



Holistic Conceptual Design of Sensor Modules for Machine Elements

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Agenda

1 Motivation & Research Questions



2 Derivation of a Development Methodology for SiME



3 Identification of Insufficiently Supported Methodology Steps/ State of the Art



4 Optimization of Identified Methodology Steps



5 Future steps + Proposal



Motivation

- SiME (Sensor-integrating Machine Elements) integrate sensory functions into standard machine elements
- Established development methodology is missing!

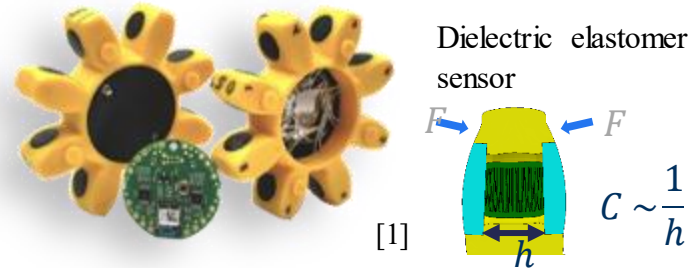


Initial Research Questions:

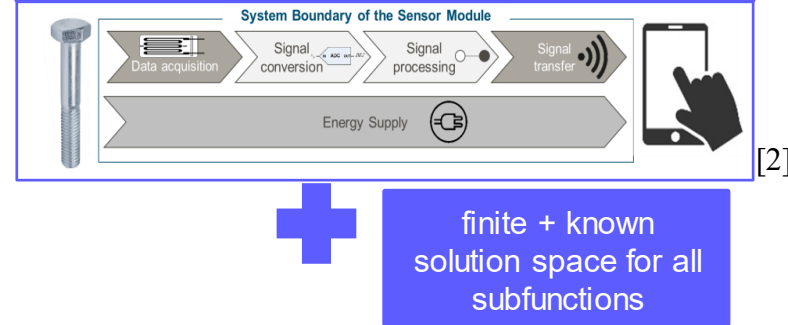
- 1. How can the development of SiME modules be achieved, enabling users to find new concepts by widening the solution space?*
- 2. Can the methods usability be increased by appropriate digital tools?*



Example:
Sensor-integrating gear coupling



Consistent function structure of SiME¹



[1] Menning et al (2025) Forschung im Ingenieurwesen 89(1), 139 (additional picture provided by authors)

[2] Kirchner 2024: A Review on Sensor-Integrating Machine Elements P. 3

- **RQ 1:** How can a holistic methodology for the development of SiME be structured?

- **RQ 1.1:** Which methodological substeps need to be considered, and how relevant are they to the user? What requirements must the methodology meet?
- **RQ 1.2:** For which of these steps are methods already available in the state of the art, and to what extent do they meet the requirements imposed on the methodology?
- **RQ 1.3:** How can previously unaddressed substeps of the overall methodology be implemented?



- **RQ 2:** How can developers' knowledge be effectively utilized?

- **RQ 2.1:** How can general engineering knowledge be permanently incorporated into the methodology?
- **RQ 2.2:** How can individual user knowledge be incorporated into specific applications of the methodology?
- **RQ 2.3:** How can individual knowledge be transferred to permanently used knowledge



- **RQ 3:** Can the methods usability, effectiveness and efficiency be increased by appropriate digital tools?

Motivation

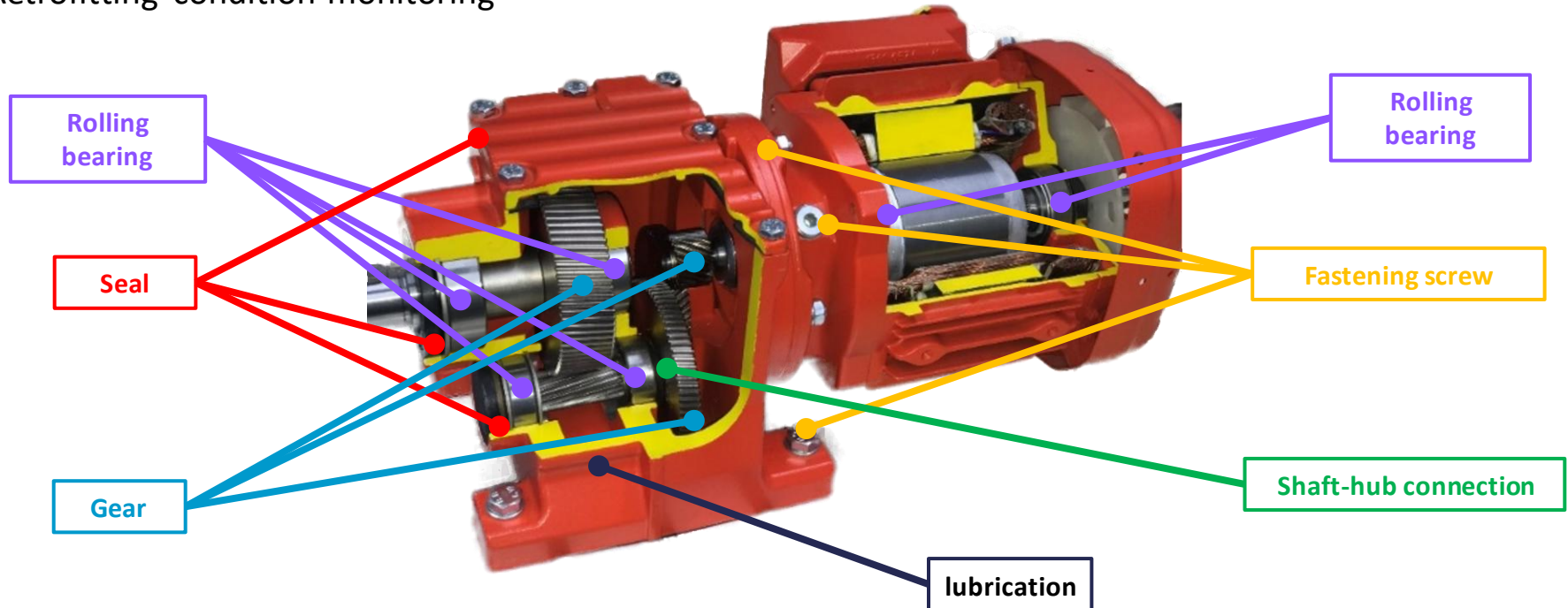
Exemplary Overall Goal



Task

Retrofitting condition monitoring

Surrounding conditions



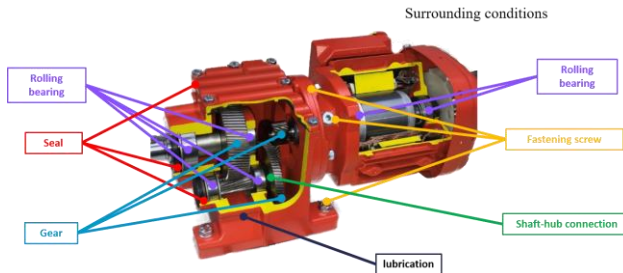
Motivation

Exemplary Overall Goal



Task

Retrofitting condition monitoring to an old motor



Methodology

Determining

- Measuring principle
- Measuring location (available ME)
- Needed components and compatibility
- Robustness/ disturbance variables
- (Weakening of the ME)
- Filtering of variants and ranking of solutions

