

CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

CRC 1574

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German Research Foundation

KIT Karlsruhe Institute of Technology

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Circular Factory for the Perpetual Innovative Product



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CCPT

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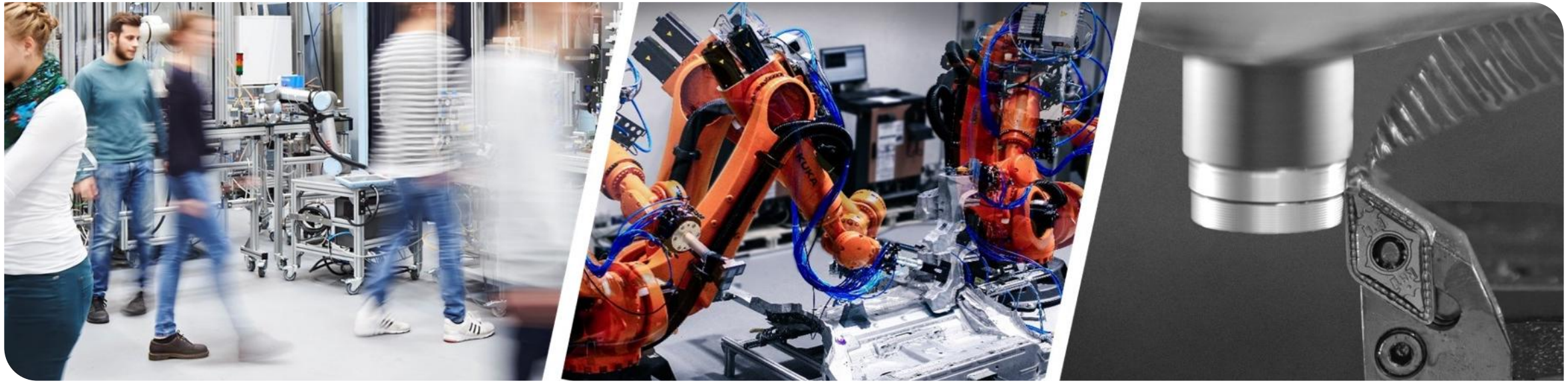
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Institut für Produktionstechnik

Circular Factory for the Perpetual Innovative Product

Collaborative Research Center 1574

Prof. Dr.-Ing. Gisela Lanza

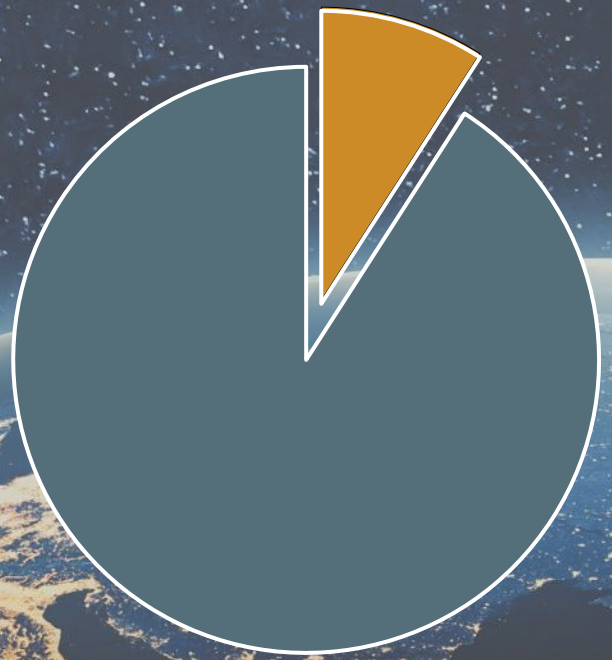




Quelle: Earth Overshoot Day (2025)

9.1% (2015)

Proportion of secondary materials in global material consumption



Quelle: The CIRCULARITY GAP report (2018)

6.9% (2021)

Share of secondary materials
in global material consumption
declines



Quelle: The CIRCULARITY GAP report (2025)

Circular Economy Action Plan of EU

Goal of Doubling the Circular Material Utilization Rate to 23% by 2030

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Use of Materials



- 15 %

Recycling Rate



+ 75%*

Fossil resources



- 33 %

* Increase in recycling rate from 40% to 70%

Quelle: EEA Report 13/2023 (2024)



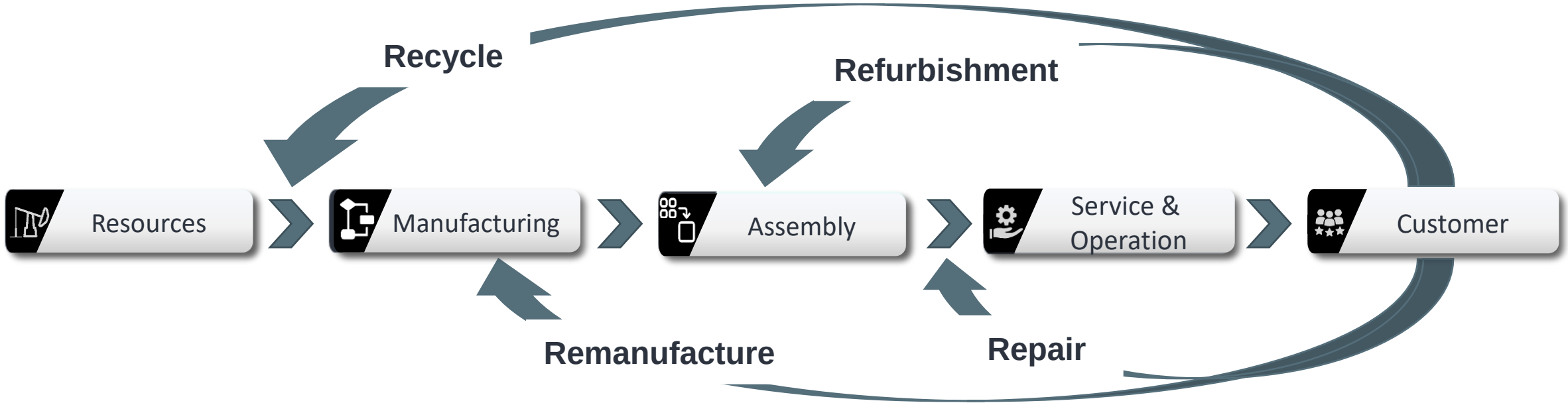
Ensure sustainable consumption and production patterns

12 RESPONSIBLE CONSUMPTION AND PRODUCTION


1 NO POVERTY
2 ZERO HUNGER
3 GOOD HEALTH AND WELL-BEING
4 QUALITY EDUCATION
5 GENDER EQUALITY
6 CLEAN WATER AND SANITATION
7 AFFORDABLE AND CLEAN ENERGY
8 DECENT WORK AND ECONOMIC GROWTH
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
10 REDUCED INEQUALITIES
11 SUSTAINABLE CITIES AND COMMUNITIES
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION
14 LIFE BELOW WATER
15 LIFE ON LAND
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
17 PARTNERSHIPS FOR THE GOALS
SUSTAINABLE DEVELOPMENT GOALS

Circular economic patterns

Remanufacturing represents an industrial standard in terms of quality and warranty



Based on : Khor & Udin (2012), Parker et al. (2015), Ellen MacArthur Foundation (2013), Benoy, et al. (2014), Tolio et al. (2017)

Ensuring maximum retention of added value

Preservation of the material composition enables great savings potential

Savings:

-88 % Ressources

-56 % Energy

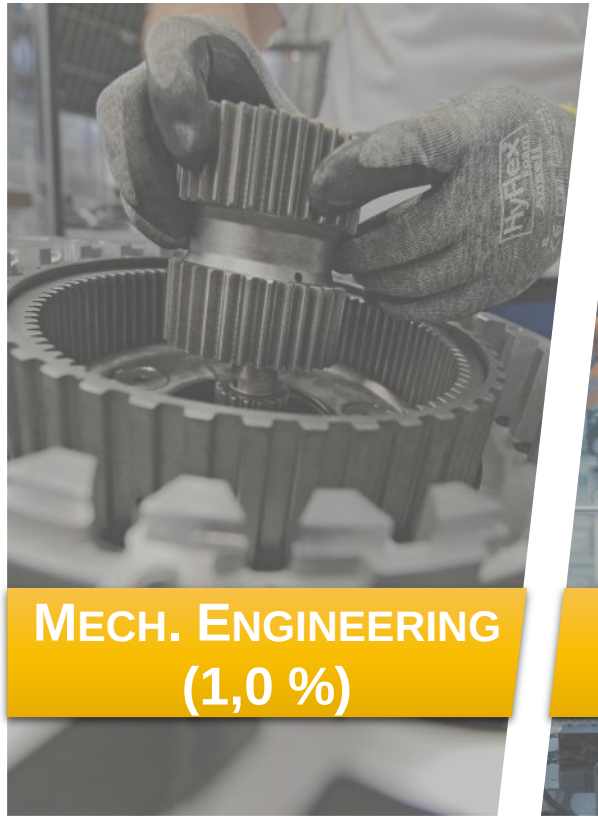
-53 % CO_2 Emissions

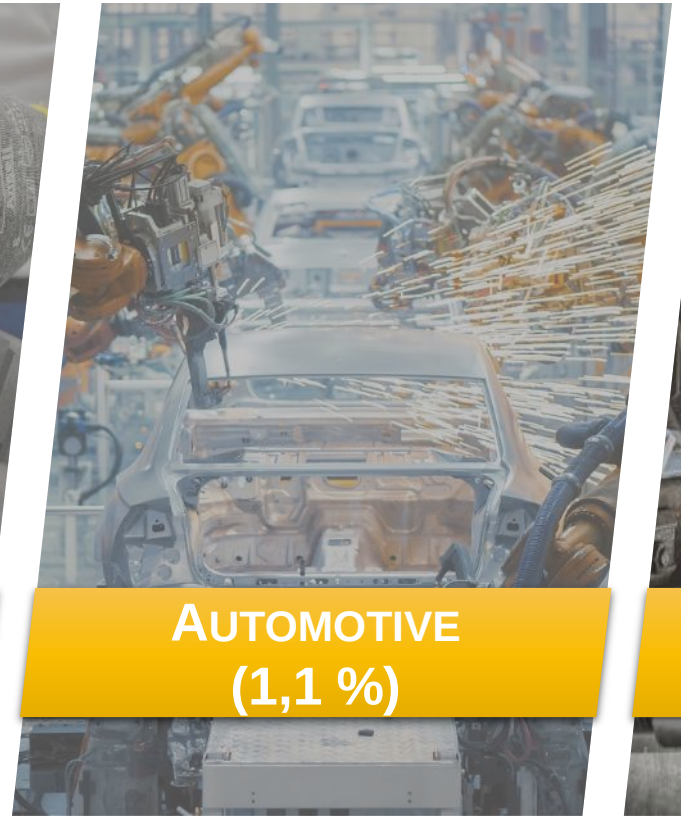


Based on Khor & Udin (2012), Parker et al. (2015), Ellen MacArthur Foundation (2013), Benoy, et al. (2014), Tolio et al. (2017)

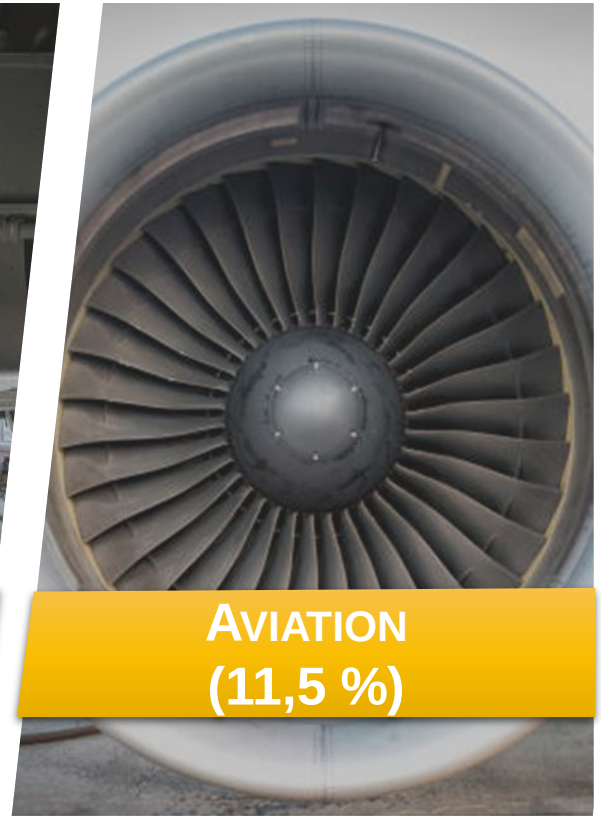
Relevant industrial sectors in remanufacturing

Remanufactured products in relation to new products









Circular economic pattern are still in the niche. Why?

Parker et al. (2015); Picture Sources: [l]-[o]

Maximum value retention through Product-Production-CoDesign

Product generation development - today



Golf I (1974–1983) | **Golf II** (1983–1991) | **Golf III** (1991–1997) | **Golf IV** (1997-2003) | **Golf V** (2003–2008) | **Golf VI** (2008-2012) | **Golf VII** (2012-2019) | **Golf VIII** (seit 2020)

Many products are developed in **product generations**, i.e. they follow a further development of a reference product, including carryover and principle variations.

Based on Albers et al. (2015), Volkswagen AG (2023); Picture Source: [b]

Maximum value retention through Product-Production-CoDesign

Product generation development - today

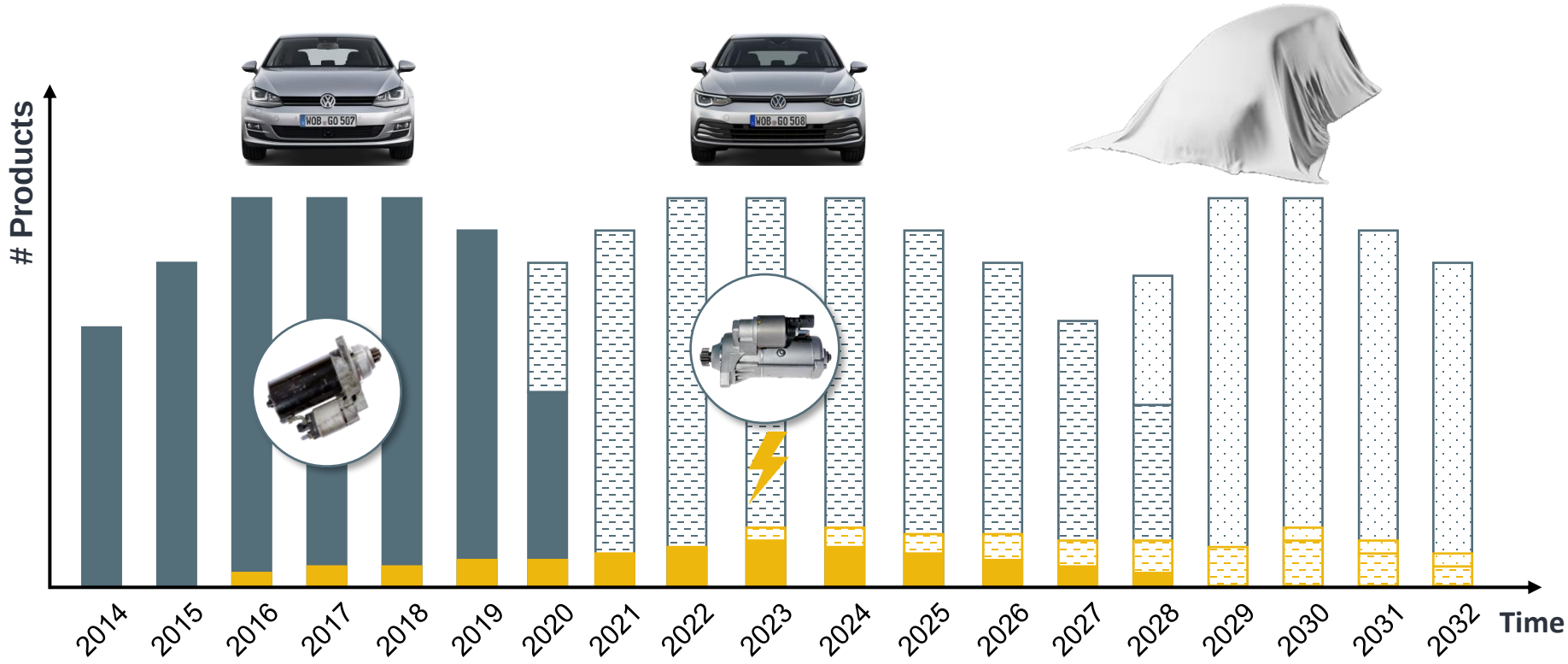


Remanufacturing products are currently primarily sold on the **secondary market as spare parts** for the **associated product generation**.

Based on Albers et al. (2015), Volkswagen AG (2023); Picture Sources: [b]-[j]

Maximum value retention through Product-Production-CoDesign

Product generation development - today



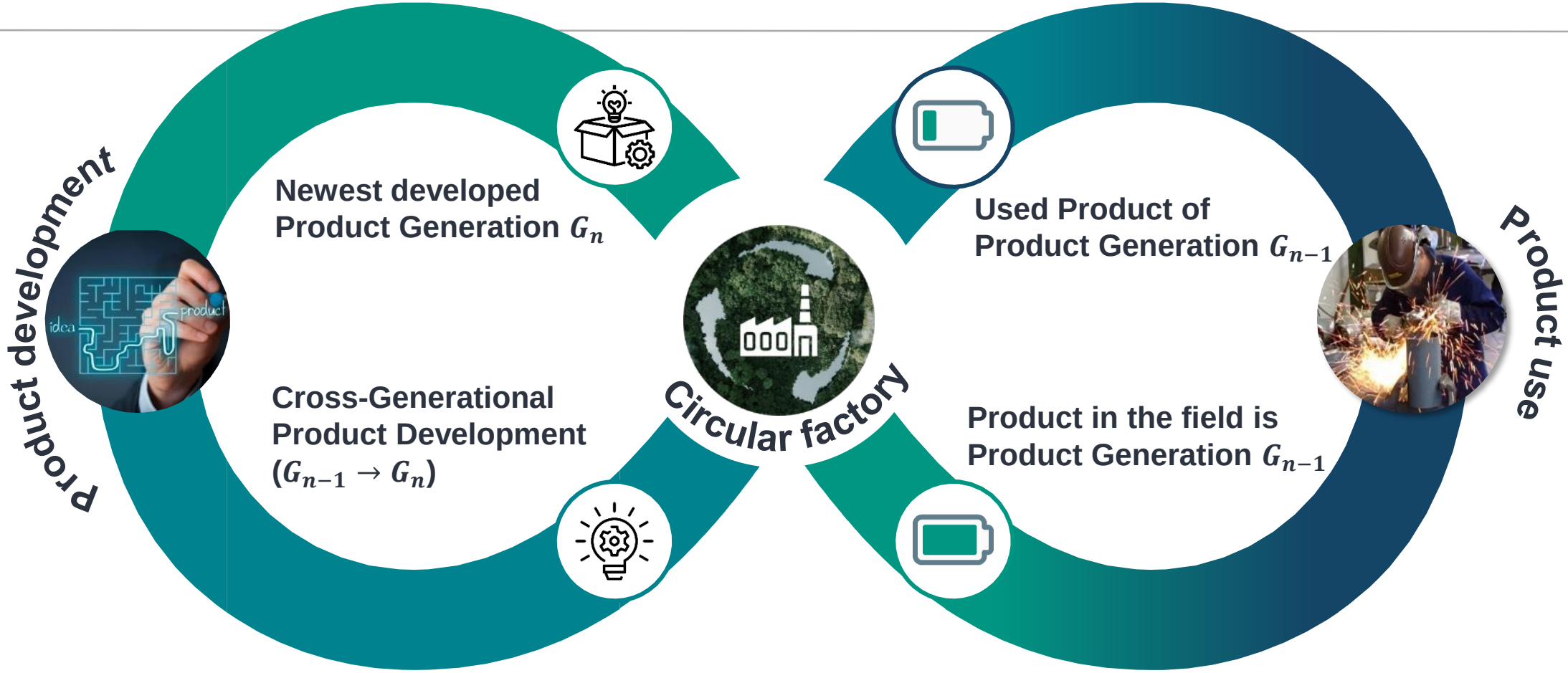


Remanufactured Products G_{n-x}

Conclusion: Sale as a spare part in **small quantities** on the **secondary market**, as remanufactured products can only be **sold through lower price**.

Based on Albers et al. (2015), Volkswagen AG (2023); Image source: [b], [k]

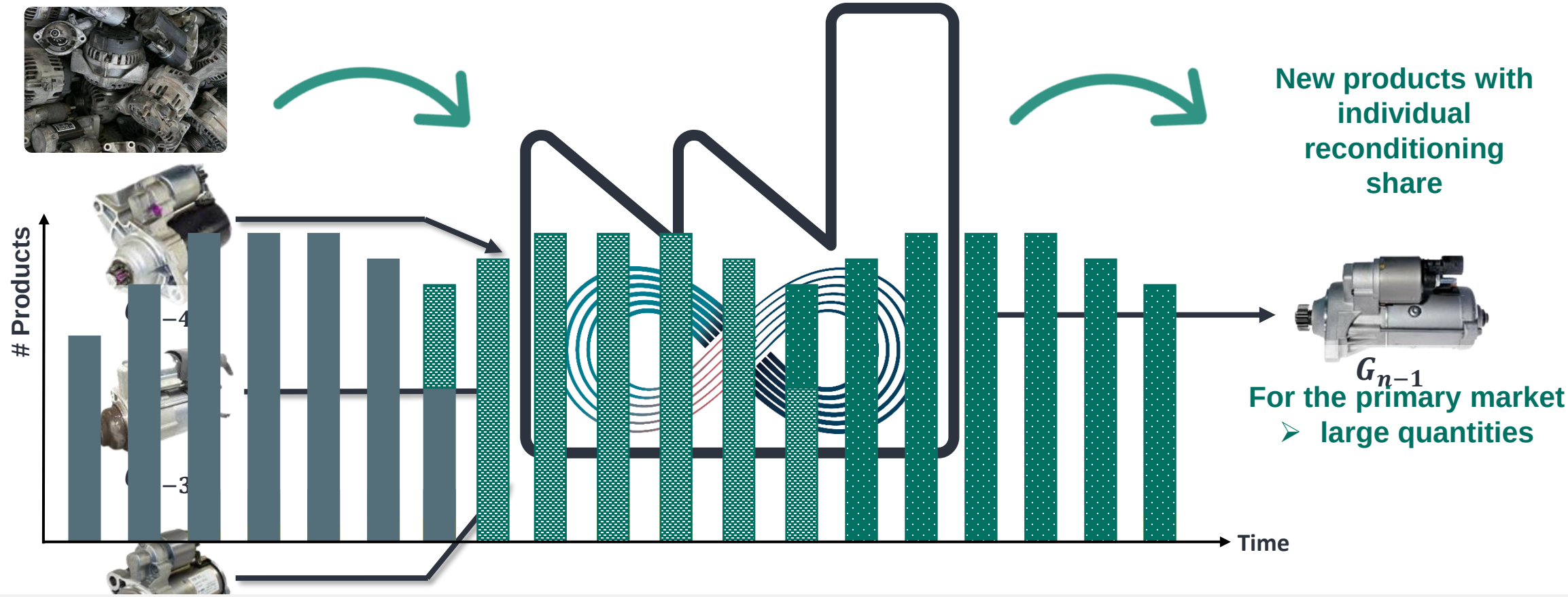
Vision of the „perpetual innovative product“



Used product instances (their subsystems, components) are continuously transferred to the same or a new product generation. This enables **theoretically perpetual product use**.

Vision of the „perpetual innovative product“

Maximum value retention through Product-Production Co-Design



Through the product upgrade of the „**perpetual** innovative **product** “, in contrast to the secondary market, as is the current state of the art, the **primary market** can be accessed with **large quantities**.

Vision of the „perpetual innovative product“

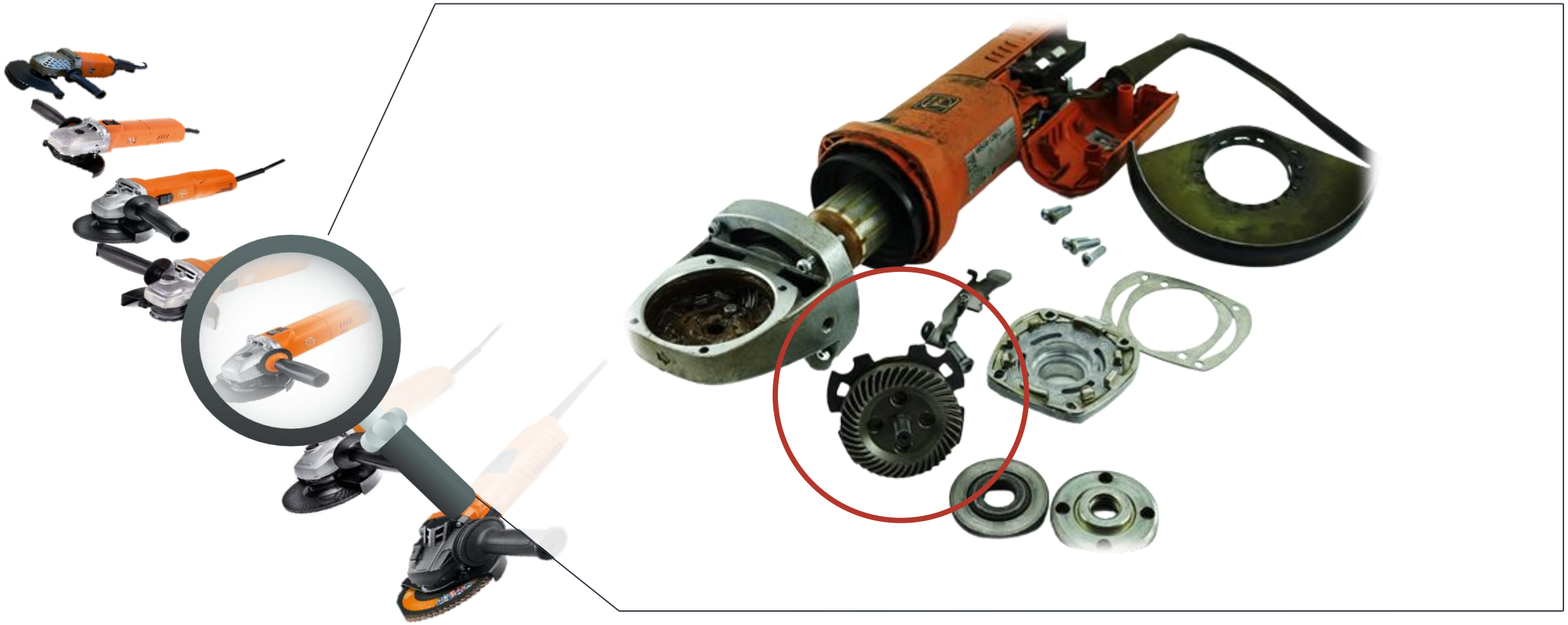
Two sample products: Electric motors in cars and angle grinders as consumer goods in large-scale production



Bildquelle: [p]

Vision of the „perpetual innovative product“

Cross-generation product and technological upgrading



Vision of the „perpetual innovative product“

Cross-generation product and technological upgrading



Leap in innovation

- Switch from corded to battery-powered devices

Vision of the „perpetual innovative product“

Cross-generation product and technological upgrading



How can subsystems and components be **inspected, reprocessed and technologically updated** in order to establish products from circular value creation on the primary market?

Prediction of the product function


FUNCTIONAL
TEST
IPEK
Antrieb Mechatron
Antrieb Moog

Production of unique products in large scale production

Every manufactured new product has unique individual subsystems and components

Linear

Resources → Manufacturing → Assembly → Service & Operation → Customer

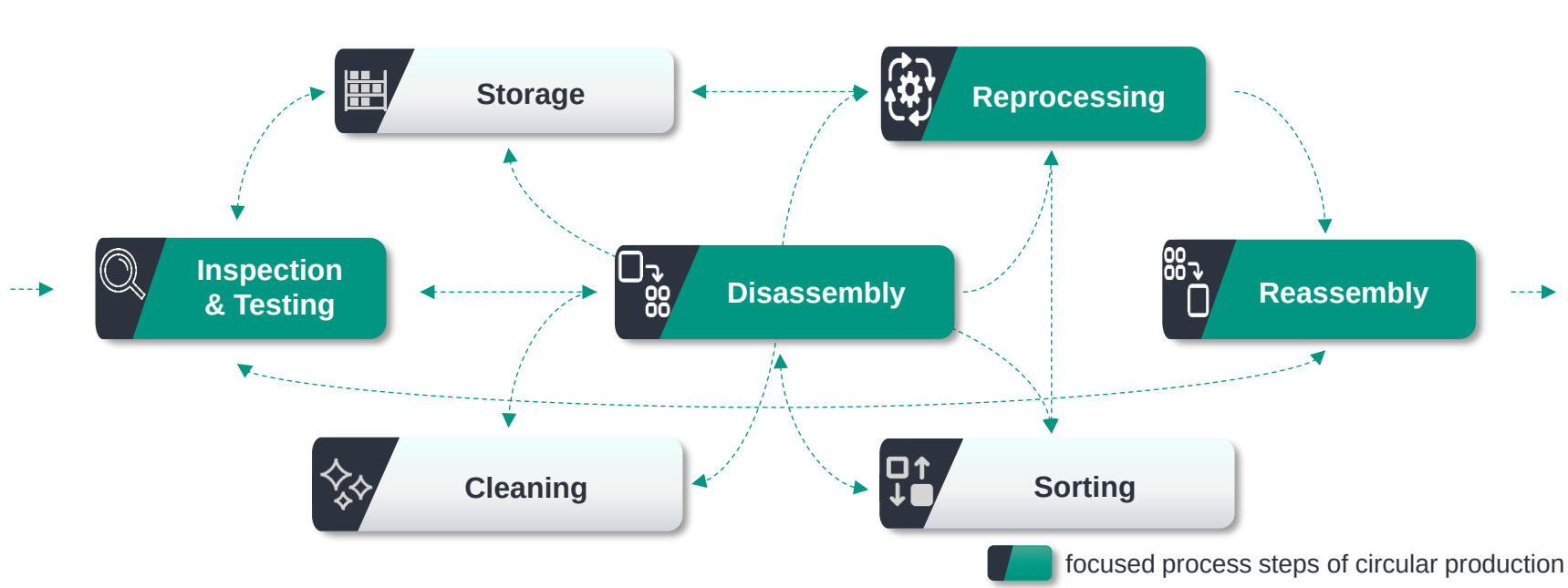
Circular

Diversity of variants and generations



High uncertainty regarding prod. condition





How can uncertainty caused by the **uncertain condition of used products** and derived **process sequences** in the circular factory be managed?

Managing uncertainty

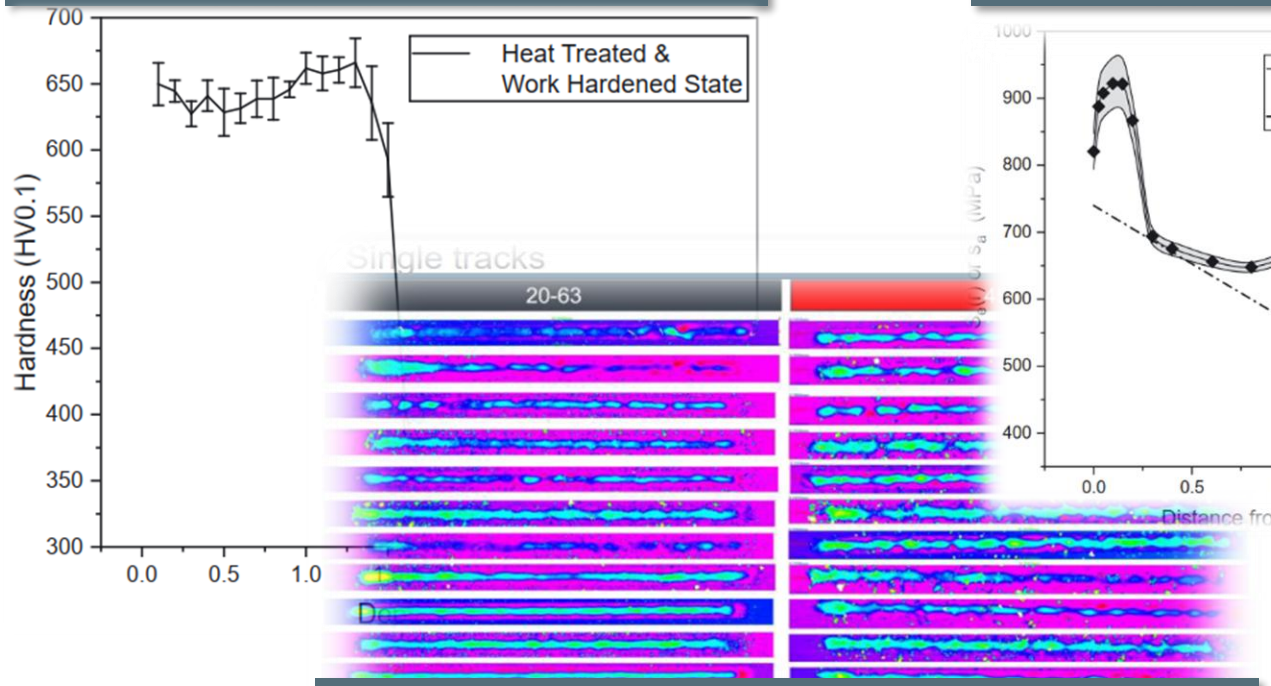
Based on Sundin (2004)

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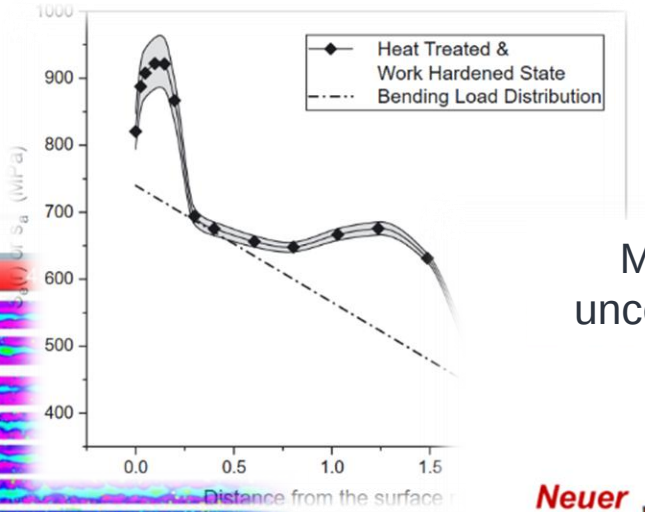
Production of unique products in large scale production

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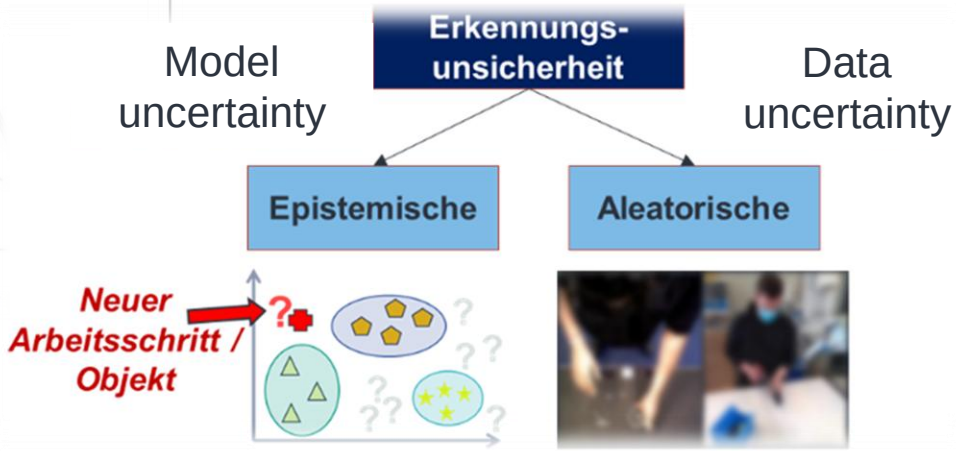
Analysis of Uncertainties in Measurement Processes



Analysis of Uncertainties in Material Properties



Analysis of Uncertainties in Reprocessing



Analysis of Uncertainties in Human Operations

How can uncertainty caused by the **uncertain condition of used products** and derived **process sequences** in the circular factory be managed?

Managing uncertainty

Based on Sundin (2004)

Production of unique products in large scale production

Economical large-scale production requires standardized, automatable industrial processes

Linear

Resources → Manufacturing → Assembly → Service & Operation → Customer

Circular

Diversity of variants and generations



High uncertainty regarding prod. condition



Lack of externalized knowledge





Source: Carl-Zeiss-Stiftung-Forschergruppe AgiProbot (2021)

Production of unique products in large scale production

Economical large-scale production requires standardized, automatable industrial processes

Linear

Resources → Manufacturing → Assembly → Service & Operation → Customer

Circular

Diversity of variants and generations



High uncertainty regarding prod. condition



Lack of externalized knowledge





How can **human action knowledge** in the execution of **complex manipulation tasks** be **learned** from human observation and **transferred** to industrial automated production technology?

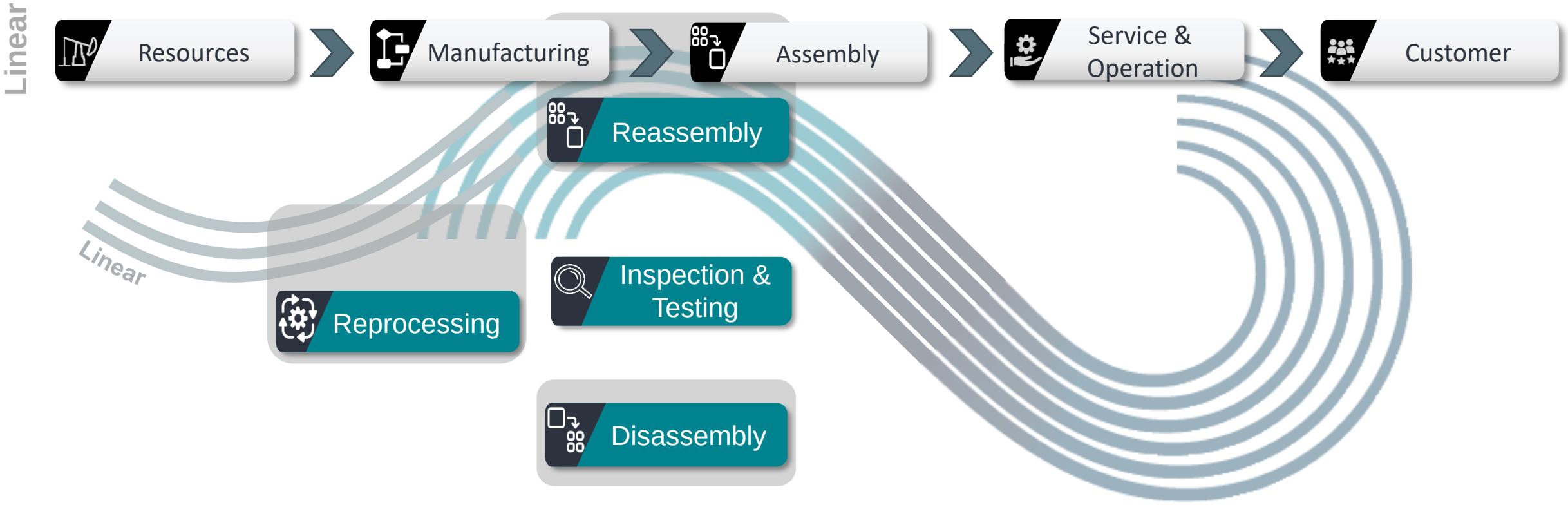
Production technology that learns from human actions

Source: CRC2025


LEARNING AUTOMATED DISASSEMBLY
BY HUMAN OBSERVATION

Integrated production system

Linear and circular production use the same production resources



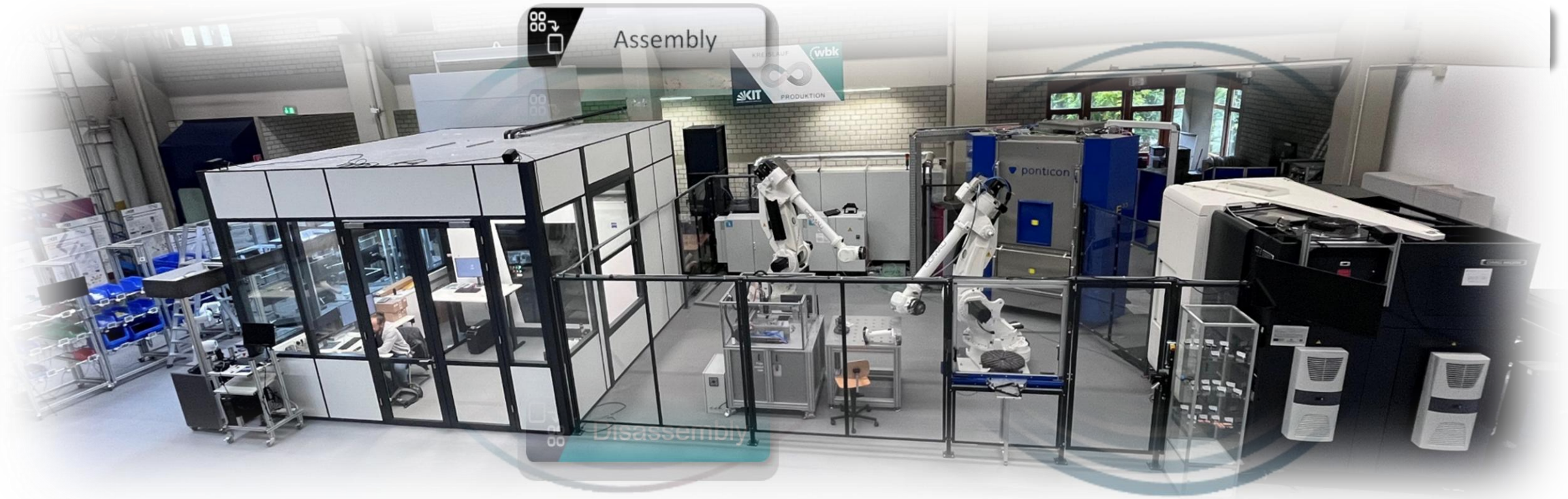
How can self-learning, **autonomously adapting production resources** be used to realize circular production **in large scale production at high-wage locations**?

Changeable, autonomous production system

Note: focused process steps of circular production in green and linear production in white

Integrated production system

Linear and circular production use the same production resources



How can self-learning, **autonomously adapting production resources** be used to realize circular production **in large scale production at high-wage locations**?

