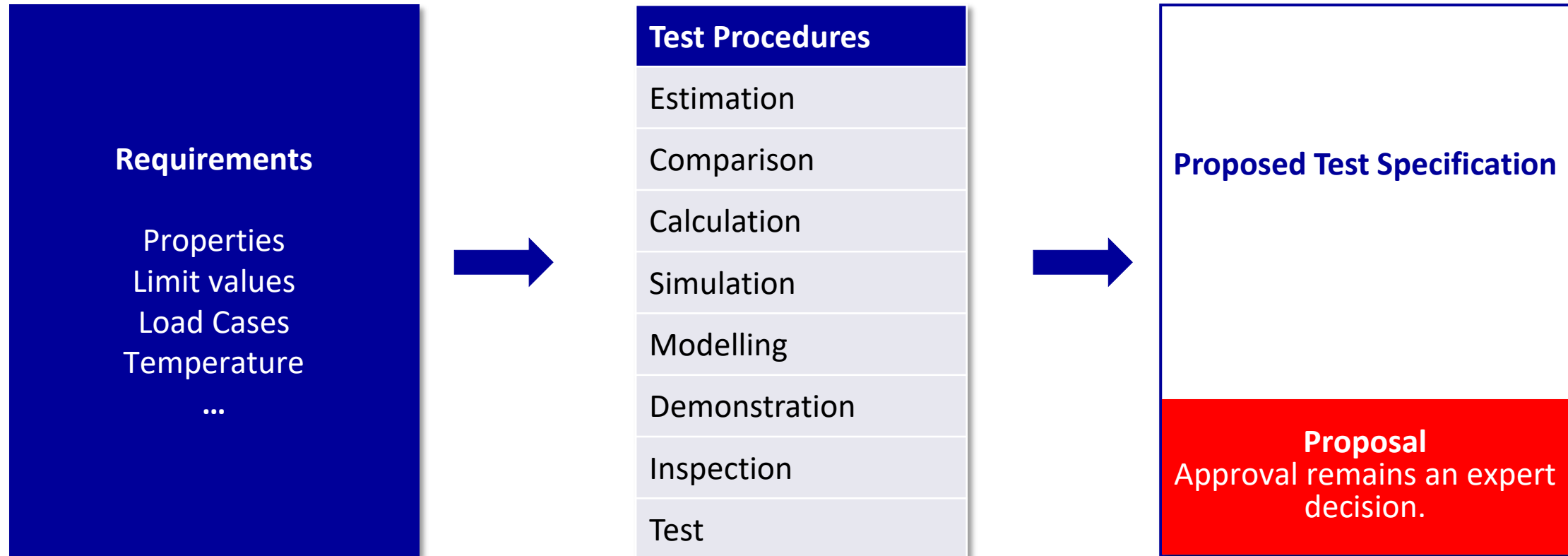
Limited data available, as research and industry have different requirements:

- The **lack of a specific application scenario** leads to implicit requirements
- A **reduced focus on commercialization** results in generic customer needs
- A **focus on general feasibility** causes detailed requirements management to take a back seat

Need for further research on data collection.



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Requirements + selected alternative $\Rightarrow$ specific, traceable test procedure proposal