Solution

measuring radial force of the motor axle through force measuring screw



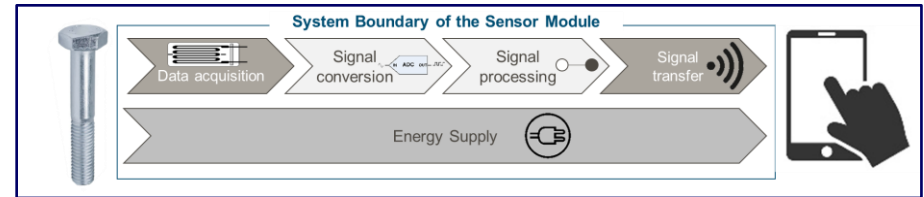
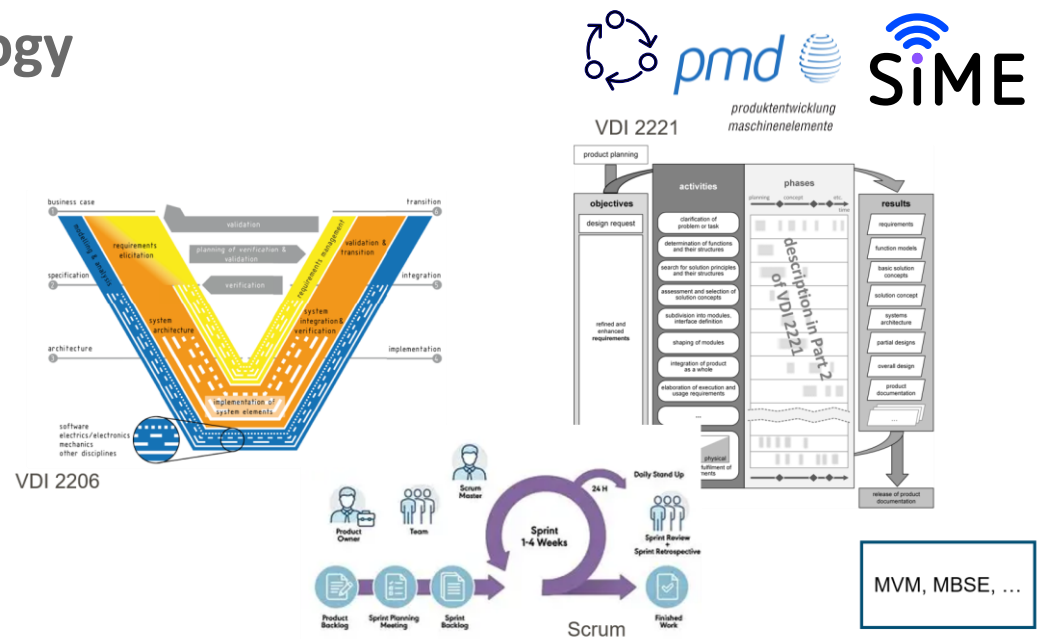
[1]

+ Distinct component list for realisation

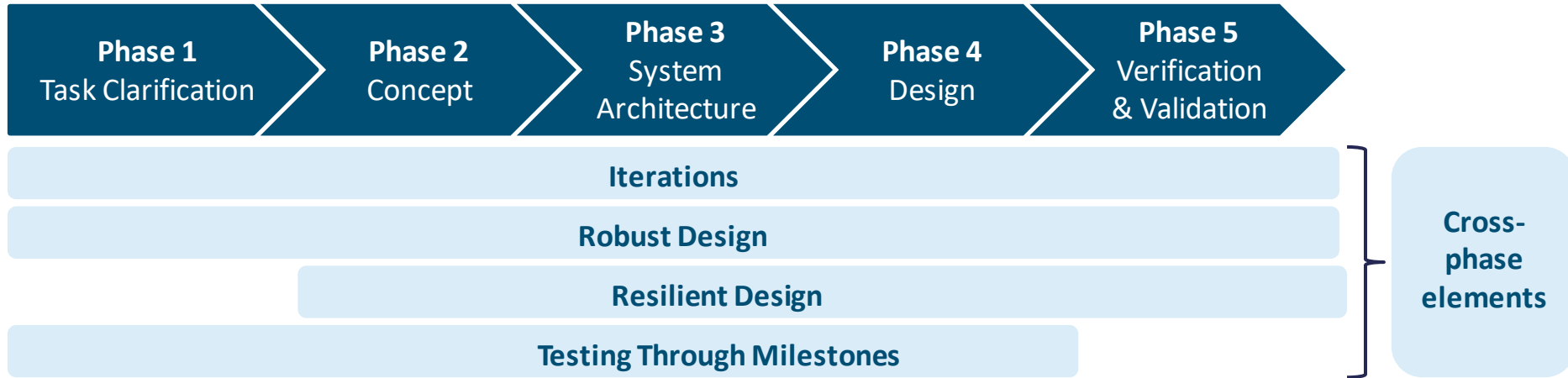
Derivation of the Methodology

Derivation through:

- Existing general development frameworks
- Analysis of SiME development processes
- Requirements
 - Literature analysis for requirements on development processes
 - Analysis of SiME development in particular
 - Questionnaire at SPP2305