Changeable, autonomous production system

Note: focused process steps of circular production in green and linear production in white

Integrated production system

Linear and circular production use the same production resources



Linear

Manufacturing

Reprocessing

Assembly

Reassembly

Inspection & Testing

Disassembly





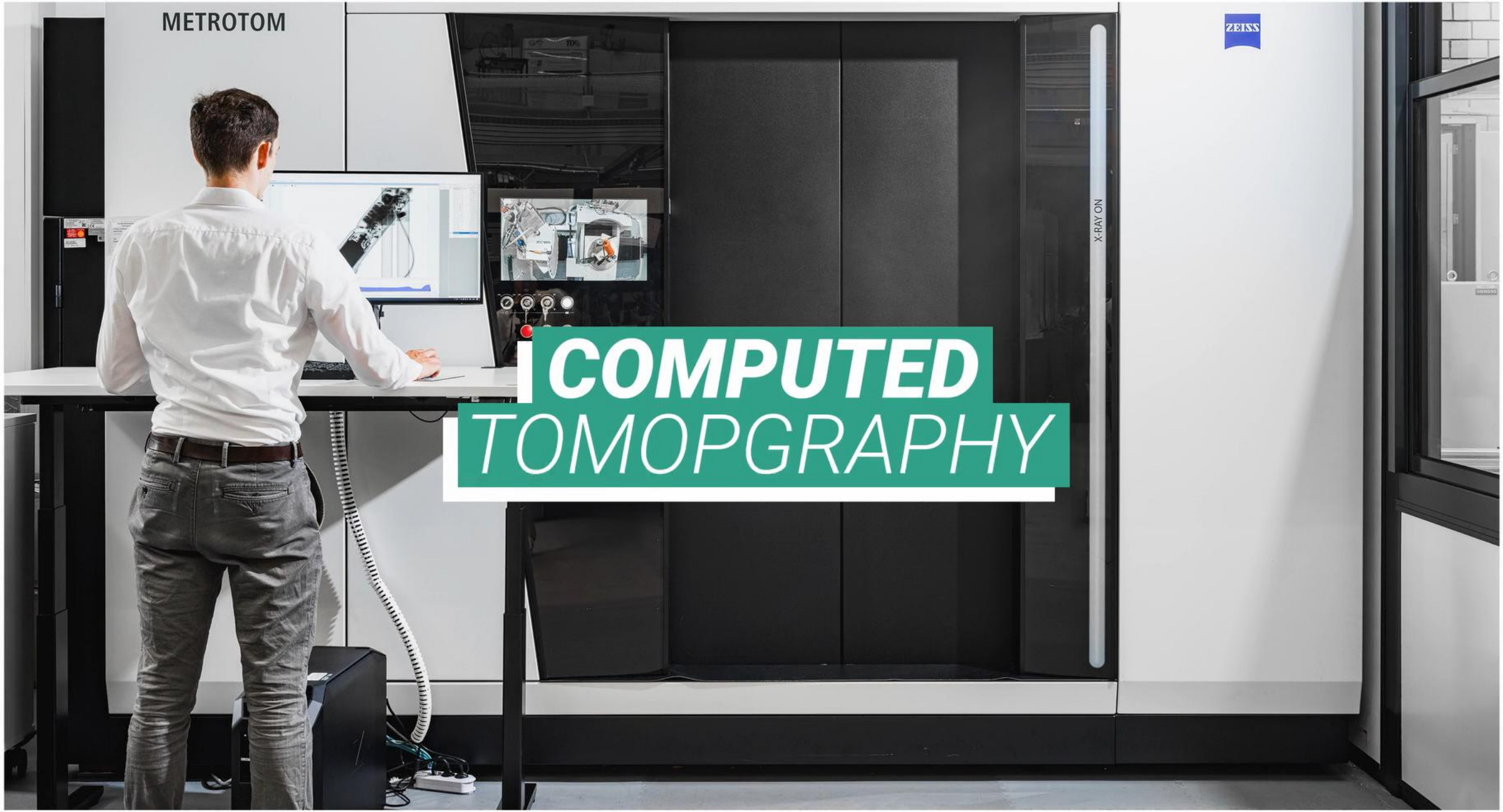
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INITIAL
INSPECTION
T-SCAN

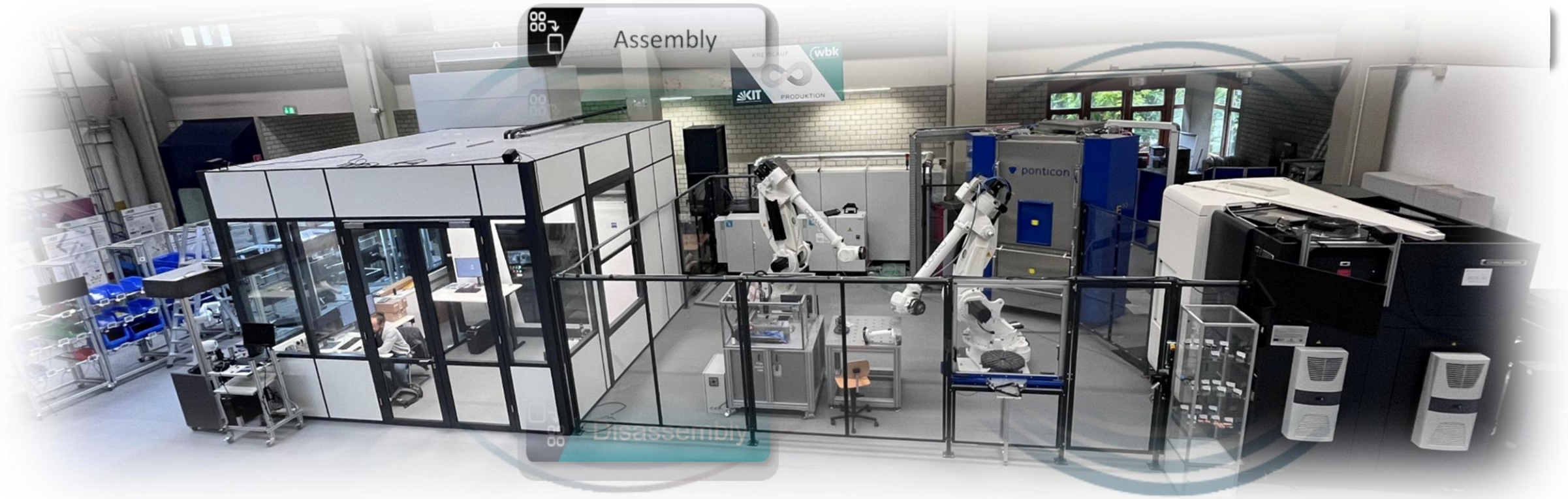

METROTOM
ZEISS
X-RAY ON
COMPUTED
TOMOPGRAPHY



AUTOMATED REPROCESSING

Integrated production system

Linear and circular production use the same production resources



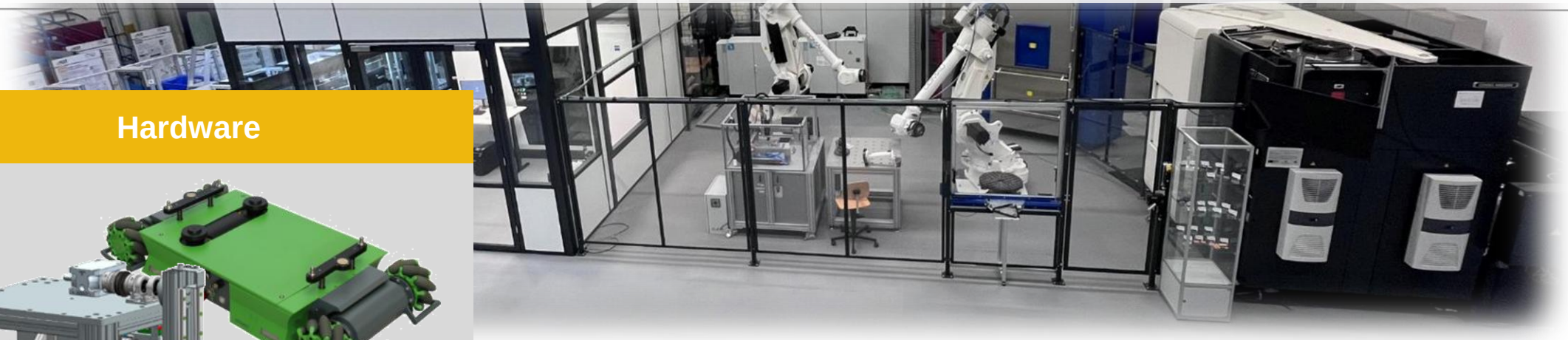
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Integrated production system

Linear and circular production use the same production resources

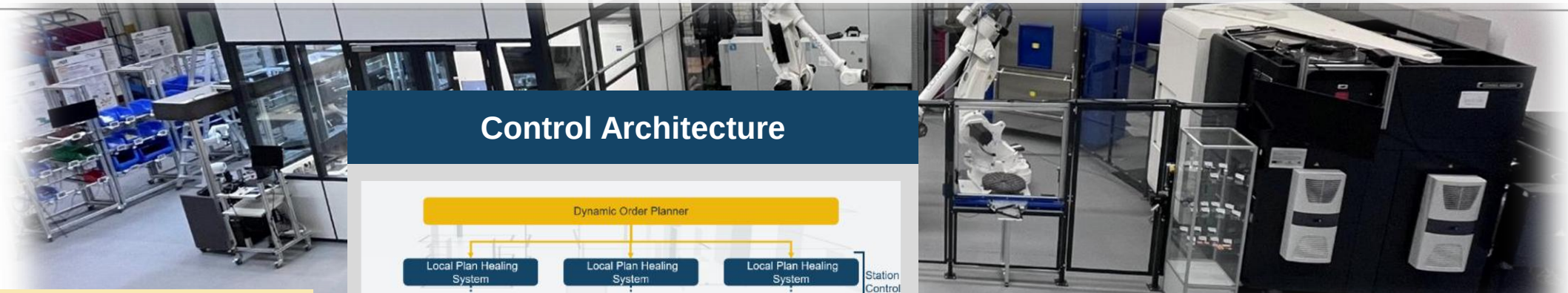


Hardware

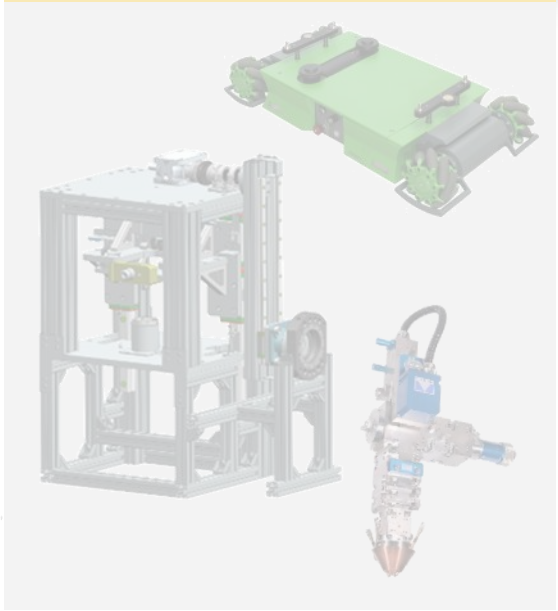


Integrated production system

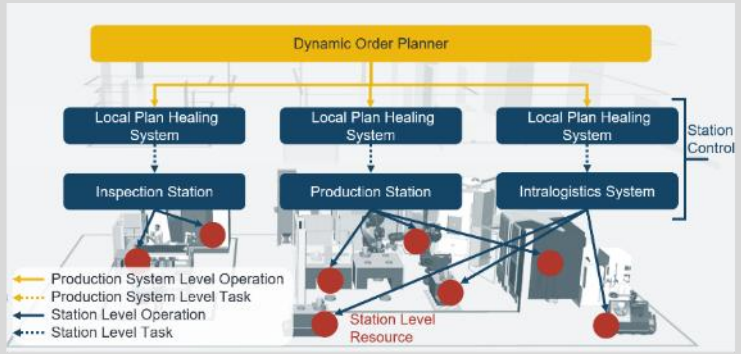
Linear and circular production use the same production resources

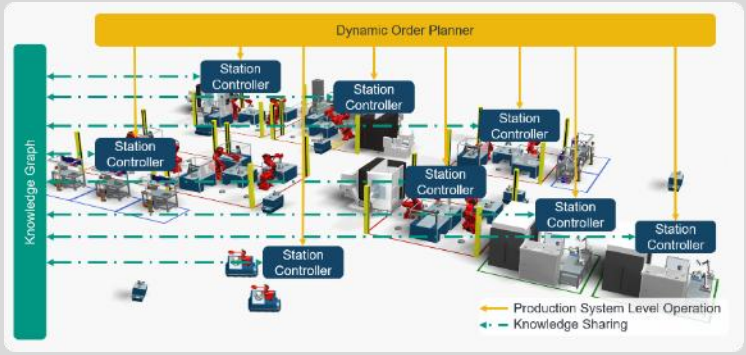


Hardware



Control Architecture



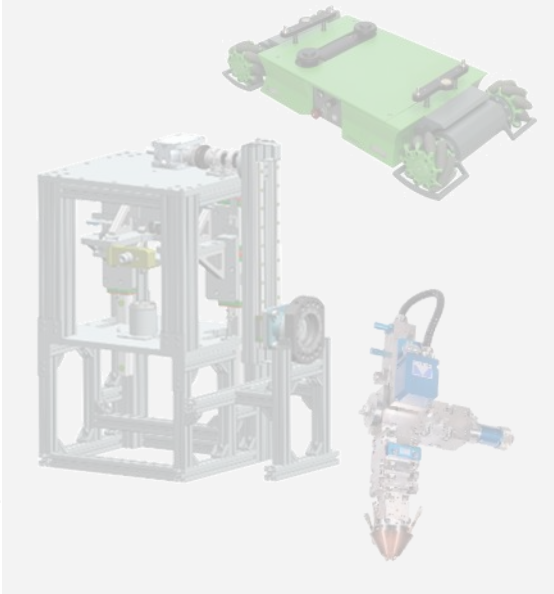


Integrated production system

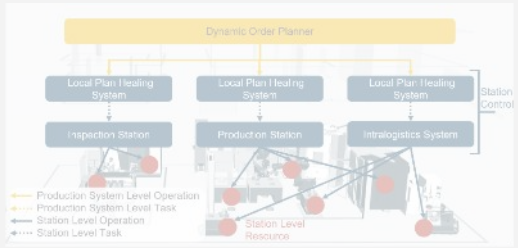
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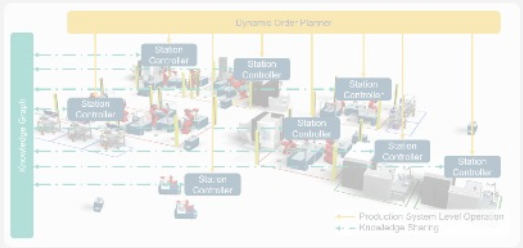


Hardware

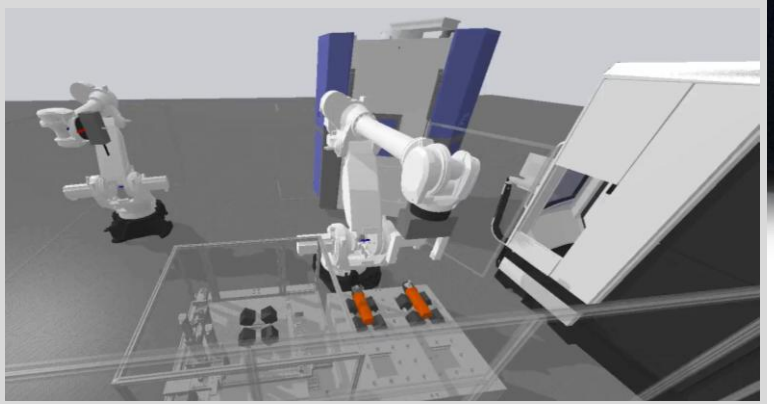


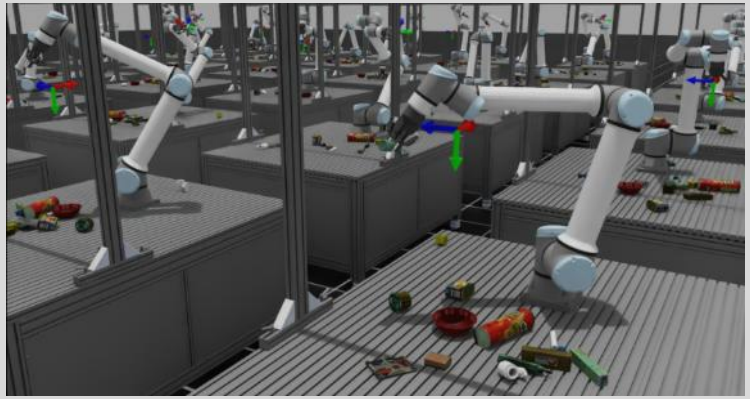
Control Architecture





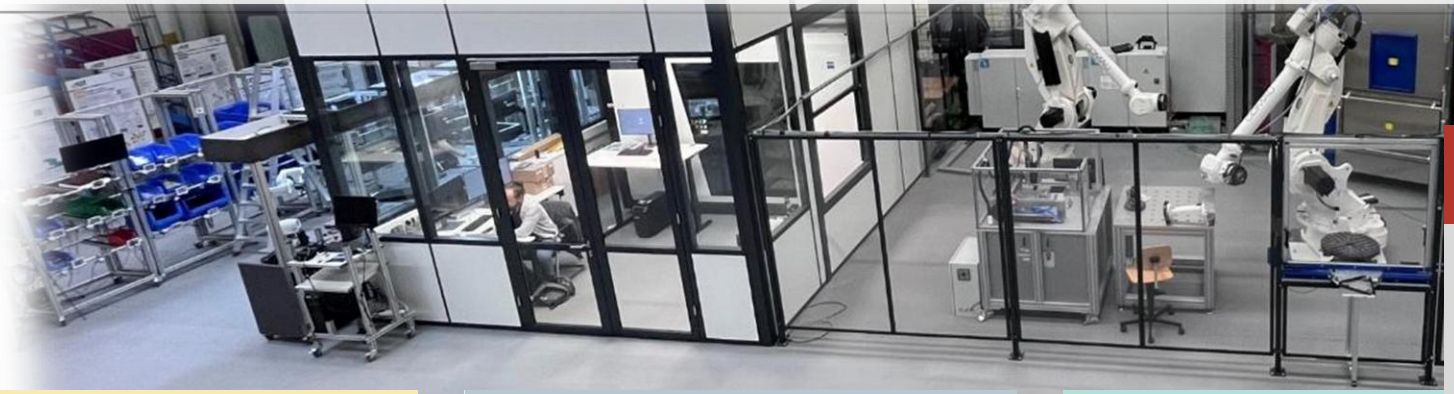
Digital Twin & Simulation





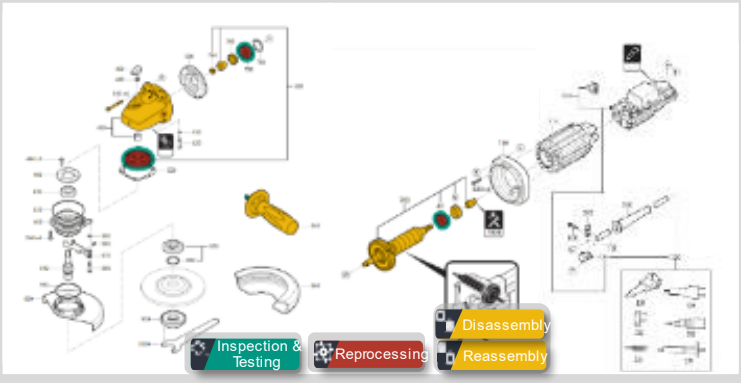
Integrated production system

Linear and circular production use the same production resources

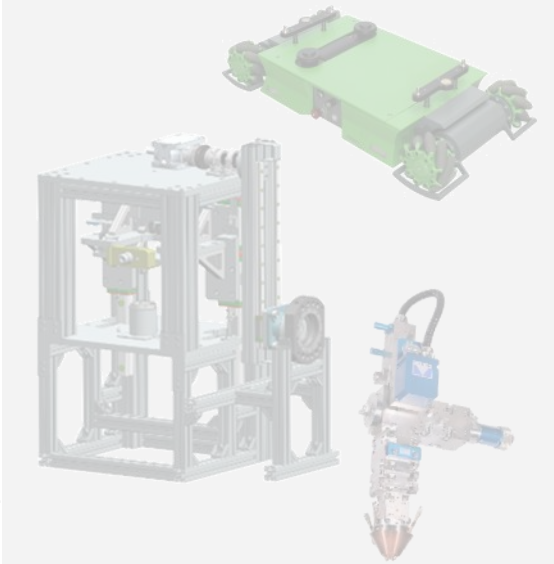


Automation

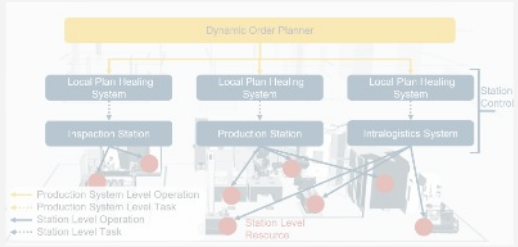


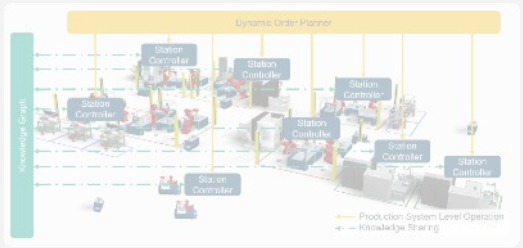


Hardware

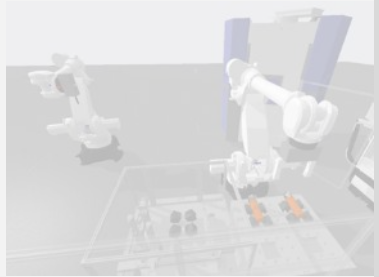


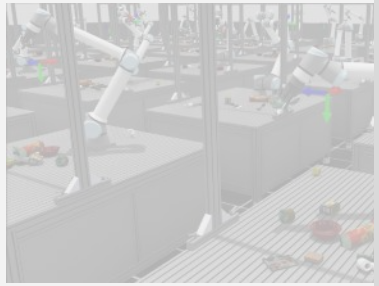
Control Architecture





Digital Twin & Simu



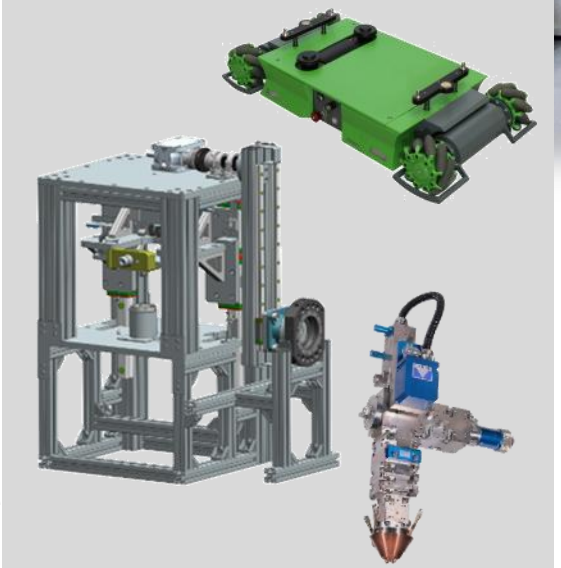


Integrated production system

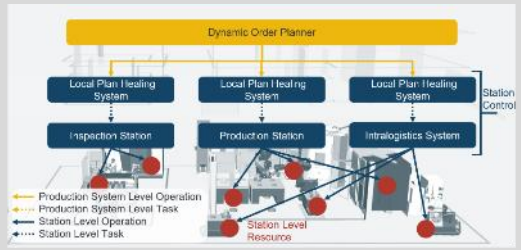
Linear and circular production use the same production resources

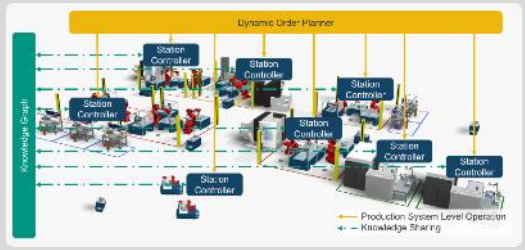


Hardware

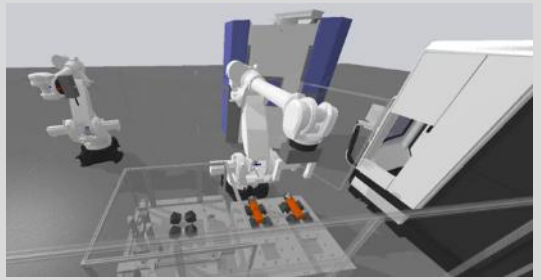


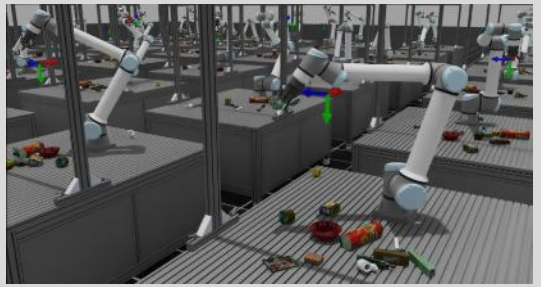
Control Architecture





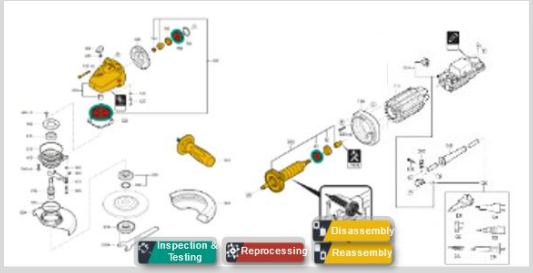
Digital Twin & Simulation





Automation



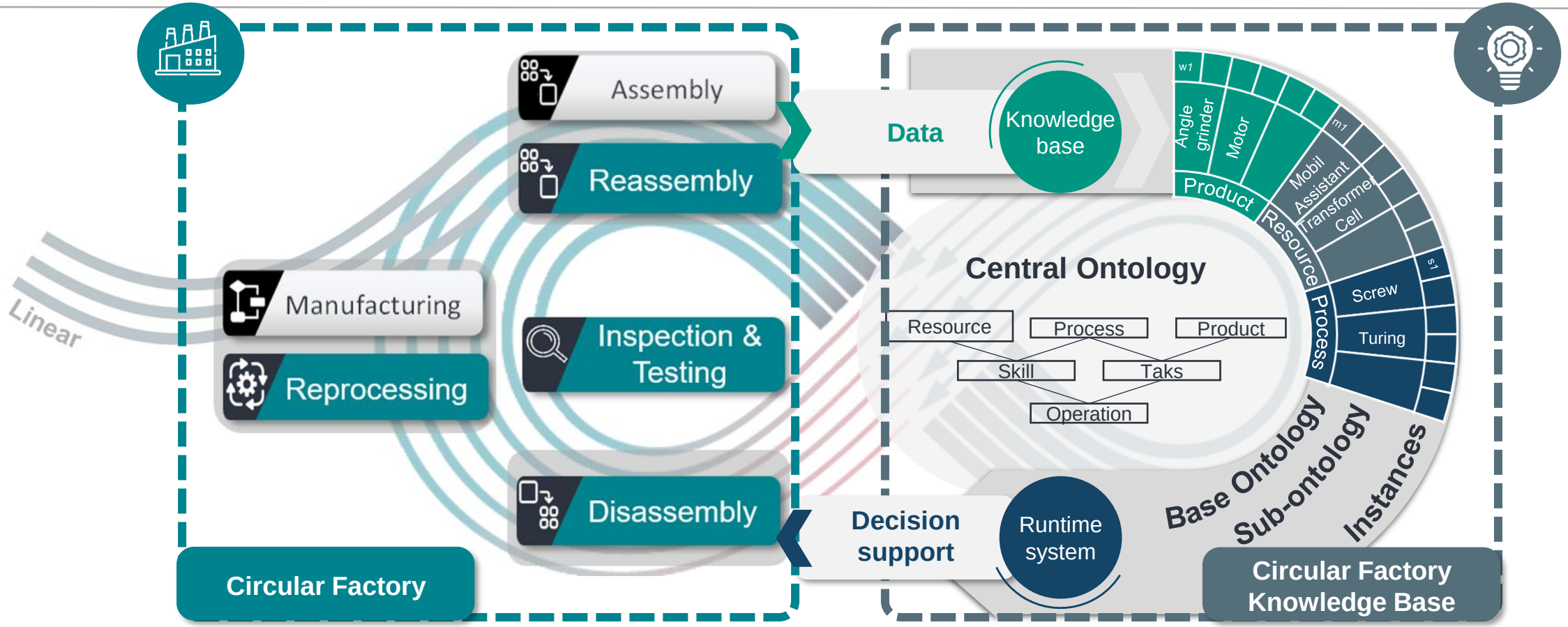


How can self-learning, **autonomously adapting production resources** be used to realize circular production **in large scale production at high-wage locations**?

Changeable, autonomous production system

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Circular Factory Knowledge Base



How can a **uniform semantic representation** of the **knowledge** of the circular factory be made possible in order to integrate information across all domains?

Knowledge modeling

Summary of the key research questions

How can subsystems and components be **inspected, reprocessed and technologically updated** in order to establish products from circular value creation on the primary market?	**Prediction of the product function**
How can uncertainty caused by the **uncertain condition of used products** and derived **process sequences** in the circular factory be managed?	**Managing uncertainty**
How can **human action knowledge** in the execution of **complex manipulation tasks** be **learned** from human observation and **transferred** to industrial automated production technology?	**Production technology that learns from human actions**
How can self-learning, **autonomously adapting production resources** be used to realize circular production **in large scale production at high-wage locations**?	**Changeable, autonomous production system**
How can a **uniform semantic representation** of the **knowledge** of the circular factory be made possible in order to integrate information across all domains?	**Knowledge modeling**

Thank you!



…Questions?

Karlsruhe Institute of Technology
Kaiserstraße 12
76131 Karlsruhe
https://www.kit.edu/

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Siemens’ Digital Path to Circularity at Scale

AI-Driven ELV Dismantling

Dr. Caroline Cassignol



Accelerating Momentum in Automotive ELV Recycling & Circularity

Drivers



DIE ZEIT

Automobilindustrie

EU will mehr Rohstoffe aus alten Autos gewinnen

Die EU hat neue Regeln für die Altfahrzeugverordnung beschlossen. Künftig sollen Autos, Motorräder, Lkws und andere Fahrzeuge besser recycelbar sein.

12. Dezem

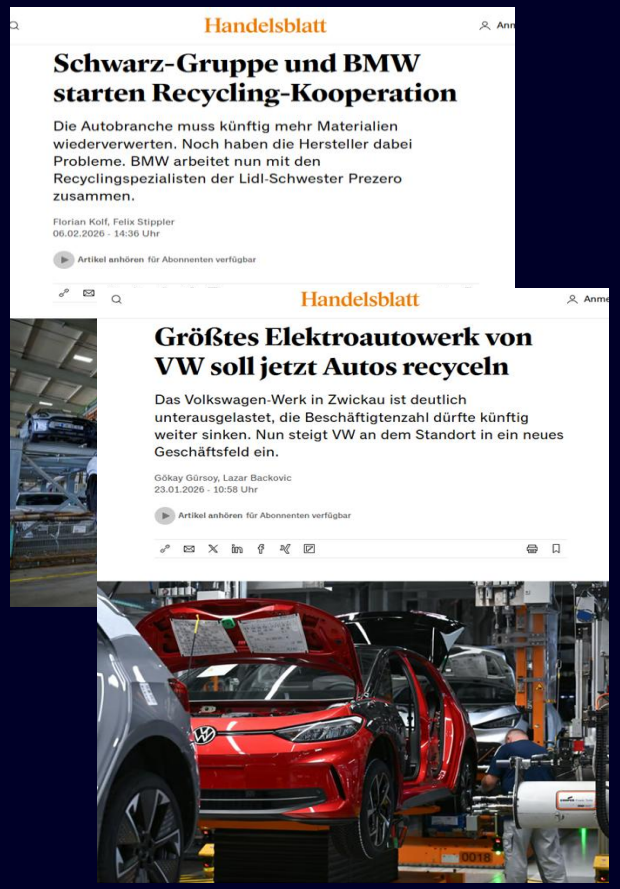
▶ 2 Min

AUTOHAUS NACHRICHTEN MEINUNGEN RECHT & STEUERN AKADEMIE AUTOMARKEN

EU-Altfahrzeugverordnung: Politik will "High-Quality-Recycling" als neue Schlüsseltechnologie

23.06.2025 07:25 Uhr | Lesezeit: 5 min

Automotive manufacturers



Handelsblatt

Schwarz-Gruppe und BMW starten Recycling-Kooperation

Die Autobranche muss künftig mehr Materialien wiederverwerten. Noch haben die Hersteller dabei Probleme. BMW arbeitet nun mit den Recyclingspezialisten der Lidl-Schwester Prezero zusammen.

Florian Kolf, Felix Stippler
06.02.2026 - 14:36 Uhr

Artikel anhören für Abonnenten verfügbar

Handelsblatt

Größtes Elektroautowerk von VW soll jetzt Autos recyceln

Das Volkswagen-Werk in Zwickau ist deutlich unterausgelastet, die Beschäftigtenzahl dürfte künftig weiter sinken. Nun steigt VW an dem Standort in ein neues Geschäftsfeld ein.

Gökay Gürsoy, Lazar Backovic
23.01.2026 - 10:58 Uhr

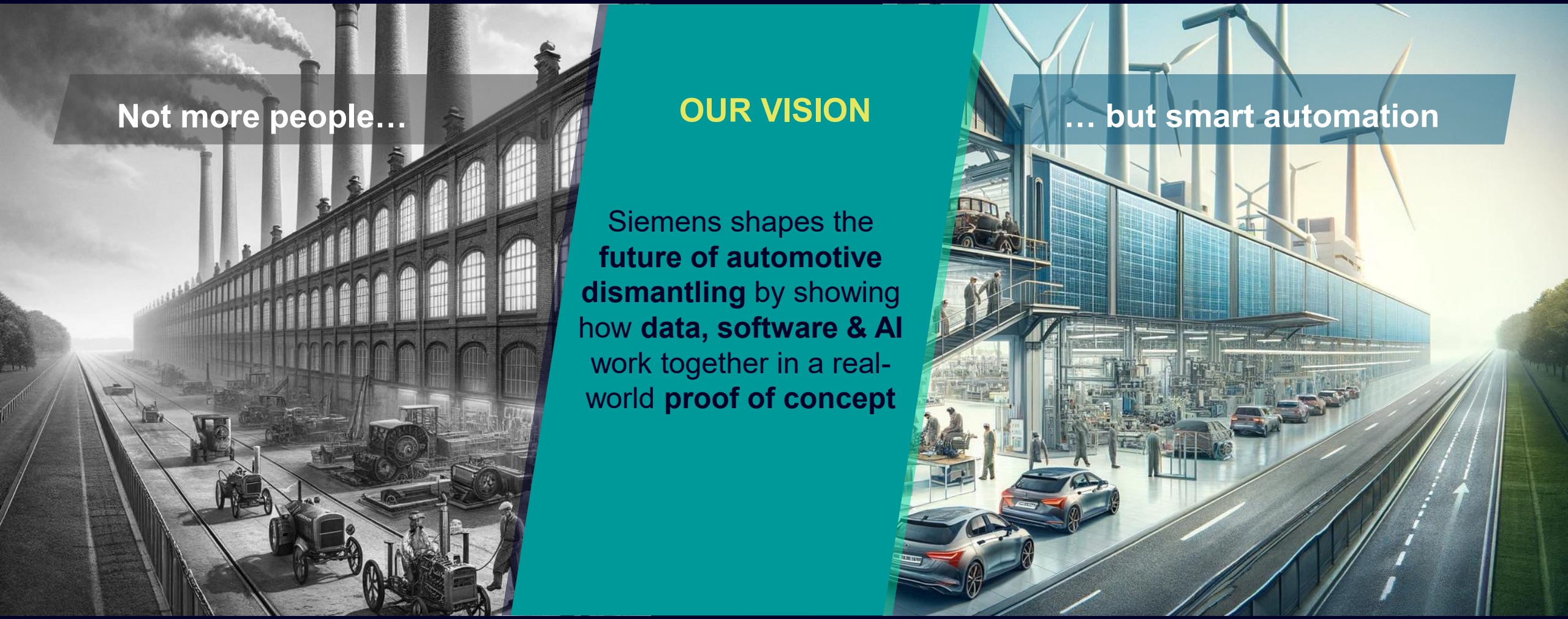
Artikel anhören für Abonnenten verfügbar

- **Surge in automotive sector initiatives** on End-of-Life Vehicle (ELV) recycling since January 2026
- **Unprecedented pace of announced collaborations** between OEMs, line builders, and recyclers
- **Industry-wide consolidation and restructuring** toward larger, more centralized recycling facilities
- **New automation opportunities** emerging—driven by increasing demand for flexible, adaptive solutions to meet evolving challenges

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The amount of mandatory scrapped cars will sharply rise due to End-of-Life Vehicle Legislation



Picture source: DALL-E

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SIEMENS

We have strong automotive factory digitalization expertise to tackle the challenges in automated disassembly

Circularity specific	Challenges	Technology specific
Limited information on EOL vehicles		Fast and accurate geometry reconstruction
High product variance		Collision-free online motion planning with uncertainty / inaccuracies in scanning data
Varying process steps and disassembly sequences		Ensuring component removal despite small movements of ELVs during operation
Uncertainties in material type & composition		Multiple Technology building blocks to be aligned

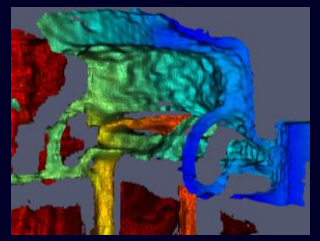
OUR GOAL **Siemens aims to enable automated disassembly through an end-to-end data and process chain via advanced automation, AI and digital twins, with technical and process validation**

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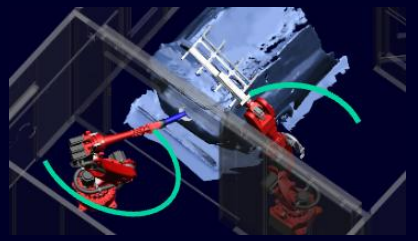
SIEMENS

AI-enabled Siemens tool chain: Connecting the data layer to real-world execution in our automated tailgate disassembly PoC









1 **Vehicle data generation:**
- Point cloud of vehicle geometry

2 **AI–driven data analysis**:
- Segmentation & Part identification
- Detection of gripping points (TCP)

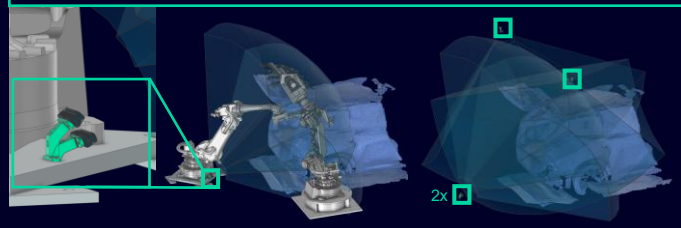
3 **Data integration for virtual process planning**:
- Dismantling process simulation
- Collision free robot motion & G-code creation

4 **Use of the data to train AI models:**
- Vehicle / parts identification
- Dismantling BOP & BOM

Data Layer (Digital Twin)

Process Layer (Real World)

1 **Vision System**:
- 4 Stereo camera setup



2 **Computing power**:
- Online on IPC & Edge

3 **Dismantling cell:**
- 2 collaborative robots & controllers
- G-code execution



4 **Computing power:**
- Online in the cloud

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Building blocks for seamless data flow in the Proof of Concept

Industrial Edge Device:

Robot Control:

Robot Motion Planner (generic app)

3D perception (AI Inference)

3D-Scans Interaction points (TCP)

Planning Workflow (application specific app)

Current Position

G-code

Controller



AI Segmentation



AI 3D Reconstruction



Process Simulate[1], Automatic Robot Motion Planner (ARMP)





Sinumerik or Simatic

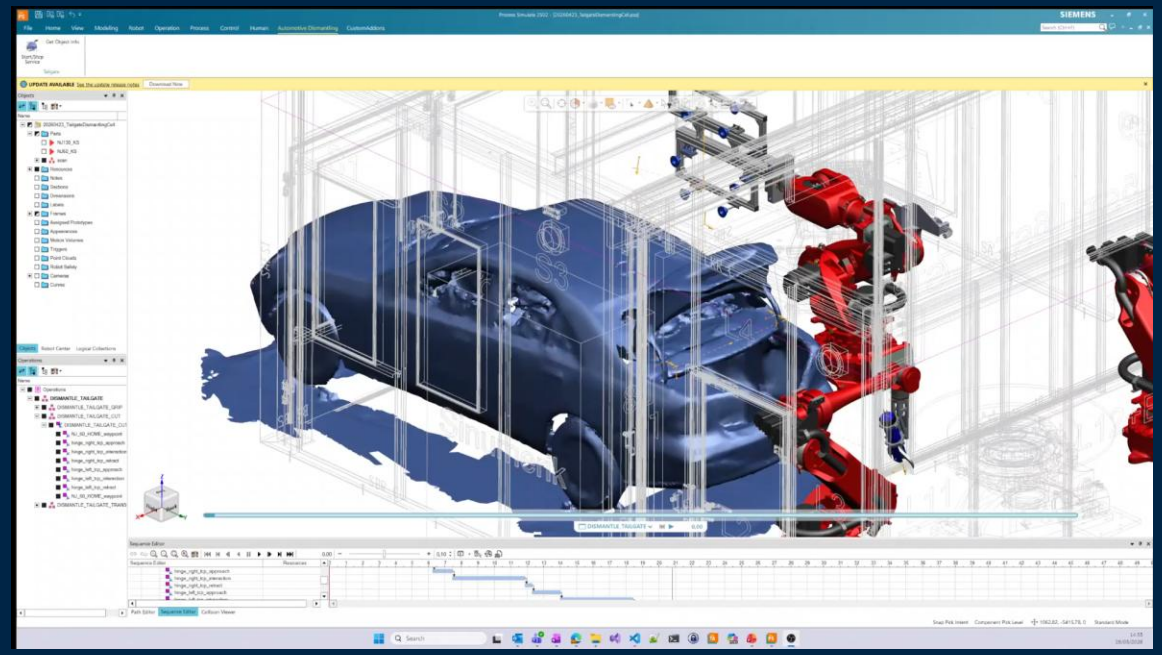
Note: 1) Runs on Windows PC

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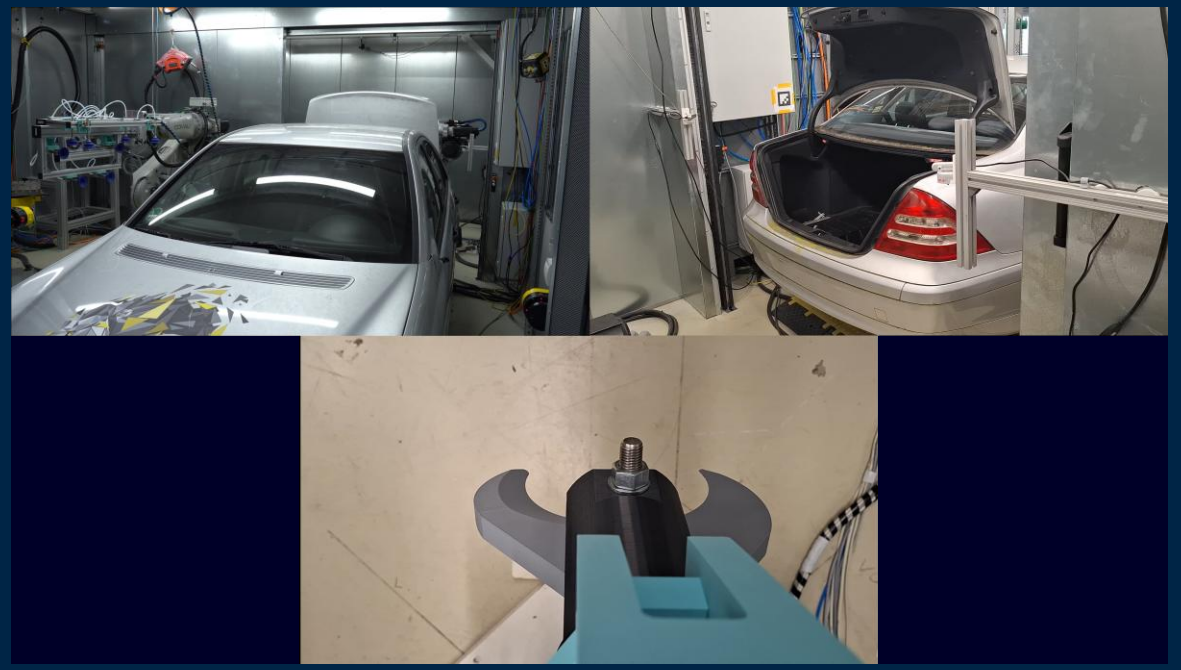
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Videos of the motion sequence and its digital twin

Data Layer:



Process Layer:



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Any questions?