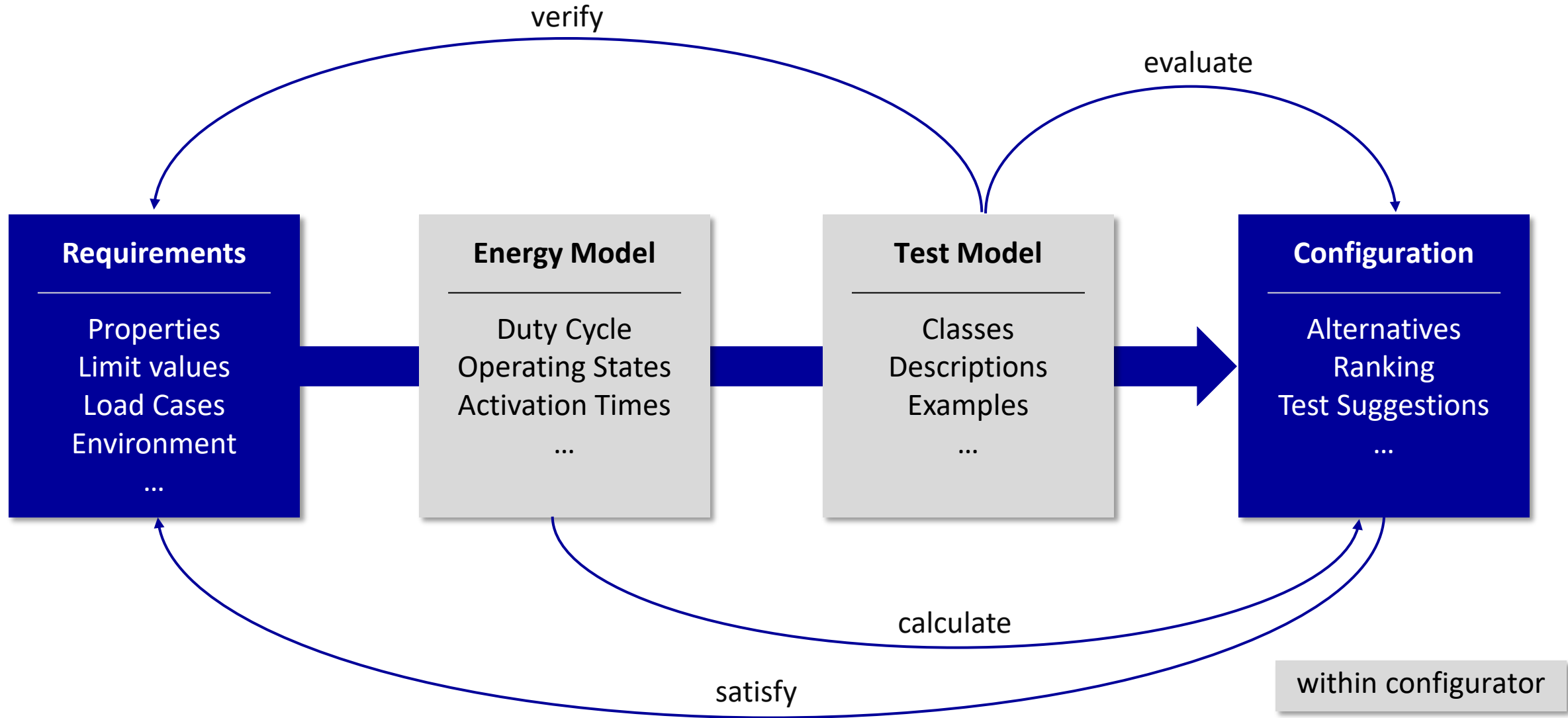
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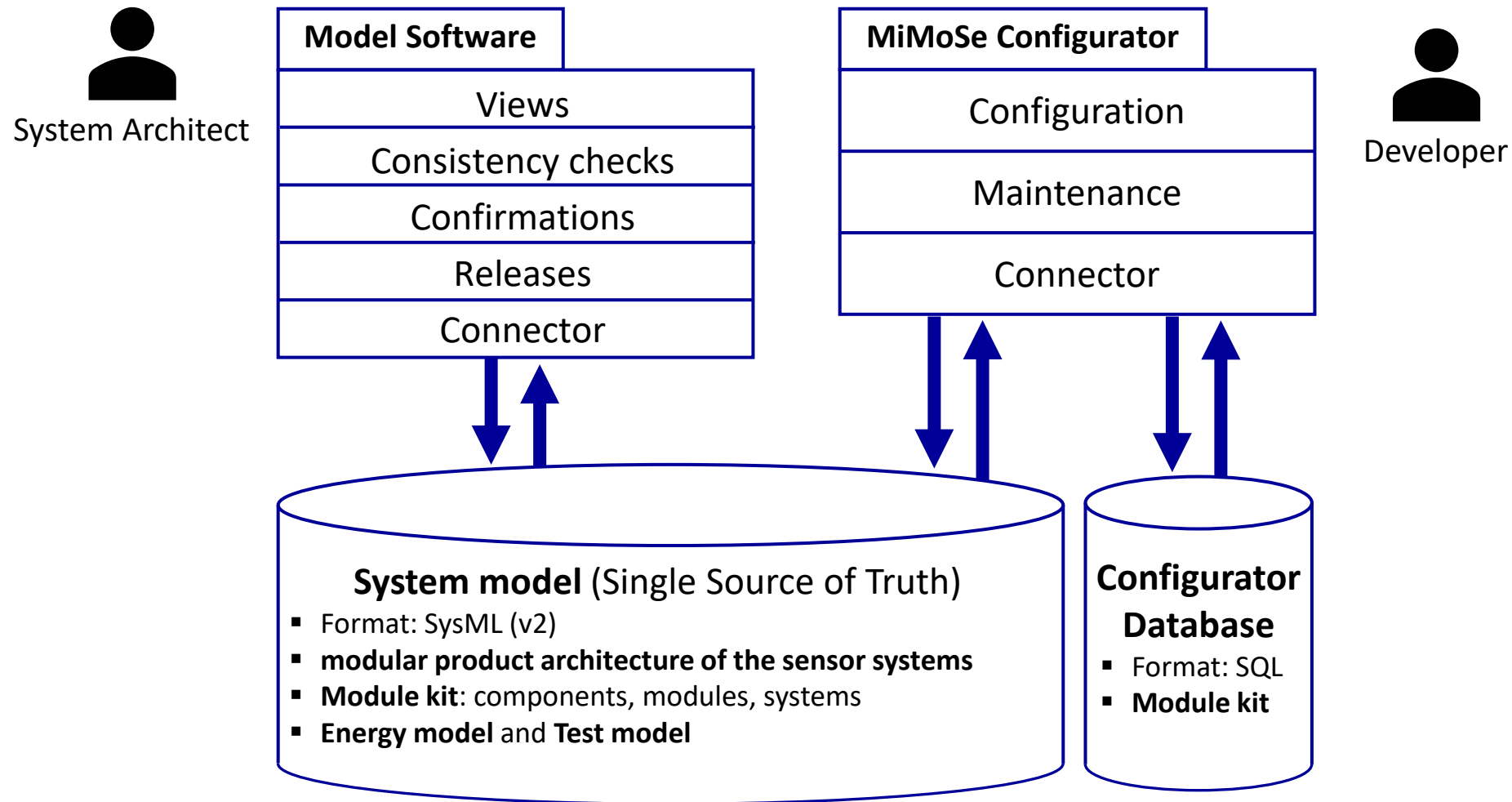
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ENGINEERING WORKSPACE
SPP2305 **MiMoSe Konfigurator** Lokale Datenbank verbunden