Macro Structure of the Methodology



Summarized key requirements

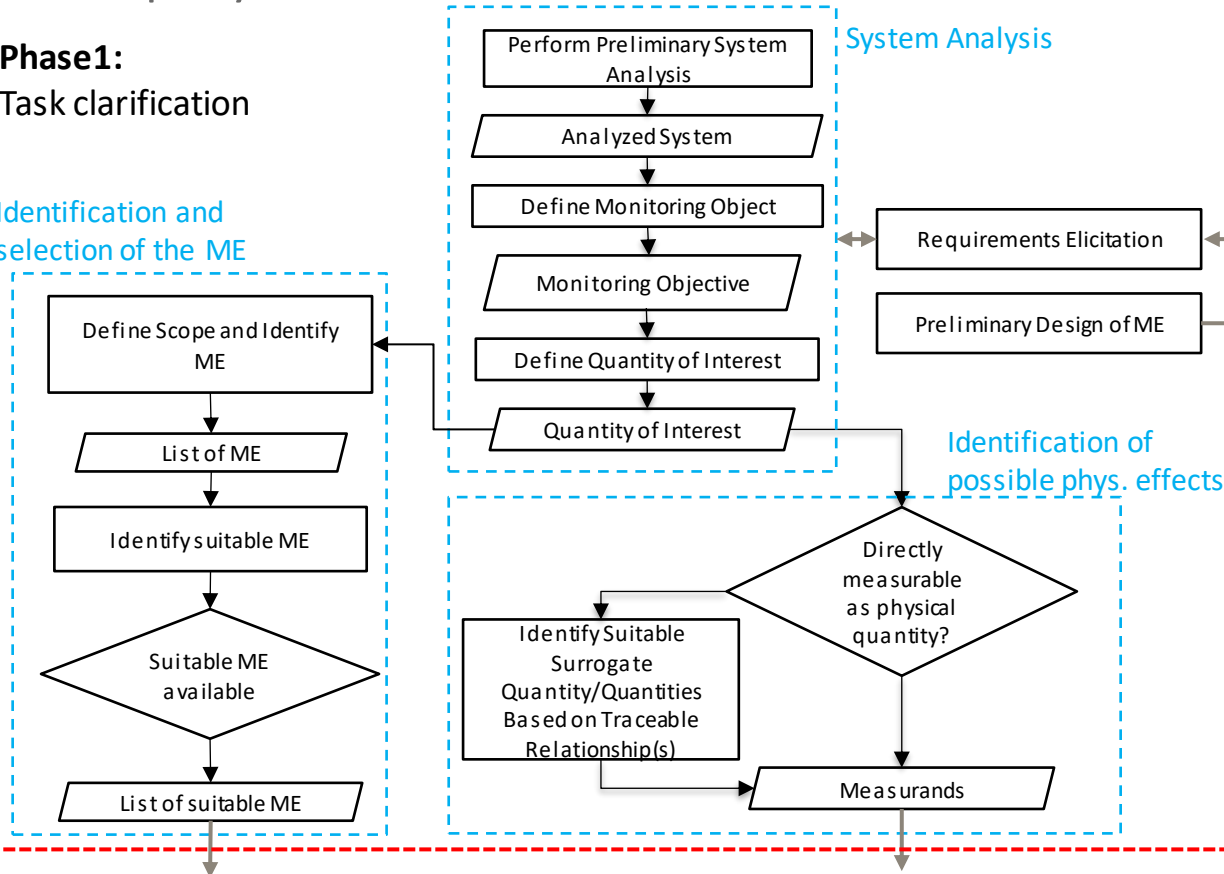
- User acceptance
- Holistic view on sensor modules
- Rise in result quality and development efficiency
- Customizability and usage of user knowledge
- Traceability of results
- Digital support

Micro-Structure of the Methodology

Exemplary for Phase 1

Phase1: Task clarification

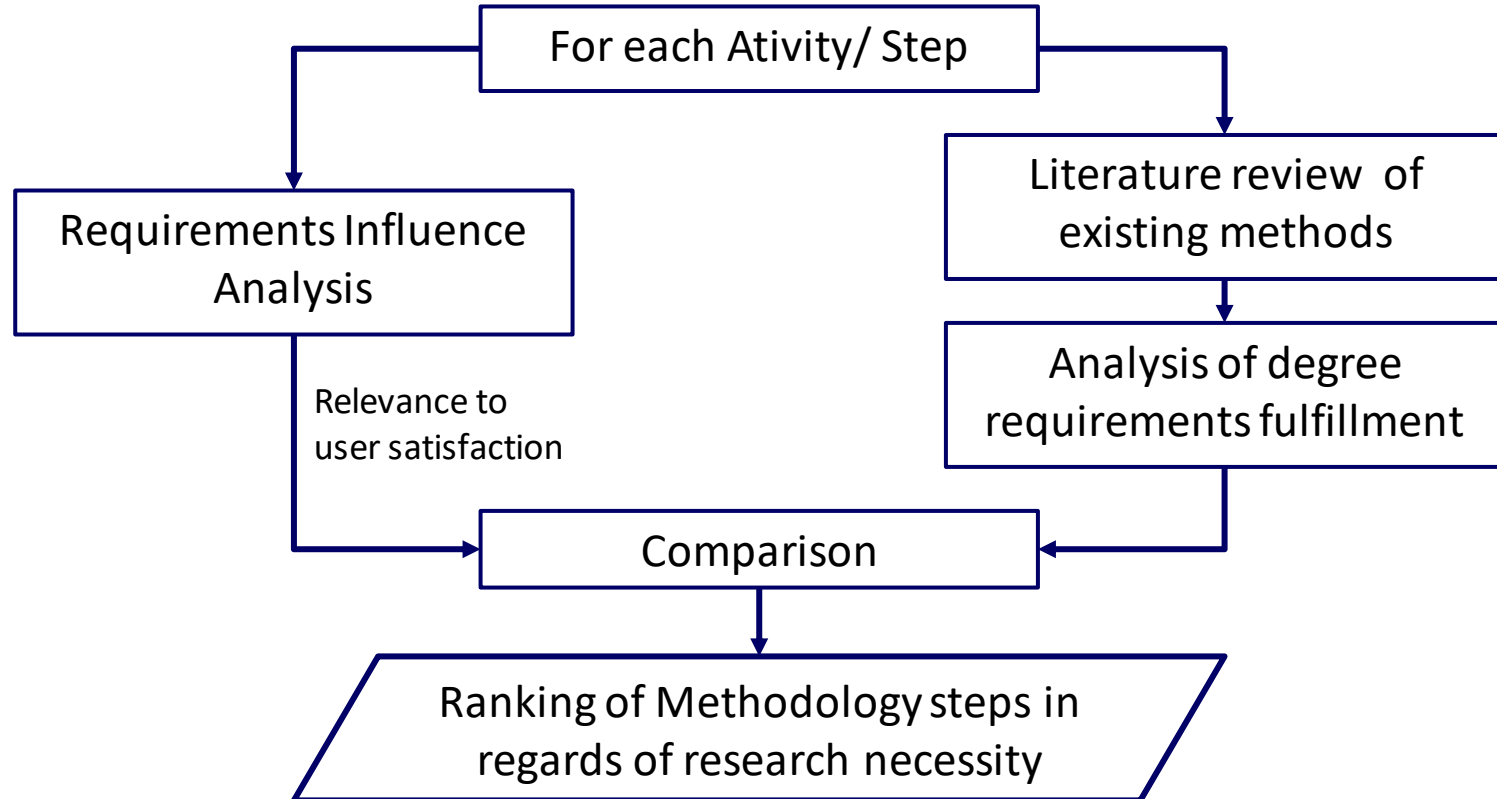
Identification and selection of the ME



- Relevance of Activities to the user can be identified through influence analysis on requirements
- For each Activity/ step individual existing methods can be identified and requirement fulfillment analyzed
- Gaps in the methodological support of individual steps become apparent.