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CCPT Conference

Remanufacturing: the most sustainable and complex industrial business lacking a reference model

Dr.-Ing. Daniel C. F. Koehler

Head of Research & Development Business Unit Truck & Trailer Components
BPW Bergische Achsen KG

Elected Chairman
Automotive Parts Remanufacturers Association AISBL (APRA EU)

we think transport

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Dr.-Ing. Daniel C. F. Köhler – Remanufacturing CV



Dr. Daniel C. F. Koehler
(Elected Chairman APRA EUROPE)

UNIVERSITÄT BAYREUTH / Fraunhofer IPA

- 2007 – 2012: University Bayreuth & Fraunhofer IPA
- Phd Student @ Prof. Dr. Rolf Steinhilper
- PhD Thesis "Regenerative Supply Chains"

MJR

- … - 2013: Guangdong Mingjie Parts Remanufacturing Co. Ltd.
- Head of Strategy and Development

KNORR-BREMSE

- … - 2020: Knorr-Bremse Commercial Vehicle Systems GmbH
- Vice President TruckServices Technical Solutions

BPW – we think transport

- Since 2020: BPW Group
- Head of Research & Development Business Unit Truck & Trailer Components (incl. Remanufacturing Business)

APRA europe

- Since 2017: Automotive Parts Remanufacturers Association Europe AISBL
- Chairman

19 years of Remanufacturing

I present not well known but fundamental pillars of Remanufacturing business

Remanufacturing and Sustainability







Remanufacturing is the most sustainable business model

The Remanufacturing Business Model

Core-Control



- Withdrawl old products (Cores) from the market
- Enabling of the remanufacturing business

2 Price-Points

- Value-based repair of vehicles
- 2 brand strategy
- Growth in the sector of alternative specifications

Q-Costs



- Remanufacturing of bad new serial production batches
- Use of remanufactured products within warranty

Field-Feedback



- Permanent return of end-of-life products
- Learning of real failure and wear reasons

Obsolescence



- Solution for long term spare parts supply
- Reduction of the risk for the last batch

Sustainability

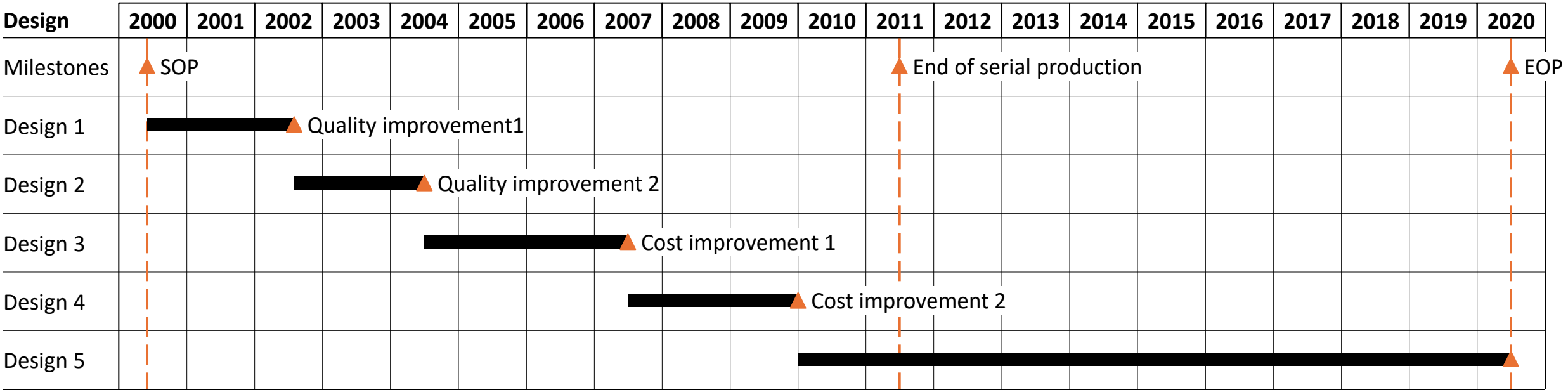


- Remanufacturing as the highest form of recycling
- Over 70%-CO_2 saving compared to new production

Remanufacturing must be considered as a comprehensive business model

No reference business or system model existing

The Product Design Changes during Serial Production



#	BOM-Level	Name	Period1	Period2	Period3	Period4	Period5
1	Product	Product	BOM1	BOM2	BOM3	BOM4	BOM5
2	Component	Housing	Housi			Housing2	Housing2
3	Component	Bridg					Bridge2
4	Component	P					Piston1
5	Component	B					Bushing1
6	Component	Lever					Lever3
7	Component	Adjuster	Adjuster1	Adjuster2	Adjuster2	Adjuster2	Adjuster3
8	Component	Cap	Cap1	Cap1	Cap2	Cap2	Cap2
9	Component	O-Ring	O-Ring1	O-Ring1	O-Ring2	O-Ring2	O-Ring2

4 Design Changes (→ 6 components)

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The Complexity in Remanufacturing

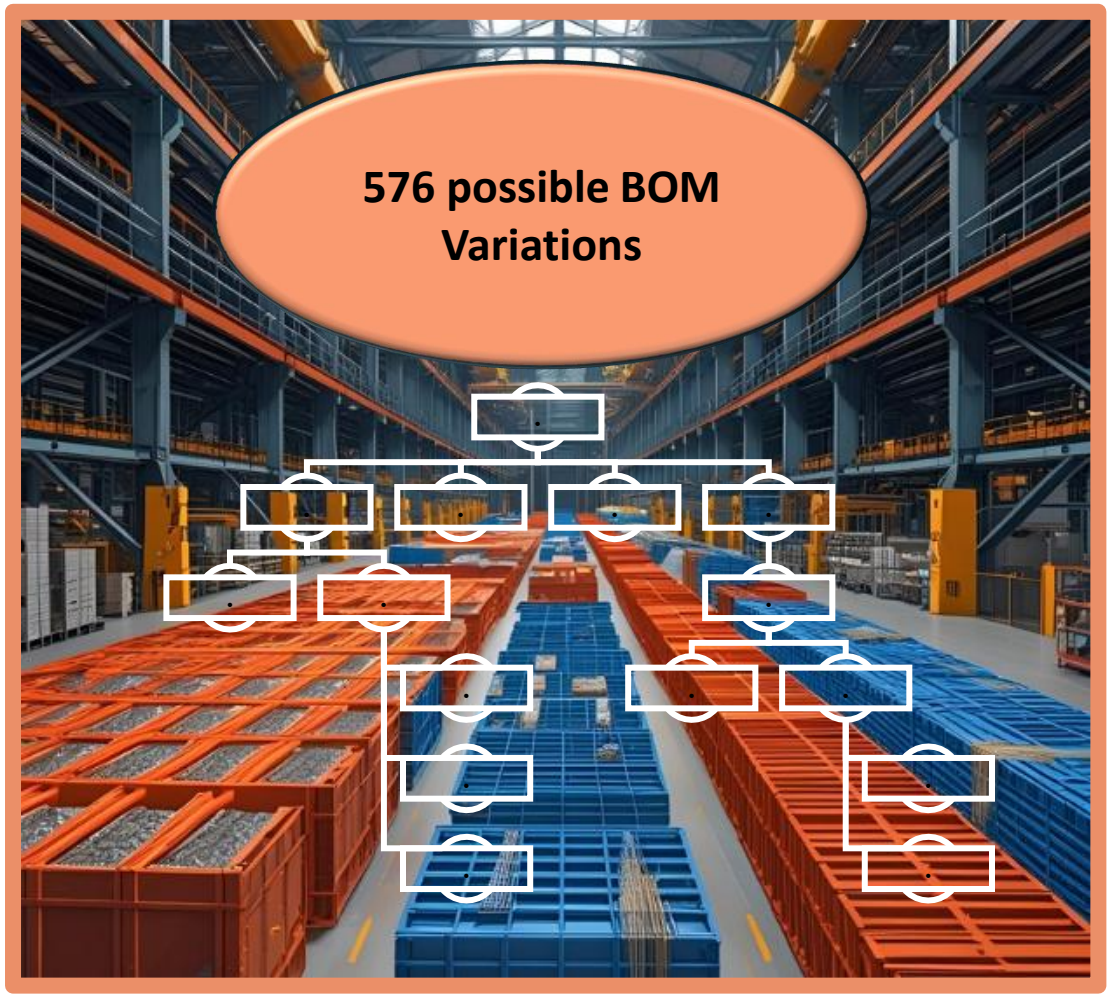
#	BOM-Level	Name	Period1	Period2	Period3	Period4	Period5
1	Product	Product	BOM1	BOM2	BOM3	BOM4	BOM5
2	Component	Housing	Housing1	Housing1	Housing1	Housing2	Housing2
3	Component	Bridge	Bridge1	Bridge1	Bridge1	Bridge1	Bridge2
4	Component	Piston	Piston1	Piston1	Piston1	Piston1	Piston1
5	Component	Bushing	Bushing1	Bushing1	Bushing1	Bushing1	Bushing1
6	Component	Lever	Lever1	Lever1	Lever2	Lever2	Lever3
7	Component	Adjuster	Adjuster1	Adjuster2	Adjuster2	Adjuster2	Adjuster3
8	Component	Cap	Cap1	Cap1	Cap2	Cap2	Cap2
9	Component	O-Ring	O-Ring1	O-Ring1	O-Ring2	O-Ring2	O-Ring2

4 Design Changes (→ 6 components)



Reconditioning

~ 1 Design Change (→ 2 components)



Remanufacturing is probably the most complex industrial business

The Compatibility Matrix by Koehler

	Housing1a	Housing1b	Housing2a	Housing2b	Bridge1	Bridge2	Piston1	Bushing1a	Bushing1b	Lever1	Lever2	Lever3	Adjuster1	Adjuster2	Adjuster3	Cap1	Cap2	O-Ring1	O-Ring2
Housing1a					y	n	y	y	n	y	y	n	y	y	n	y	y	y	y
Housing1b					y	n	y	n	y	y	y	n	y	y	n	y	y	y	y
Housing2a					n	y	y	y	n	y	y	y	y	y	y	y	y	y	y
Housing2b					n	y	y	n	y	y	y	y	y	y	y	y	y	y	y
Bridge1	y	y	n	n			y	y	y	y	y	n	y	y	n	y	y	y	y
Bridge2	n	n	y	y			y	y	y	y	y	y	y	y	y	y	y	y	y
Piston1	y	y	y	y	y	y		y	y	y	y	y	y	y	y	y	y	y	y
Bushing1a	y	n	y	n	y	y	y			y	y	y	y	y	y	y	y	y	y
Bushing1b	n	y	n	y	y	y	y			y	y	y	y	y	y	y	y	y	y
Lever1	y	y	y	y	y	y	y	y	y				y	n	n	y	y	y	y
Lever2	y	y	y	y	y	y	y	y	y				n	y	n	y	y	y	y
Lever3	n	n	y	y	n	y	y	y	y				n	n	y	y	y	y	y
Adjuster1	y	y	y	y	y	y	y	y	y	y	n	n				y	y	y	y
Adjuster2	y	y	y	y	y	y	y	y	y	n	y	n				y	y	y	y
Adjuster3	n	n	y	y	n	y	y	y	y	n	n	y				y	y	y	y
Cap1	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y			y	n
Cap2	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y			n	y
O-Ring1	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n		
O-Ring2	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n	y		

y = yes, compatibility given

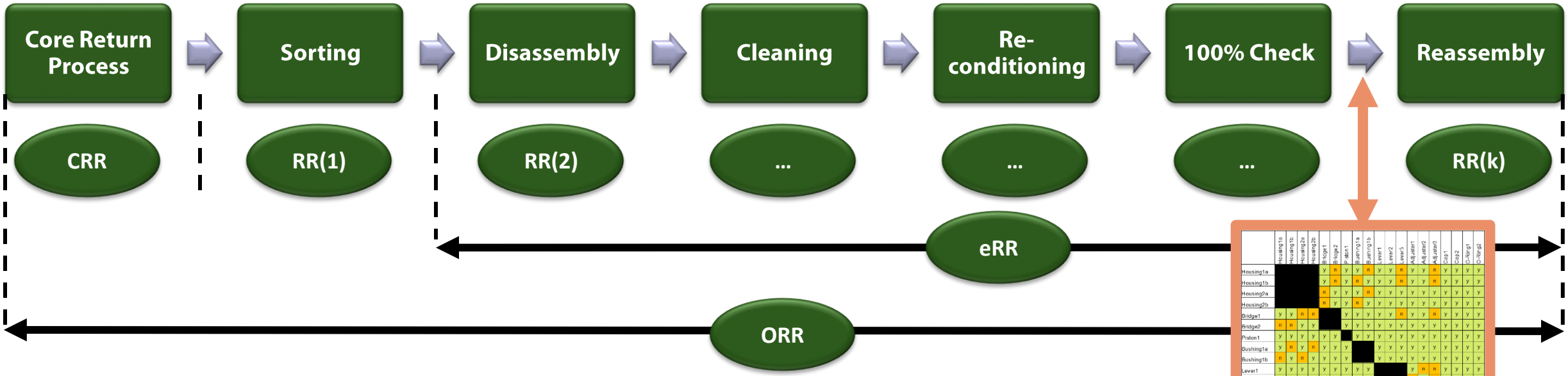
n = no, compatibility not given

= no possible combination

- Defines the compatibility of the single components with respect of their individual design level
- The single component variations created by reconditioning methods (e.g. oversized bore and bushing) shall also be reflected
- Deliverable of the R&D function in a remanufacturing product development project

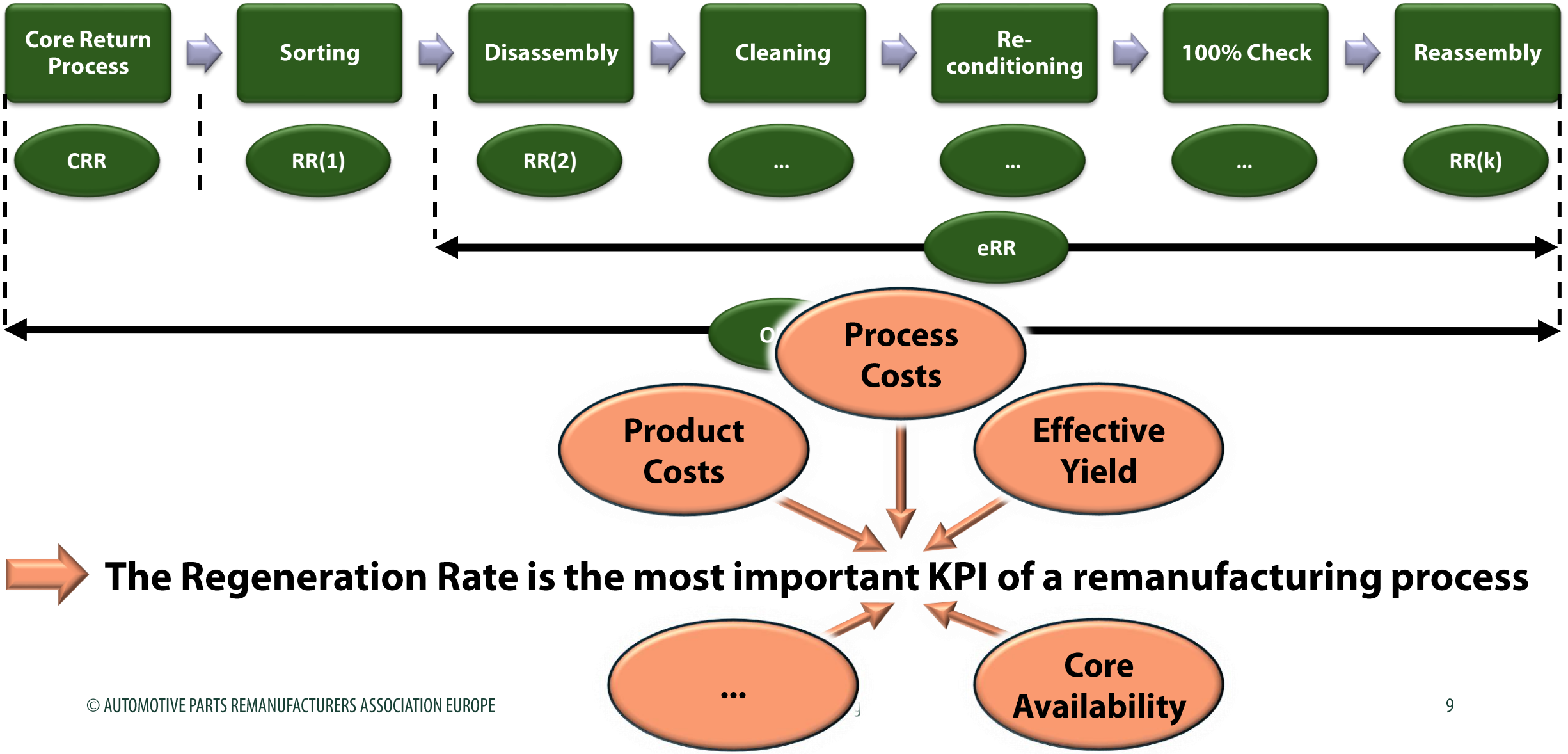
The Compatibility Matrix by Koehler can manage Complexity in Remanufacturing

The Remanufacturing Process Chain Level



- CRR = Core Return Rate
- RR(k) = Regeneration Rate (~ Yield) of specific process step „k“
- eRR = external Regeneration Rate
- ORR = Overall Regeneration Rate

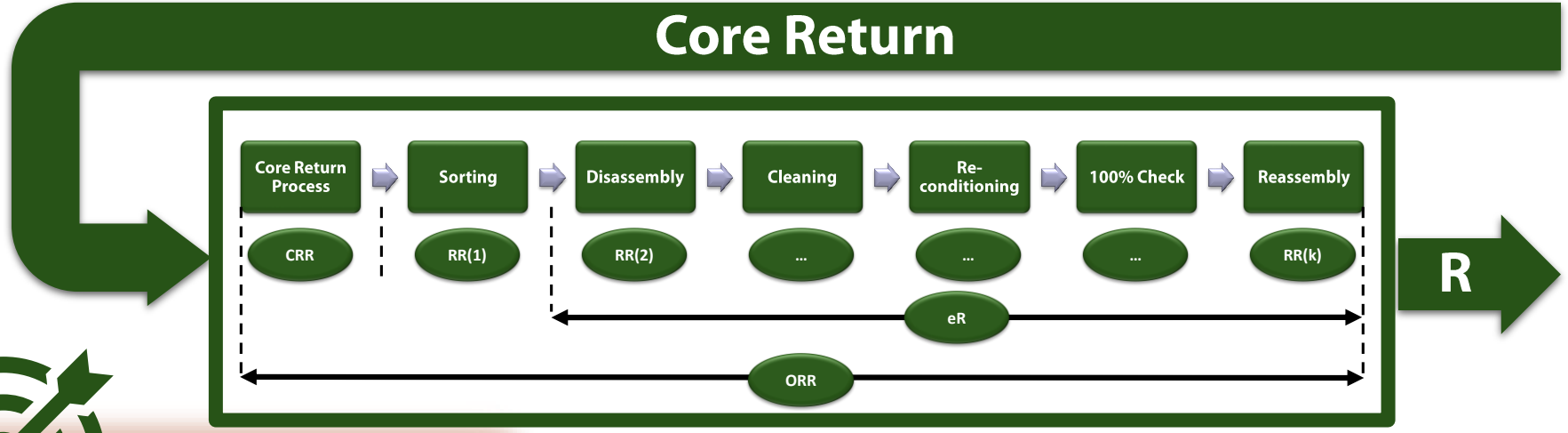
The Remanufacturing Process Chain Level



The Regeneration Rate is the most important KPI of a remanufacturing process

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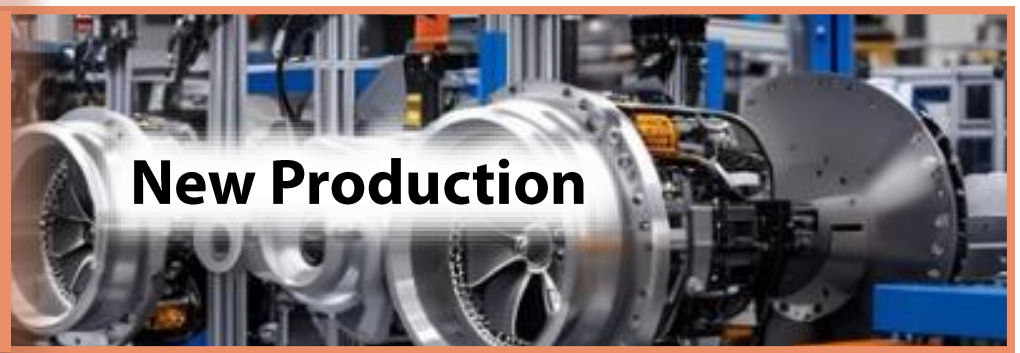
The Remanufacturing System and Value Chain Level



R



$$ORR \geq RS = \frac{R}{R + N}$$

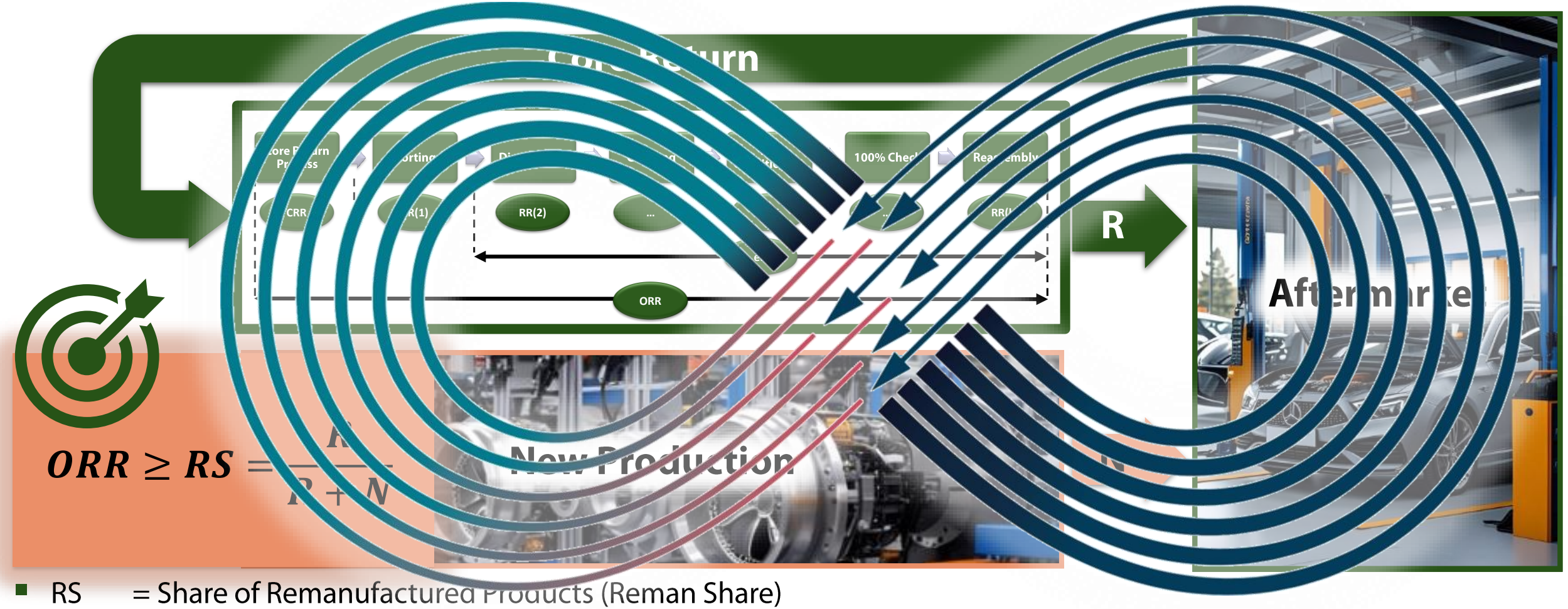


N

- RS = Share of Remanufactured Products (Reman Share)

System and value chain level embeds the process chain level into the market

The Remanufacturing System and Value Chain Level



$$ORR \geq RS = \frac{R}{P + N}$$

- RS = Share of Remanufactured Products (Reman Share)

System and value chain level embeds the process chain level into the market

Conclusion

The absence of a reference business and system model causes a multitude of negative implication in the practical daily business, that could have been avoided. Some examples:



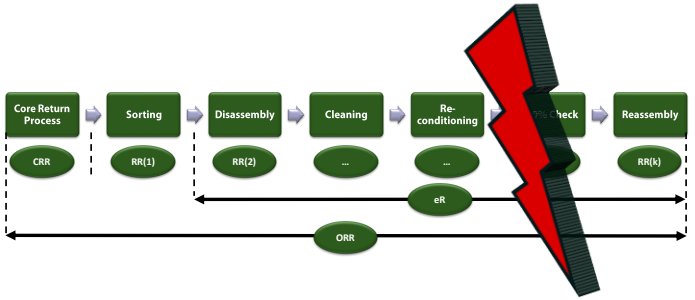
Wrong Business Case & Set Up

ERP Pain

$$ORR \geq RS = \frac{R}{R+N}$$



Fake Reman Trap



Wrong Design & Management

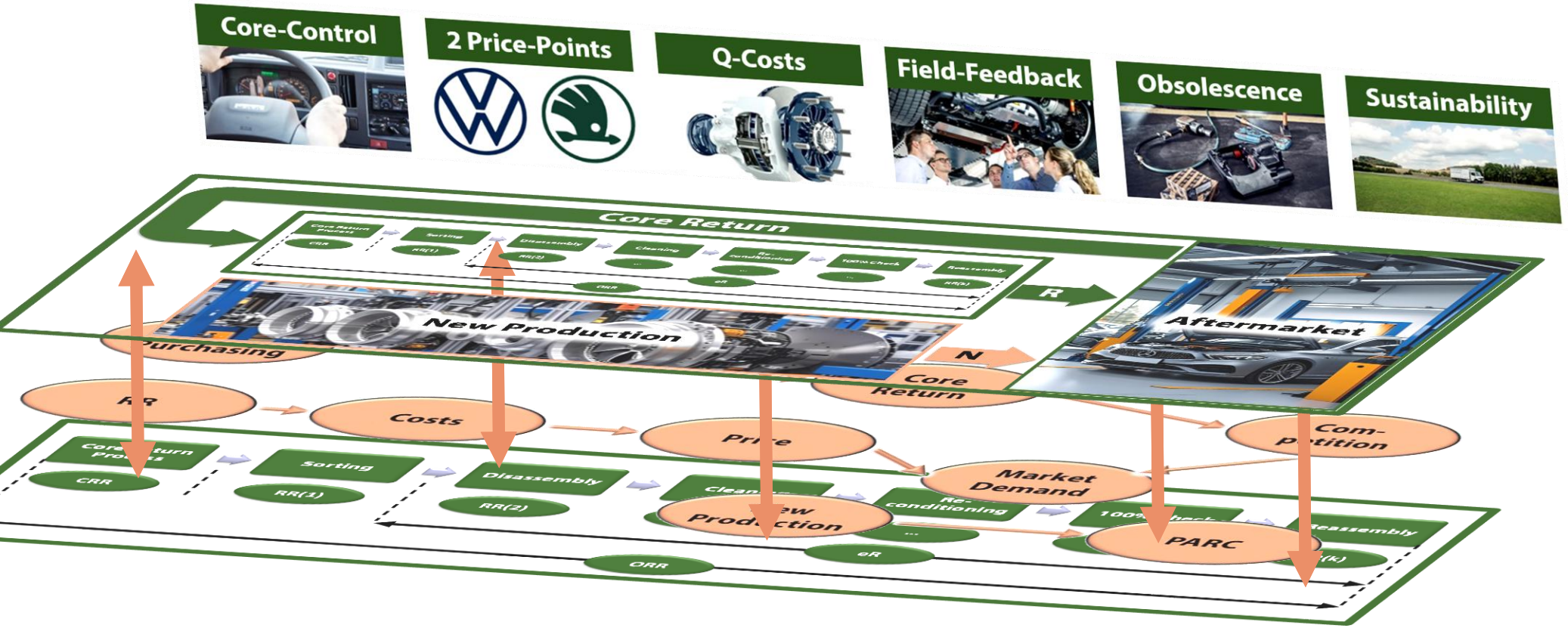




Controlling Pain

There is a huge potential of more robust designed remanufacturing businesses

Thank you very much for your attention!



Business Model

System and Value Chain Level

Process Chain Level

- I will dedicate my humble capacity to that topic
- Thank you very much for your attention

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Conference on Circular Production Systems and Technologies (CCPT)
Karlsruhe, Germany, 9th and 10th June 2026

Flexible remanufacturing using AI and advanced robotics for circular value chains

09/06/2026

Prof. Sotiris Makris
makris@lms.mech.upatras.gr

LABORATORY FOR MANUFACTURING SYSTEMS and AUTOMATION (LMS)
University of Patras, GREECE

1

Core Ideas

01 **Setting the scene**
Standard production today vs. closed-loop remanufacturing value chains

02 **Why now — drivers & challenges**
Industrial drivers, sustainability goals and the gaps that hold remanufacturing back

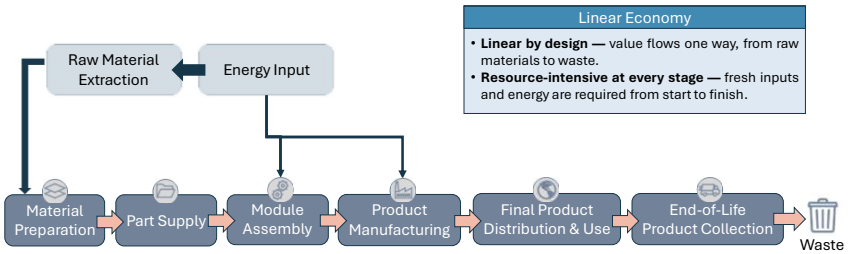
03 **The Flexible Remanufacturing paradigm**
An AI- and robotics-driven approach designed for open-world product variability

04 **Enabling technologies in action**
Multi-agent data governance for decision support, planning & orchestration, open-world reasoning, human-centric support and HRC pilots

05 **Conclusions & outlook**
What we have learned and where flexible remanufacturing goes next

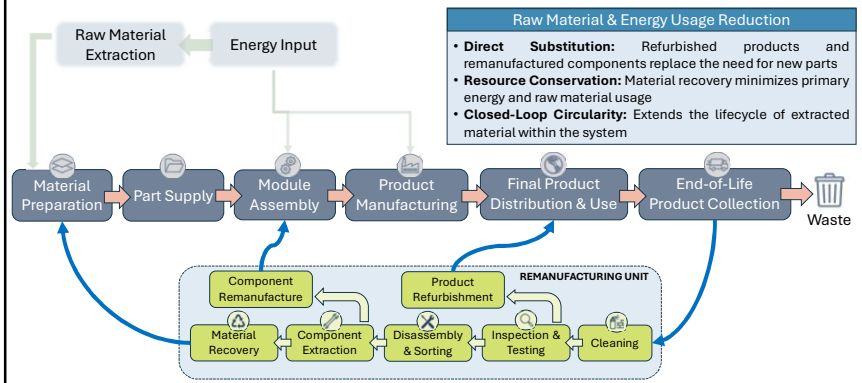
2

Standard Production Flow



3

Closed-loop Remanufacturing Value Chain



4

The case for remanufacturing

Why circular value chains are no longer optional

20%[1]
of global GHG emissions
Manufacturing alone is responsible for roughly one fifth of the EU's greenhouse-gas footprint.

54%[2]
of world's energy
Industrial production consumes more than half of all energy generated worldwide.

> €180bn[3]
annual disruption cost
Supply-chain shocks now cost the European economy hundreds of billions of euros every year.

Remanufacturing is now a strategic priority — tightening EU regulation, volatile raw-material supply and customer demand for circular products are converging into a clear industrial mandate.

[1] European Parliament [link]
[2] U.S. EIA Industrial Sector Energy Consumption Report [link]
[3] JS Held: Global Risk Report [link]

5

What's driving it now

Four converging forces are pulling remanufacturing into the industrial mainstream

MARKET PULL
$63B+
Auto reman, 2025
Projected $143B by 2034 (CAGR 9.5%) as EV components enter the cycle [1]

EU REGULATION
ESPR
In force since Jul 2024
Mandates durability, repairability and Digital Product Passport [2]

OEM COMMITMENT
Key Players
of OEMs Market participate
Bosch, ZF, Renault, Volvo, Caterpillar run scaled reman lines [3]

MATERIALS RISK
40-60%
vs. new-part cost
Critical raw materials drive OEMs to close loops and cut exposure [4]

Sources: [1] Research and Markets 2025 [link]; [2] European Commission ESPR (in force 18 July 2024) [link]; [3] Automobile Remanufacturing Market Report 2026 ; [link]; [4] McKinsey & Company [link]

6

Challenges towards Flexible Remanufacturing Adoption

From open-world uncertainty to industrial-scale circularity

THE CHALLENGE
Used products are unpredictable
Variability in core condition, geometry and history makes traditional automation fail

OPERATIONAL GAPS
- High capex
- Variable cores
- Rigid automation
- Manual labour

THE FLEXIBLE REMANUFACTURING PARADIGM

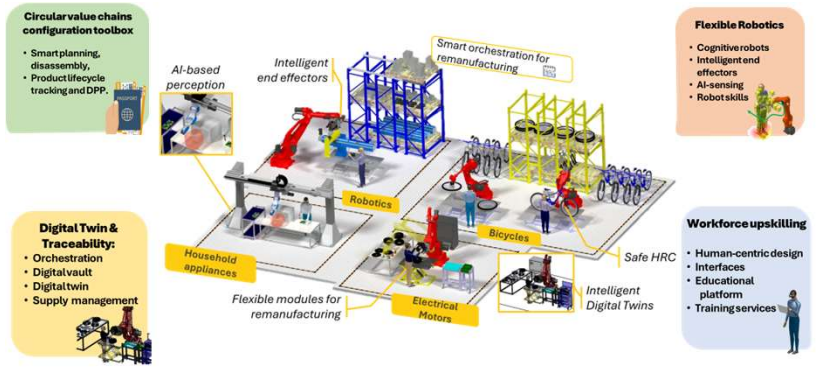
AI — Open-World AI Reasoning
LLMs and AI perception generate flexible robotic skills and disassembly plans on the fly — identifying and unscrewing components without rigid programming.

DI — Digital Infrastructure
A circular value chain toolbox of intelligent tools and digital systems for decision support, data governance and smart workflow orchestration.

HC — Human-Centric Collaboration
Safe human-robot collaboration and intelligent interfaces that support and upskill operators through complex remanufacturing tasks.

7

Flexible remanufacturing paradigm



8

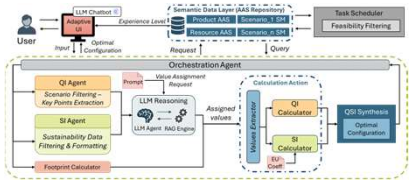
Multi-Agent Evaluation framework for workspace configurations

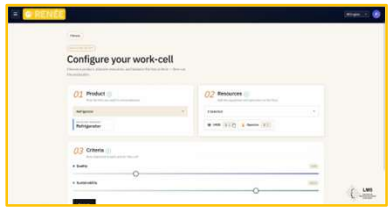
A decision-support platform that helps engineers select optimal workstation layouts under conflicting Quality & Sustainability goals

EVALUATE
Automated scenario generation & quality/sustainability scoring

REASON
LLM-driven qualitative assessment & user-defined weighting

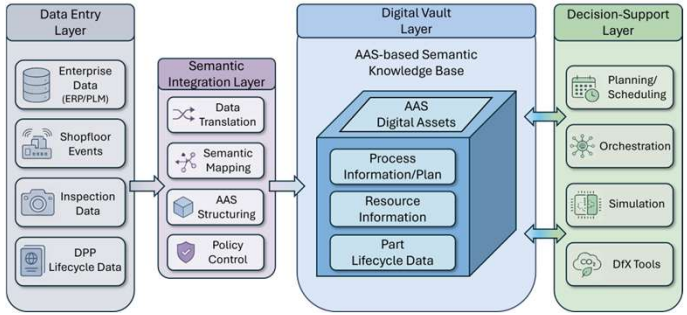
INTERACT
Adaptive UI + multilingual AI chatbot assistant





9

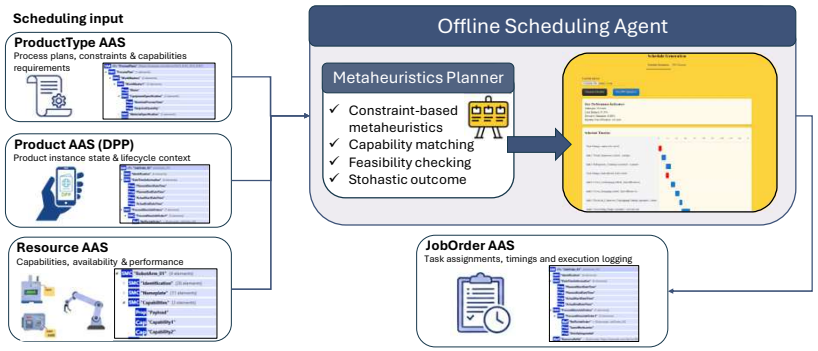
Multi-Agent Scheduling & Orchestration Framework



10

Multi-Agent Scheduling & Orchestration Framework

Offline Scheduling



11

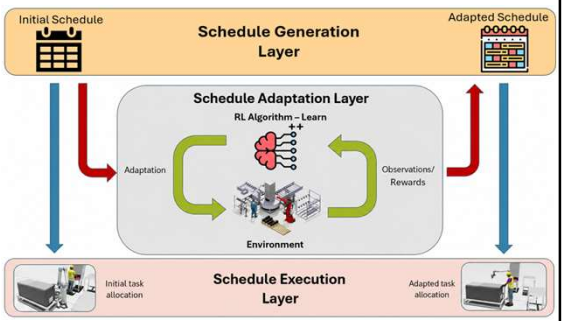
Multi-Agent Scheduling & Orchestration Framework

Online Scheduling Agent

Use RL algorithm to refine scheduling based on continuous learning

Schedule Adaptation layer

- Observations/Rewards from the environment
  - Positive rewards for meeting deadlines, minimizing idling of resources
  - Penalties for task delays, overloaded resources
- RL to online learn from execution events and make adaptations
  - ✓ Offline schedule as baseline
  - ✓ Online reallocate tasks
  - ✓ Adjust task sequence



12

Multi-Agent Scheduling & Orchestration Framework

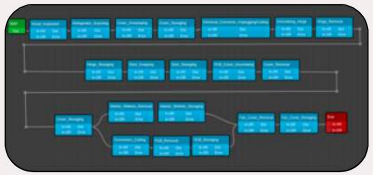
Orchestration Agent

Task Dispatching
Decomposes scheduled tasks into executable actions

Abstraction Management
Supports multiple execution granularities (tasks – actions – behaviours)

Monitor & Control
- ✓ Tracks execution state & triggers recovery/rescheduling actions
- ✓ Supports ROS2 based action server-client architecture

Orchestrator UI (Runtime Execution Graph)



13

Human-centric Decision Support

Supervised Autonomy

Human-Agent Communication → Engineers validate and tune agents' decisions

Agent Recommendations
Propose scheduling & orchestration decisions

Live Monitoring & Alerts
Report deviations, events & anomalies

Shopfloor

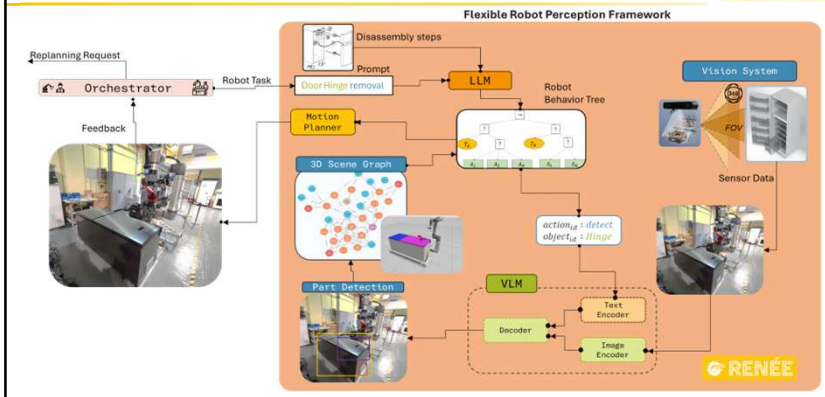




Confirm/ Override Plans | Adjust / Reschedule Tasks | Trigger Interventions

14

Reconfigurable robotic skills with Open-World reasoning



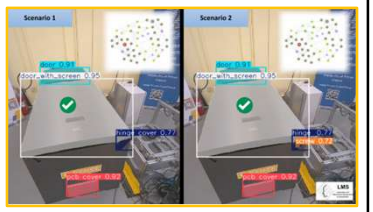
15

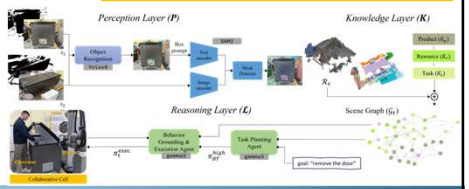
Reconfigurable robotic skills with Open-World reasoning

Robotic framework combining Open-World Perception with Multimodal Reasoning (LLMs)

Key Steps:

- **Perception Layer (P):** Multimodal scene understanding using RGB-D, YOLOv8 and SAM2
- **Knowledge Layer (K):** Semantic representation via a Dynamic Scene Graph (Gt), stored in Neo4j, which connects vision with ontology
- **Reasoning Layer (L):** Adaptive decision-making using LLM Agents to build executable Behavior Trees



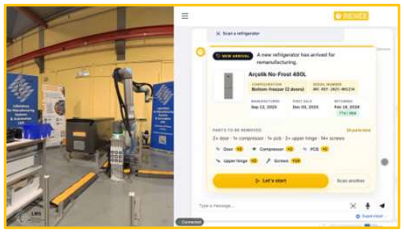


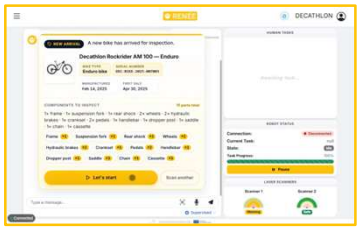
16

Multi-Agent Human Operator Support

Operator Support during Disassembly/Inspection

- Live **updates** to the operator with assigned tasks from the **orchestration agent**.
- Interface with **Human Action Recognition** agent for **automated task completion** and **robot controllers** to **project and validate** tasks to be executed
- **Notifications** to the operator upon **task completion** and triggering **orchestration agent** for next task.
- Fully-time availability for step-by-step **guidance** throughout the entire process.





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Remanufactured products

EV Motors			**Green Mobility Support** More affordable and sustainable electric mobility options by reusing components
Household appliances			**CO_2 Emissions Avoided** Every remanufactured unit saves approx. 280 kg of CO_2e. **~14,000 tons CO_2e savings/year.**
Industrial Robots			**Local Industrial Impact** Strengthening European service networks and reducing reliance on importing new robots
Bicycles			**Affordable Mobility** Provide low-cost, reliable bicycles for customers, promoting sustainable mobility

18

HRC for Household Appliances Disassembly



19

Cooperative Robots for EV motor disassembly



20

Conclusions

Flexible, AI-enabled remanufacturing turns variability from a blocker into a tractable industrial workflow

KEY TAKEAWAYS

1. **A strategic mandate**
   Market pull; EU regulation and supply-chain risk are converging → circularity has moved from CSR to P&L.
2. **Variability is the core blocker**
   Used products arrive unpredictable; conventional automation fails without adaptive, open-world reasoning.
3. **Three pillars unlock scale**
   Open-world AI reasoning, digital infrastructure and human-centric collaboration close the circular remanufacturing gaps.
4. **Proven on real product families**
   Approach demonstrated on realistic industrial scenarios including disassembly with cooperative robots and human-robot collaboration.

NEXT STEPS

- **Design products for circularity**
  Embed disassembly, repairability and material traceability into product design, not as an afterthought.
- **Build the data backbone**
  Adopt the Digital Product Passport so cores carry their material, design and service history across the value chain.
- **Mature adaptive automation**
  Move open-world AI and reconfigurable robotics from labs to standard industrial practice.
- **Align policy, skills and incentives**
  Harmonise regulation, reskill the workforce and create the market signals that make circular flows the default.

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Thank you for your attention!

Prof. Sotiris Makris
makris@lms.mech.upatras.gr

This project has received funding from the European Union's Horizon Europe Framework Programme under grant agreement nº 101138415.

Funded by the European Union

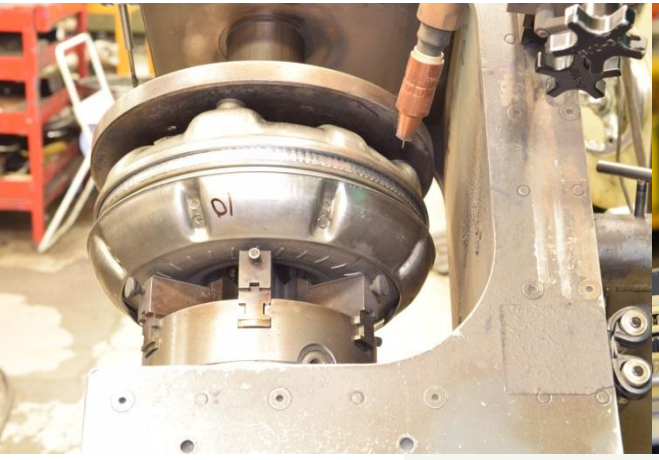
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Remanufacturing: A Lucrative Untapped Clean Growth Strategy

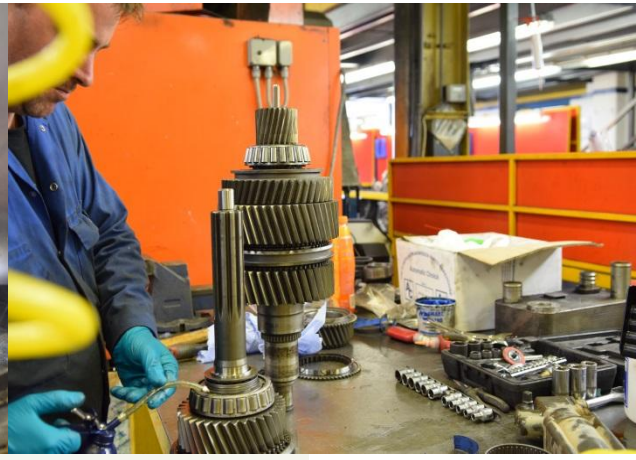
Prof. Winifred Ijomah

Director: Scottish Institute for Remanufacture (SIR)

w.l.Ijomah@strath.ac.uk (https://winifred-ijomah.com/)







www.scot-reman.ac.uk @SIRemanufacture

Reasons for Remanufacturing: Opportunities

The Market

2015

£30 Billion — EU market pa

£4.4 Billion — UK's value pa

Projected growth by 2030 in EU:

£100 Billion — EU

500K Jobs — Job Creation

21m tonnes — Carbon Emissions avoidance

United Nations (UN) report

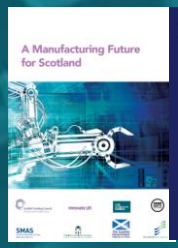


Re-defining Value: The Manufacturing Revolution - Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy

UK Government reports



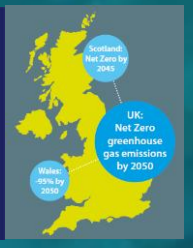
Scottish Government SD Initiatives:



Manufacturing Strategy



Energy Mix



Net Zero

Emergent Global Opportunities:

- Circular Economy, Low Carbon Manufacture

Economic, Environmental Benefits

- 20% - 80% production cost savings
- 50% - 80% less energy
- 85% of weight of remanufactured product is from used parts

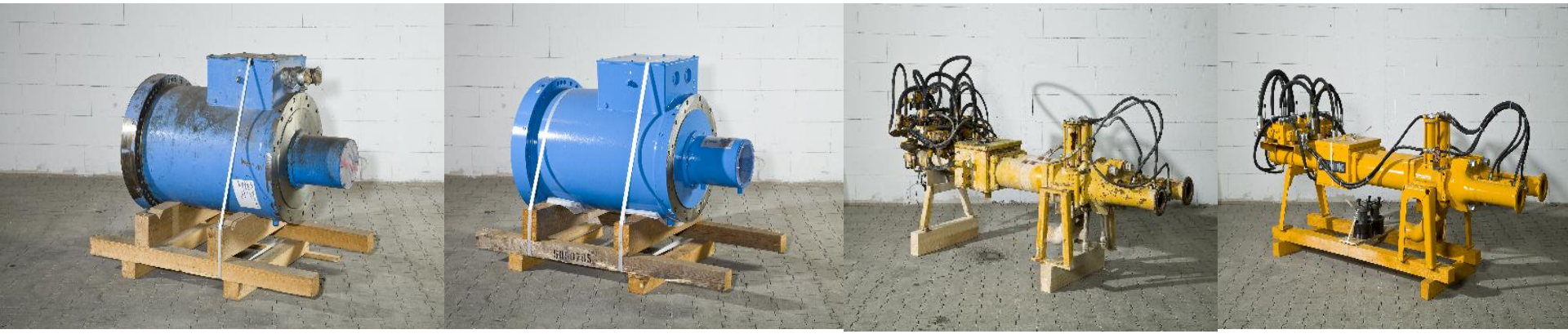
Global race to acquire expertise

What is remanufacturing?