Außendurchmesser D	Innendurchmesser d
20 mm	10 mm
Abstand z von der Mitte	Nutzbare Länge L
2 mm	60 mm
Maximale Spannung σ_{max}	
500 N/mm ²	

Berechnung
Verfügbares Volumen **1.630,54 mm³**
Maximale Axialkraft **117.809,72 N**
Berechnen

D: Außendurchmesser · d: Innendurchmesser · z: Abstand von der Mitte · L: nutzbare Länge

Currently Implemented

- ✓ Capture requirements and boundary conditions
- ✓ Calculate mechanical element parameters
- ✓ Filter admissible configuration alternatives
- ✓ Handle multi-functional components
- ✓ Present solutions in a comparable form

New generation configurator for space optimized configurations



ENGINEERING WORKSPACE

MiMoSe Konfigurator

Lokale Datenbank verbunden

Maschinenelement

Strategie

Umgebung

Messziele

Elementparameter

Datenübertragung

Energie

Lösungen

SCHRITT 7

Energieversorgung und Lebensdauer

Die Energiequelle bestimmt, welche Versorgungsfunktionen benötigt werden.

Energiequelle

☐

Kabelgebundene Versorgung

Externe Energieversorgung

☒

Batterie

Autarke Versorgung durch Energiespeicher

☐

Energy Harvesting

Energie aus der Umgebung gewinnen

Ziellebensdauer

5

Jahre

Nutzungsprofil / Duty Cycle

8 h/Tag, Messung alle 10 s

Partially Implemented

Component parameters
I(active), I(sleep), U, ...

Operating profile
states, frequencies, duration

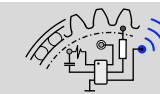
Calculation
P, energy demand, lifetime

Decision
filtering, ranking

Energy-related Metrics For Each Alternative



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ENGINEERING WORKSPACE
SPP2305 MiMoSe Konfigurator
Lokale Datenbank verbunden

Batterie · Schema 64%

Power-Management-Funktion · Schema 90%

MAX77734 82,4
 Power-Management-Funktion · Schema 90%

TPS65561 82,2
 Power-Management-Funktion · Schema 90%

Lösungsvorschläge

Empfohlene Variante 71,8 / 100
 Bewertung 71,8 bekanntes Volumen 124,52 mm³ bekannte Leistung 0,0512 W

Kraft / Drehmoment	1-kΩ-Dehnungsmessstreifen (Typ offen)	Temperatur	adt7410
Verarbeitung + Datenübertragung	CY8C27643	Batterie	BCT1812M101AG
Energieversorgung	LTC3107		

Name der Systemkonfiguration

Lösung auswählen

Variante 2 71,8 / 100
 Bewertung 71,8 bekanntes Volumen 119,97 mm³ bekannte Leistung 0,0519 W

Requirement Specification + Selected Alternative

Rule-Based Derivation

Parameters from requirements
Verification methods for component types

Test Procedure Proposal

Setup · Load profile ·
Measured quantities ·
Acceptance criterion · Traceability

Expert Review Remains Mandatory

Energy Consumption

Duty Cycle · Standby Current ·
Peak Load

Testing Procedures

Actual loads · Measurable
Criteria

Energy Harvesting

Source · Conversion ·
Availability

Data Transmission

Range · Reliability · Safety

Data Optimization

Sampling Rate ·
Preprocessing

Update Strategies

Safety · Low-energy ·
Roll-backs

We also present the current configurator live at our conference booth

Visit us, try a configuration, and discuss the configurator with us!

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