Phase 2

Identification of Insufficiently Supported Methodology Steps



Existing Methods – State of the Art



pmD
produktentwicklung
maschinenelemente



Prof. J. Walter Labor Informationstechnik Hochschule Karlsruhe Technik und Wirtschaft				Anforderungsliste für Linienverfolger				Auftrag: Informationstechnik Labor WS20 Auftragsnummer: iM-L09			
Organisations- Daten		Prozess-Daten		Anforderungen				Wert - Daten			
Nr.	Name	Art	Phase	Physikalisch-Technische Funktion				Mindest- Erfüllung	Soll- Erfüllung	Ideal- Erfüllung	Einheit
F01	MaWe	F	P	Sensorenempfang				3,3V			Volt
F02	MaWe	J/N	P	Funktion auf Whiteboard							
F03	MaWe	J/N	P	Verwendung des ESP-32							
F04	MaWe	W	P	Farberkennung				0,00 & 255,255,255	0,00 & 255,255,255	0,00 & 255,255,255	RGB
F05	MaWe	W	P	Funktion auf Monitor							
F06	MaWe	W	P	Erkennung der Ledelanlage							

Quality Function Deployment (QFD)

House of Quality

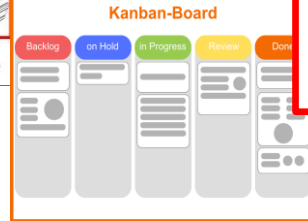


IONOS

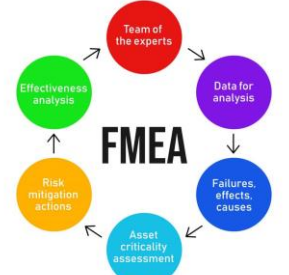
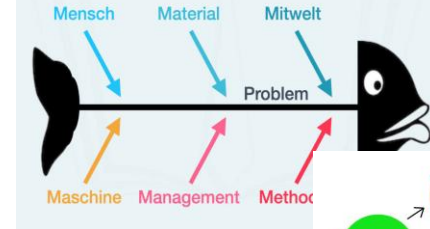
Nutzwertanalyse											
Beurteilung 10 - 1 Höherwertig ist besser											
Teilnutzen (Wert) = Gewicht x Beurteilung											
Nutzwertanalyse											
Kriterien / Maßnahmen	Gewicht (G)	Projekte / Alternativen									
		1	2	3	1	2	3	1	2	3	
		Beurteilung (B)	Wert (G*B)		Beurteilung (B)	Wert (G*B)		Beurteilung (B)	Wert (G*B)		
Strategie	20	10	200		4	80		10	200		
Dauer	15	8	120		4	60		2	30		
Ressourcen	15	6	90		5	75		2	30		
IT-Architektur	10	6	60		6	60		1	10		
Sicherheit	15	4	60		7	105		6	90		
Weitere Nutzung	5	4	20		8	40		7	35		
Imagegewinn	5	10	50		9	45		8	40		
Kosten	15	9	135		10	150		9	135		
Nutzwert	100		735								

Paarweiser Vergleich											
0 weniger wichtig 1 gleich wichtig 3 wichtiger											
Bewertung											
Nähe zum Strand	1	3	1	0	1	0	1	1	0	7%	
Sauberkeit des Wassers	1	3	1	0	1	0	1	1	0	7%	
Kulturelles Angebot	0	0	1	0	1	0	1	1	0	4%	
Freizeitangebot	1	1	1	0	1	0	1	1	0	6%	
Sicherheit im Urlaub	3	1	3	1	0	1	0	1	0	12%	
Nähe zum Strand	3	1	0	1	0	1	0	1	0	6%	
Sauberkeit des Wassers	3	1	0	1	0	1	0	1	0	18%	
Kulturelles Angebot	1	1	1	0	1	0	1	1	0	7%	
Freizeitangebot	1	1	1	0	1	0	1	1	0	7%	
Sicherheit im Urlaub	3	3	3	3	3	3	3	3	3	25%	

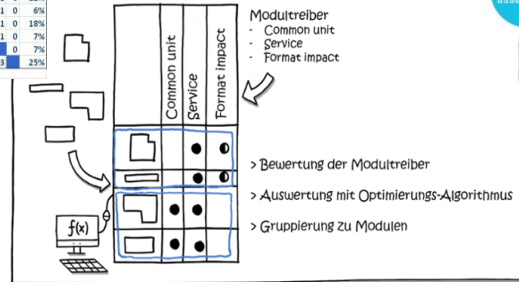
...and so on...



Ishikawa-Diagramm



MFD Modular Function Deployment



State of the Art

Effect Catalogues by VORWERK-HANDING & KRAUS



pmd
produktentwicklung
maschinenelemente

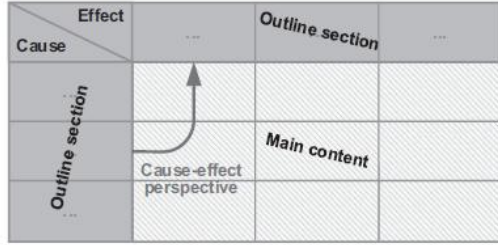
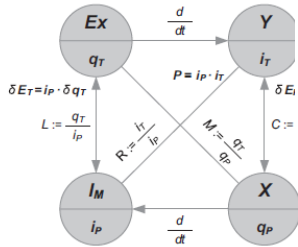
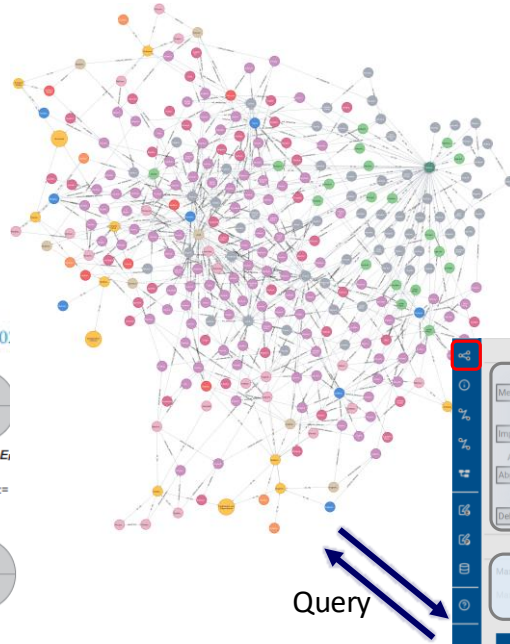


Figure 7. Schematic structure of the effect matrix [Harder et al. 20]



Goal: linkage of physical cause and wanted physical quantity through effect chains to derive usable sensor principles



Example: force (interest) → voltage (needed for ADC) can be linked through
force → strain effect → strain → mechanical resistance variation → Resistance → Ohm's law → voltage

Graphical user interface (GUI)