Alternative manufacturing approach

- *Definition (Ijomah 2002; BSI 2009)*
  - *The process of returning a used product to at least as new performance specification and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent*
    - USA remanufacturers > 73,000
    - Combined sales: $53 billion
    - Av. annual sales > $21 million

(from early 1970's USA-UN study- Lund)



Before and after pictures for tunnelling equipment parts remanufacture

Critical Material

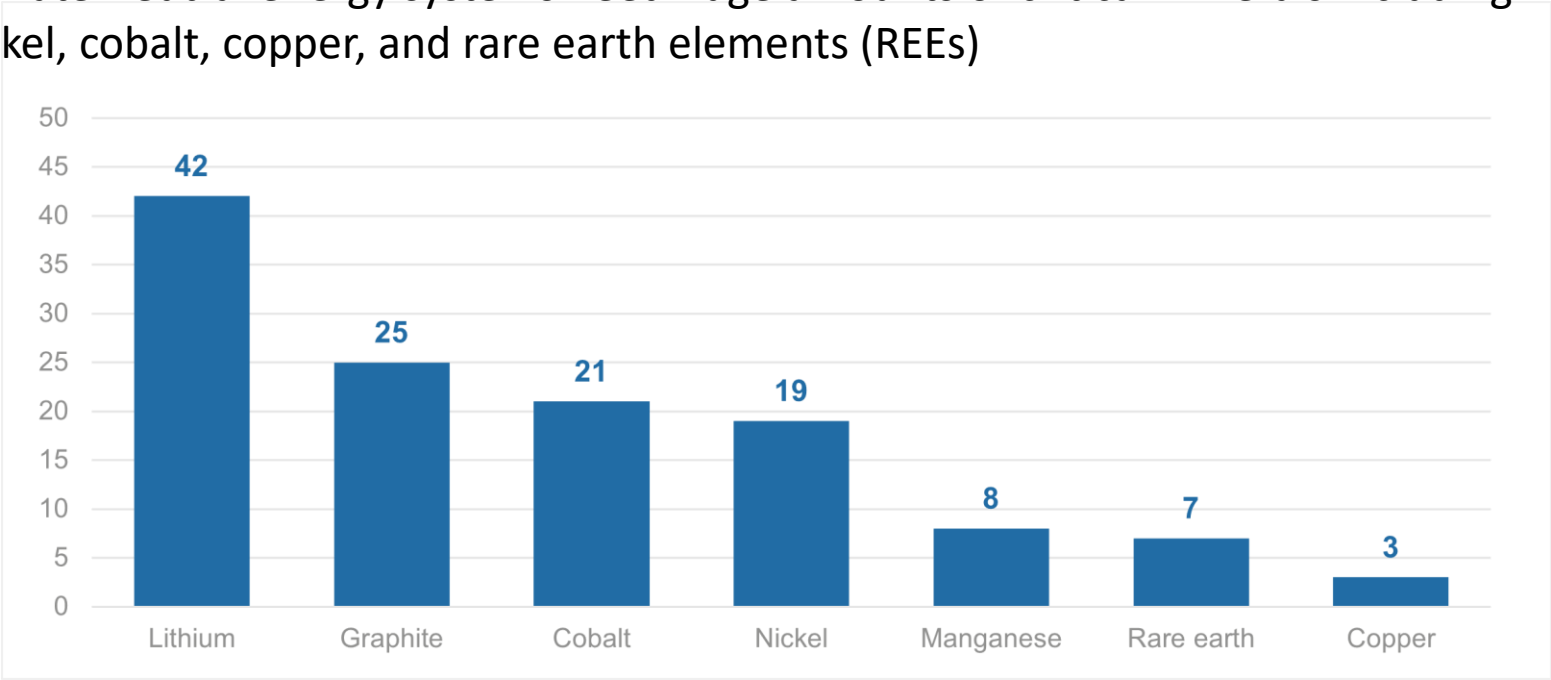
Definition

Substance used in technology that has supply risks and no easy substitutes.

Importance

Key for manufacturing thus international competition.

- Traditional sectors: aerospace, automotive, energy and chemical sectors, which rely on materials typically extracted and processed abroad.
- New technologies: electric vehicles, renewable energy (wind turbines), and digital technologies (computers, smartphones).
- Climate-neutral energy systems need huge amounts of critical minerals including lithium, nickel, cobalt, copper, and rare earth elements (REEs)

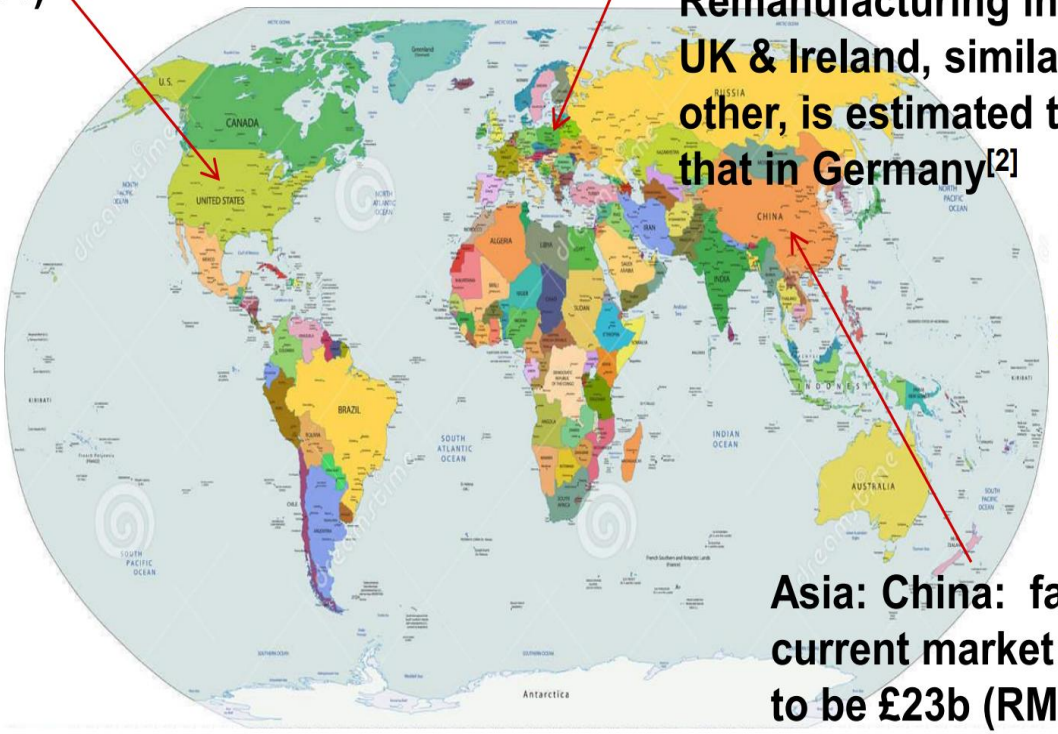


Critical minerals projected demand increase by 2040 (based on 2022 levels)

Global Remanufacturing

US: Largest market, (€ 40 billion in 2011)[1]

EU: €30bn, 70% in Germany, the UK & Ireland, France and Italy, Remanufacturing in France and in the UK & Ireland, similar in size to each other, is estimated to be around half that in Germany[2]



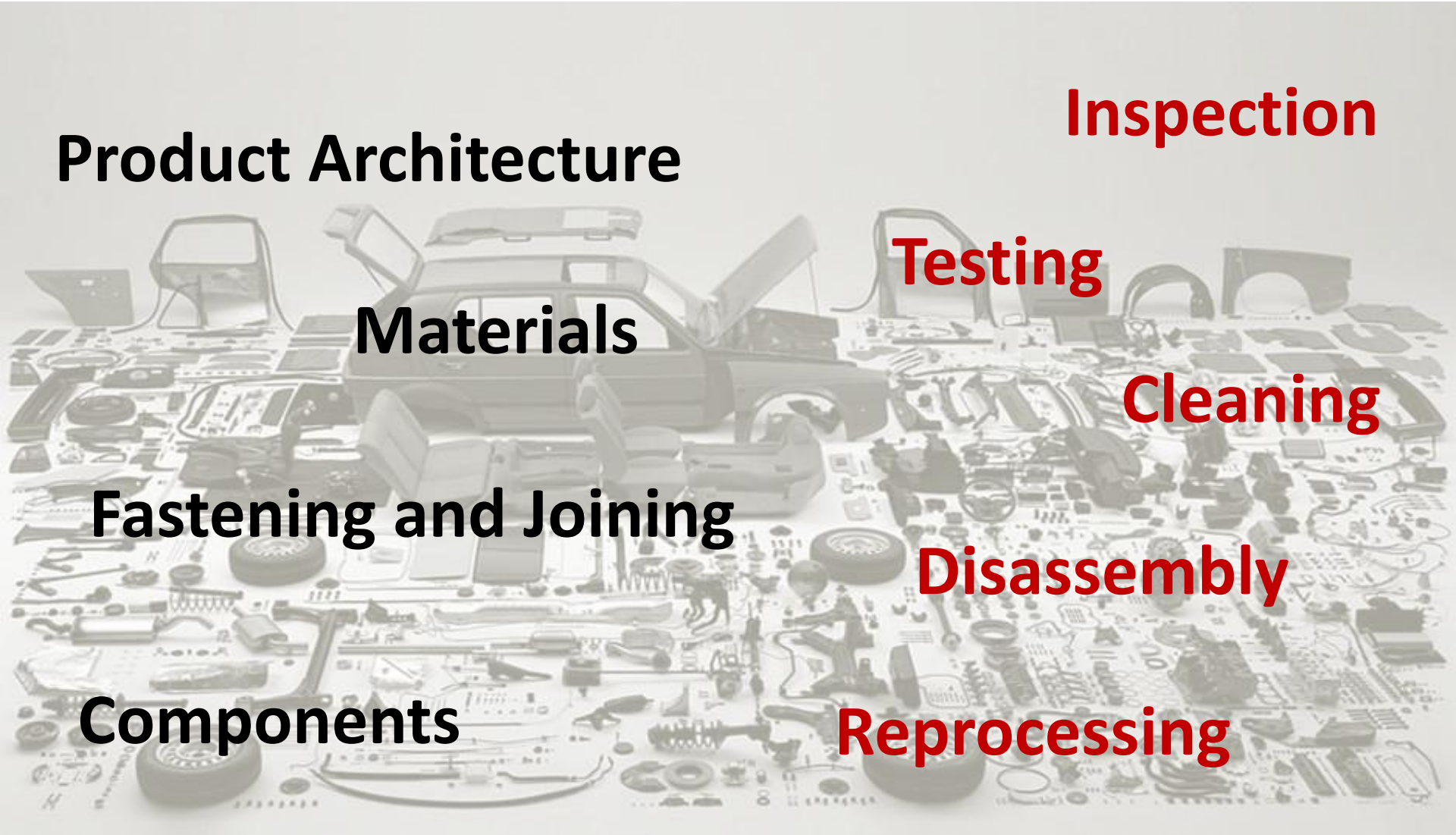
Remanufacturing in the UK is £5.6billion[1]

Asia: China: fastest growing, current market size: around to be £23b (RMB200b) in 2020 (MIIT), only 30 years history[3]

My work in Remanufacturing

My work in Remanufacturing: DfRem Challenges

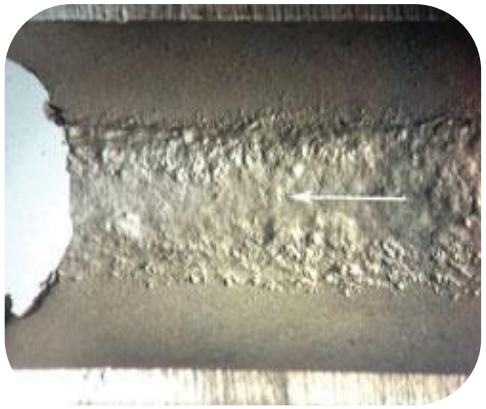
Technical Issues



Technical Remanufacturing Challenges



Disassemble without damage?



Clean without corroding?



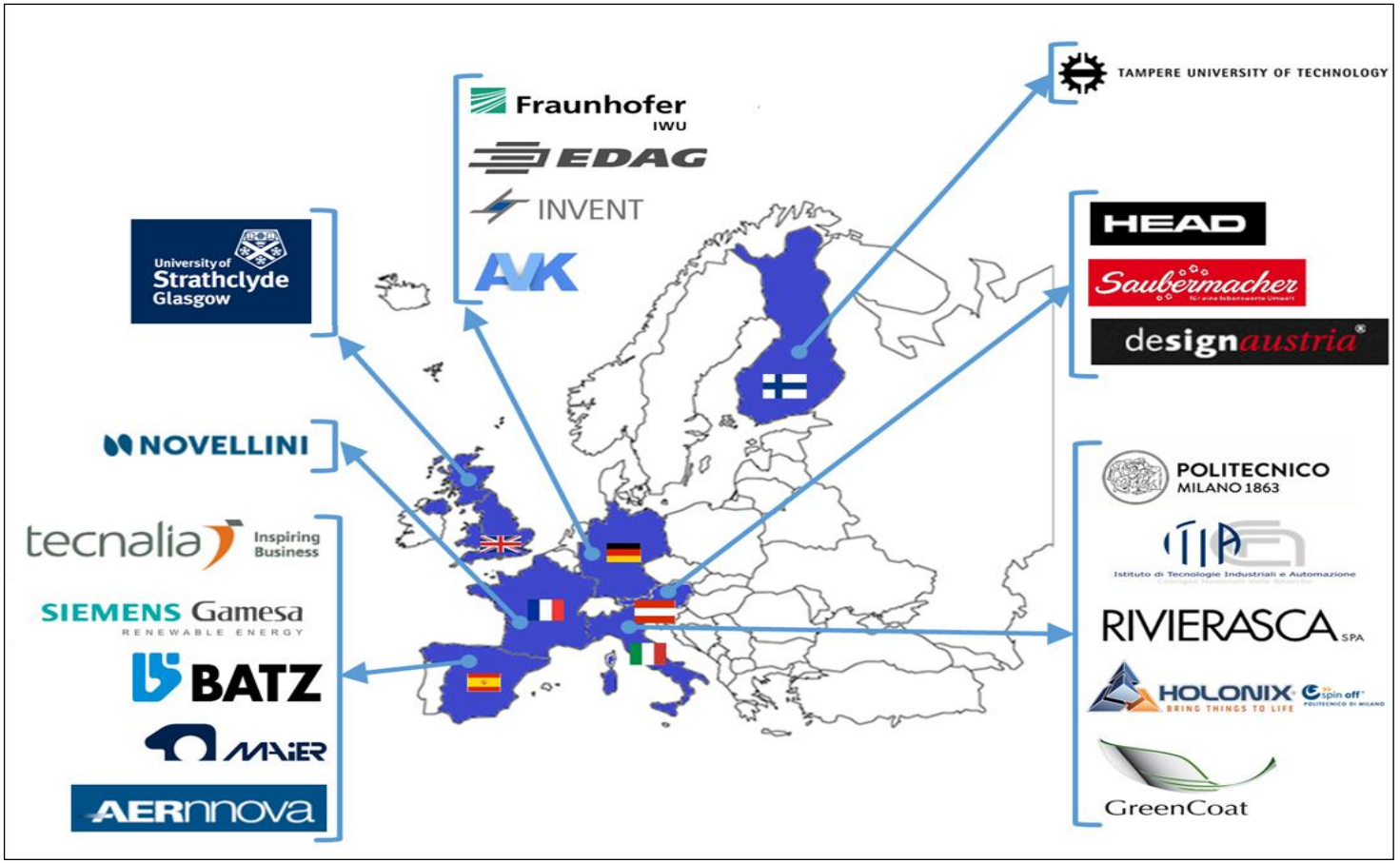
Recognise material and part number?

- Ijomah W, McMahon, C A, Hammond G P, Newman S T, (2007) ""Development of design for remanufacturing guidelines to support sustainable manufacture" DOI:10.1016/j.rcim.2007.02.017,
- W L Ijomah, C A McMahon, G P Hammond, S T Newman (2007) ""Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development DOI:10.1080/00207540701450138

Large scale demonstration of new circular economy value-chains based on reuse of EoL fibre reinforced composites, (FiberEUse).

Management of EoL Composites

- Enhance composite reuse profitability by developing and integrating different innovations in a holistic manner
- €9.8M EU, H2020 Project: 20 partner institutes from 7 EU countries



7 Nations:
Austria, Finland; Germany, Italy, UK Spain, France,.

20 Organisations:
12 industrial,
6 research,
2 industry associations

Partners' & Geographical location

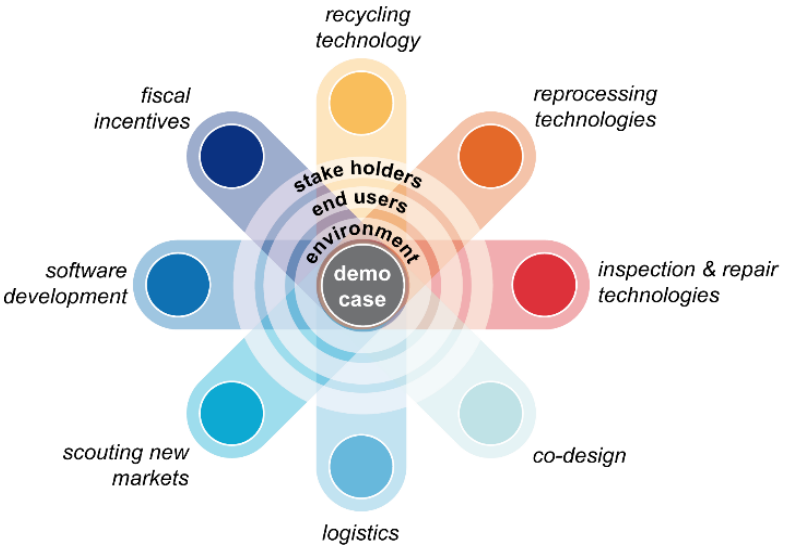
www.fibereuse.eu

FiberEUse objectives

Demonstrate profitable reuse of EoL composites on a large scale

1. Determine new profitable reuse options for mechanically/ thermally recycled EoL GFRP and CFRP composites
   - Develop then Integrate innovative reclaim technologies.
   - ✓ Enhance operational ease/cost, Meet EU Directives

2. Develop strategies to enhance composite supply and re-supply chains communication coordination.
   - OEMs, tier 1 suppliers, logistics operators, technology providers and exploiters, designers, end-user associations
   - ✓ mobilize and network stakeholders from all the sectors related to the composites



FiberEUse Concept

Increasing FiberEUse solutions' economic/environmental sustainability

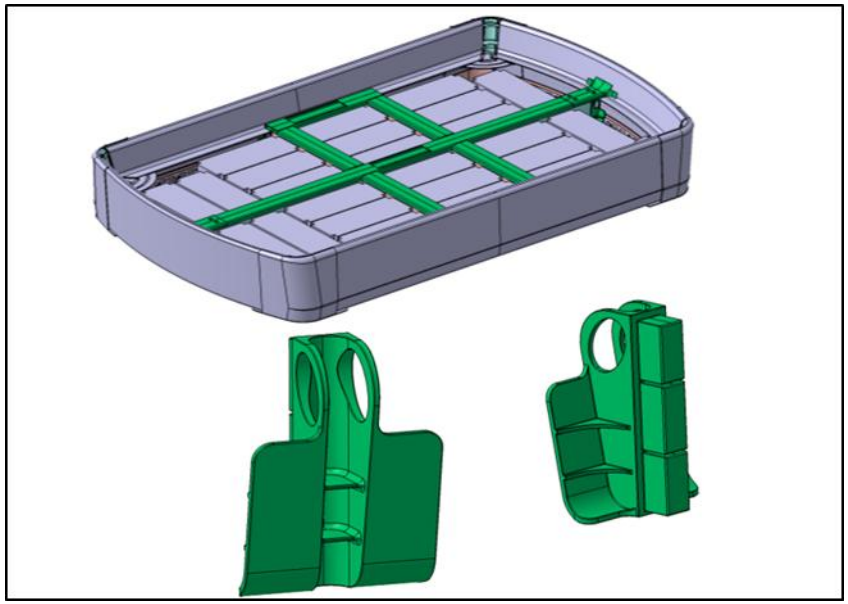
3: Addresses the key non-technical hindrances to reuse:

- Lack of market due to lack of understanding and knowledge of their properties
  - Ambiguity in definition of reuse processes
  - What properties would they have thus how can the be used
- Low revenue
  - Low economic value e.g. compared to metals
- Efficiency losses from inappropriate value-chain infrastructures
  - Damage in transit, not time/cost effective
- Lack of supporting legislation and incentives for composite reuse.

Solutions obtained

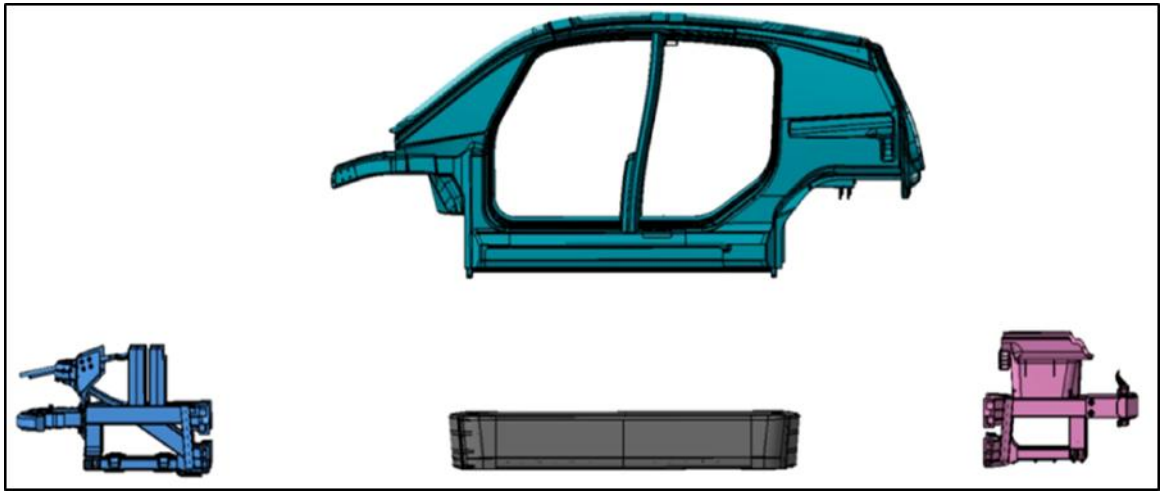
- New service-oriented business models.
- Optimised reverse logistics network architecture.
- Cloud-based ICT platform for value-chain integration.
- LCA and LCC of the developed solutions.
- Profitability and risk assessment of the innovative value-chain business cases.
- Legislation boundaries and recommendations for legislators .
- Showcasing reclaimed parts in virtual and physical product library

Dissemination and Exploitation



Storage platform fortified by new recycled fibre parts (in green) from UC2

Modularity assists assembly and disassembly, thus reuse



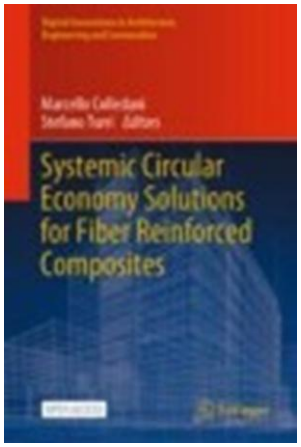
Dissemination and Exploitation



Glebanite grade 34%,
Vs marble water tap



Internal/External tiles



The FiberEUse book springer.com/book/10.1007/978-3-031-22352-5:



Glebanite
44% recycled,
laminated,
milled,
assembled



Glebanite Wine Cooler/tableware ©Martina Hatzenbichler Design

- Andrea Tuni, Fiona Gutteridge, Winifred L. Ijomah, Maryam Mirpourian (2024) “Risks in circular business models innovation: A cross-industrial case study for composite materials; //doi.org/10.1002/bse.3618
- Tuni, Andrea and Ijomah, Winifred L. and Gutteridge, Fiona and Mirpourian, Maryam and Pfeifer, Sarah and Copani, Giacomo (2023) Risk assessment for circular business models : a fuzzy Delphi study application for composite materials. //doi.org/10.1016/j.jclepro.2022.135722
- Yan, Yijun and Ren, Jinchang and Zhao, Huan and Windmill, James F.C. and Ijomah, Winifred and Wit, Jesper De and Freeden, Justus Von (2022)“Non-destructive testing of composite fibre materials with hyperspectral imaging – evaluative studies in the EU H2020 FibreEUse project”. www.researchgate.net/publication/355993331_Nondestructive_Testing_of_Composite_Fibre_Materials_with_Hyperspectral_Imaging_Evaluative_Studies_in_the_EU_H2020_FibreEUse_Project

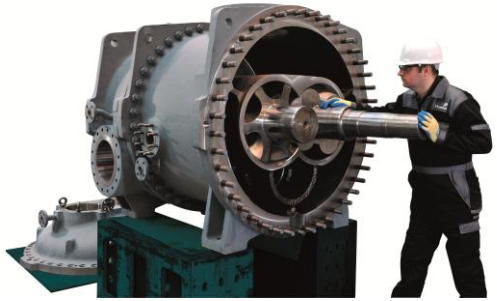
ReMake Glasgow Projects

£14M funding to support Glasgow manufacturers to become greener and more productive

Invigorate Circular Economy in the Glasgow City Region

- Advance technologies for Remake processes
  - Design for remanufacturing, LCA for remanufacturing
  - Digital Product Passport (DPP), Lead Time Improvement
- Mainstream reuse
- Establish a world-class ReMake Glasgow Hub".
- Six partners







Manufacturing Research Hub in Resource-Enabled Sustainable Circular Automation Manufacturing (RESCu-M2)

Empowering UK to be a world leader in circular manufacturing.

- Create manufacture ecosystem for circular resource use of high value products by unlocking advances in AI, Robotics and Intelligent Automation.
- £34.6M (£11M from EPSRC and £23.6M from project partners)
- 7 UK research institutions & 35 stakeholder organisations



University of Sheffield

University of Sheffield

Loughborough University

mtc Manufacturing Technology Centre

UNIVERSITY OF BIRMINGHAM

University of Leeds

University of Brighton

University of Strathclyde Glasgow

Critical Challenges and Opportunities

- The UK is reliant on strategic elements and technology-critical materials.
- A large percentage is from outside UK.
- Lacking direct access, UK resource strategy must focus on transforming value retention processes (Re-X: re-use, repair, refurbish, remanufacture, and recycle).
- Emerging Re-X processes and eco systems are 3-6 times less productive.
- Smart machines and processes to upscale Re-X processes in parallel with their development is required

Economic, Environmental Benefits (2030):

- 20% - 80% production cost savings
- 50% - 80% less energy
- 85% of weight of remanufactured product is from used parts
- 500K jobs created
- 21m tonnes of Carbon emissions avoided
- £100 Billion market (smart machines and technologies)



Objectives and Grand Challenges

Objectives

O1: Establish an ecosystem for circular manufacturing

O2: Create more effective Smart RE-X processes

O3: Develop smart systems robust to variation

O4: Support designers at the onset of the circular process

Grand Challenges:

1: Radically transform **sustainable use of critical materials**.

Goals:

>75% Critical components reuse;

>20% critical material use decrease;

>50% component reclaim increase.

2: Radically improve **productivity of Re-X manufacturing processes** on par with or exceeding traditional manufacturing processes.

Goal: >10 times improvement.

Announcement

The first International Europe-Africa Workshop on Remanufacturing (www.euareman.org)

National Research Council of Italy, Palermo, Italy; 7-9th October 2026



Africa and Europe working together to futureproof remanufacturing for our common future

The 8th International Conference on Remanufacturing (ICoR)

The University of Strathclyde will host ICoR 2027 13-15 April 2027, in Amsterdam in conjunction with ReMaTec 2027.

https://remanufacturing-conference.com/index.php



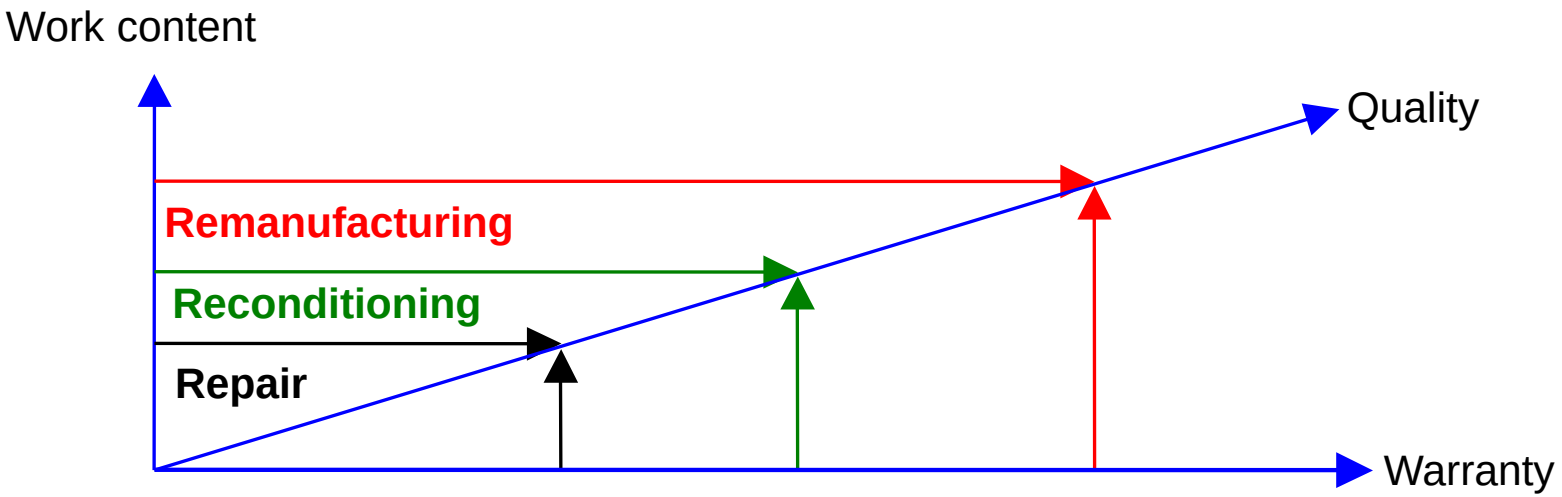
THANK YOU

Journal paper Selection

- Harris, R.S. and Ijomah, W.L. and Windmill, J. (2023) Evaluation and validation of Damage Assessment Tracking Criteria models within the UK automotive remanufacturing. Journal of Cleaner Production, 414. 137494. ISSN 0959-6526.
- Damola Ikeoluwa Akano, Solomon Eze; Winifred Ijomah; James Windmill (2022), “Characterisation of Medical Devices Remanufacturing: An Exploratory Study on the Nature, Mechanisms, and Implication”, J. Cleaner production.
- Pawlik, Elzbieta and Ijomah, Winifred and Corney, Jonathan and Powell, Daryl (2022), “Exploring the application of lean best practices in remanufacturing: empirical insights into the benefits and barriers.” Sustainability.
- Sitcharangsie, S, Wong, A.TC. Ijomah, W (2021), “Bi-objective optimisation of remanufacturing decisions with component commonality under different” reworking scenarios”, International Journal of Computer Integrated Manufacturing.
- C. Nwankpa, S. Eze, W. Ijomah, A. Gachagan, and S. Marshall, (2021), “Design for Automated Inspection in Remanufacturing A Discrete Event Simulation Process Improvement Approach,” J. Cleaner Engineering and Technology,
- Akano D, Ijomah WL, Windmill J, (2021), “Hierarchical Analysis of Factors Influencing Acceptance of Remanufactured Medical Devices”, Cleaner and Responsible Consumption. https://doi.org/10.1016/j.clrc.2021.100017

What is remanufacture?

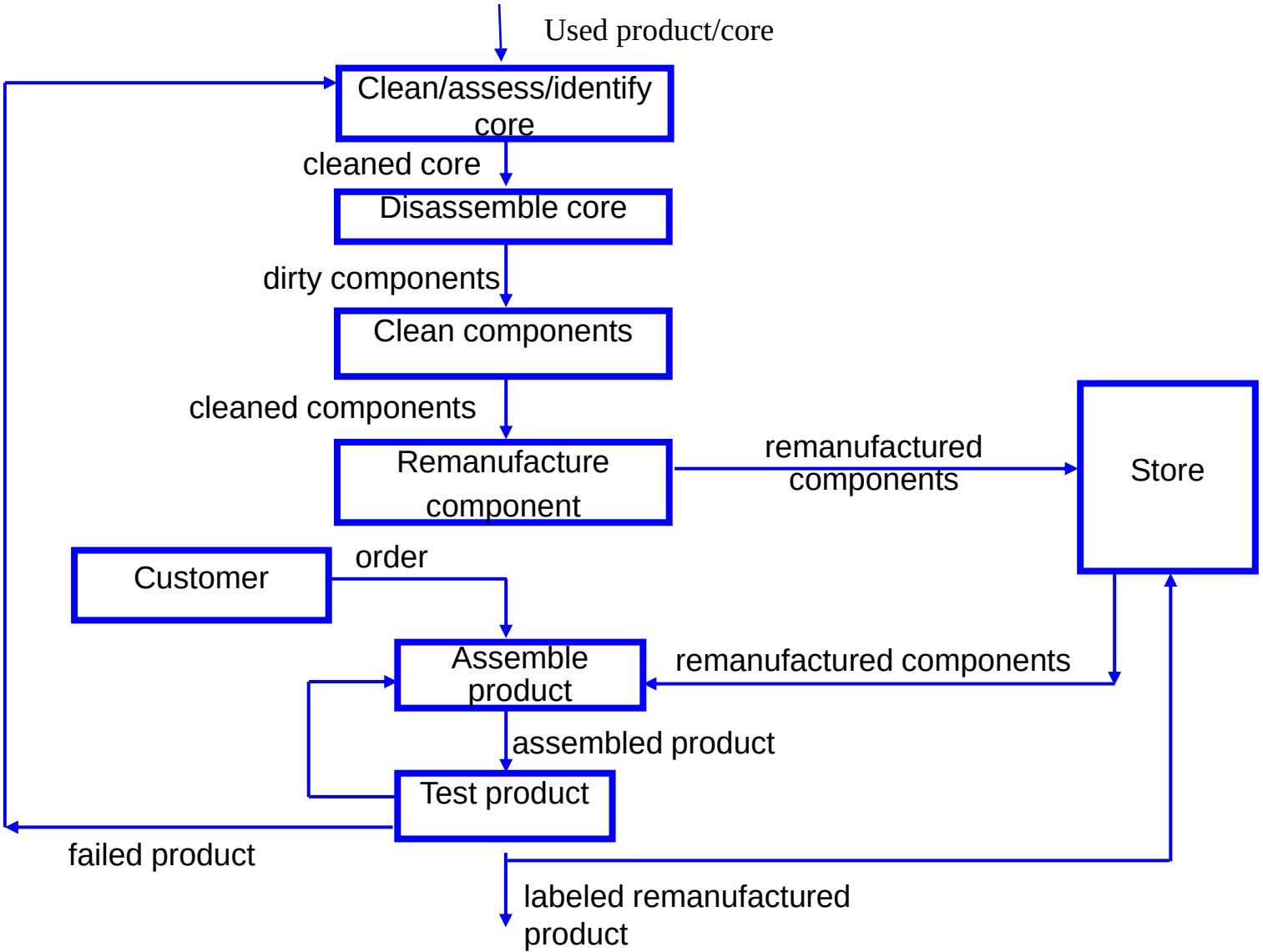
- A hierarchy of secondary market processes (Ijomah WL 2002; BSI 2009)



- Remanufacture
  - Product loses identity, performance & warranty greater/equal to new
- Reconditioning
  - Product retains identity, performance & warranty below new
- Repair
  - Product retains identity, performance & warranty below new

How do does remanufacture happen?

A generic remanufacturing process chart (Ijomah W)



Circular Products and Production Technologies for Next Generation Sustainable Manufacturing Systems

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Sustainability, Sustainable Development and Sustainable Manufacturing

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Global Challenges to Society, Environment and Economy

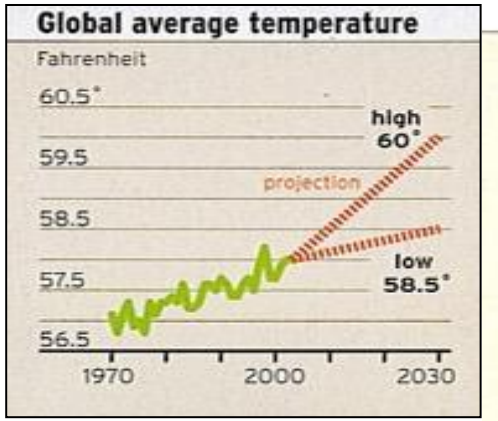




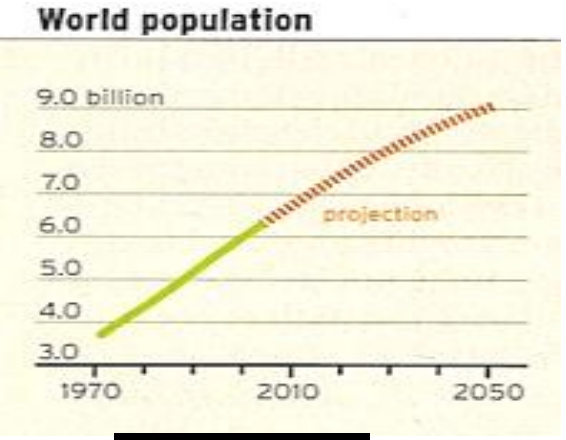
Water and Air Pollution



Landfills and Wastes



Global Warming

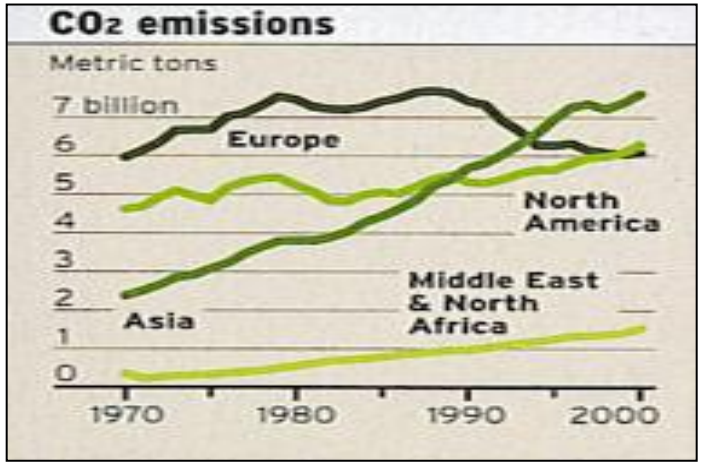


Population



Ecological Footprint





Emissions and Toxicity

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From Sustainment to Sustainability with Varying Levels and Scales



Sustainable Value Creation

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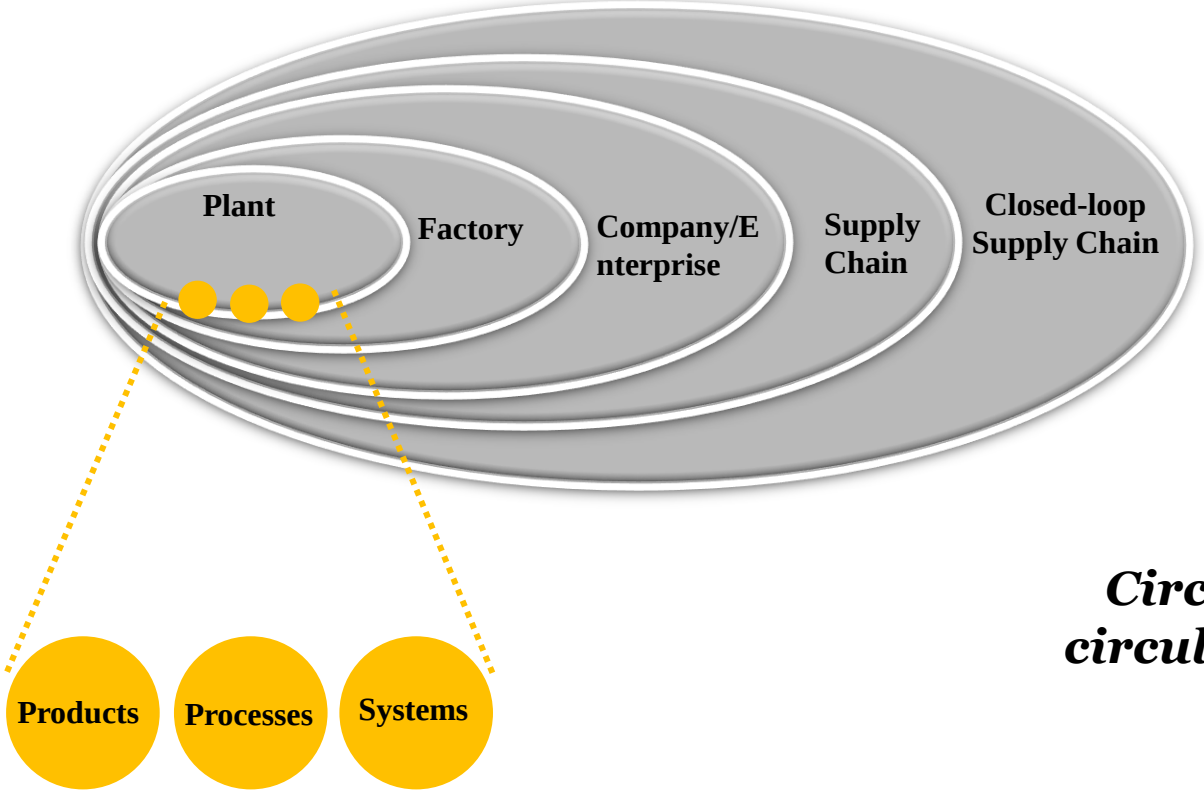
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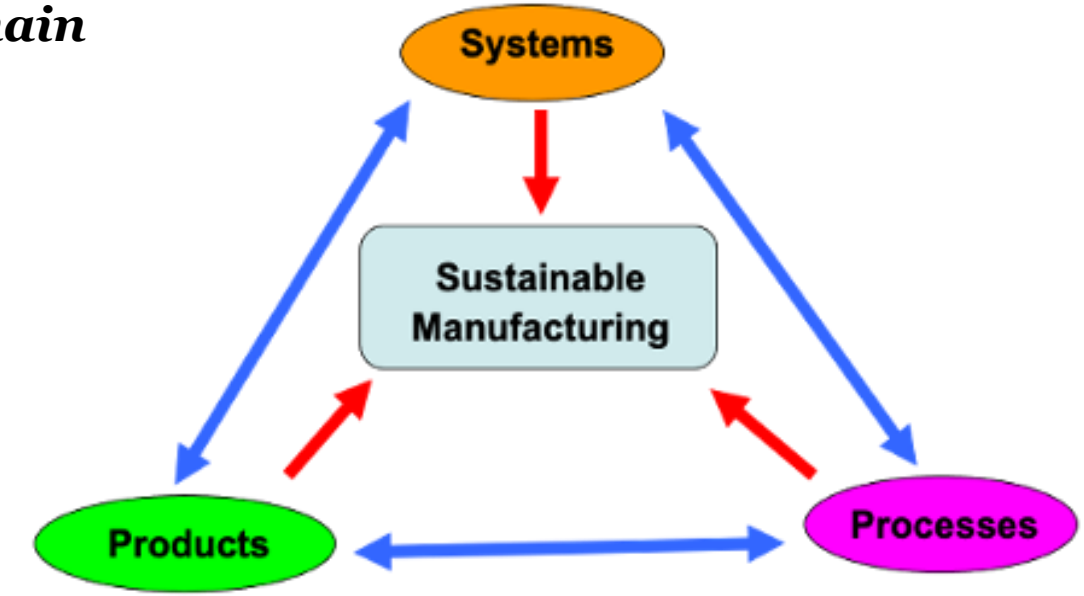
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Focus on Products, Processes and Systems and their Integration

Sustainability Applications in Manufacturing Value Chain





Circular manufacturing involves an integrated circularity system for manufactured products and manufacturing processes

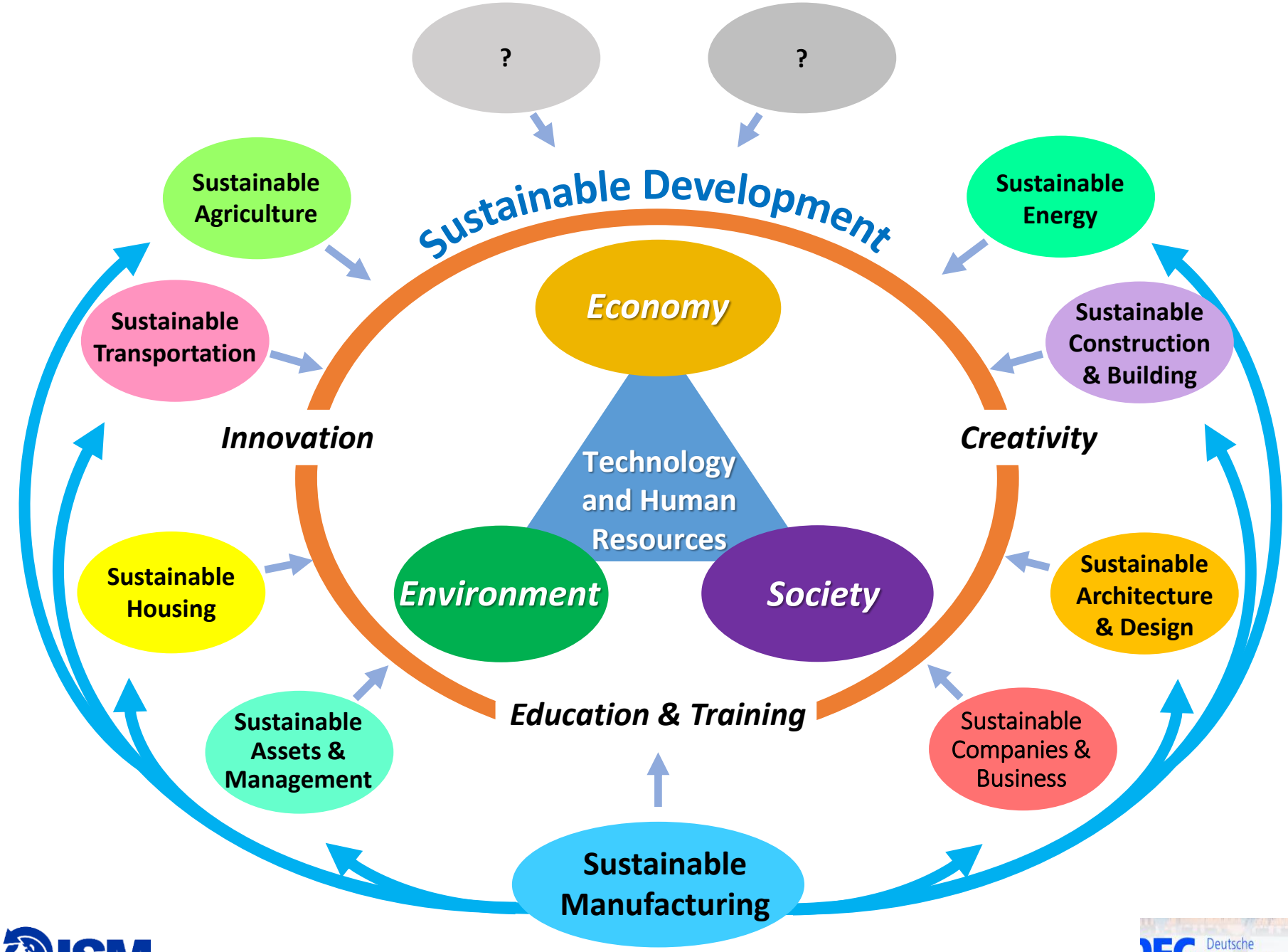
- ***Sustainable Manufacturing is built from the foundation of Circular Manufacturing***
- ***Circularity in nature is the inspiration for circular manufacturing***

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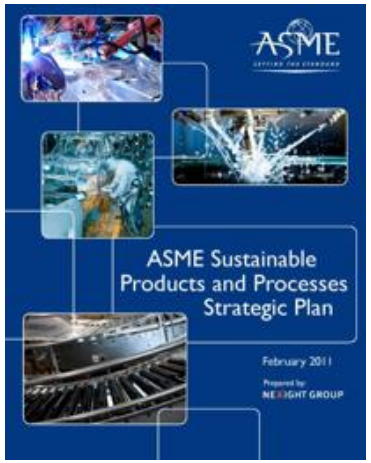
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Definitions for Sustainable Manufacturing

Attempts to Define Sustainable Manufacturing

- ***Numerous definitions*** and descriptions exist for sustainable manufacturing:
  - US Department of Commerce, 2009
  - NACFAM, 2009
  - NIST, 2010
  - US EPA, 2011
  - ASME, 2011, 2014
  - NSF, 2013
  - GCSM, 2013
  - NIST-sponsored Workshop, 2014
  - US Department of Energy, 2016





Sustainable manufacturing is the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources. Sustainable manufacturing also enhances employee, community and product safety.

- Almost all definitions fall short of showing the connectivity among the integral elements – ***No connectivity shown between sustainability and innovation or value creation***
- Sustainable manufacturing offers a new way of ***producing functionally superior products with innovative sustainable technologies and manufacturing methods***
- Sustainable manufacturing must enable ***sustainable value creation for all stakeholders***
- ***(Manufacturers, Consumers/Users and Society at-large).***

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Sustainable Manufacturing: Broader and Refined Definition (2014)

Sustainable manufacturing at ***product, process and systems*** levels must:

- demonstrate reduced ***negative environmental impact,***
- offer improved ***energy and resource efficiency,***
- generate ***minimum quantity of wastes***,
- provide ***operational safety,*** and
- offer improved ***personnel health***

while maintaining and/or improving the ***product and process quality*** with the overa***life-cycle cost benefits.***

Source: NIST Sustainable Manufacturing Technology Roadmapping Workshop, (2014) – Adapted from US Department of Commerc (2009) and EPA (2011)



Sustainable Manufacturing – A Business Perspective

A Technology Roadmap

February 25, 2015

Sponsored by the University of Kentucky, Institute for Sustainable Manufacturing

Funding Provided through the National Institute of Standards and Technology, Advanced Manufacturing Technology Consortia Program

This Draft Report Captures the Results of a Workshop that was conducted on November 13 and 14, 2014 in Lexington Kentucky

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IMTI Integrated Manufacturing Technology Initiative



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Metrics Clusters for Sustainable Manufacturing Processes (2024)



Need for modeling and optimization

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Total Life Cycle Products from Closed-loop Sustainable Manufacturing

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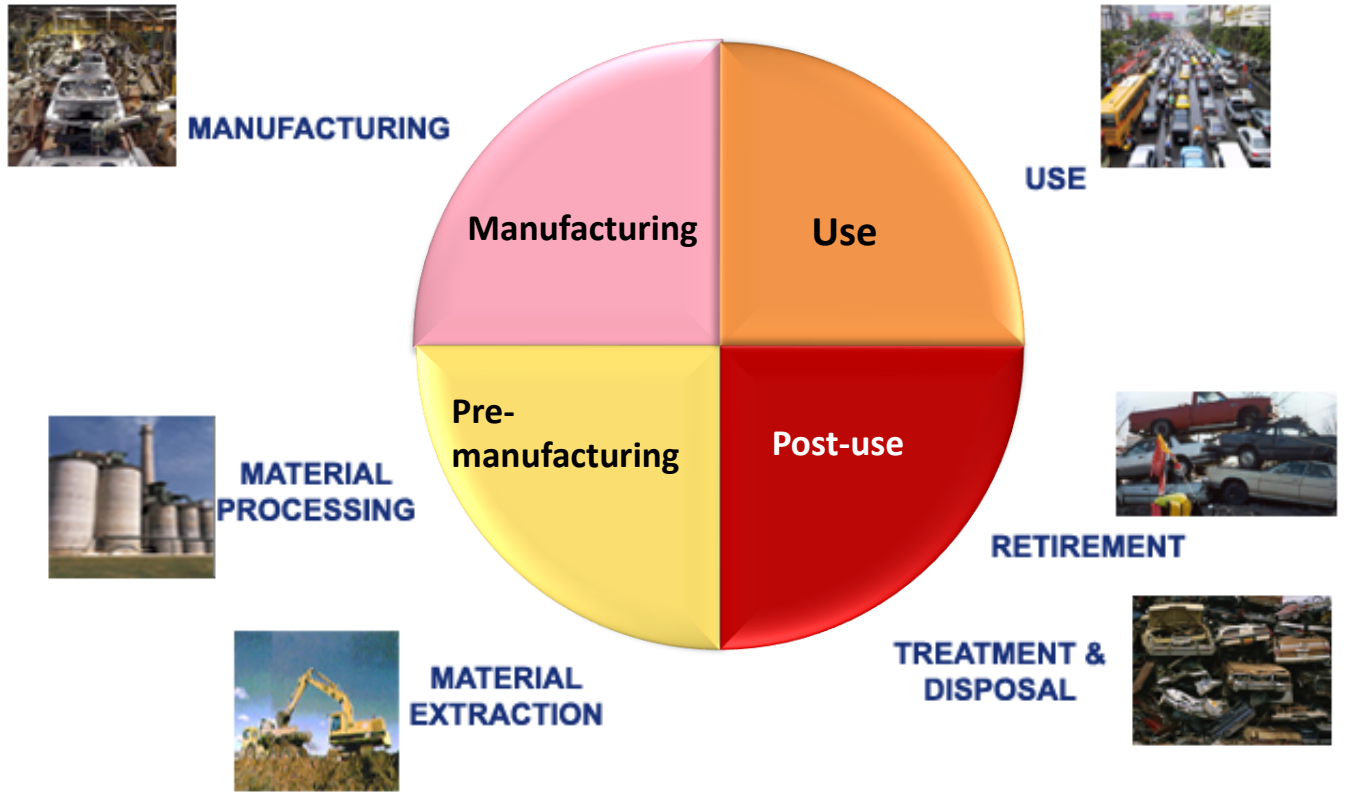
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Holistic and Total Life-cycle Approach

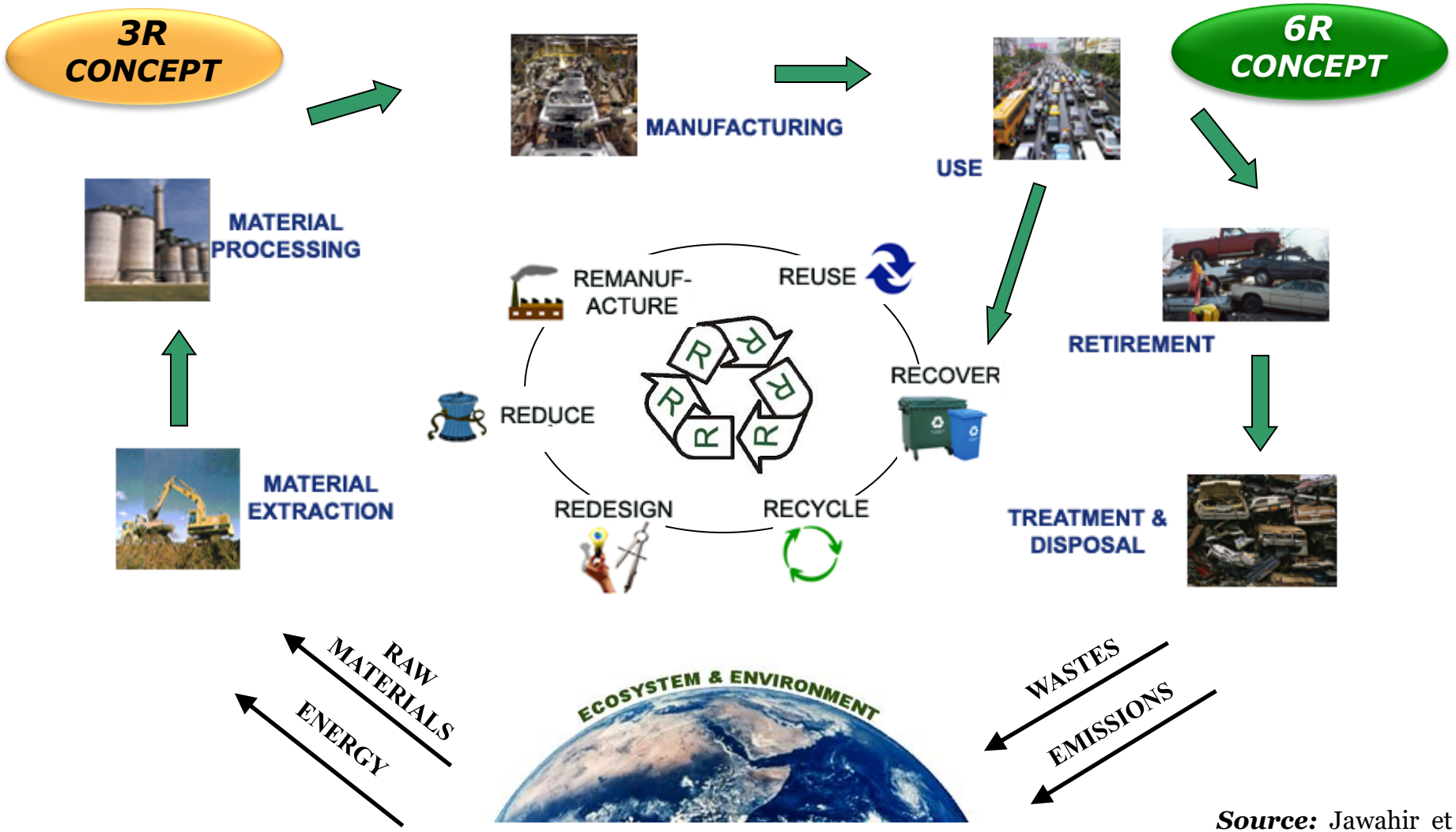
Emphasis on all four stages of product life-cycle



Source: Badurdeen (2009)

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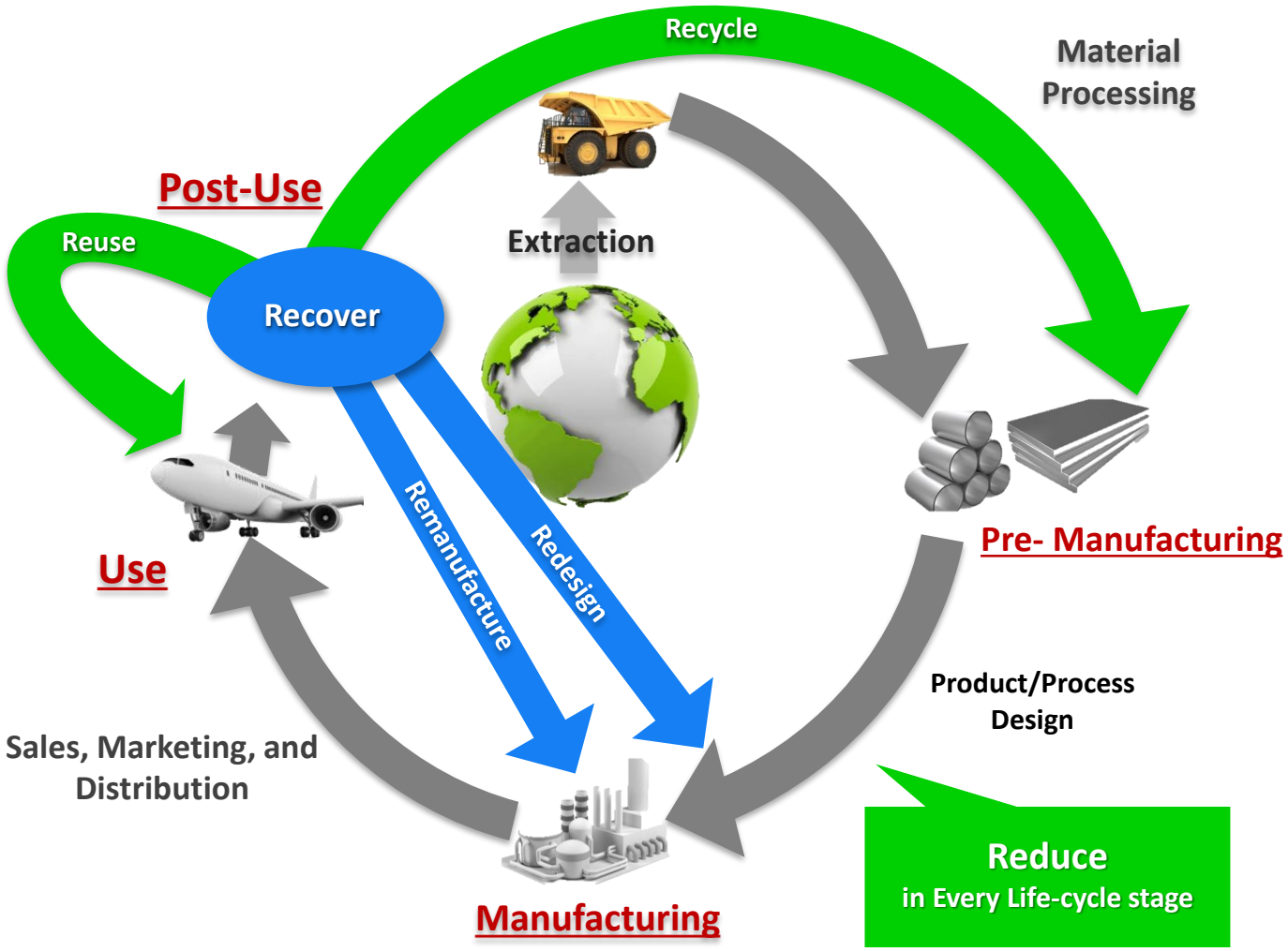
Closed-loop Material Flow – The 6R Approach for Sustainable Manufacturing



Source: Jawahir et al. (2006)

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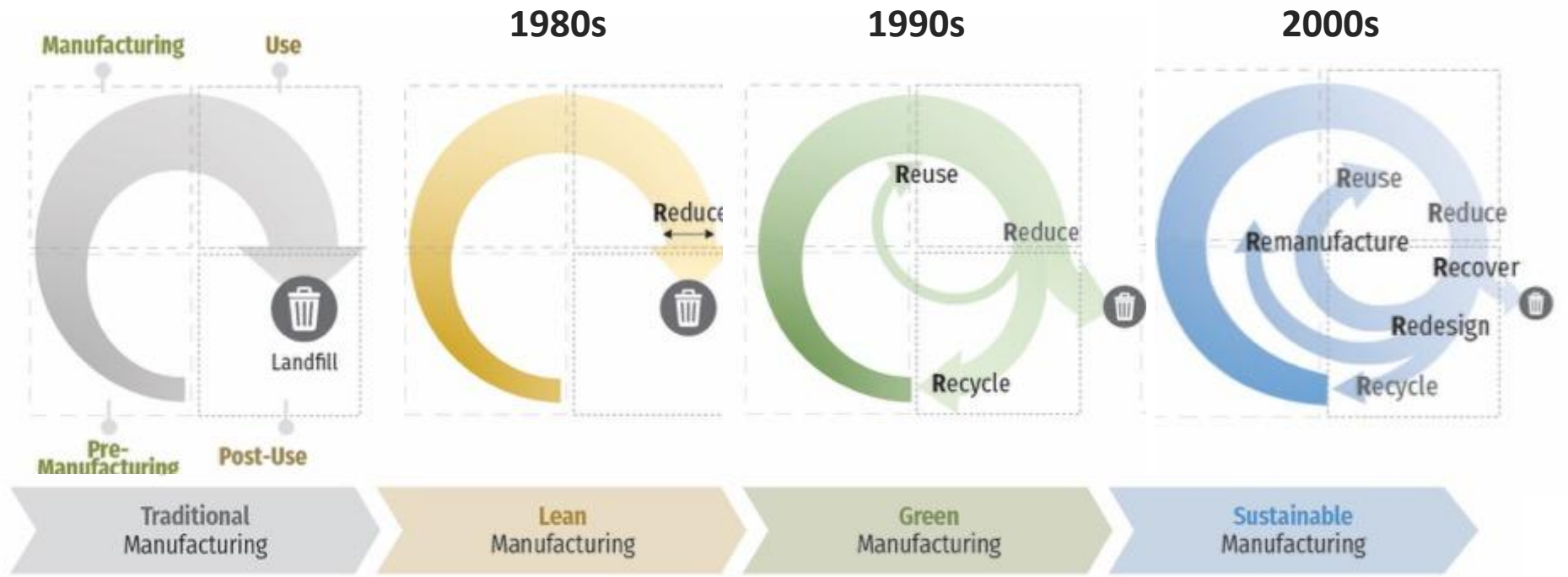
The 6Rs within the Four Life Cycle Stages



Source: Jawahir and Bradley (2016)

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Evolution of Closed-loop Sustainable Manufacturing



Exponential Increase in Value for all Stakeholders by Managing Embodied Energy and Material/Resource Flow in Closed-Loop Life cycles

6R-based approach enables a 'Circular Economy'

Source: Badurdeen and Jawahir (2017)

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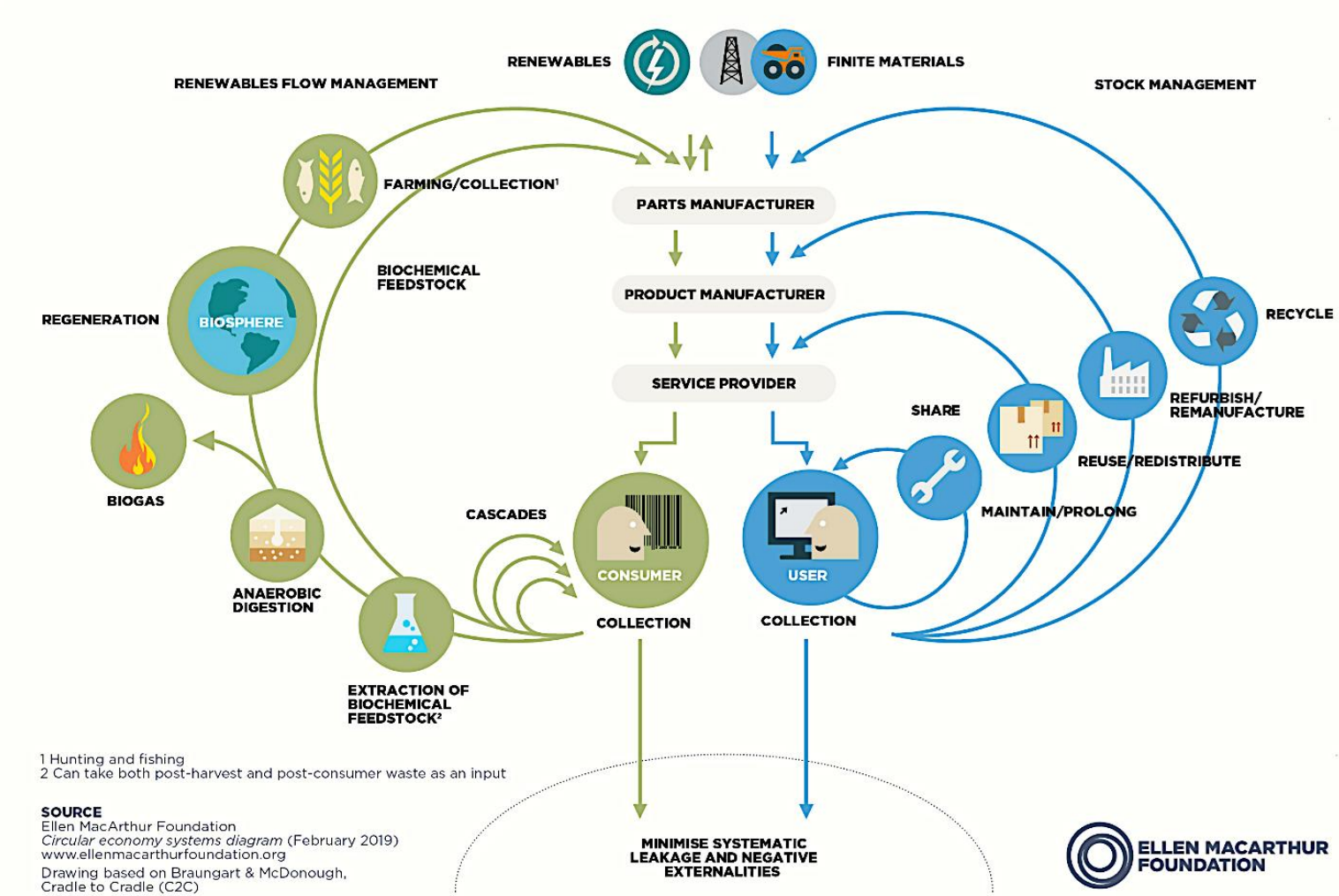
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Multi Generational Circular Products

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The Butterfly Diagram (EMF)



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From Linear Economy to Circular Economy



Linear Economy



Circular Economy

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Circularity in Nature



Summer: Leaves fully grown



Autumn: Leaves senescence and drop





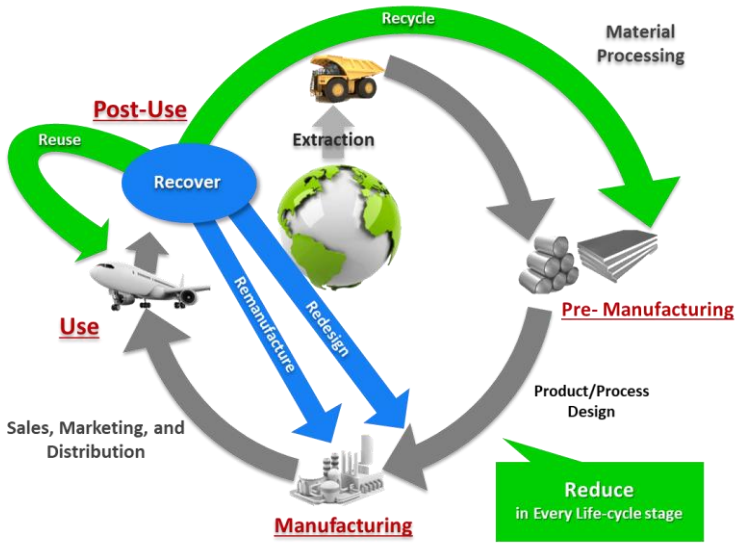
Winter: Leaves litter decompose to nourish the tree



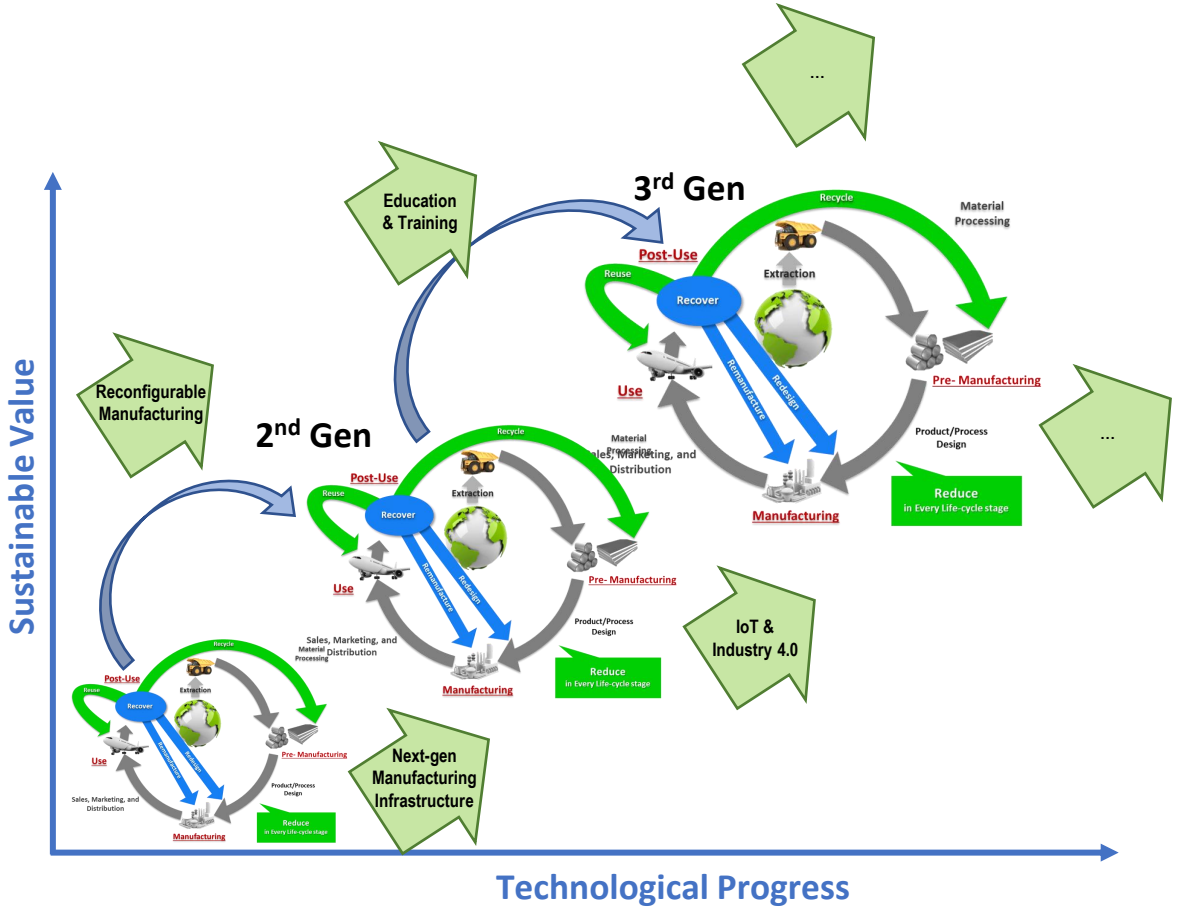
Spring: New leaves emerge

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From Linear to Circular to Helical Economy for Multi-Generation Products



Source: Jawahir and Bradley (2016)



Source: Bradley et al. (2016)

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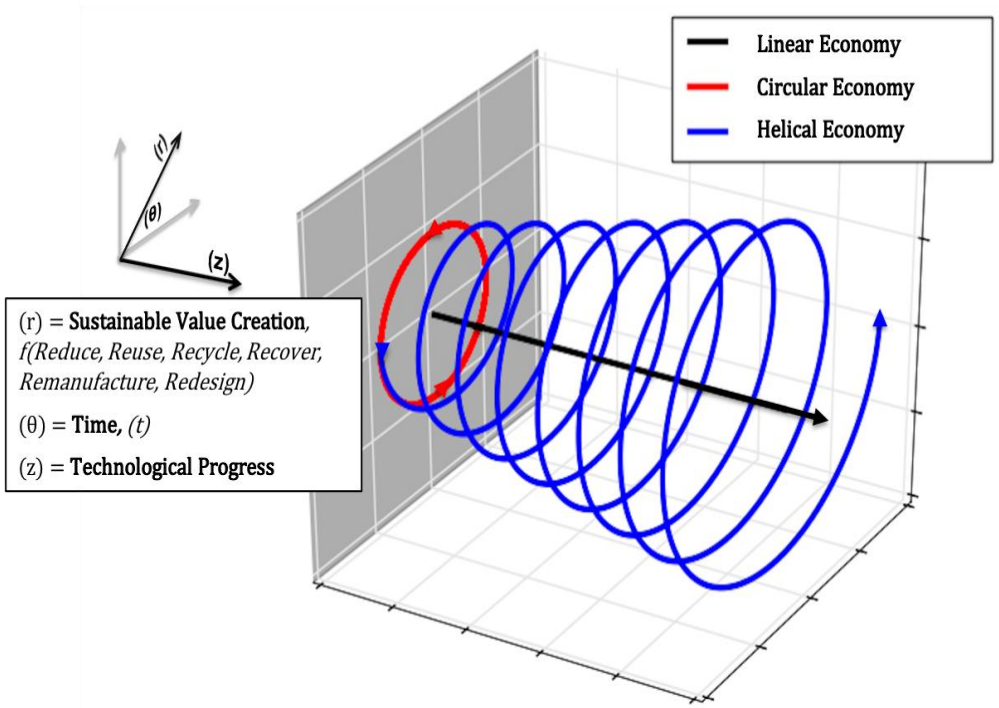
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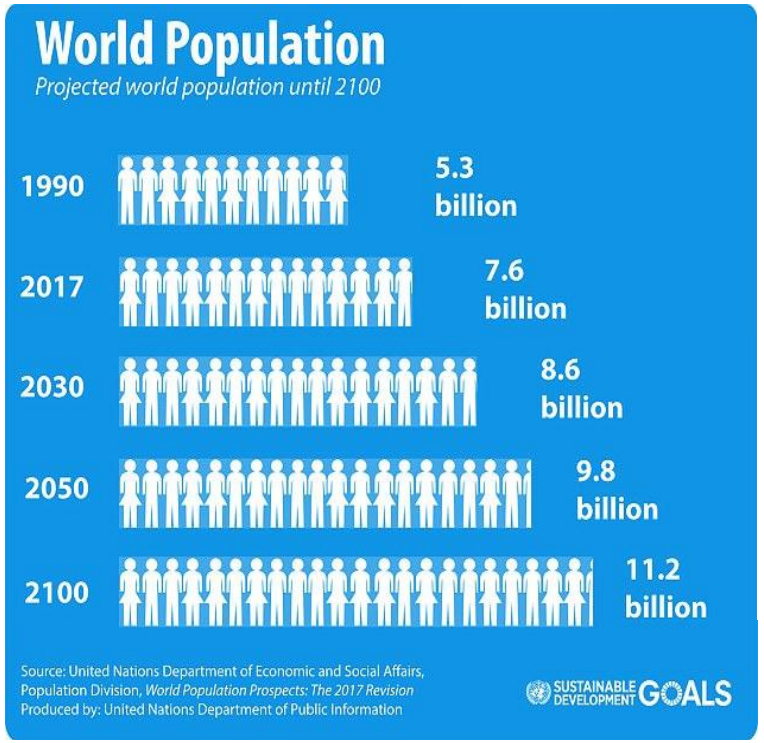
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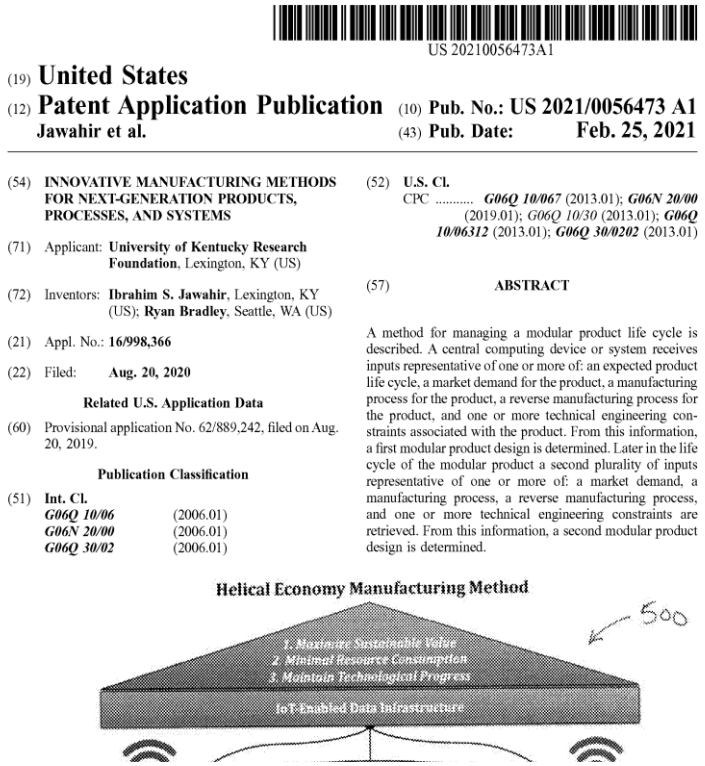
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Sustainable Value Creation from Innovative Products, Processes and Systems

Foundation of Helical Economy







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(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2021/0056473 A1**

Jawahir et al. (43) **Pub. Date: Feb. 25, 2021**

(54) **INNOVATIVE MANUFACTURING METHODS FOR NEXT-GENERATION PRODUCTS, PROCESSES, AND SYSTEMS**

(71) Applicant: **University of Kentucky Research Foundation**, Lexington, KY (US)

(72) Inventors: **Ibrahim S. Jawahir**, Lexington, KY (US); **Ryan Bradley**, Seattle, WA (US)

(21) Appl. No.: **16/998,366**

(22) Filed: **Aug. 20, 2020**

Related U.S. Application Data

(60) Provisional application No. 62/889,242, filed on Aug. 20, 2019.

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G06N 20/00	(2006.01)
G06Q 30/02	(2006.01)

(52) **U.S. Cl.**

CPC ***G06Q 10/067*** (2013.01); ***G06N 20/00*** (2019.01); *G06Q 10/30* (2013.01); ***G06Q 10/06312*** (2013.01); ***G06Q 30/0202*** (2013.01)

(57) **ABSTRACT**

A method for managing a modular product life cycle is described. A central computing device or system receives inputs representative of one or more of: an expected product life cycle, a market demand for the product, a manufacturing process for the product, a reverse manufacturing process for the product, and one or more technical engineering constraints associated with the product. From this information, a first modular product design is determined. Later in the life cycle of the modular product a second plurality of inputs representative of one or more of: a market demand, a manufacturing process, a reverse manufacturing process, and one or more technical engineering constraints are retrieved. From this information, a second modular product design is determined.

Helical Economy Manufacturing Method

Source: Bradley and Jawahir (2019)

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Circular Product Design for Advancing Sustainable Manufacturing

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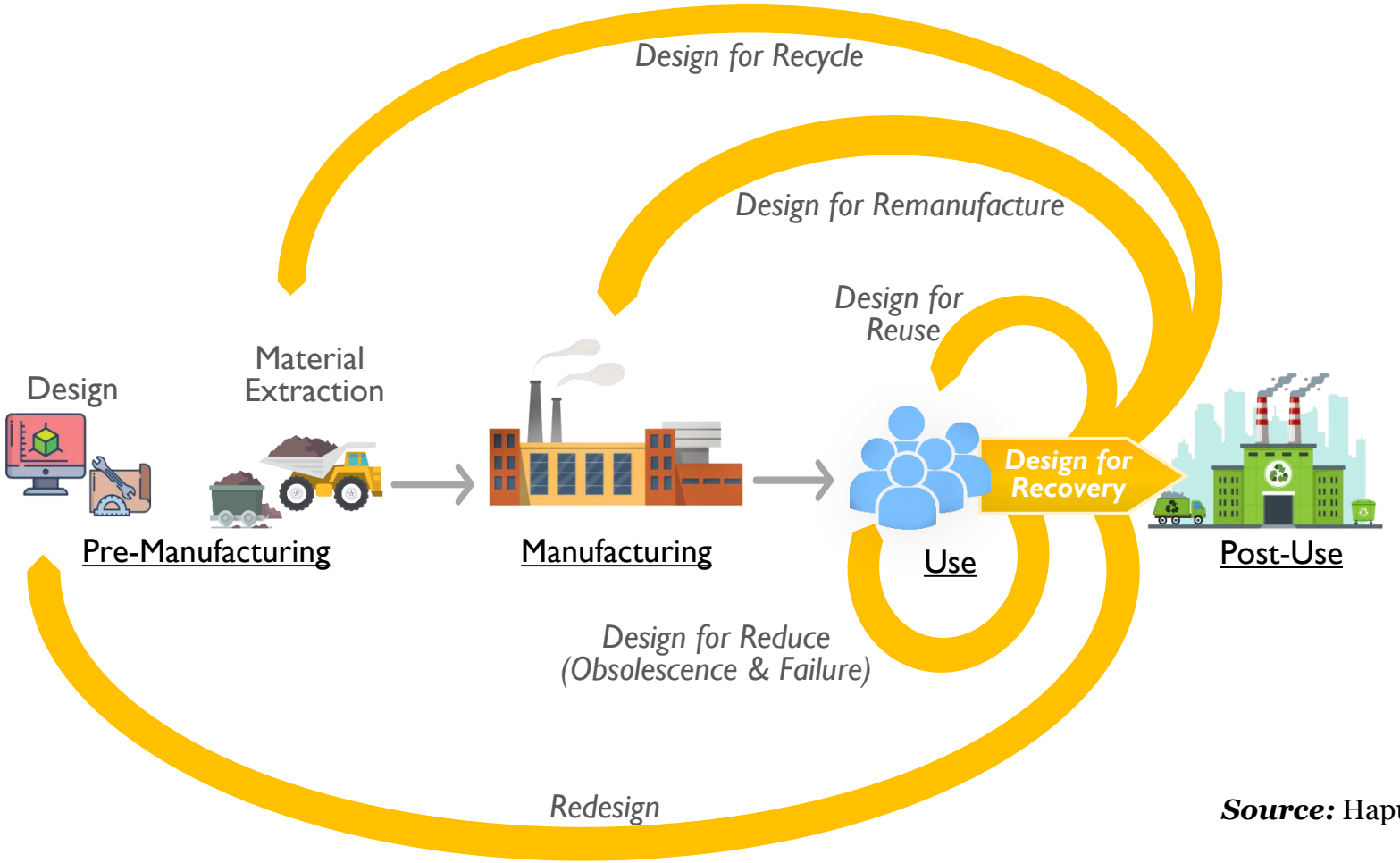
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Sustainable Product Design from the Technological Elements of Closed-loop Sustainable Manufacturing



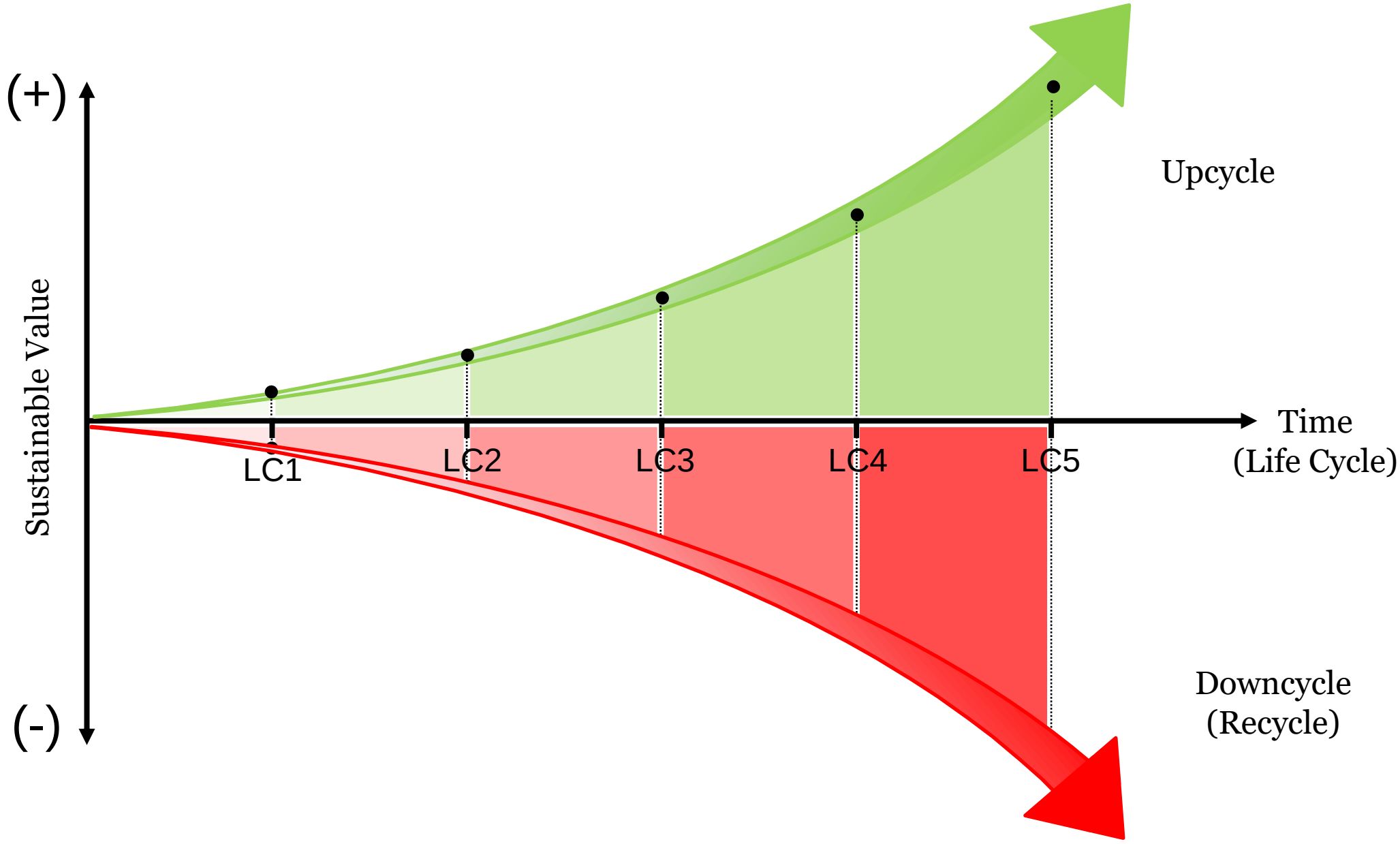
Source: Hapuwatte et al. (2026)

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Recent ISO and Other Standards on Circular Economy and Circular Products Design

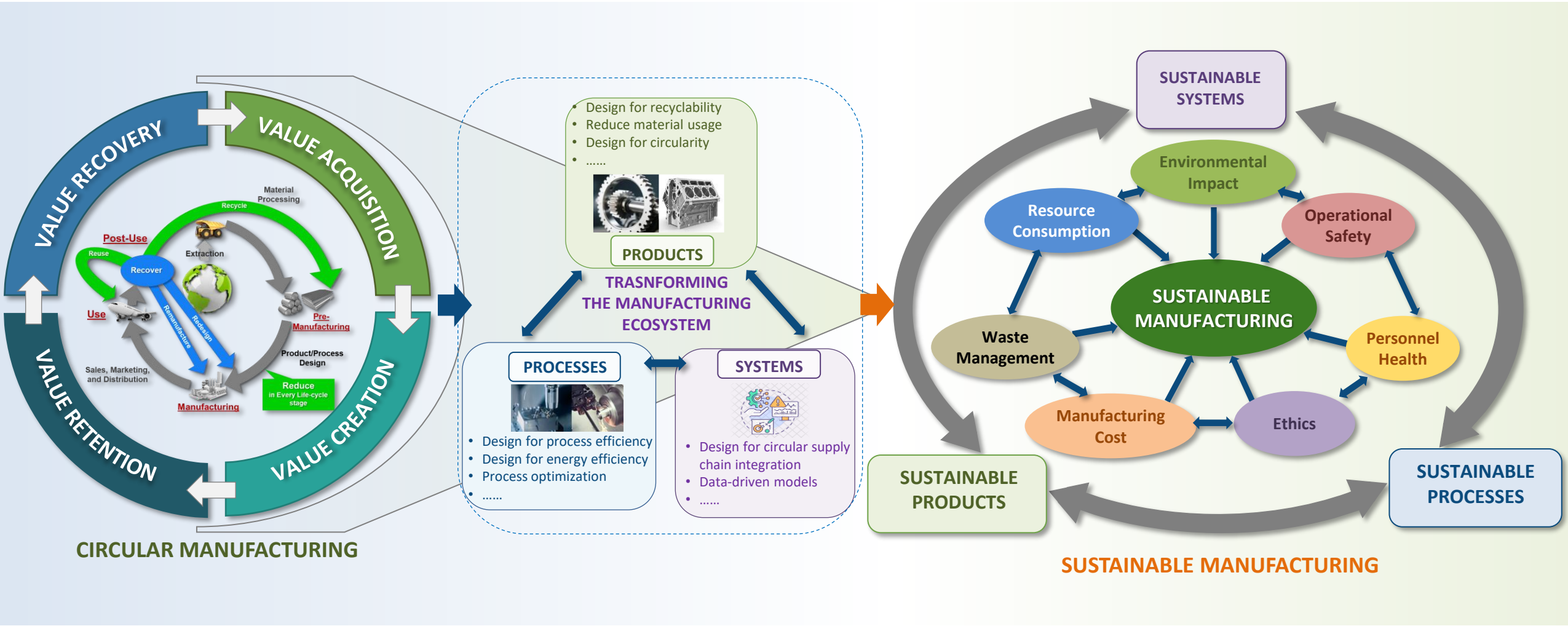
ASTM E3461-25	Standard guide for principles of circular product design	[Published: 2025-06]
EN 45560:2024	Method to achieve circular designs of products	[Published: 2024-11]
UL 3600 Ed. 2-2024	Standard for sustainability for measuring and reporting circular economy aspects of products, sites and organizations	[Published: 2024-10]
ISO 59004:2024	Circular economy — Vocabulary, principles and guidance for implementation	[Published: 2024-05]
ISO 59010:2024	Circular economy — Guidance on the transition of business models and value networks	[Published: 2024-05]
ISO 59020:2024	Circular economy — Measuring and assessing circularity performance	[Published: 2024-05]
ISO 59040:2025	Circular economy — Product circularity data sheet	[Published: 2025-02]