Selection of dependent and independent functional variables

Filter options for the query

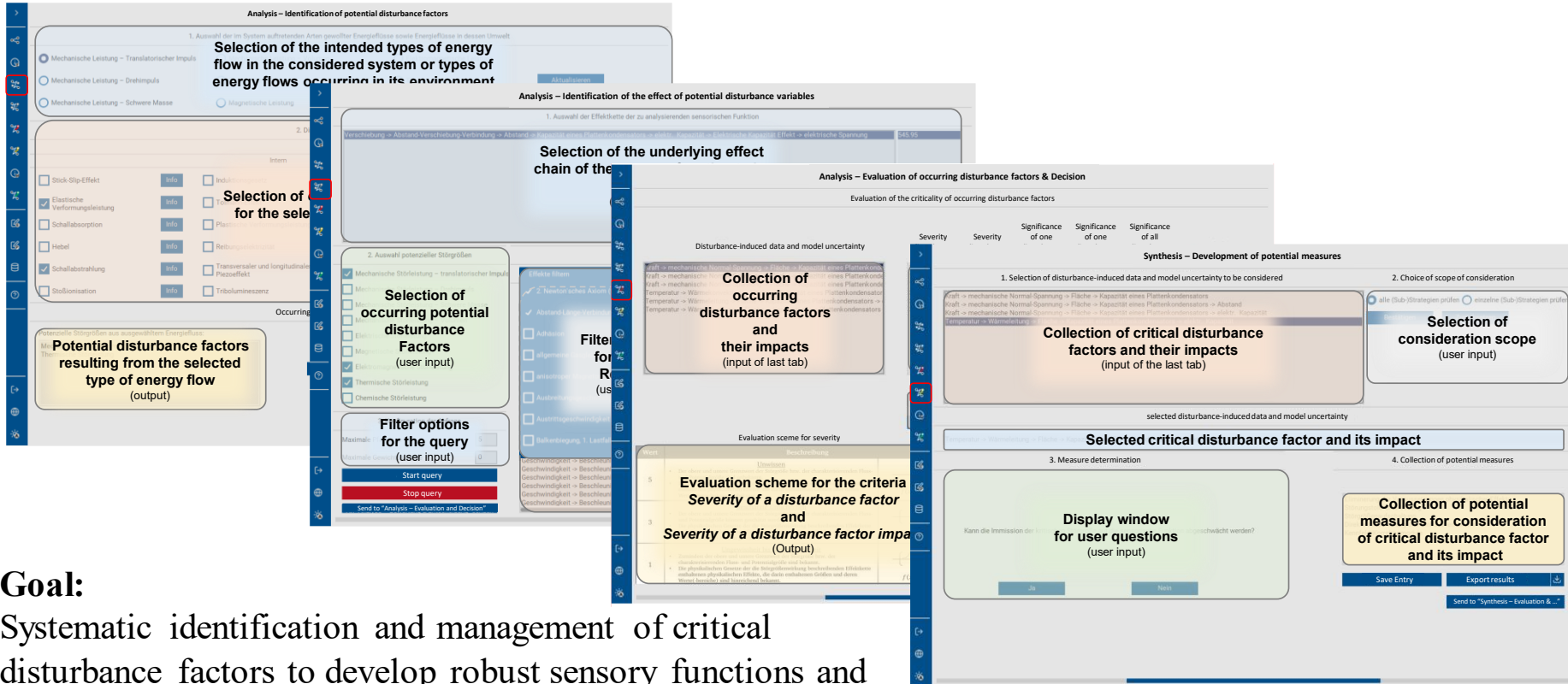
Visual representation of the selected query result

List display of all found effect chains

Filter options for query results

State of the Art

Robustness for Sensory Systems by WELZBACHER



Analysis – Identification of potential disturbance factors

1. Auswahl eines Systems auf dessen Verhalten untersucht werden soll (z.B. ein Sensor, eine Funktion, ein Bauteil, ein System)

Selection of the intended types of energy flow in the considered system or types of energy flows occurring in its environment

Mechanische Leistung – Translatatorischer Impuls
 Mechanische Leistung – Drehimpuls
 Mechanische Leistung – Schwere Masse
 Magnetische Leistung

Selection of the underlying effect chain of the

2. Auswahl der Effekte der zu analysierenden sensorischen Funktion

Verschiebung → Abstand Verschiebung Verschiebung → Abstand → ...

Selection of occurring potential disturbance factors (user input)

2. Auswahl potentieller Störgrößen

Mechanische Störleistung – translatorischer Impuls
 Mechanische Störleistung – Drehimpuls
 Mechanische Störleistung – Schwere Masse
 Magnetische Störleistung
 Elektrische Störleistung
 Thermische Störleistung
 Chemische Störleistung

Filter options for the query (user input)

Maximaler ...
 Minimaler ...
 Start query
 Stop query
 Send to "Analysis – Evaluation and Decision"

Collection of occurring disturbance factors and their impacts (input of last tab)

Disturbance-induced data and model uncertainty

Collection of critical disturbance factors and their impacts (input of the last tab)

1. Selection of disturbance-induced data and model uncertainty to be considered

Kraft → mechanische Normal Spannung → Fläche → Kapazität eines Plattenkondensators
 Kraft → mechanische Normal Spannung → Fläche → Kapazität eines Plattenkondensators → Abstand
 Kraft → mechanische Normal Spannung → Fläche → Kapazität eines Plattenkondensators → Abstand → Kapazität eines Plattenkondensators

Selection of consideration scope (user input)

2. Choice of scope of consideration

alle Sub-Strategien prüfen
 einzelne Sub-Strategien prüfen

Selected critical disturbance factor and its impact

selected disturbance-induced data and model uncertainty

Evaluation scheme for the criteria Severity of a disturbance factor and Severity of a disturbance factor impact (Output)

Evaluation scheme for severity

Display window for user questions (user input)

3. Measure determination

Kann die Immission der ... schwächer werden?

ja
 nein

Collection of potential measures for consideration of critical disturbance factor and its impact

4. Collection of potential measures

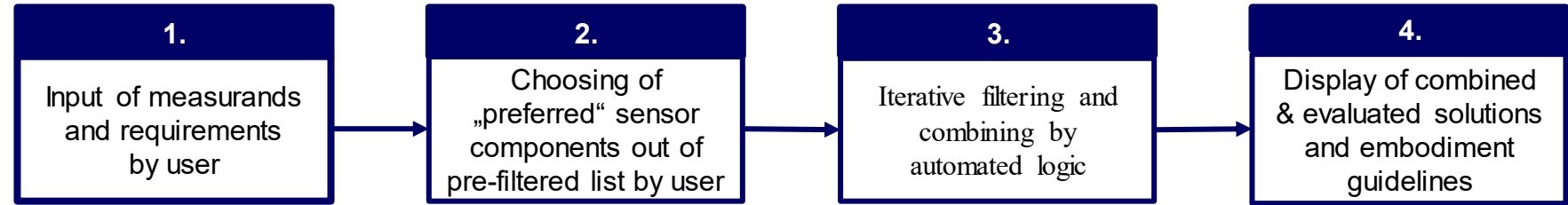
Save Entry
 Export results
 Send to "Synthesis – Evaluation & ..."