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Moving from Circular Manufacturing to Sustainable Manufacturing



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Next Generation Sustainable Manufacturing with Circular and Sustainable Product Design

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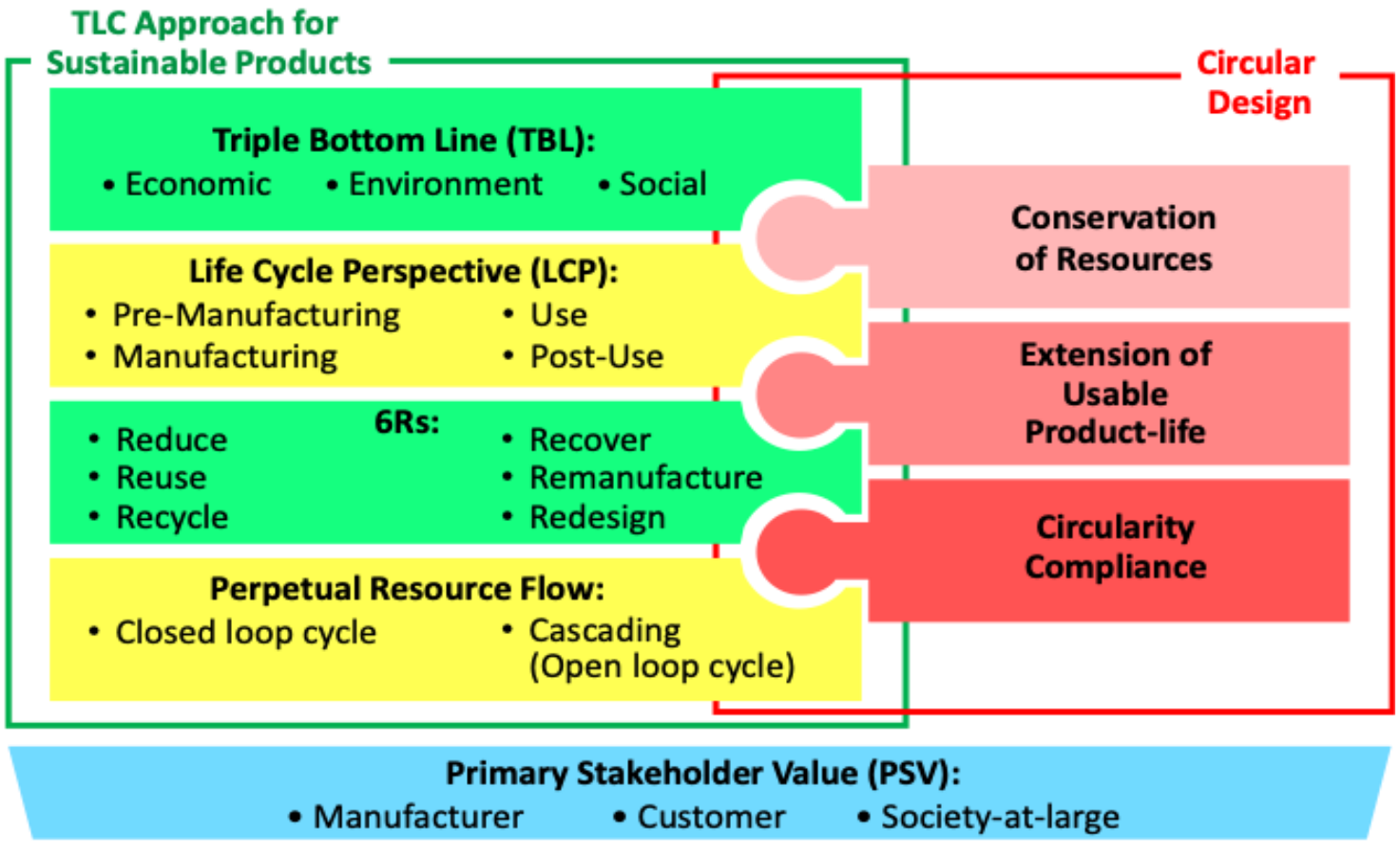
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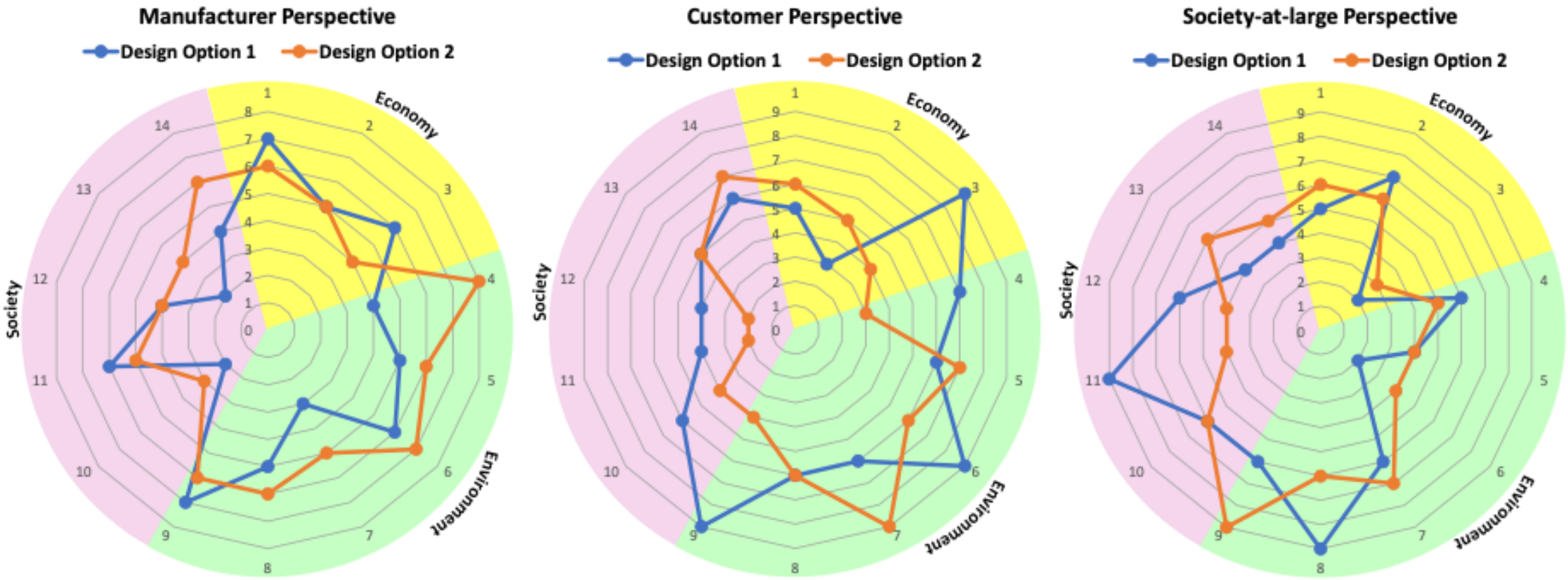
Integral Considerations of Circular Product Design



Source: Hapuwatte et al. (2021)

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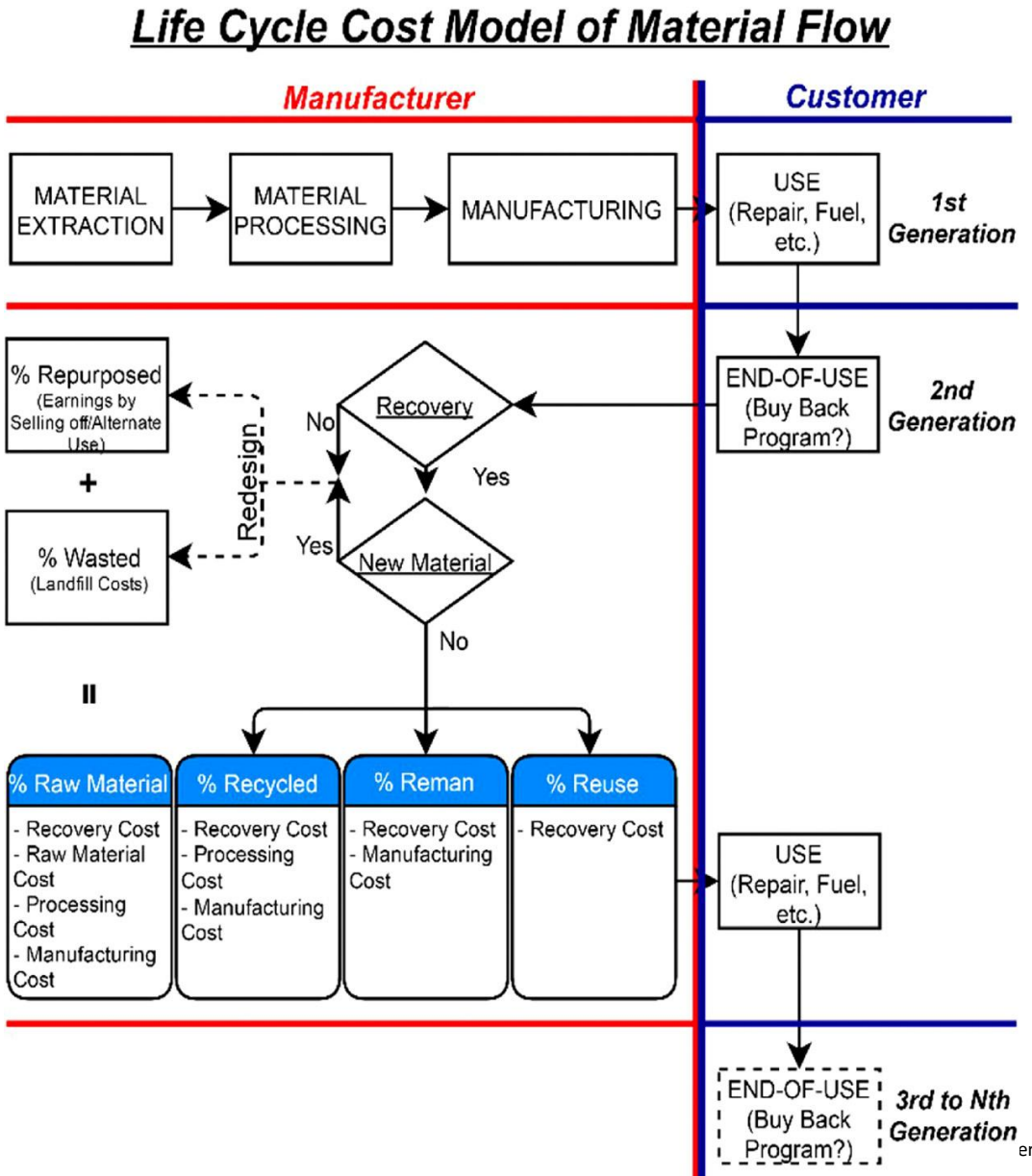
Product Circularity Evaluation from Stakeholders' Perspective: Analysis of Case Studies



Source: Hapuwatte et al. (2021)

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Total Life-cycle Cost Model (Generic)



$$TLCC = C_{MFG} + C_{CUST}$$

$$C_{MFG} = (1+Q)\left[(1-x_4)\left(RM + \sum_{i=1}^{N_1} PM_i\right) + \left(x_4 \sum_{i=1}^{N_2} RE_i + (x_4 - x_3)\sum_{i=1}^{N_3} RRR_i + \sum_{i=1}^{N_4} ES_i\right)\right]$$

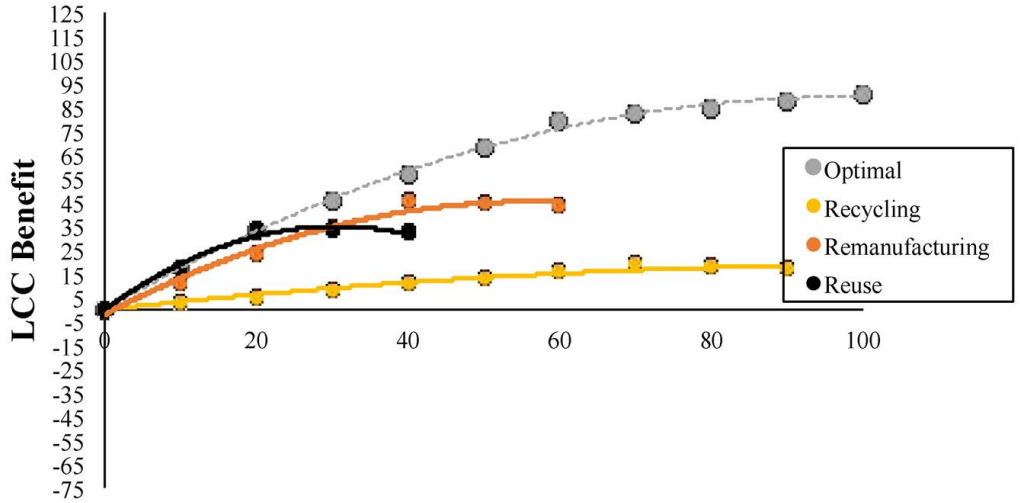
$$C_{CUST} = (1+Q)\left((C_{MFG}\cdot K - I) + \sum_{i=1}^{N_1} U_i + \sum_{i=1}^{N_2} M_i\right)$$

$$\text{where,}\quad Q = \frac{(1+j)^{(G-T)-1} - 1}{j(1+j)^{(G-T)-1}}$$

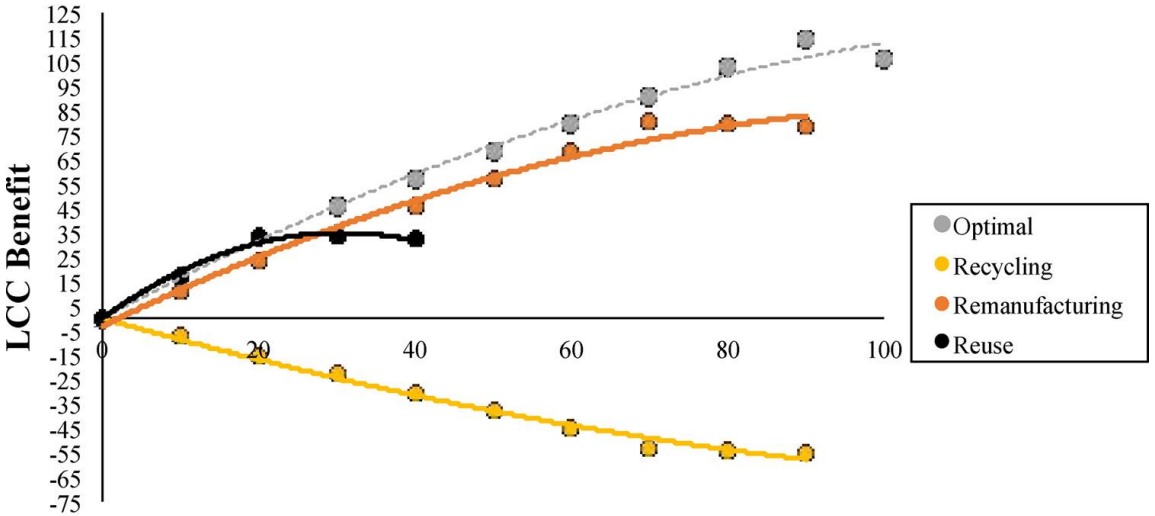
Source: Bradley et al. (2018)

Total Life-cycle Cost Model for Multi-generational Circular Products

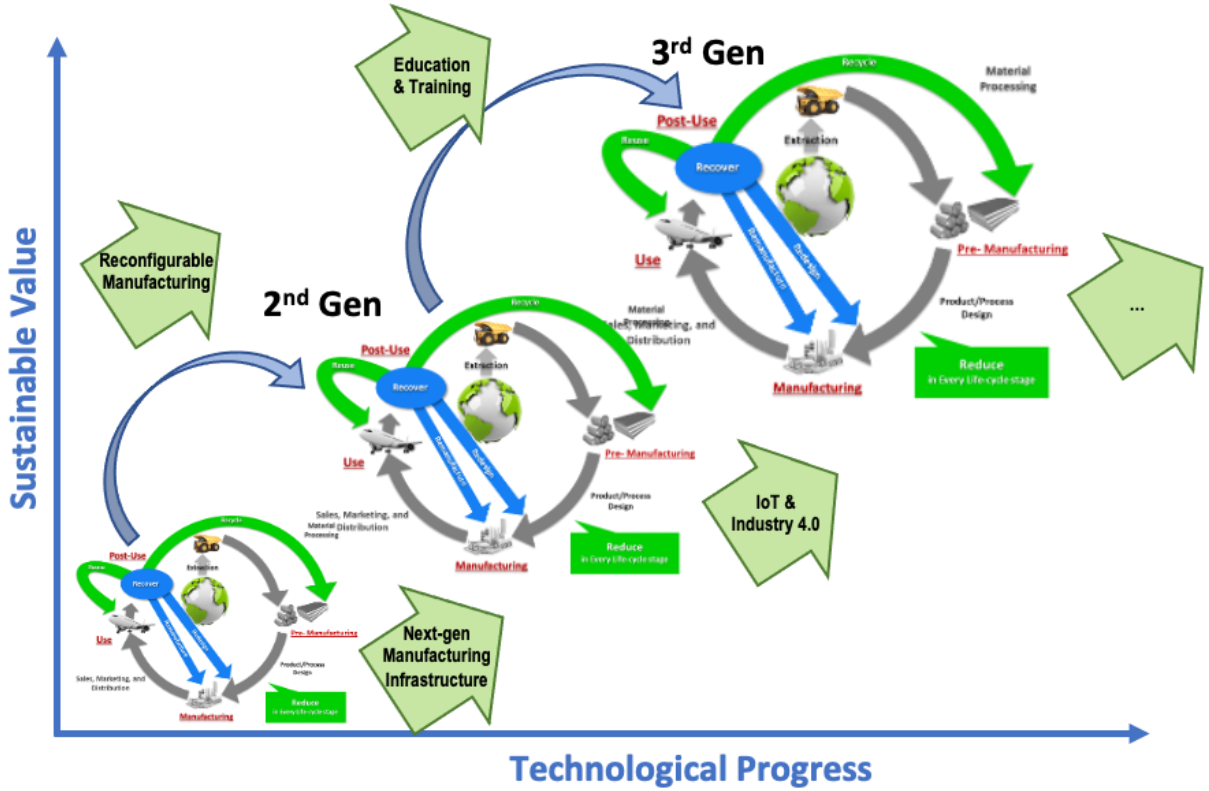
Post-Recovery Allocation LCC Benefit Case #1



Post-Recovery Allocation LCC Benefit Case #2



Percent Material in Stream



Source: Bradley et al. (2018)

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NIST-Sponsored Projects on Product Circularity (2021-27)

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Product Sustainability from Product Circularity



Product Sustainability Index *(ProdSI)*
with Sub-indices, Clusters, Sub-clusters and Metrics

Clusters / 6R Elements	Product Sustainability													
	Economy			Environment					Society					
	Initial investment	Direct/indirect costs & overheads	Benefits & losses	Material use & efficiency	Energy use & efficiency	Other resources use & efficiency	Waste & emissions	Product EoL	Product quality & durability	Functional performance	Product EoL management	Product safety & health impact	Product societal impact regulations & certification
Reduce	x	x	x	x	x	x	x	x			x	x	x
Reuse	x		x	x	x	x	x	x			x		
Recycle			x	x			x	x			x		x
Recover				x			x	x			x		x
Redesign		x		x	x	x	x	x	x	x	x	x	x
Remanufacture				x	x	x	x	x			x		

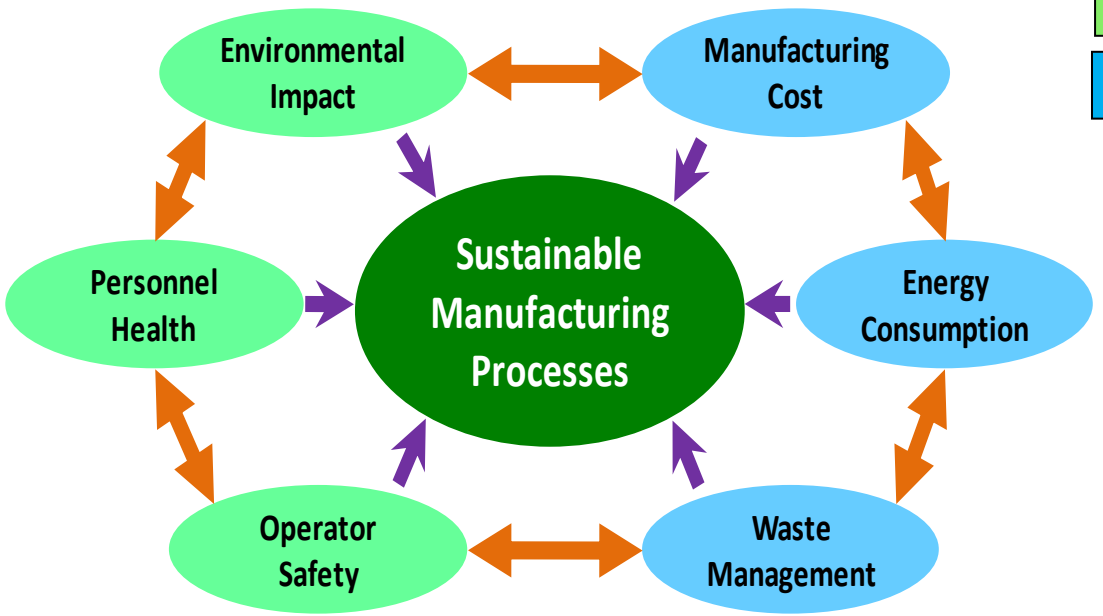
Evaluation of All 6Rs using *ProdSI*

Source: Hapuwatte et al. (2016)

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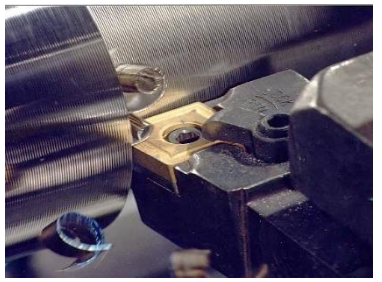
Process Sustainability Rating System for Manufacturing Processes

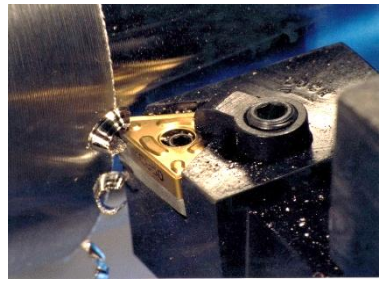
Basic Sustainability Elements in Manufacturing

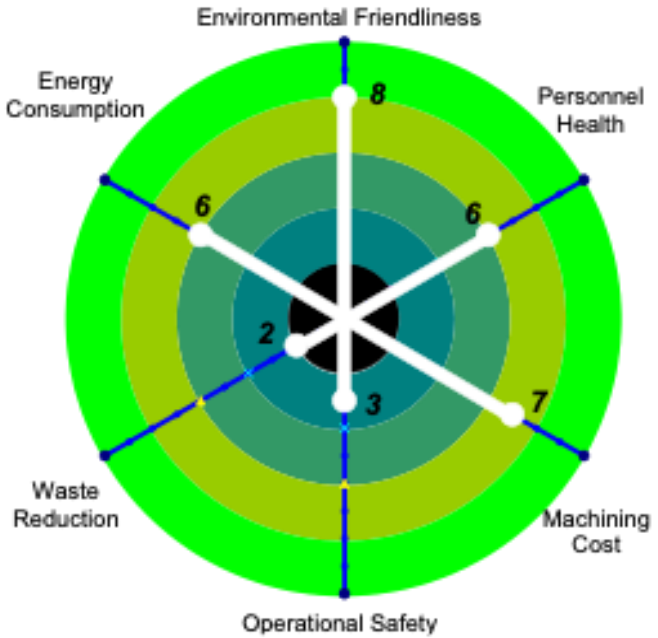


Fuzzy nature

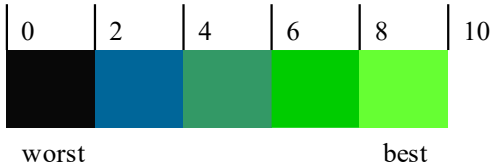
Analytical







A Simple Sustainability Rating System for Manufacturing Processes



Modeling and optimization are requirements

Source: Wanigarathne et al. (2004)

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ProdSI and ProcSI Evaluation

Product Sustainability Index (ProdSI)

$$ProdSI = \frac{1}{3}\left(Ec + Ev + So\right) = \frac{1}{3}\left(\sum_{i=1}^{3} w_i^c C_i + \sum_{i=4}^{8} w_i^c C_i + \sum_{i=9}^{13} w_i^c C_i\right)$$

$$C_m = \sum SC_j w_j^{sc} \quad \forall j$$

$$SC_n = \sum M_k w_k^m \quad \forall j$$

Process Sustainability Index (ProcSI)

$$ProcSI = \frac{1}{6}\sum_{i=1}^{6} C_i = \frac{1}{6}\left(C_1 + C_2 + \frac{1}{5}\sum_{i=10}^{14} w_i^{sc} SC_i + \frac{1}{4}\sum_{i=15}^{18} w_i^{sc} SC_i + \frac{1}{3}\sum_{i=19}^{21} w_i^{sc} SC_i + \frac{1}{2}\sum_{i=22}^{23} w_i^{sc} SC_i\right)$$

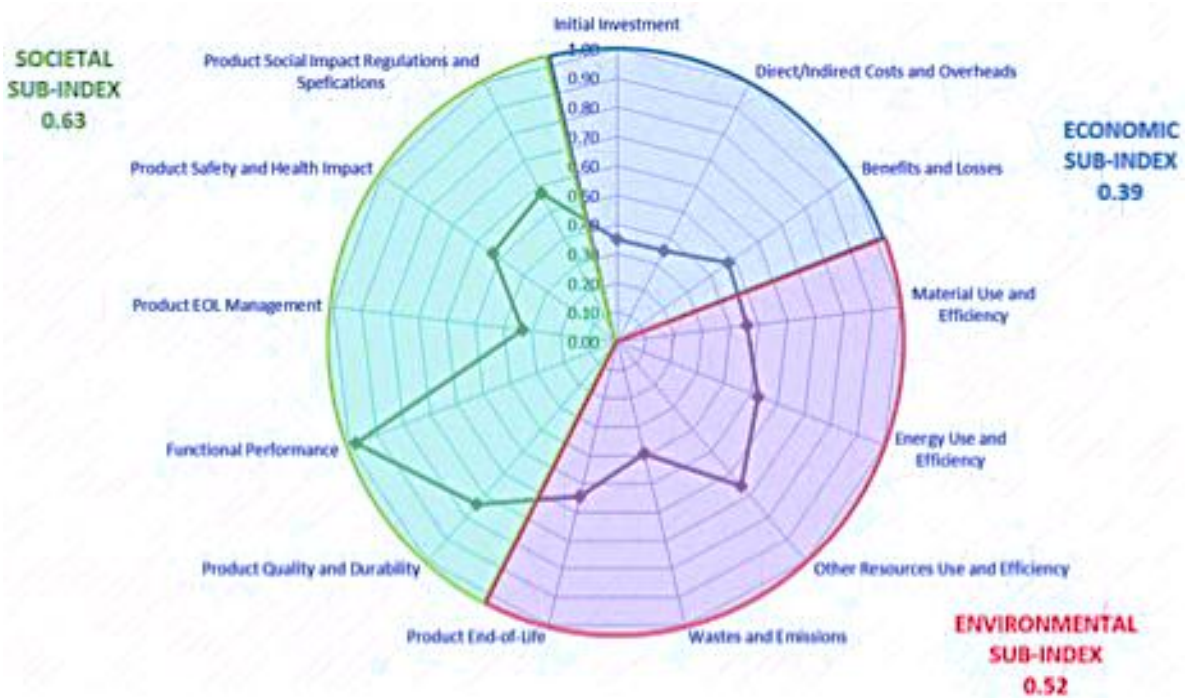
$$SC_n = \sum w_j^m M_j \quad \forall j$$

Source: Shuaib et al. (2014)

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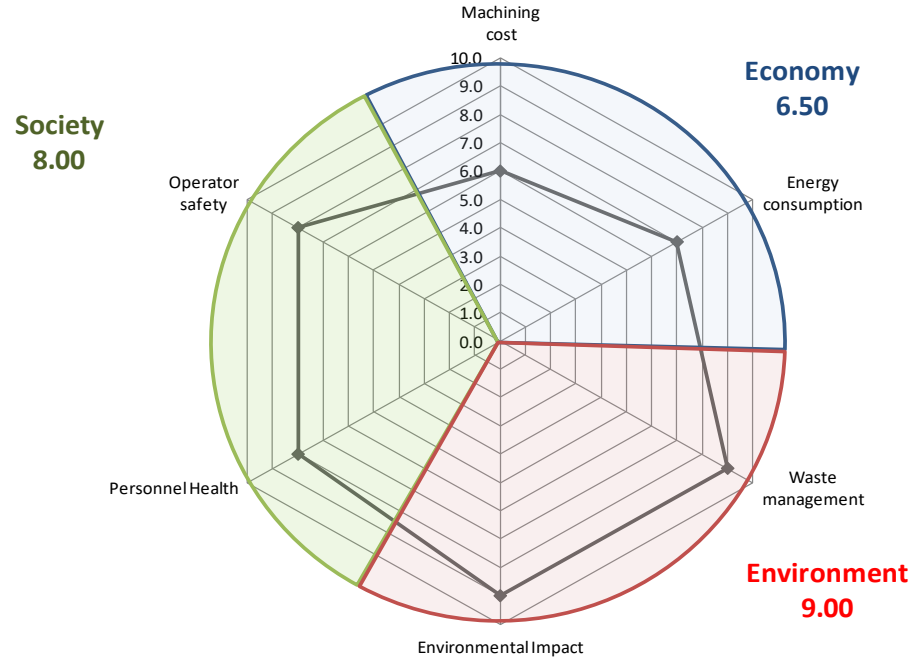
Examples of ProdSI and ProcSI

Product Sustainability



(a) ***ProdSI***

Process Sustainability



(b) ***ProcSI***

Source: Tao et al. (2015)

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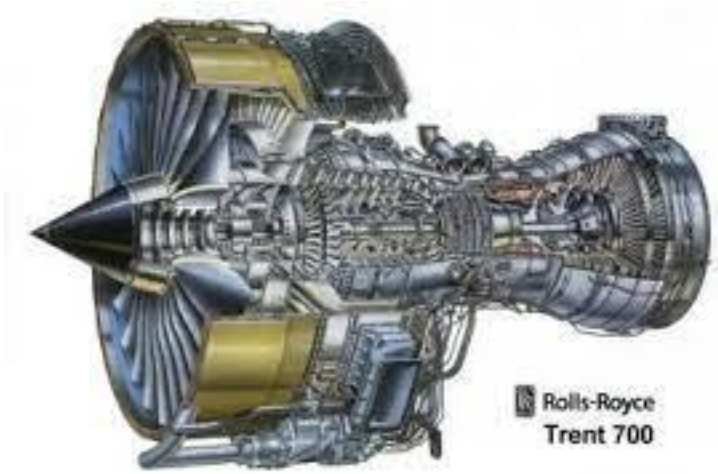
Sustainability Improvement in Products and Processes through ProdSI and ProcSI Analyses

Case studies were conducted on three major manufactured products





Automotive Product





Aerospace Product





Consumer Electronic Product

University of Kentucky College of Engineering

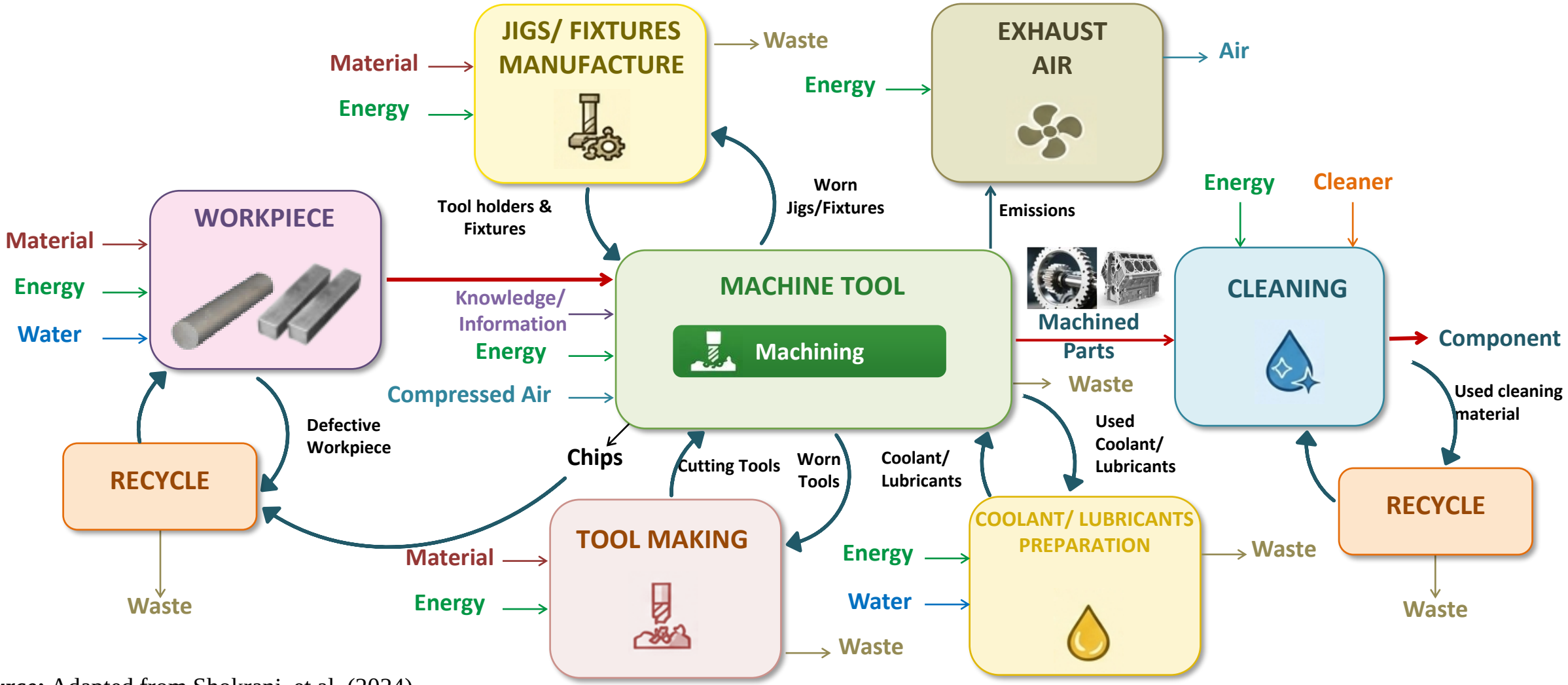
ISM Institute for Sustainable Manufacturing

CCPT Conference on Circular Production Systems and Technologies
9th & 10th June 2026

CRC 1574 DFG Deutsche Forschungsgemeinschaft German Research Foundation KIT Karlsruhe Institute of Technology

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Circular Manufacturing Processes: The Machining System



Source: Adapted from Shokrani et al. (2024)

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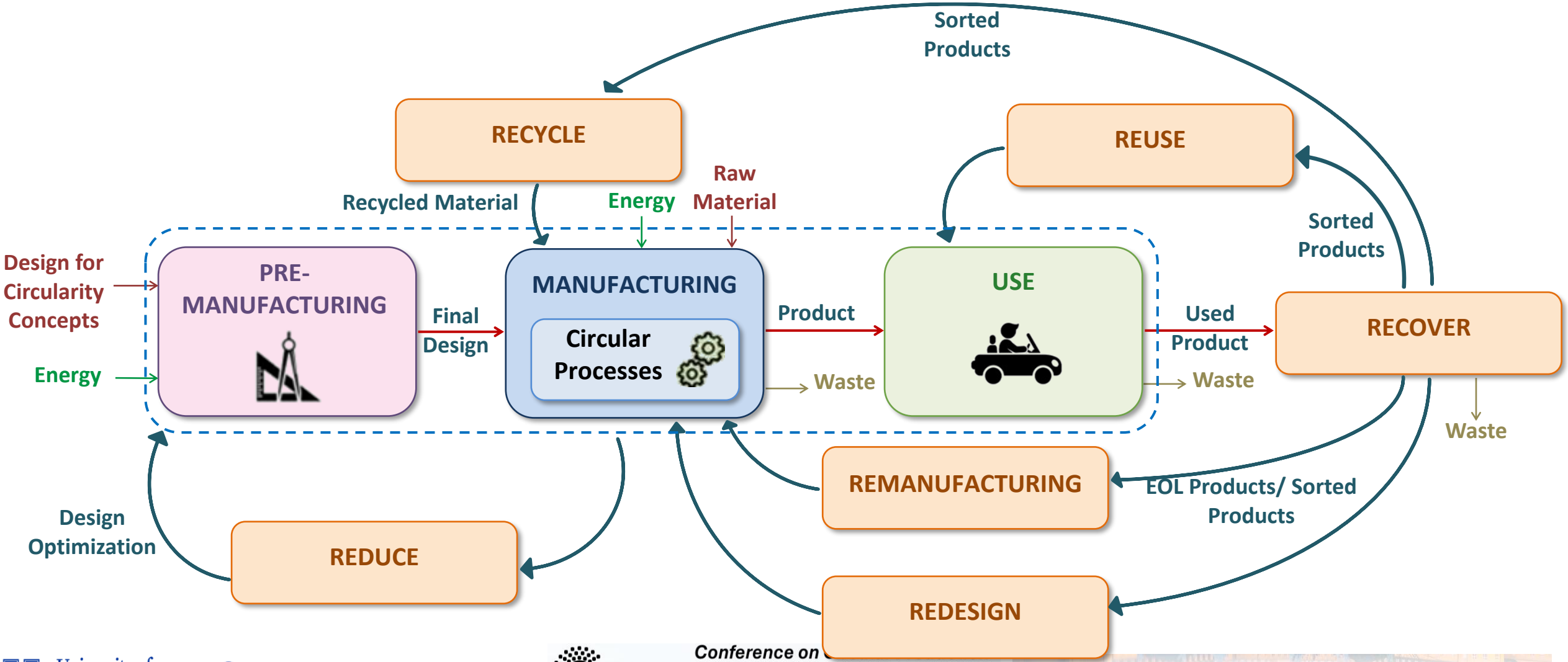
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Circular Products from Circular Manufacturing



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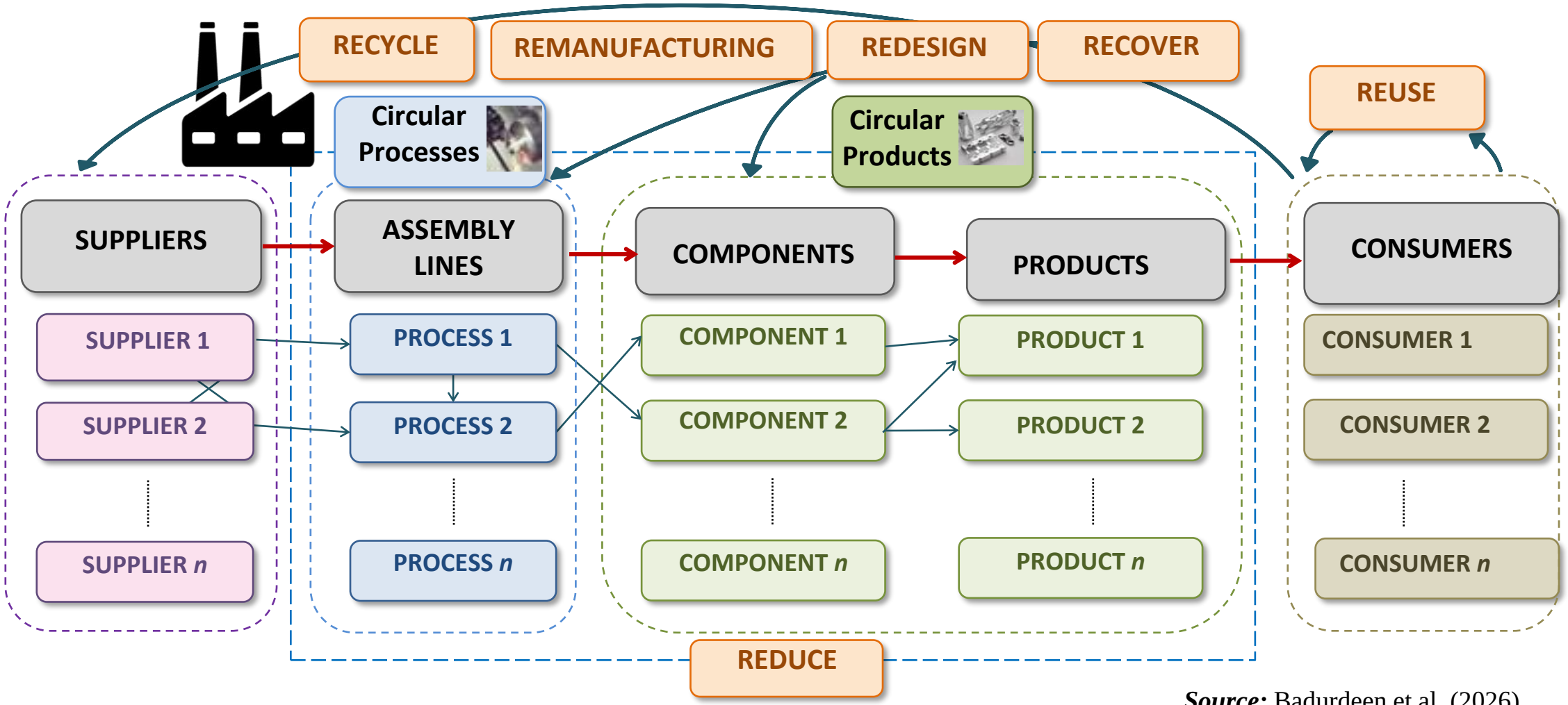
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Circular Manufacturing Systems



Source: Badurdeen et al. (2026)

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Recently Adopted Upcycling Methodology for Circular Economy

SOLID STATE UPCYCLING



Discarded metal scrap



Metal shredder



Shredded metal chips and alloying



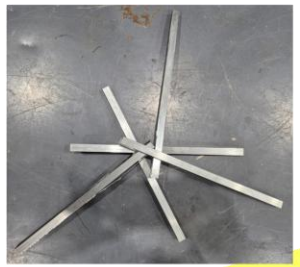
Punch and die setup



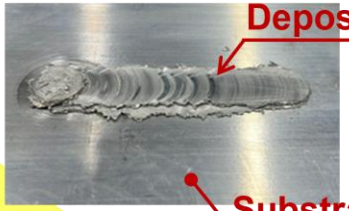
Compressed billets



Friction Extrusion Machine



Friction extruded rods



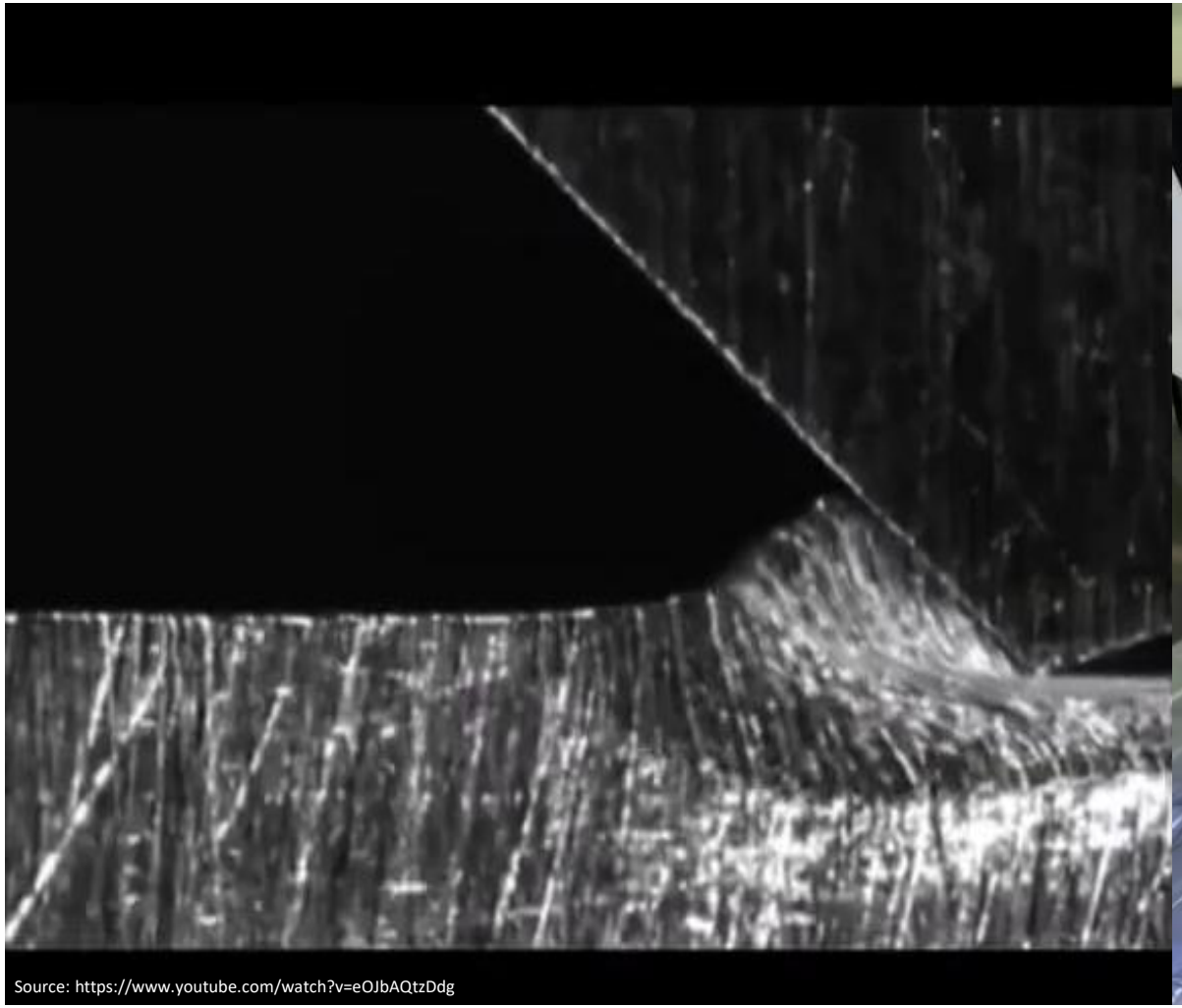
Additive friction stir deposit



Additive Friction Stir Deposition Machine

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Solid State Processes: Machining (Subtractive) and AFSD (Additive)



Source: https://www.youtube.com/watch?v=eOJbAQtzDdg



Source: NextGen AMRL, ISM, University of Kentucky, USA

Machining

AFSD

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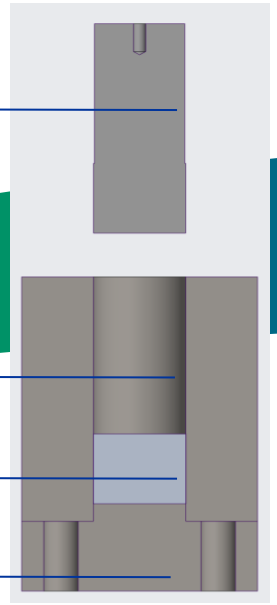
From Waste to Products: Upcycling for Circular Economy

Collection, Shredding, Mixing, and Compaction

- A total of 2.1 kg of aluminum pans and lids were collected, cleaned, shredded.
- The material was divided into two containers of 1kg each and mixed with the necessary alloying elements to change the mixture towards AA 6061.
- Compressed billets ~65% density.









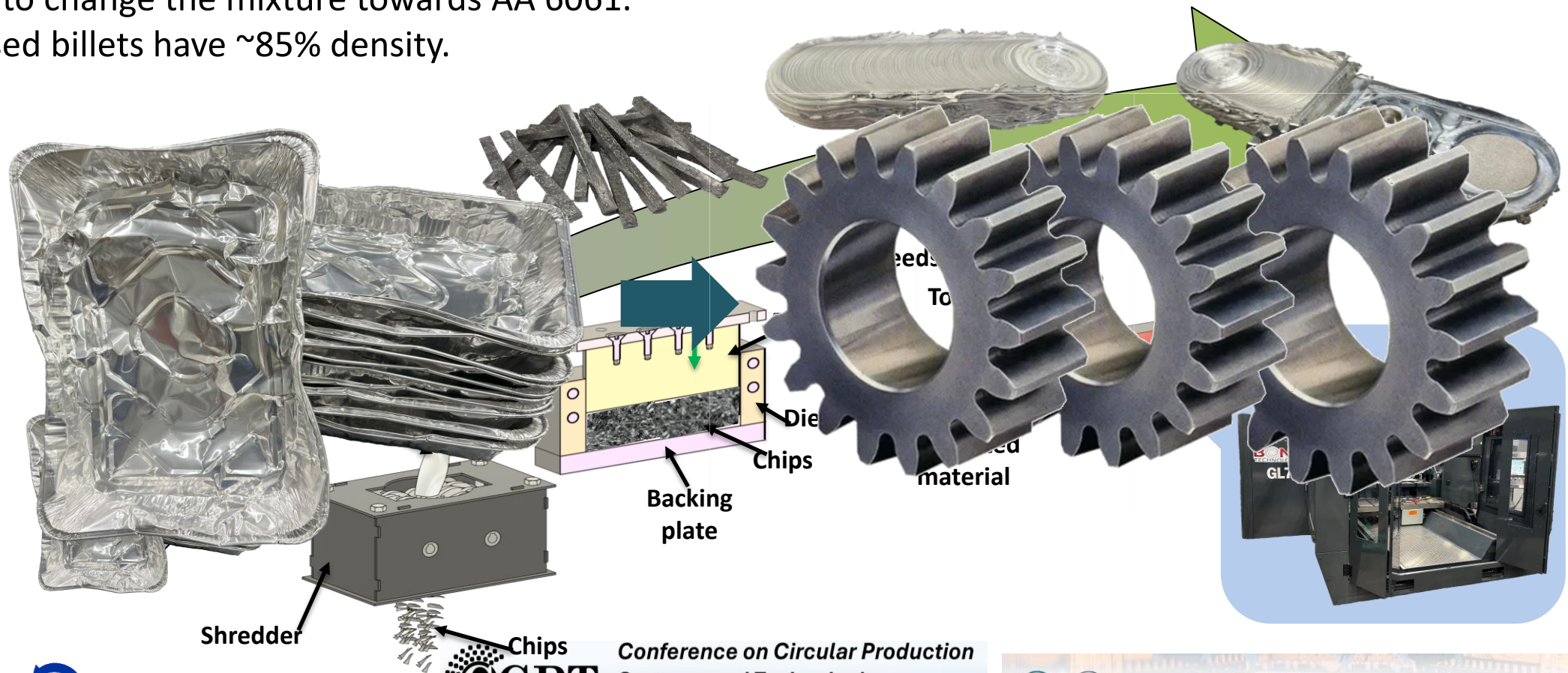




Source: Amantia et al. (2026)

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- A total of 2.1 kg of used aluminum pans and lids were collected, cleaned, shredded.
- The material was divided into two containers of 1kg each and mixed with the necessary alloying elements to change the mixture towards AA 6061.
- Compressed billets have ~85% density.



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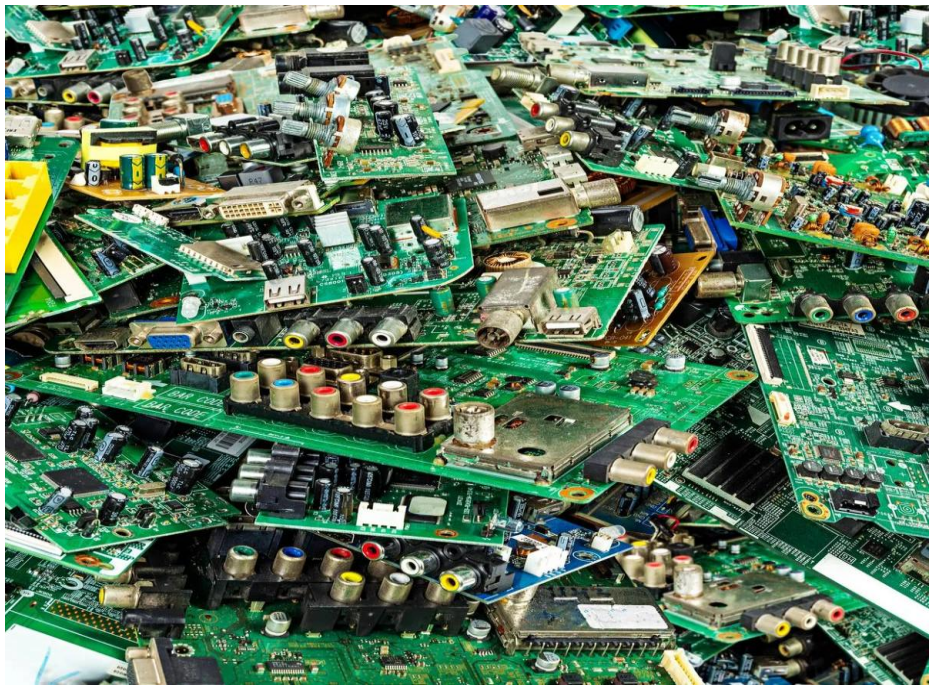


MACHINED CHIPS



WRENCHES

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E-WASTE



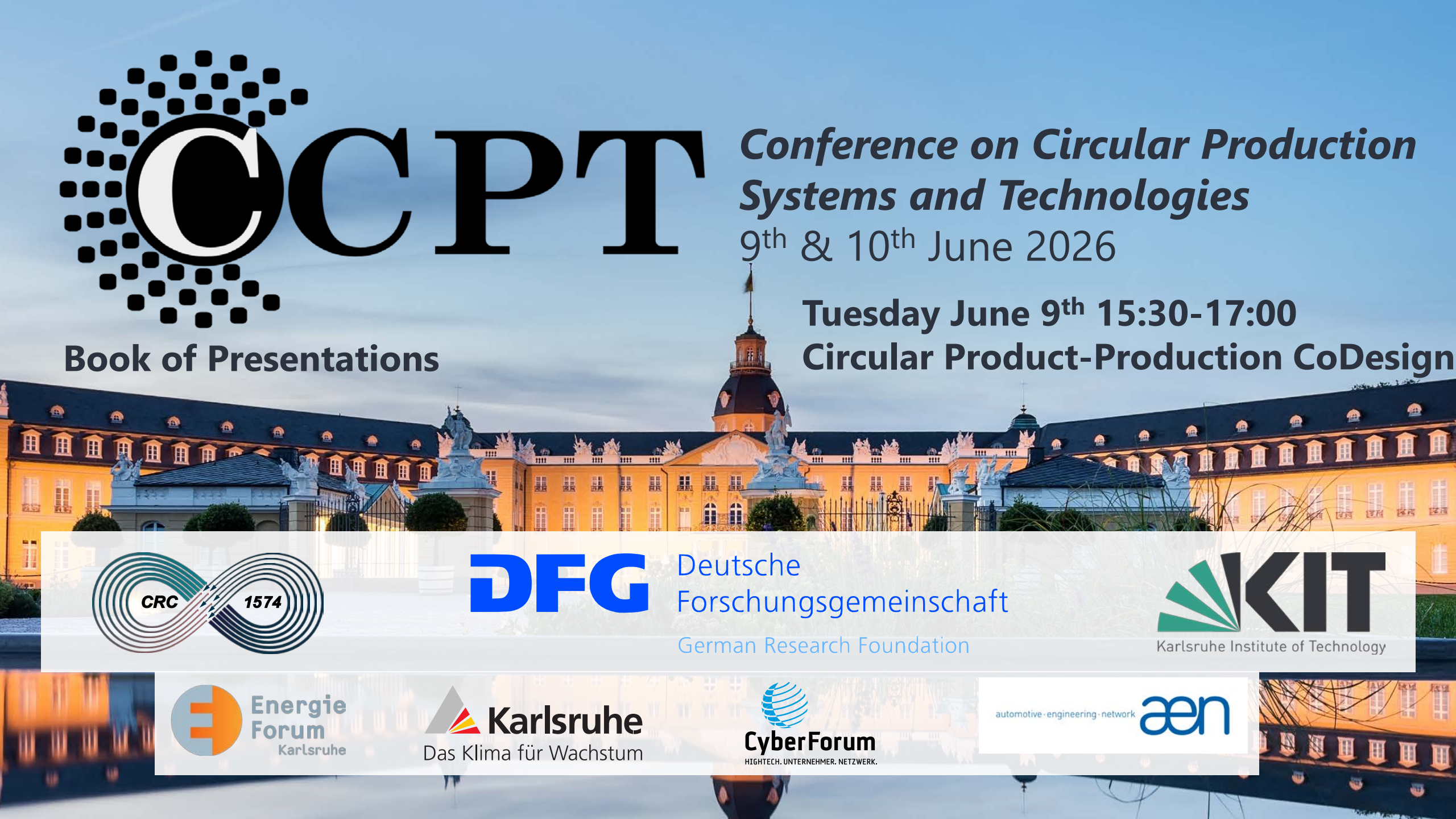
IMPELLER

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Concluding Remarks

- ***Product circularity principles*** are shown as critically important for ***sustainable manufacturing*** at product, process and system levels for ***sustainable value creation.***
- The ***6Rs are serving as the foundational technological elements*** of the closed-loop systems in sustainable manufacturing for implementing the circular economy.
- Sustainable manufacturing driven by ***technological innovation*** facilitates ***6R-based sustainable value creation*** across ***multiple generations of products for all stakeholders.***
- Sustainable manufacturing is the ***driver for promoting circularity at the micro level*** for products and processes to enable circular economy at the meso and macro levels.
- ***Product circularity principles,*** shown as the basis for next generation sustainable manufacturing, would require ***integrated metrics-based approaches*** at product, process and system levels for advancing circular economy.

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CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Tuesday June 9th 15:30-17:00
Circular Product-Production CoDesign

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Material choice alone is misleading; From Mass-Based to Function-Based Carbon Footprints: A Comparative LCA of Machine Tool Structural Materials

inspire AG
Eduard Relea, Raphael Pellin, Konrad Wegener

Agenda

- Introduction to machine tool beds: stiffness vs strength
- Motivation for next generation alternative materials
- Conventional vs Alternative materials
  - Grey cast (GC)
  - Mineral cast (MC)
  - Ultra-high performance concrete (UHPC)
- From Mass-Based to Function-Based Carbon Footprints
- Results
- Discussion



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Introduction to machine tool beds

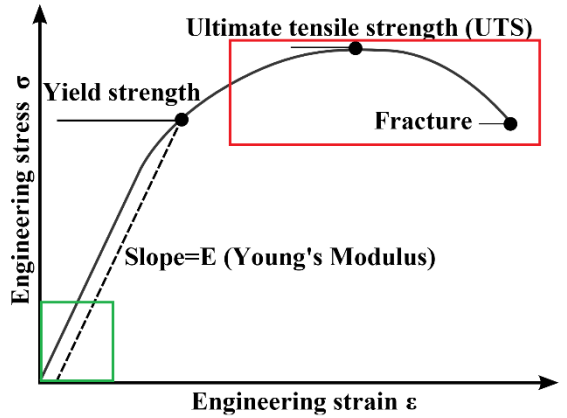
- MTs are designed to operate over an extensive period of time in the tenth of thousands of hours
- MT structures represent high-mass, long-service-life components whose material selection significantly influences **embodied emissions** and system durability
- The MT industry requires high control on the geometrical and dimensional stability of the machine structure to ensure precise and accurate parts in the micrometer range



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Machine tool (MT) design for stiffness

- MTs demand high stiffness and moderate strength → **design for stiffness**:
  - Strain can be limited by employing high Young's modulus materials and limiting the loads
  - Stresses are low, lower than the strength of the materials



- Precision machinery employs a variety of materials for its structures:

Property	Unit	Welded Steel	Cast iron	Granite	Mineral cast	UHPC
Density	[g/cm³]	7.8	7.2	2.9	2.4	2.45
Elastic modulus	[kN/mm²]	210	110	50 - 100	41	45
Tensile strength	[N/mm²]	300	200	39	14	8
Compression strength	[N/mm²]	700	840	150	105	130
Thermal conductivity	[W/m*K]	50	45	3	3	2
Specific heat capacity	[kJ/kg*K]	0.5	0.46	0.79	0.8	0.75
Thermal expansion coefficient	[µm/m*K]	12	12	9	15	11
Poisson ratio		0.3	0.26	0.25	0.25	0.21



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Motivation for next generation alternative materials

- New material properties and cost reduction
  - Research and development in the field of Mineral Cast (MC) and Ultra High Performance Concrete (UHPC) offers new opportunities for machine design
  - Local sourcing & appeal of artificial stone
  - Function integration
  - Lower costs

- Dynamic key elements
  - For dynamic parts: significant increase in eigenfrequency is hardly possible with conventional materials, since ratio stiffness/mass cannot be improved significantly →Maximum stiffness on small cross section (high specific stiffness)
  - High inertia of dynamic machine parts limited by conventional materials

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MT structures should be designed to deliver the same target stiffness, not the same mass

- Life Cycle Assessments (LCA) of structural materials typically rely on mass-based carbon footprints, implicitly assuming functional equivalence between structurally dissimilar materials.

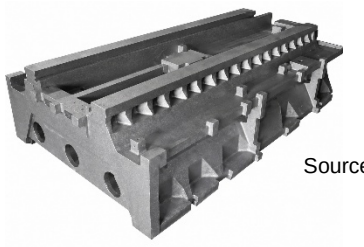
- In addition to conventional mass-based indicators (kg CO_2e/kg), functionally equivalent units are defined based on stiffness and static deflection requirements representative of precision manufacturing systems.

- Performance-oriented functional units into a cradle-to-gate carbon footprint comparison of:
  - Mineral cast (MC)
  - Ultrahigh-performance concrete (UHPC)
  - Grey cast (GC) iron for machine bed applications

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Grey cast (GC) vs Mineral Cast (MC) vs Ultra-high performance concrete (UHPC)

- **GC**
  - Fe-C-Si alloy with graphite flakes
  - Hot casting process in sand moulds
  - High stiffness and good damping behavior
  - Good machinability for precision surfaces
  - Residual stresses require ageing / stress relief
  - High design freedom with ribs and hollow structures



Source: CADEM

- **MC**
  - 85% vol. **gravel & sand** + 15% vol. **epoxy**
  - Cold casting process & high precision from mould
  - Low residual stress, low shrinkage
  - High freedom of design
  - Function integration
  - Chemical resistance
  - Added value by secondary operations



Source: Schneeberger

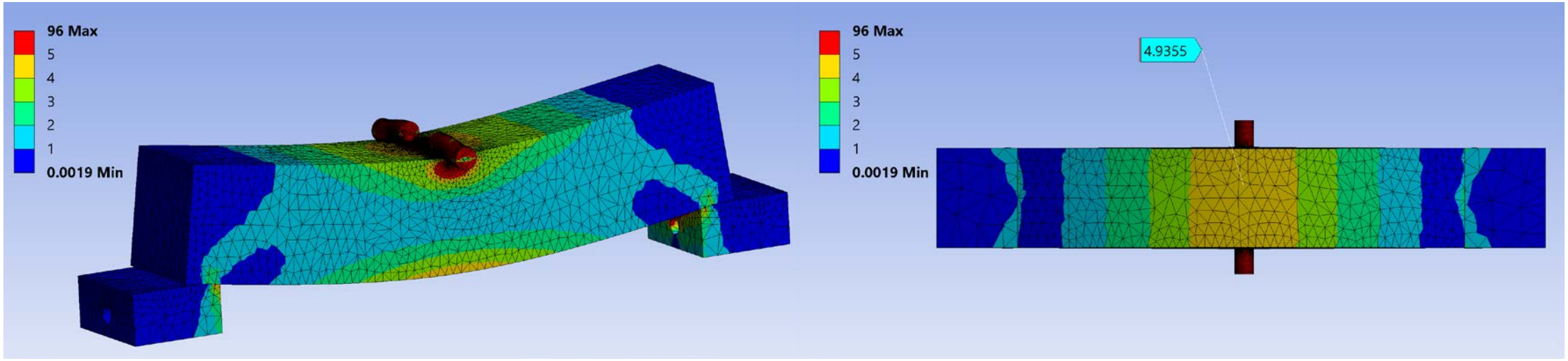
- **UHPC**
  - fine sand, cement, crushed quartz, silica fume, low water content (10% vol.)
  - Cold casting process
  - High stiffness and low dimensional stability
  - Function integration
  - High design freedom through mould casting
  - Precision interfaces require machining or inserts



Source: Ducrete

Mass-normalized carbon metrics alone are insufficient for sustainability-driven material

- Shift from “material per kg” to “functional equivalence” → **stiffness** is fundamental for machine tool structures.
- Introduce a **functional unit tied to performance**, stiffness-normalized, so from [kg CO_2e / kg material] to [kg CO_2e / (kN/mm stiffness)]
- Which material is cleaner per kilogram leaving the factory gate vs kg CO_2e per kN/mm asks which material-geometry combination delivers the required structural stiffness with the lowest embodied burden.

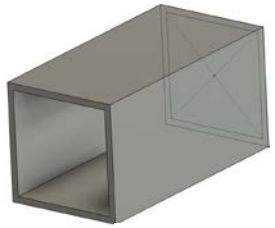


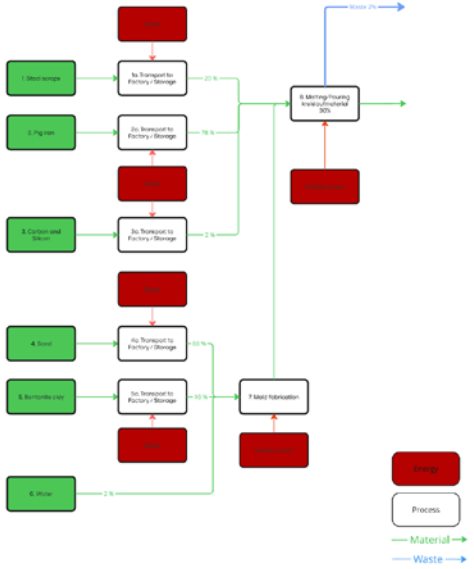
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Functional Unit: one component for high precision MT structures with the same vertical stiffness, width and length manufactured in Switzerland which will be utilized for 20 years

- **GC**
  - Closed box section with uniform walls thickness

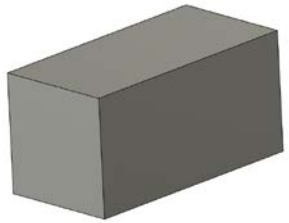
  LxWxH=2x1x1m, t=0.055m

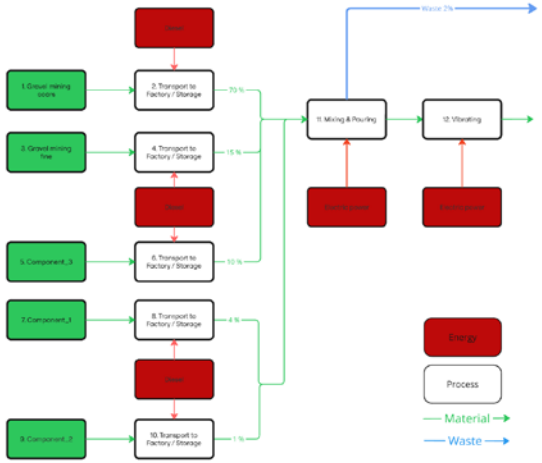




- **MC**
  - Solid rectangular prism

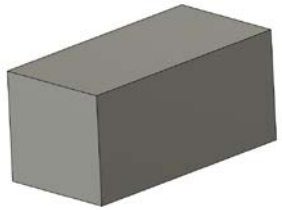
  LxWxH=2x1x1m

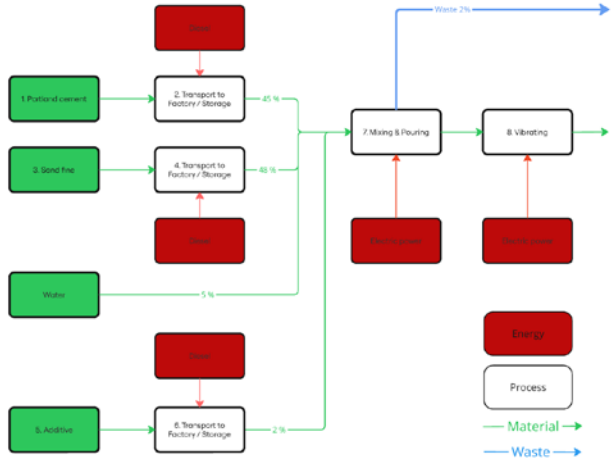




- **UHPC**
  - Solid rectangular prism

  LxWxH=2x1x0.94m

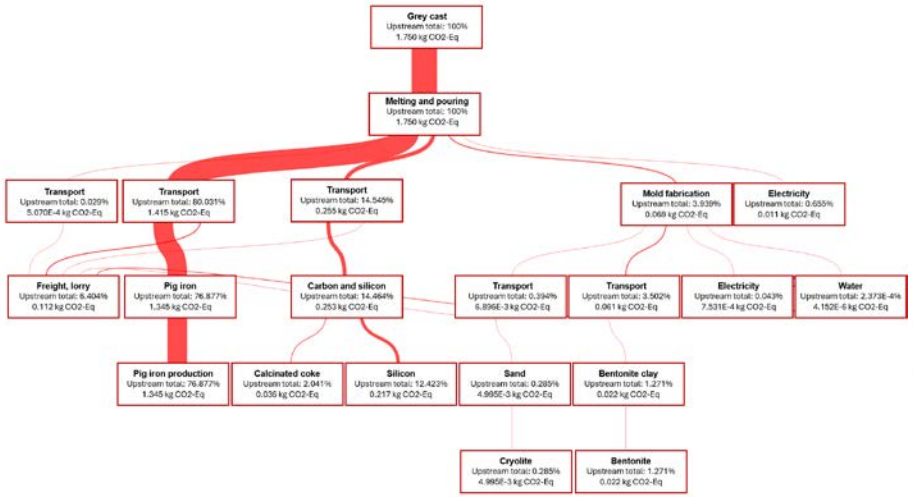


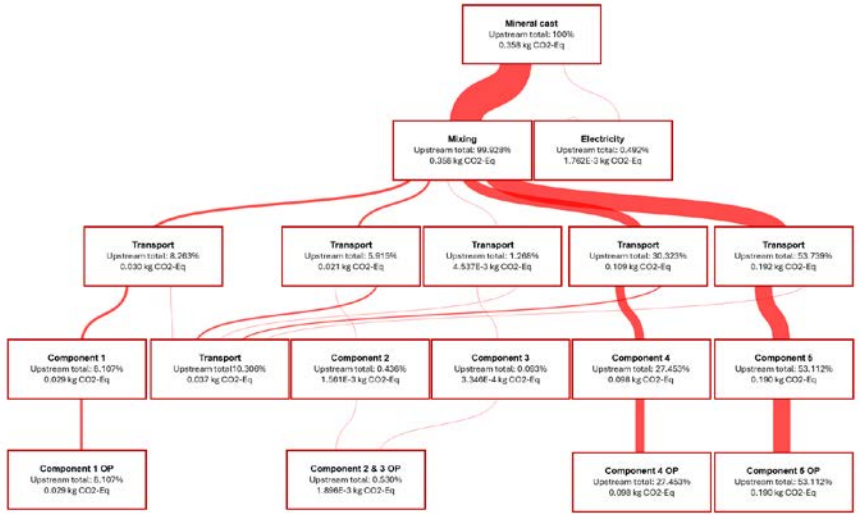


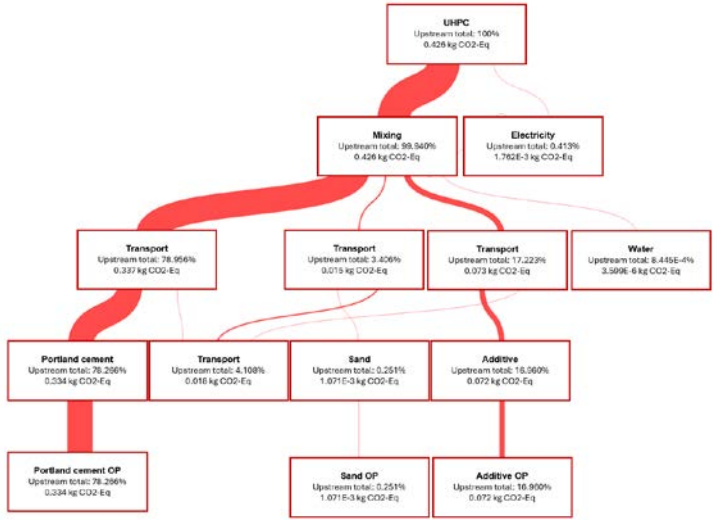
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Hotspots openLCA modelling → EF v3.1

- **GC**
  - Pig iron is the main source of high GWP in the foundries, ahead of transported final components and electricity
- **MC**
  - The decisive hotspot is resin. Because the filler-to-binder ratio in machine-tool mineral cast is typically aggregate-rich, the burden of the epoxy fraction dominates the carbon result
- **UHPC**
  - Clinker-rich binder production, material production contributes more than 90% of the climate and energy footprints





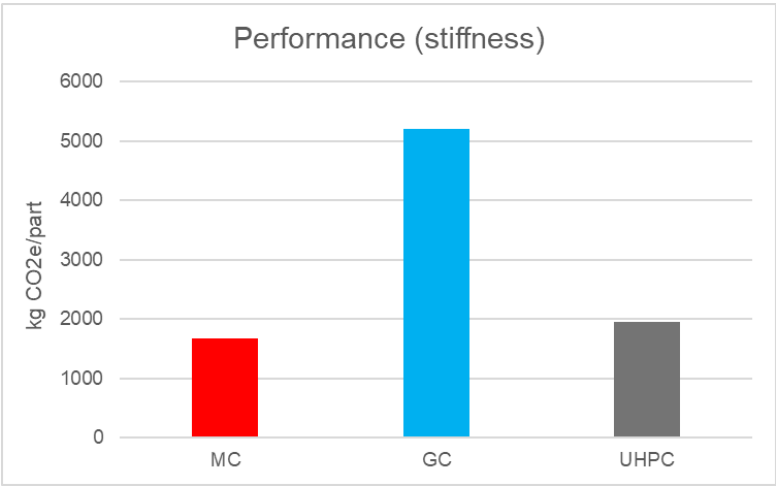


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Results and conclusion

- **Results**

Material	kg CO_2e / kg material	kg CO_2e / part
MC	0.358	1669
GC	1.750	5213
UHPC	0.426	1950



- **GC** requires a significantly higher CO2e emission despite very favorable design considerations. Cast iron benefits from high E-modulus, which allows thinner walls, but it also carries potentially high upstream burdens through pig iron production, melting, and electricity use

- **MC** and **UHPC**, by contrast, operate with much lower density and bulkier sections; they therefore cannot be judged meaningfully from kg CO_2e/kg alone because the design mass required for equal stiffness is part of the environmental story

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Discussion

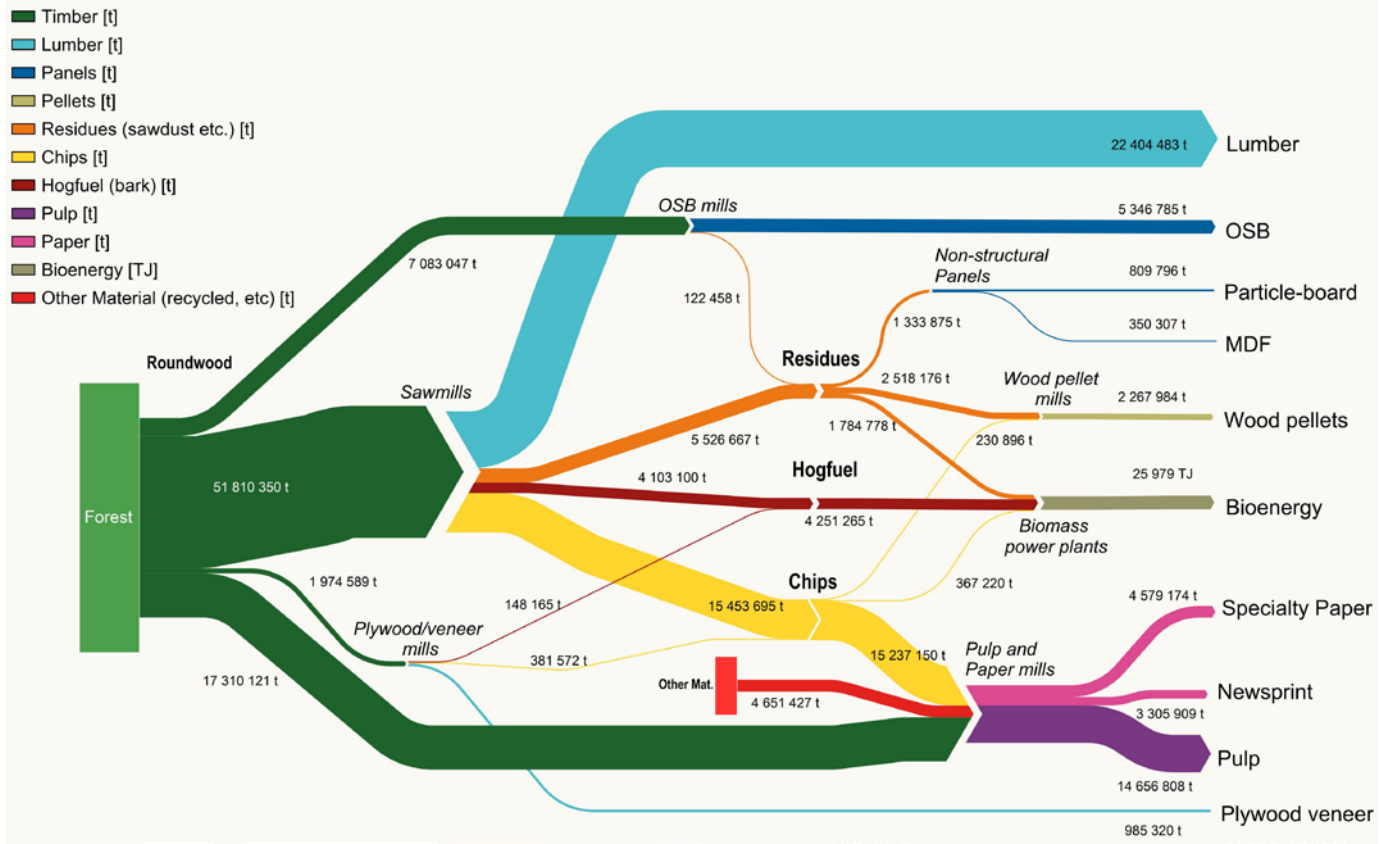
- **Thank you for your attention!**
- **Q&A**
- **Contact**

Eduard Relea
+41 44 556 58 53
+41 76 302 03 78
eduard.relea@inspire.ch

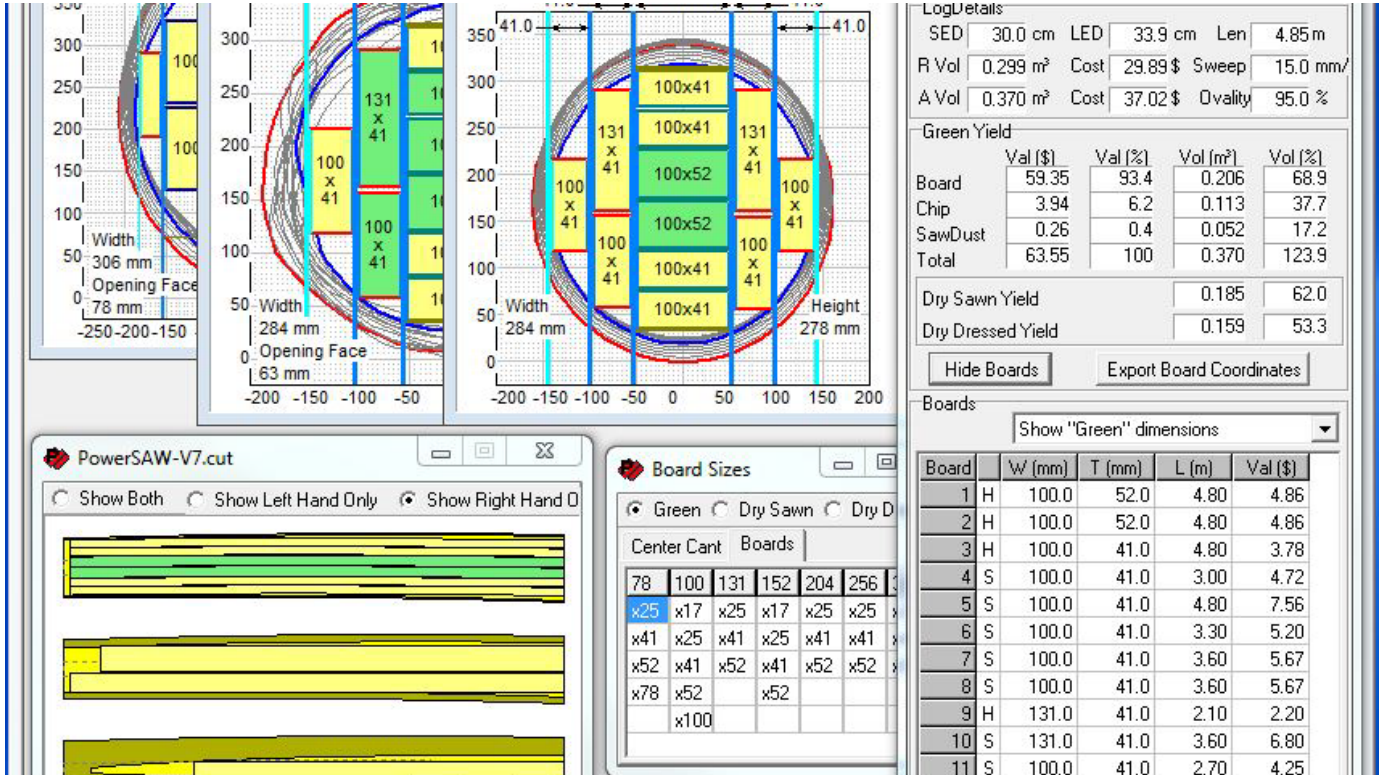
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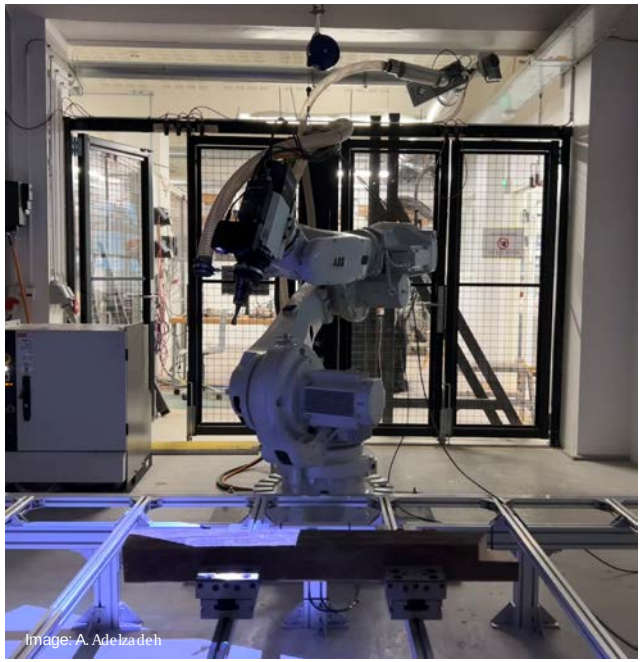
Timber Beyond Carbon:
Sustainability-based resource allocation in the timber value chain

Nadja Gaudillière-Jami, Tom Svilans, Martin Tamle
CITA, Institute of Architecture and Technology, Royal Danish Academy.

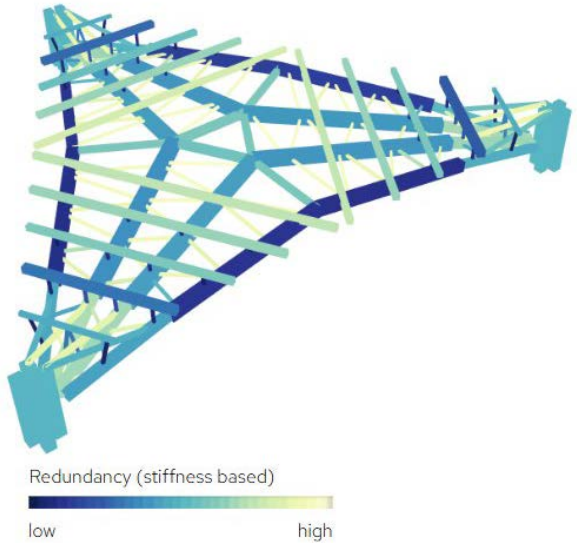


SPRUCE-UP, 2017

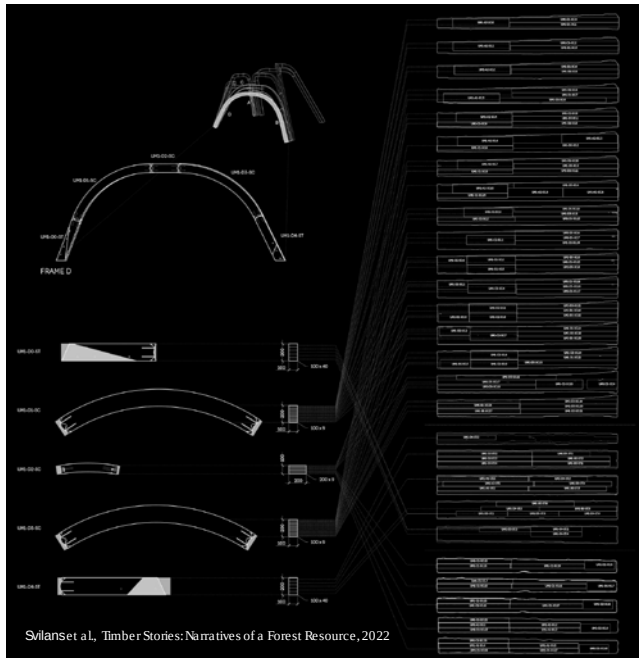

Width
306 mm
Opening Face
78 mm
Width
284 mm
Opening Face
63 mm
Width
284 mm
Height
278 mm
100x41
100x52
PowerSAW-V7.cut
Show Both
Show Left Hand Only
Show Right Hand O
Board Sizes
Green
Dry Sawn
Center Cant
Boards
LogDetails
SED 30.0 cm LED 33.9 cm Len 4.85 m
R Vol 0.299 m³ Cost 29.89 $ Sweep 15.0 mm/
A Vol 0.370 m³ Cost 37.02 $ Ovality 95.0 %
Green Yield
Val ($) Val (%) Vol (m³) Vol (%)
Board 59.35 93.4 0.206 68.9
Chip 3.94 6.2 0.113 37.7
SawDust 0.26 0.4 0.052 17.2
Total 63.55 100 0.370 123.9
Dry Sawn Yield 0.185 62.0
Dry Dressed Yield 0.159 53.3
Hide Boards
Export Board Coordinates
Boards
Show "Green" dimensions
Board W (mm) T (mm) L (m) Val ($)
1 H 100.0 52.0 4.80 4.86
2 H 100.0 52.0 4.80 4.86
3 H 100.0 41.0 4.80 3.78
4 S 100.0 41.0 3.00 4.72
5 S 100.0 41.0 4.80 7.56
6 S 100.0 41.0 3.30 5.20
7 S 100.0 41.0 3.60 5.67
8 S 100.0 41.0 3.60 5.67
9 H 131.0 41.0 2.10 2.20
10 S 131.0 41.0 3.60 6.80


Image: A. Adelzadeh


Larsen et al. 2022

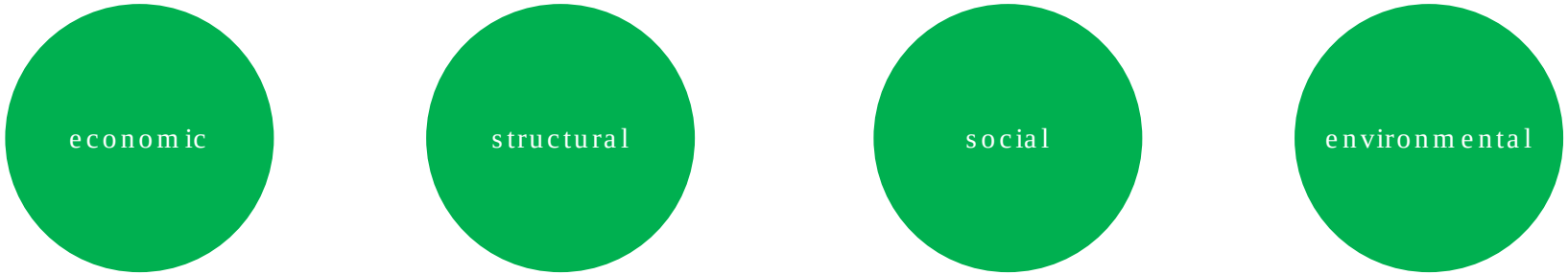


ITECH Studio 2025



Svilans et al., Timber Stories: Narratives of a Forest Resource, 2022

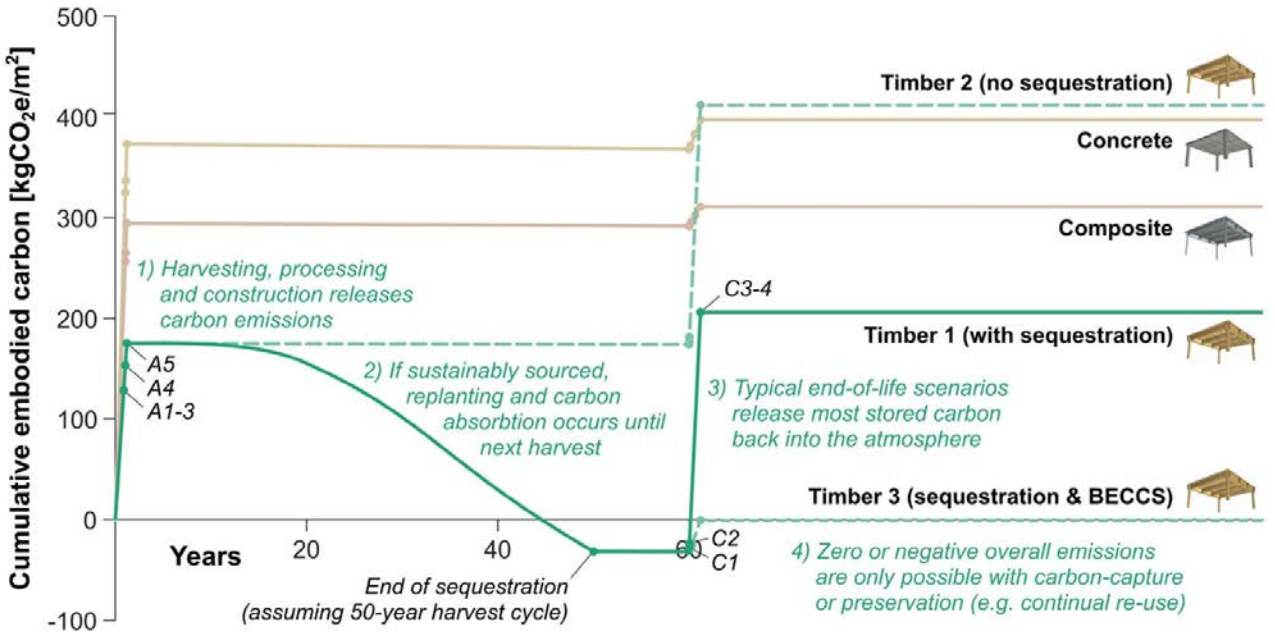
performance criteria for resource allocation



economic	structural	social	environmental
Tunes et al. 2006	Brütting et al. 2020	Babuka et al. 2018	Mantau 2014
Korpunen et al. 2010	Tamke et al. 2020	Boukherroub et al. 2015	Garcia et al. 2020
Pradenas et al. 2020	Svilans et al. 2022		
Ramos-Maldonado et al. 2024	Svilans & Thomsen 2024		

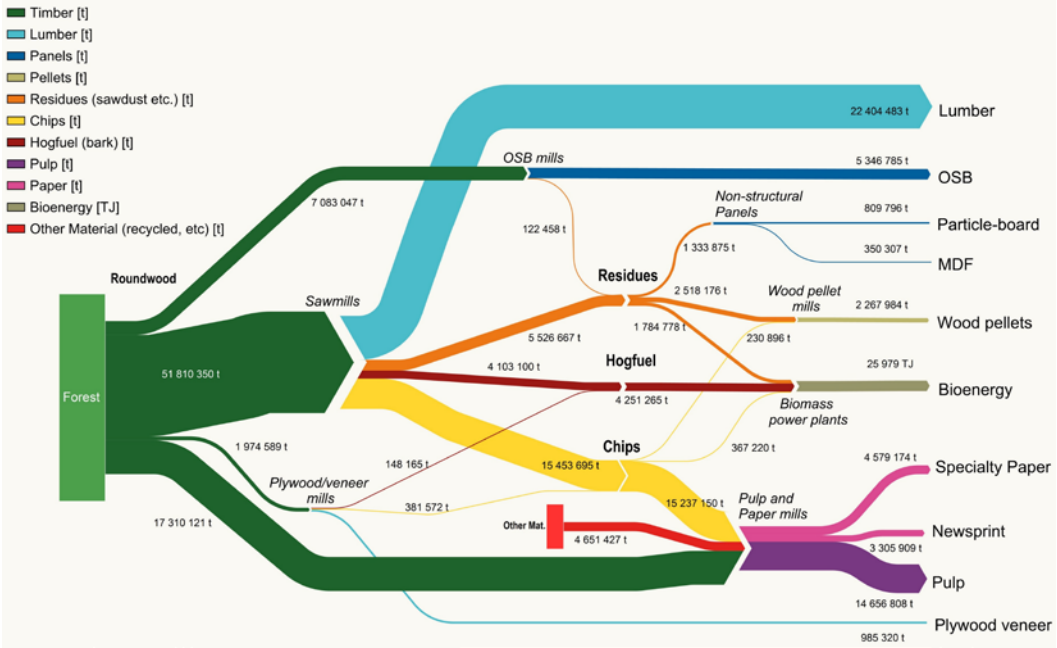
how can environmental metrics be integrated into resource allocations for timber?