Goal:

Systematic identification and management of critical disturbance factors to develop robust sensory functions and ensure reliable measurement data.

State of the Art

Combination and Selection Method by KILIAN ET AL.



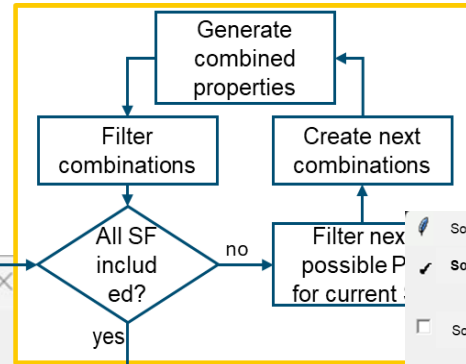
SSI-Tool – Set Requirements

criterion	Min value Downsize	Max value Upsize	unit	New min value	New max value	selection	Use selection criterion?	Required Subfunctions
Rotating system?	-	-	-	-	-	☐ stationary ☐ oscillating ☐ rotating	☐	☐ Acquire signal ☐ Filter signal ☐ Convert signal ☐ Cache signal ☐ Transfer signal ☐ Supply energy ☐ Transfer energy ☐ control energy transfer ☐ Send signal ☐ Receive signal ☐ (De)activate signal ☐ Control system ☐ Manage Database
Physical Effect	-	-	-	-	-	☐ optical ☐ resistive ☐ acoustic	☐	
Measuring range lower end	0.001	100	mm			-	☐	
Measuring range upper end	0.1	100 000	mm			-	☐	
precision	0.05	1.0	%			-	☐	
Resolution	0.01	0.1	%			-	☐	
Analog/digital	-	-	-	-	-	-	☐	
Manufacturer	-	-	-	-	-	-	☐	

Partial Solution Overview:
Acquire signal

- ☒ Photo CCD Detector
Model pmd 352819 [More Information](#)
- ☐ Piezo-Element
Model pmd 63292-50 [More Information](#)

[Continue Combination](#)



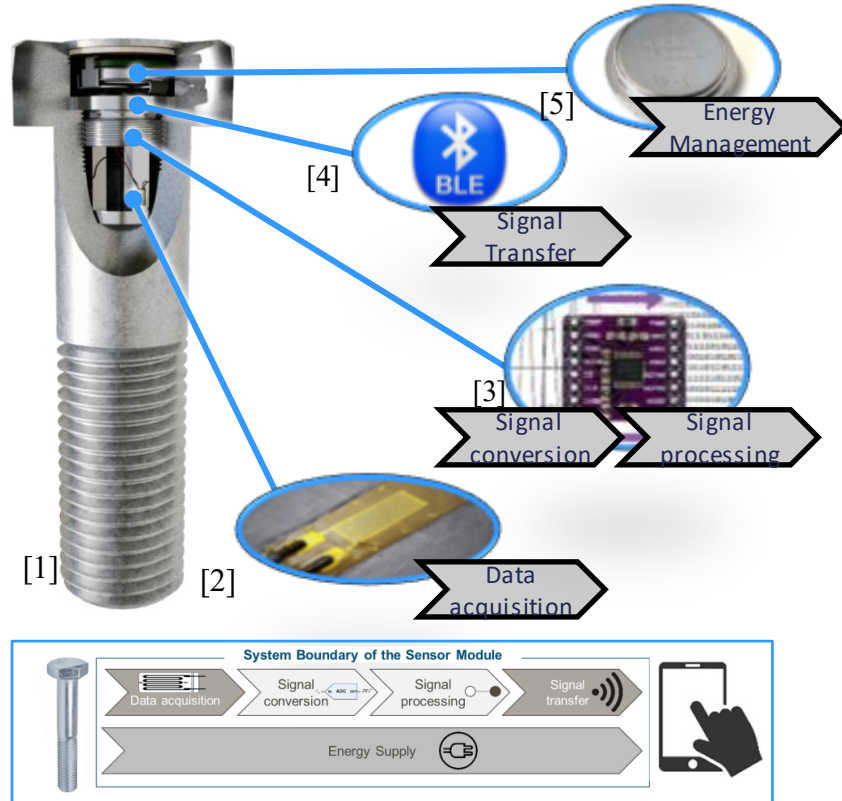
Solution-Space

Solutions	Subfunction A	Subfunction B	Subfunction C	Actions
☒ Solution 1	PS 1 PS Properties	PS 2 PS Properties	PS 3 PS Properties	Show aggregated properties
☐ Solution 2	PS 4 PS Properties	PS 5 PS Properties	PS 6 PS Properties	Show aggregated properties

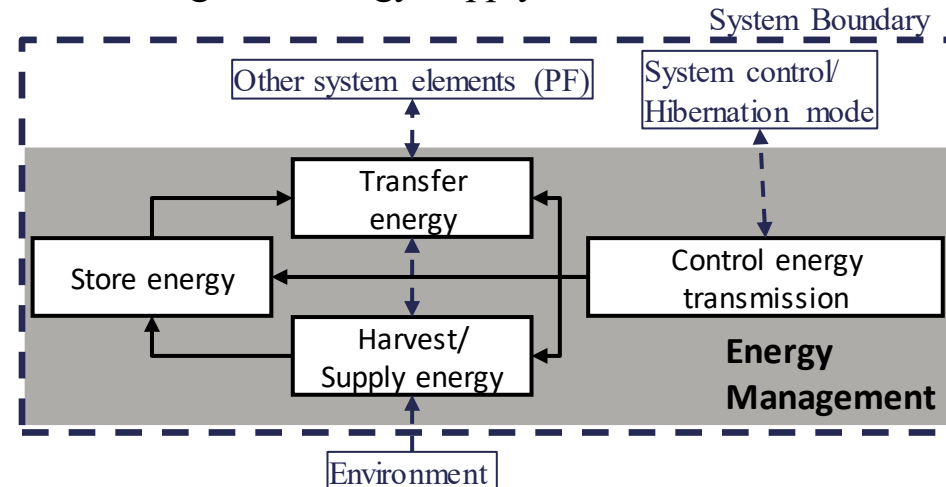
[Delete selected solutions](#)

State of the Art

Detailation of Funtion Structure – SPP2305 + Enhancement



- Additional functions are analyzed; e.g.
 - „Sleep“/Standby-Mode
 - Update & Calibration
 - Data & System Control
- Functions are decomposed into subfunctions
→ e.g. for Energy supply:

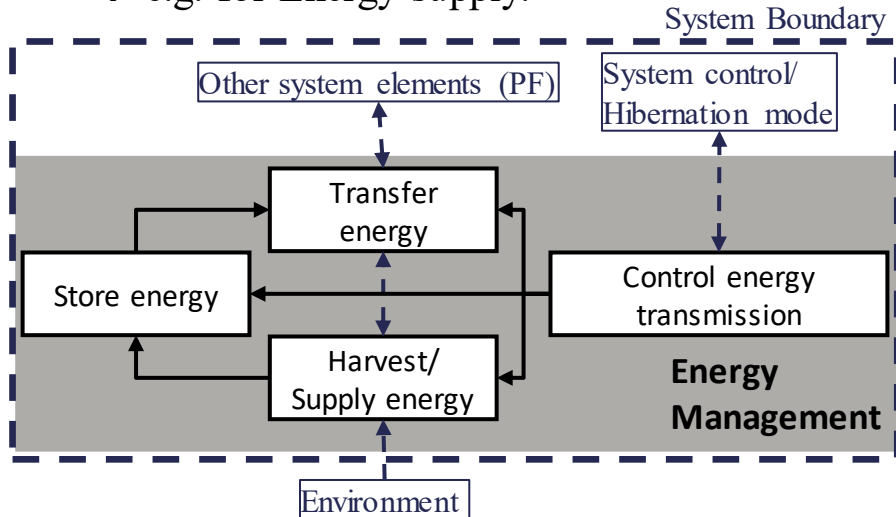


State of the Art

Function Structures Importance for the Development Method

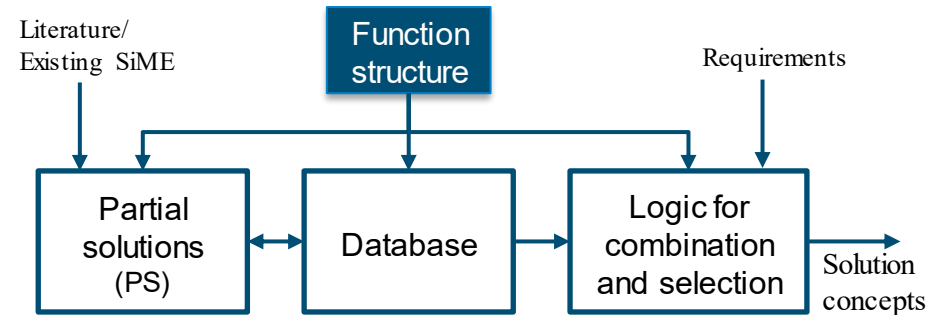


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 - „Sleep“/Standby-Mode
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→ e.g. for Energy supply:



SiME function structure enables the method development towards supported conceptualization

- Allows systematic analysis of suitable partial solutions for all identified subfunctions
- Database contains reasonable function carriers and their properties for all identified subfunctions
- Sequential combination logic of the search algorithm uses subfunctions and their interdependencies



Methodological Steps Identified as Most Relevant for Further Research

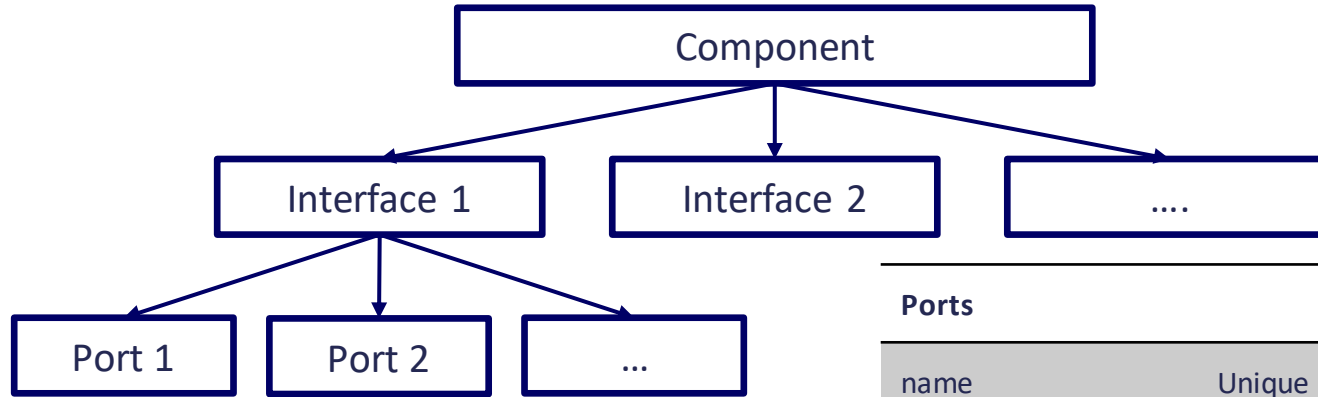
Focus Topic 1: Measurement task → measurand and measruement location	Focus Topic 2: Design for robustness	Focus Topic 3: Combination and selection of module-components
Extremely complex step with highest impact on following development steps	High relevance for functional safety	Most relevant step of the concept phase
➤ Especially insufficient: ➤ Linkage of effect chains to sensory principles ➤ Identification of potential measurement location in a system context ➤ Combining existing machine elements with effects that can be utilized within them	➤ Especially insufficient ➤ Early stage evaluation of disturbance impacts ➤ Continuos usage of robustness as evaluation criterion ➤ Recommendations for countermeasures in the design phase.	➤ Especially insufficient: ➤ Selection through compatibility checks of electronic components ➤ Evaluation of solutions ➤ Building space check

Methodological Steps Identified as Most Relevant for Further Research

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Compatability Checks

Description of Components



General Attributes of components, interfaces and technology profiles

As well as

Individual attributes for different technology profiles

Signal Port	
General	
- name	
- direction: input / output / bidirectional	
- signal_domain: electrical / optical / electromagnetic / acoustic	
- port_type: measurement_output / control_input / data_interface / status_outpup	
- role: sender / receiver / master / slave / client / server / central / peripheral	
Signal Description	
- signal_type: analog / digital / PWM / bus / wireless_packet	
- measured_quantity	
- data_format	
- value_range	

Ports	
name	Unique name of the port.
contains SignalPorts	Reference to the contained signal ports.
contains EnergyPorts	Reference to the contained energy ports.
contains CouplingInterfaces	Reference to the associated coupling interfaces.
standards	References to relevant standards, specifications, or protocols.
source	Source of the information, e.g., data sheet, norm, ...

Basic Compatability Rules

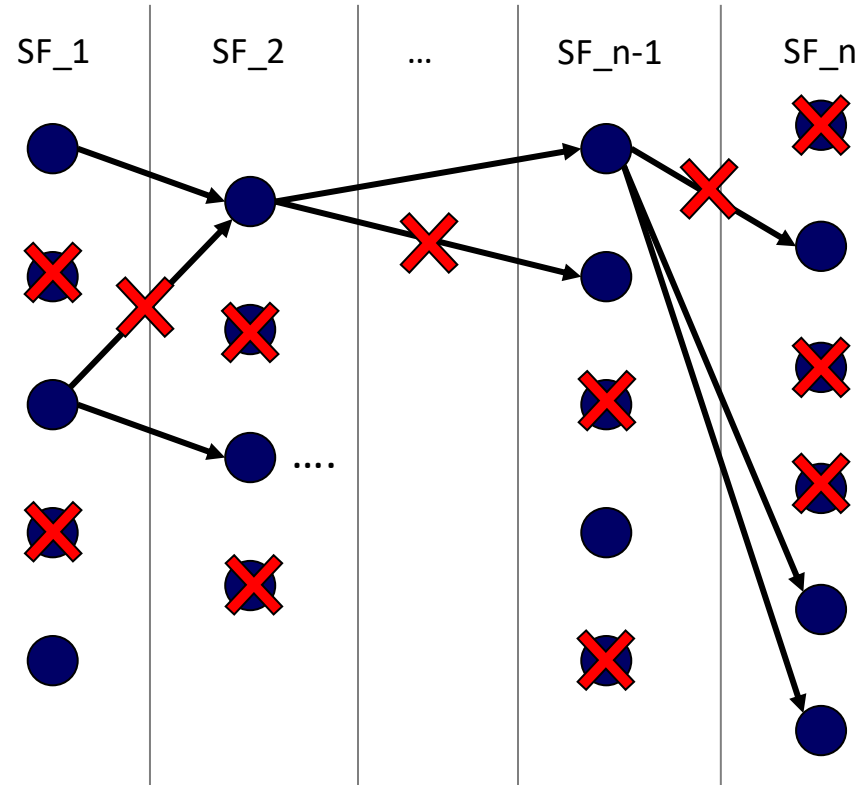
Rule 1		Rule 2
CP1.Parameters1.id = CP2.Parameters2.id CP1.Parameters1.value = CP2.Parameters2.value CP1.Parameters1.unit = CP2.Parameters2.unit	OR	CP1.Parameters1.id = CP2.Parameters2.id CP1.Parameter1.value < CP2.Parameters2.maxValue CP1.Parameter1.value > CP2.Parameters2.minValue CP1.Parameter1.unit = CP2.Parameters2.unit
„Parameters of components must be equal“ e.g. working voltage		„Parameters of one component must be larger or smaller than the ones of the other“ e.g. downwards compatability of protocols

Individual Rules by developers are potentially needed to enhance efficiency

- For combination of two interfaces, compatability rules for ALL ports must be evaluated

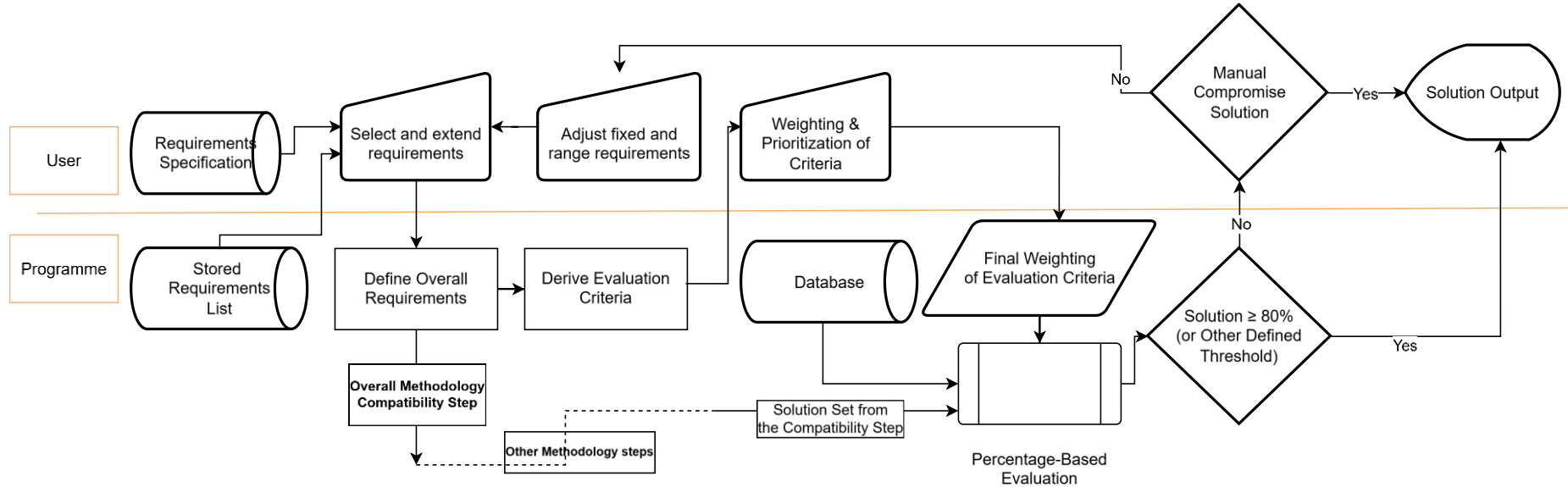
Adaption of Combination Method by KILIAN

Nr.	Process step
1	Functional pre-filtering of suitable single components by requirements
2	Development of a measurement-chain solution proposal (SP)
3	Calculation of the SP's energy demand
4	Analysis and clustering of the SP
5	Derivation and design of the Energy Network
6	Installation-space and integration check
7	Plausibility and feasibility check of the SP
8	Comparison and evaluation of different SPs



SF - Subfunction

Evaluation of concepts



Definition of **25 evaluation criteria** divided in **7 macro-categories**

- Macro-categories based on Trade-Offs between criteria
- Identification of criteria basis weighting for SiME development context

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Future Steps

Optimization of Focus Topics 2&3

Focus Topic 1: Measurement task → measurand and measruement location	Focus Topic 2: Design for Robustness 	Focus Topic 3: Combination and selection of module-components
Extremely complex step with highest impact on following development steps	High relevance for functional safety	Most relevant step of the concept phase
➤ Especially insufficient: ➤ Linkage of effect chains to sensory principles ➤ Identification of potential measurement location in a system context ➤ Combining existing machine elements with effects that can be utilized within them	➤ Especially insufficient ➤ Early stage evaluation of disturbance impacts ➤ Continuous usage of robustness as evaluation criterion ➤ Recommendations for countermeasures in the design phase.	➤ Especially insufficient: ➤ Selection through compatibility checks of electronic components ➤ Evaluation of solutions ➤ Building space check

Do these results match your experience?

Proposal: (Review-)Paper

- Which individual development processes were used in your project?
- What success factors or drawbacks were experienced?
- Can this process be described by the presented methodology?
- Would the methodology proposed support the development of new SiME?

If interested, register
via QR-Code, Mail or
physical List



<https://forms.gle/F934YprtPC8bFNgZ8>

Thank you

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Function Structure of SiME