Fine particulate matter formation	kg PM2.5 eq
Fossil resource scarcity	kg oil eq
Freshwater ecotoxicity	kg 1,4-DCB
Freshwater eutrophication	kg P eq
Global warming	kg CO2 eq
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Ionizing radiation	kBq Co-60 eq
Land use	m2a crop eq
Marine ecotoxicity	kg 1,4-DCB
Marine eutrophication	kg N eq
Mineral resource scarcity	kg Cu eq
Ozone formation, human health	kg NOx eq
Ozone formation, terrestrial ecosystems	kg NOx eq
Stratospheric ozone depletion	kg CFC11 eq
Terrestrial acidification	kg SO2 eq
Terrestrial ecotoxicity	kg 1,4-DCB
Water consumption	m3
Non-hazardous waste disposed	kg
Components for reuse	kg
Materials for recycling	kg



Hawkins, 2021

Fine particulate matter formation	kg PM2.5 eq
Fossil resource scarcity	kg oil eq
Freshwater ecotoxicity	kg 1,4-DCB
Freshwater eutrophication	kg P eq
Global warming	kg CO2 eq
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Ionizing radiation	kBq Co-60 eq
Land use	m2a crop eq
Marine ecotoxicity	kg 1,4-DCB
Marine eutrophication	kg N eq
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Ozone formation, human health	kg NOx eq
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Terrestrial ecotoxicity	kg 1,4-DCB
Water consumption	m3
Non-hazardous waste disposed	kg
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SPRUCE-UP, 2017

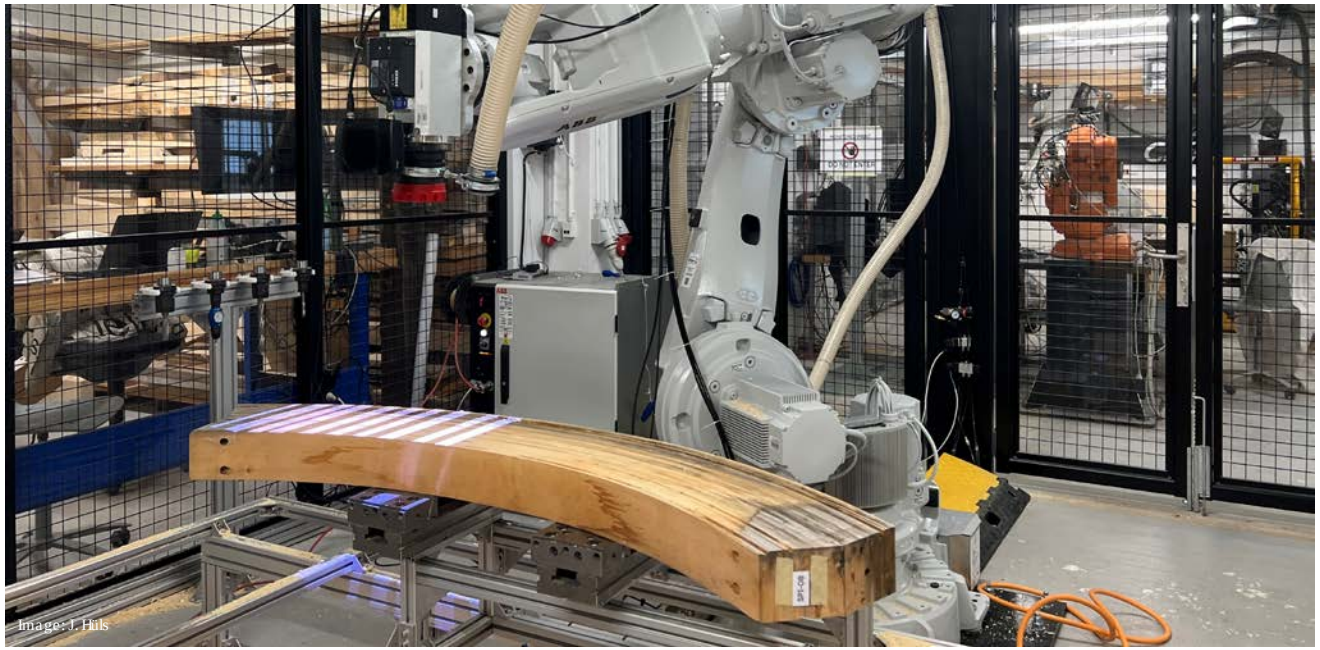
Fine particulate matter formation	kg PM2.5 eq
Fossil resource scarcity	kg oil eq
Freshwater ecotoxicity	kg 1,4-DCB
Freshwater eutrophication	kg P eq
Global warming	kg CO2 eq
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Ionizing radiation	kBq Co-60 eq
Land use	m2a crop eq
Marine ecotoxicity	kg 1,4-DCB
Marine eutrophication	kg N eq
Mineral resource scarcity	kg Cu eq
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Water consumption	m3
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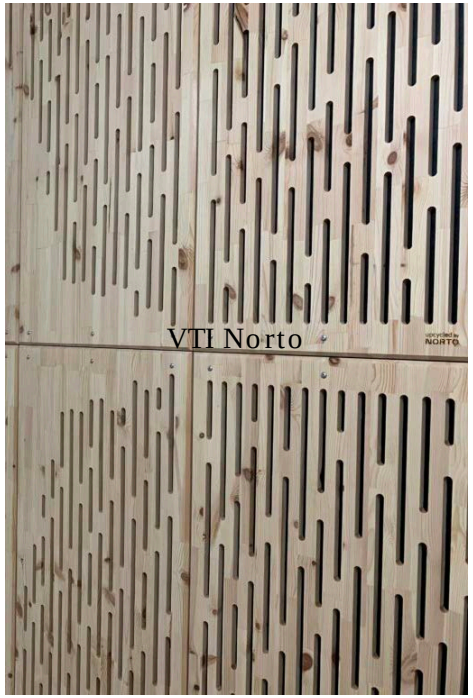
Fine particulate matter formation	kg PM2.5 eq
Fossil resource scarcity	kg oil eq
Freshwater ecotoxicity	kg 1,4-DCB
Freshwater eutrophication	kg P eq
Global warming	kg CO2 eq
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Ionizing radiation	kBq Co-60 eq
Land use	m2a crop eq
Marine ecotoxicity	kg 1,4-DCB
Marine eutrophication	kg N eq
Mineral resource scarcity	kg Cu eq
Ozone formation, human health	kg NOx eq
Ozone formation, terrestrial ecosystems	kg NOx eq
Stratospheric ozone depletion	kg CFC11 eq
Terrestrial acidification	kg SO2 eq
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Water consumption	m3
Non-hazardous waste disposed	kg
Components for reuse	kg
Materials for recycling	kg

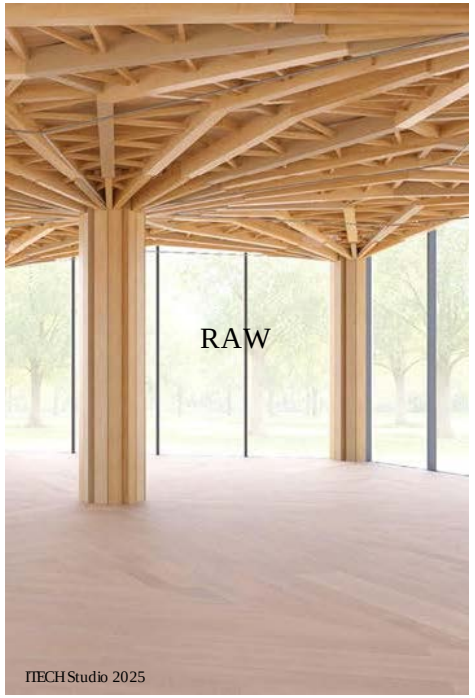


Fine particulate matter formation	kg PM2.5 eq
Fossil resource scarcity	kg oil eq
Freshwater ecotoxicity	kg 1,4-DCB
Freshwater eutrophication	kg P eq
Global warming	kg CO2 eq
Human carcinogenic toxicity	kg 1,4-DCB
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Terrestrial ecotoxicity	kg 1,4-DCB
Water consumption	m3
Non-hazardous waste disposed	kg
Components for reuse	kg
Materials for recycling	kg




Raw Lam
Svilans 2020


VTI Norto


RAW
ITECH Studio 2025


restructuration
Image: J. Hüls


diversification


integration
INSTRON
Image: A. Adelzadeh

three strategies for integrating environmental metrics



	computational efficiency	environmental risk reduction	economic yield
economic normalization	highly efficient	high risk of impact transfer	stability / reliability
carbon normalization	efficient	high risk of impact transfer	integration with carbon policies and credits
holistic sustainability	challenging	selection and development of metrics	fine-tuning of weights by stakeholders


RAW

Towards the Systematic Development of Adaptive Vacuum Grippers for the Robotic Disassembly of End-of-Life (EOL) Products

Manuel Eber, Christoph Feichtgruber, Lucas Janisch, Zheng Xiang, Benjamin Schleich



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Motivation & Introduction

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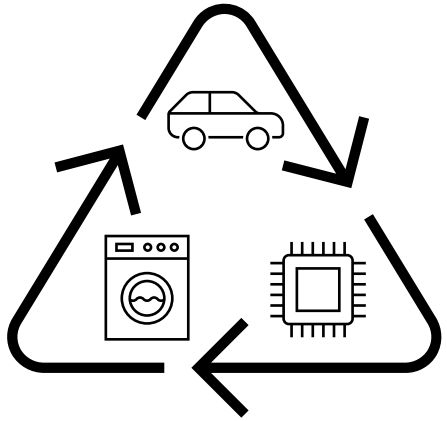
Initial situation

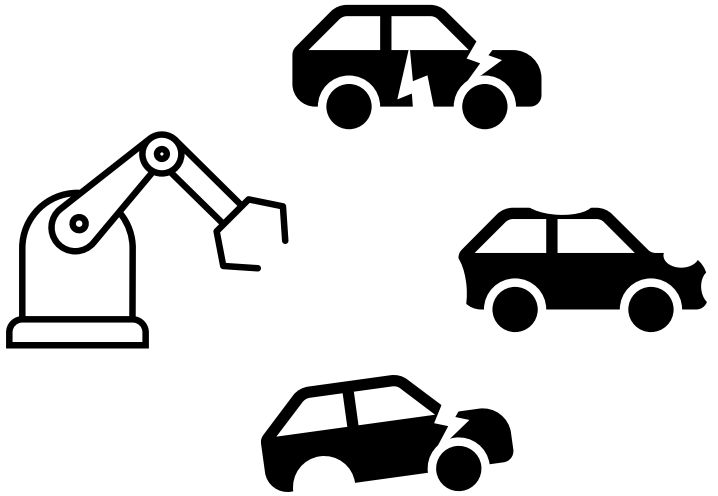
Circular economy

- Waste reduction → Circular economy [1]
- End-of-life (EOL) products with complex material mix [2]
- Disassembly necessary to be able to use materials [2]

Use of automation

- Appropriate disassembly increases quantity and quality [3]
- Key role of robotics in industry [4] → Disassembly with robots is reasonable
- Challenges due to unknown conditions in EOL product disassembly (especially vehicles) [5]





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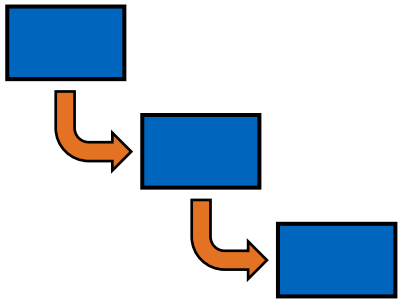
Objective

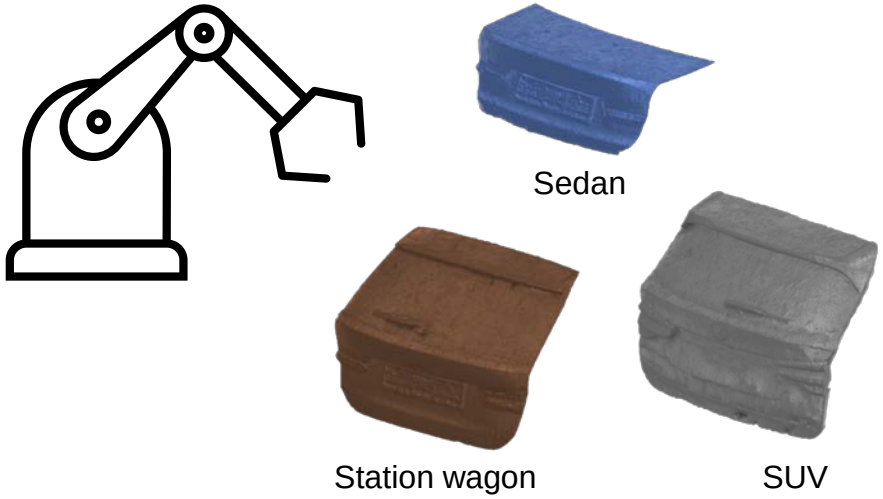
Establish a vacuum gripper development process model

- Support for future developments
- Reproducible development results
- Traceability
- Additive-Manufacturing-specific considerations

Validation based on an automotive use case

- Development of a vaccum gripper for three different tailgates
  - ➢ Adaptability to deviations and irregularities





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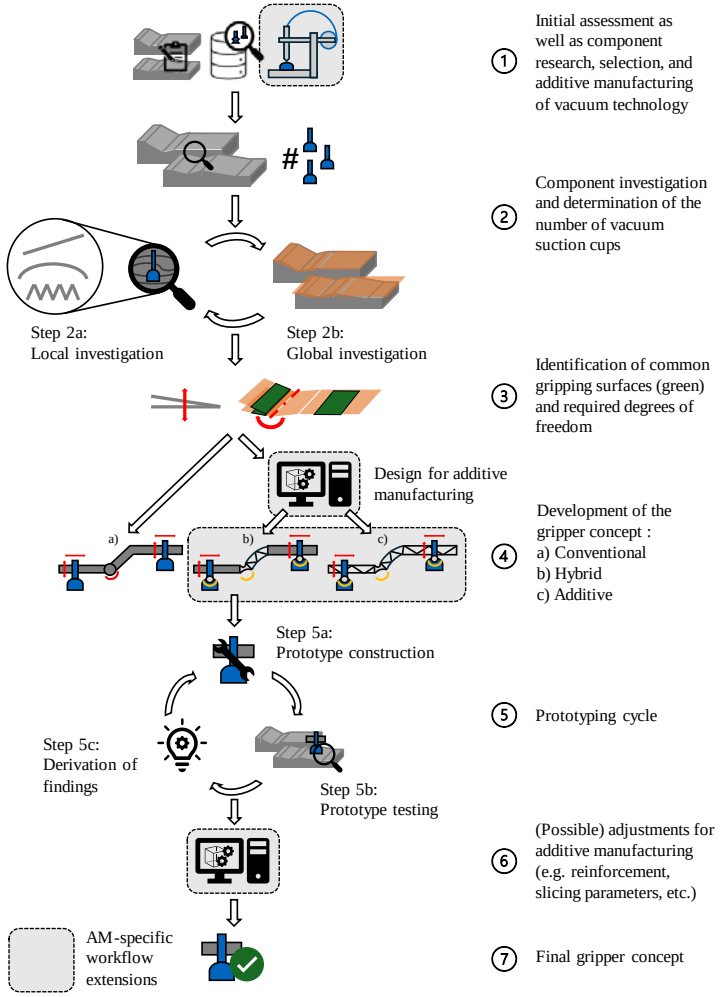
Procedure



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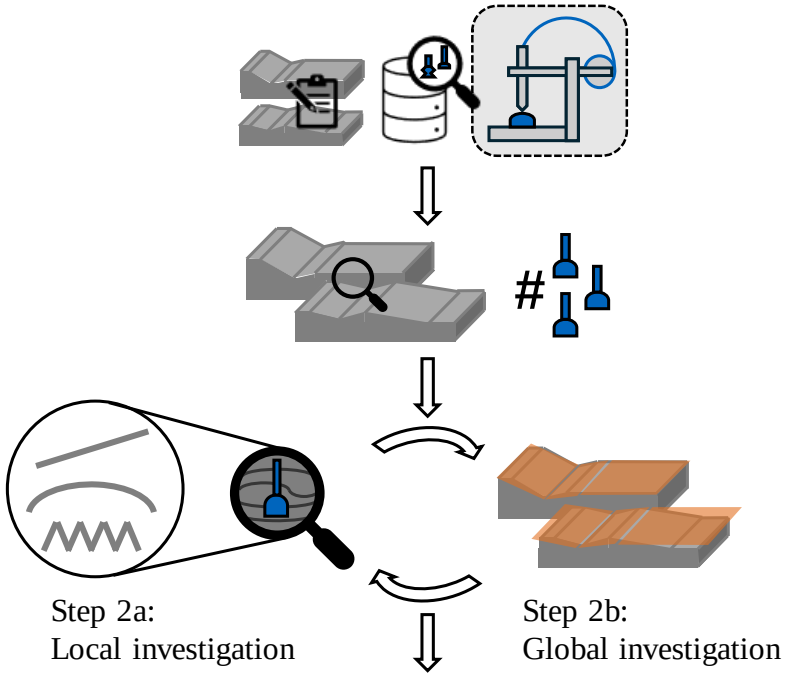
Vacuum Gripper Development Process Model



1. Initial assessment as well as component research, selection, and additive manufacturing of vacuum technology
2. Component investigation and determination of the number of vacuum suction cups
3. Identification of common gripping surfaces (green) and required degrees of freedom
4. Development of the gripper concept :
   a) Conventional
   b) Hybrid
   c) Additive
5. Prototyping cycle
6. (Possible) adjustments for additive manufacturing (e.g. reinforcement, slicing parameters, etc.)
7. Final gripper concept

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Vacuum Gripper Development Process Model

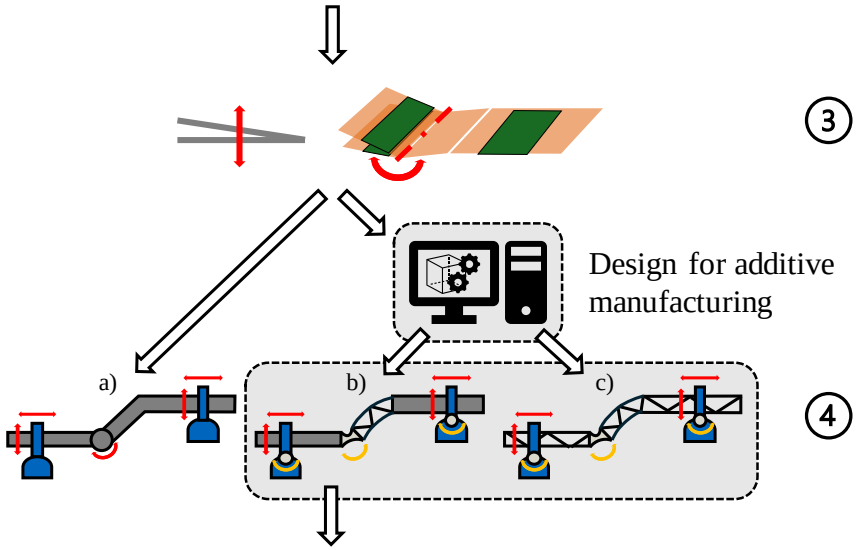


① Initial assessment as well as component research, selection, and additive manufacturing of vacuum technology

② Component investigation and determination of the number of vacuum suction cups

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Vacuum Gripper Development Process Model



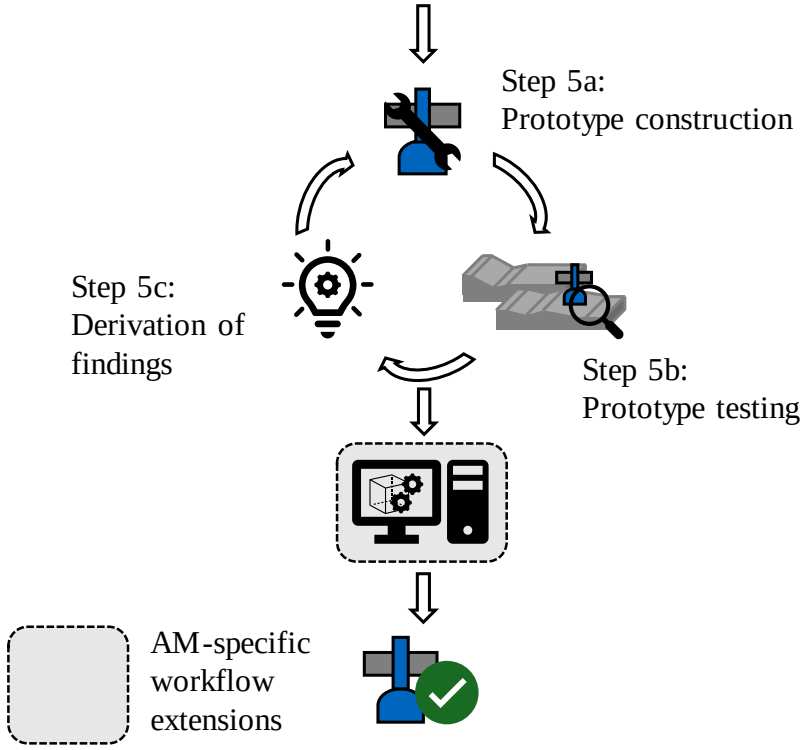
③ Identification of common gripping surfaces (green) and required degrees of freedom

Design for additive manufacturing

④ Development of the gripper concept :
a) Conventional
b) Hybrid
c) Additive

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Vacuum Gripper Development Process Model



5 Prototyping cycle

6 (Possible) adjustments for additive manufacturing (e.g. reinforcement, slicing parameters, etc.)

7 Final gripper concept

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Gripper Development Case Study & Validation

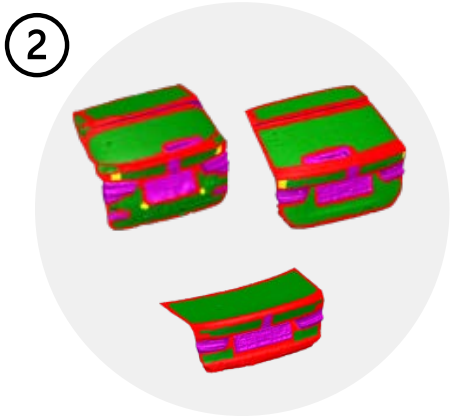
① …

Gripper Development Case Study & Validation

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① … ⇨ ②

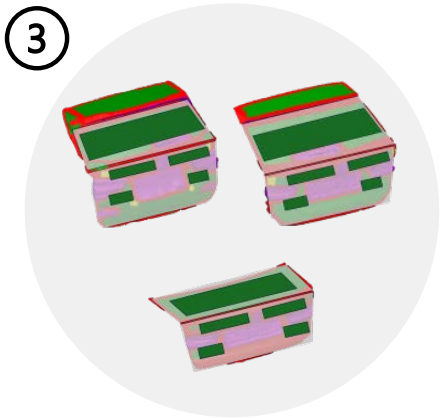
Analysis of tailgates



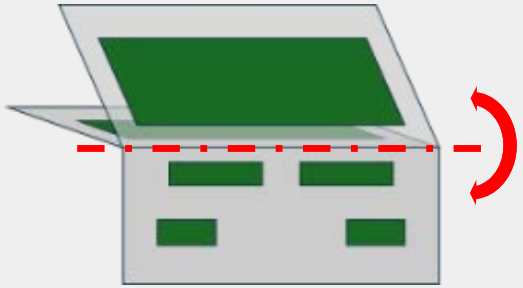
Suitable
Partially suitable
Not suitable
Initially excluded

③

Identification of common gripping regions

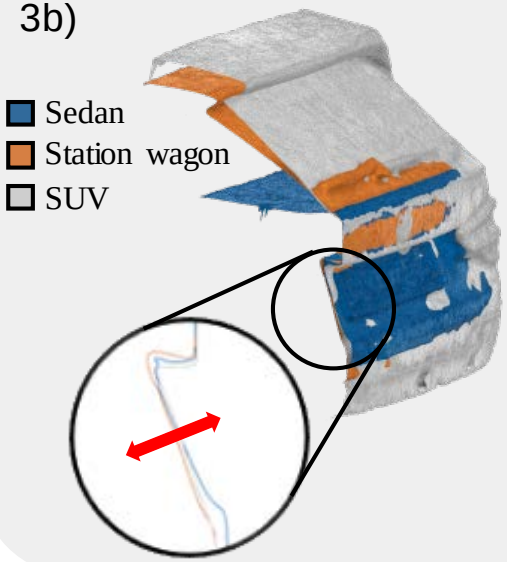


3a)

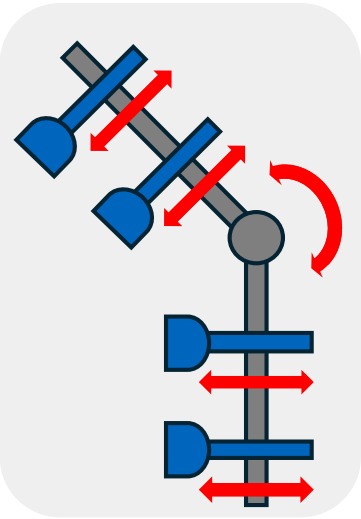


Common gripping regions

3b)



④



Derived gripper concept with necessary degrees of freedom

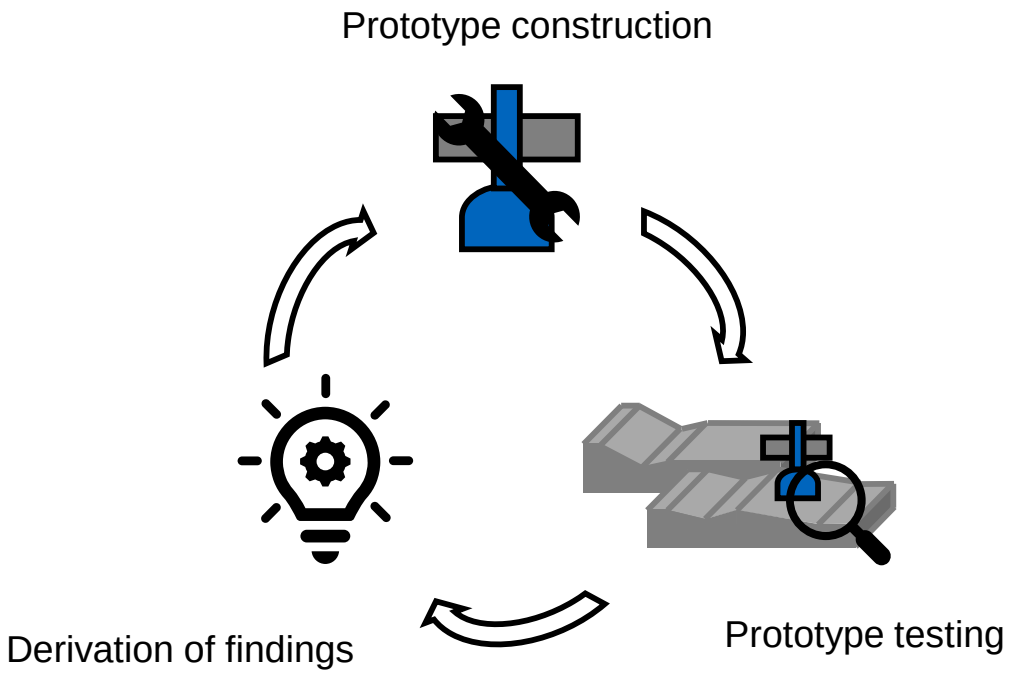
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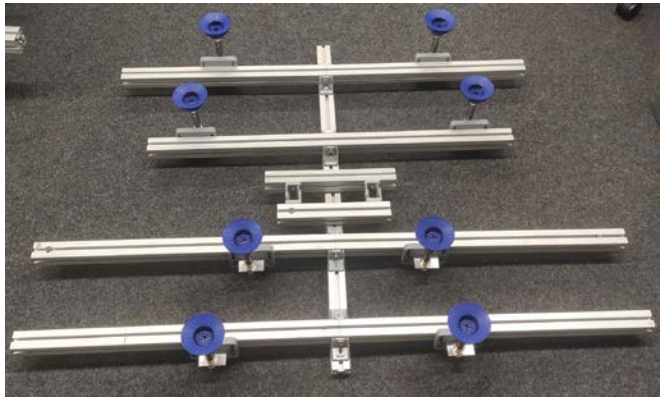
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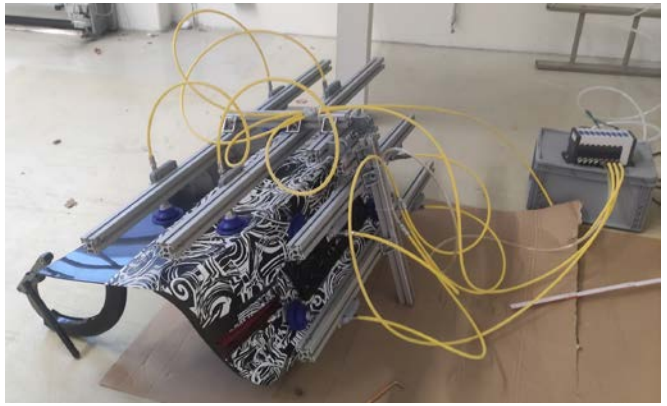
Gripper Development Case Study & Validation
Prototyping Cycle

5





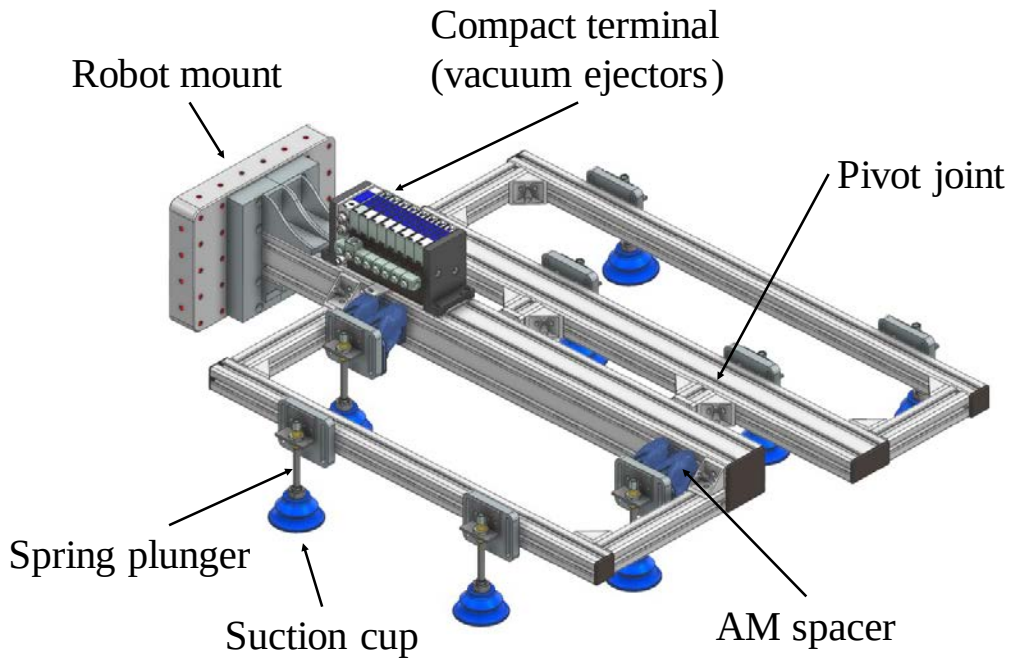
Proof of concept



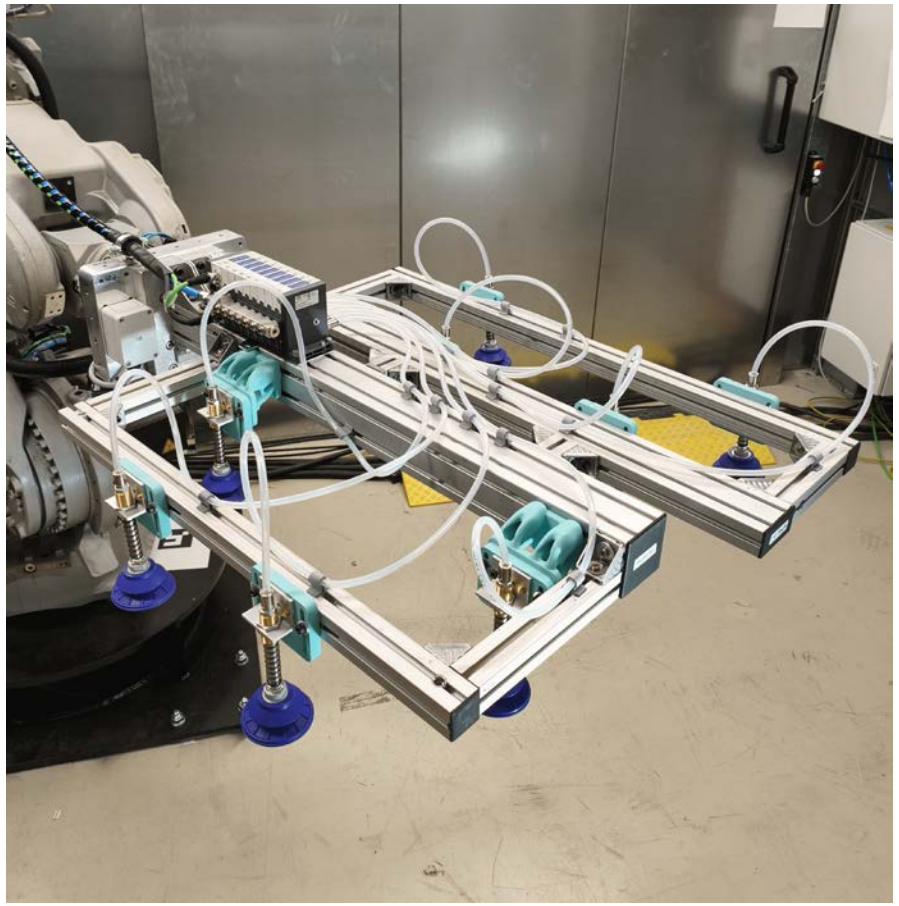
Functional prototype

Gripper Development Case Study & Validation
Final Gripper Design

⑥



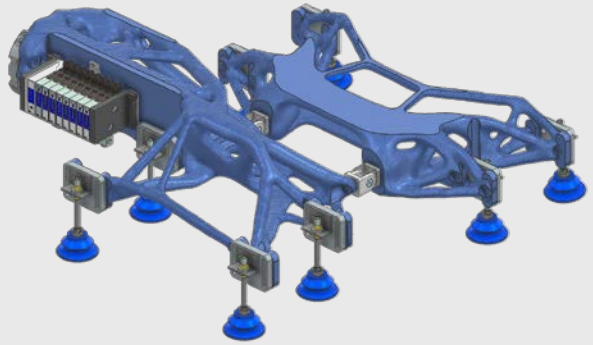
Annotated CAD model



Gripper mounted on robot

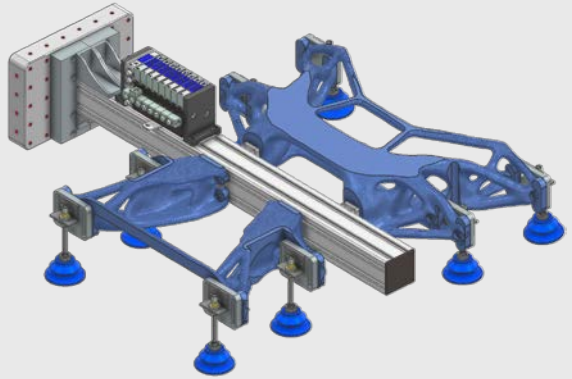
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Gripper Development Case Study & Validation
AM Gripper Design

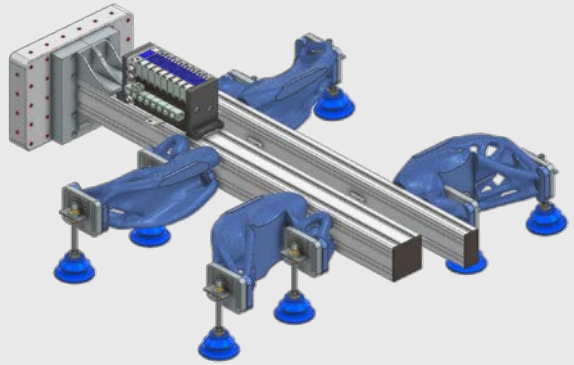


Fully AM Design

- Two gripper halves + pivot joint
- Material: PLA
- Topology optimization
  - Mass reduction: ca. 35%
  - Large scale → Large FDM printers required



Hybrid design „Two Halves“



Hybrid design „Gripper Arms“

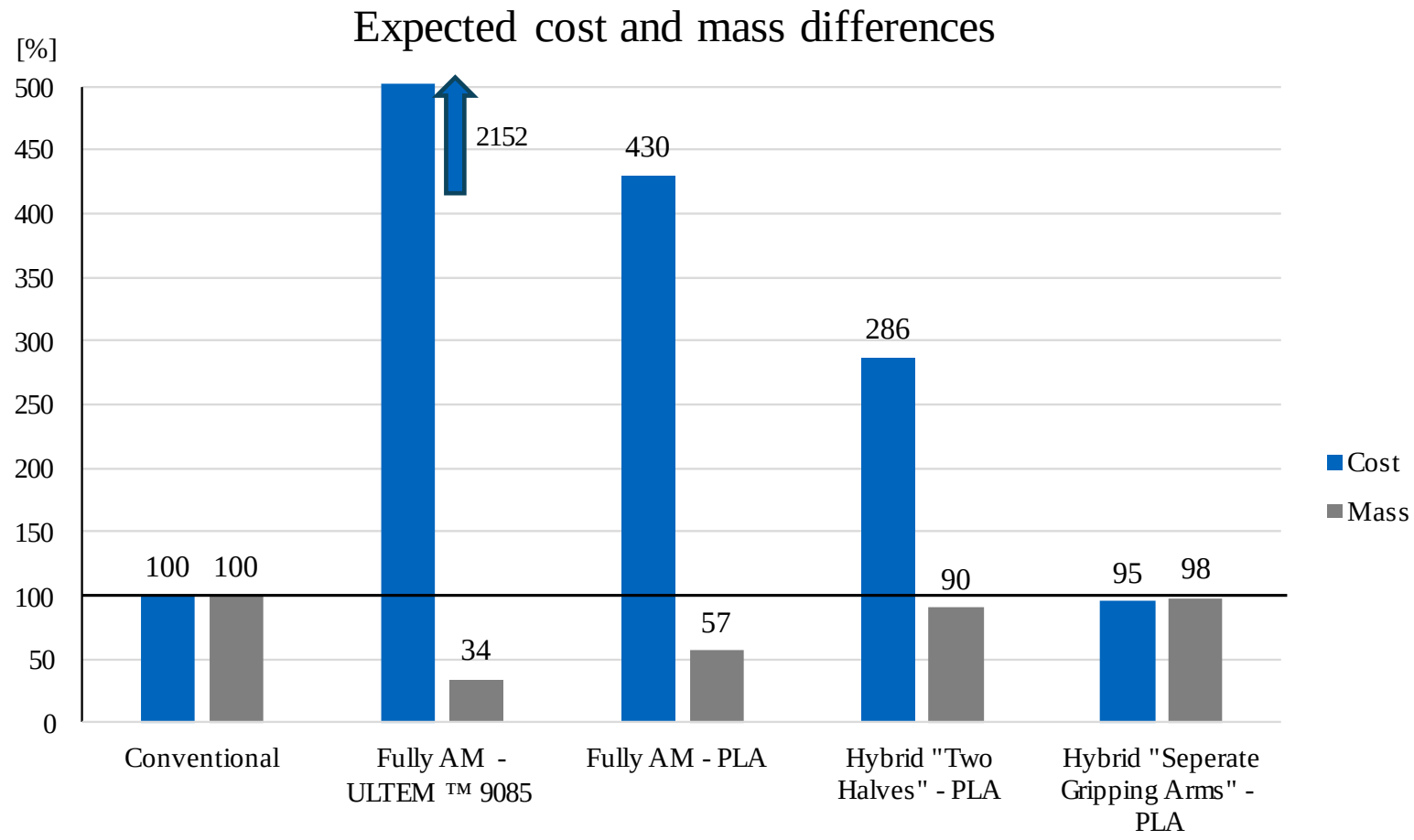
- Two gripper halves + conventional main frame

  or
- Four separate gripper arms + conventional main frame
- Combining advantages of the conventional and AM design
  - Aluminium profiles for load bearing
  - AM arms that can be rapidly redesigned

- Reduced gripper complexity by minimizing spatial footprint & component count

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Gripper Development Case Study & Validation
AM Gripper Design



Values are shown relative to the conventional baseline (approx. 34.4 kg, 465 €).
Also, ULTEM™ (polyetherimide), as a high-performance polymer, is considered.

Gripper Development Case Study & Validation
Conclusion, Limitations & Outlook

Conclusion

- Six-step workflow that increases transparency and reproducibility in gripper development
- Including AM-specific considerations
- Validated on three EOL tailgates
- Reliable gripping performance in handling tests along realistic robotic trajectories

Limitations

- Initial vacuum cup selection in step 1 introduces a path dependency conditioning all subsequent decisions
  - ➢ Evaluate multiple cup type candidates in parallel
- Validated with a single case study only
  - ➢ Requires further validation with different handling component types

Outlook

- Hardware side:
  - ➢ Active angle adjustment and alternative locking concepts would enable fully automated reconfiguration
- Software side:
  - ➢ Rule-based nature of plane approximation, gripping area identification, and DoF derivation for computational automated gripper development

References

[1] European Parliament. (2023). Circular economy: definition, importance and benefits. Last accessed 2026/03/11. https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits

[2] Tarrar, M., Despeisse, M., & Johansson, B. (2021). Driving vehicle dismantling forward - A combined literature and empirical study [PII: S0959652621006302]. *Journal of Cleaner Production, 295*, 126410.

[3] Xiang, Z., Bernhard, T., & Fottner, J. (2025). A multi-level filtering framework for disassembly sequence planning utilizing various detailed information. *2025 IEEE 21st International Conference on Automation Science and Engineering (CASE)*, 1654–1659.

[4] IFR - International Federation of Robotics. (2025). World Robotics - Industrial Robots (IFR -International Federation of Robotics, Hrsg.). Last accessed 2025/09/26. https://ifr.org/ifr-press-releases/news/global-robot-demand-in-factories-doubles-over-10-years#downloads

[5] Wünnenberg, M., Xiang, Z., & Fottner, J. (2024). Automatisierung der Demontage zur Optimierung der Altfahrzeugverwertung [PII: 2160]. ATZ – Automobiltechnische Zeitschrift, 126(12), 74–77.

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Thank you!

Questions?

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Contact

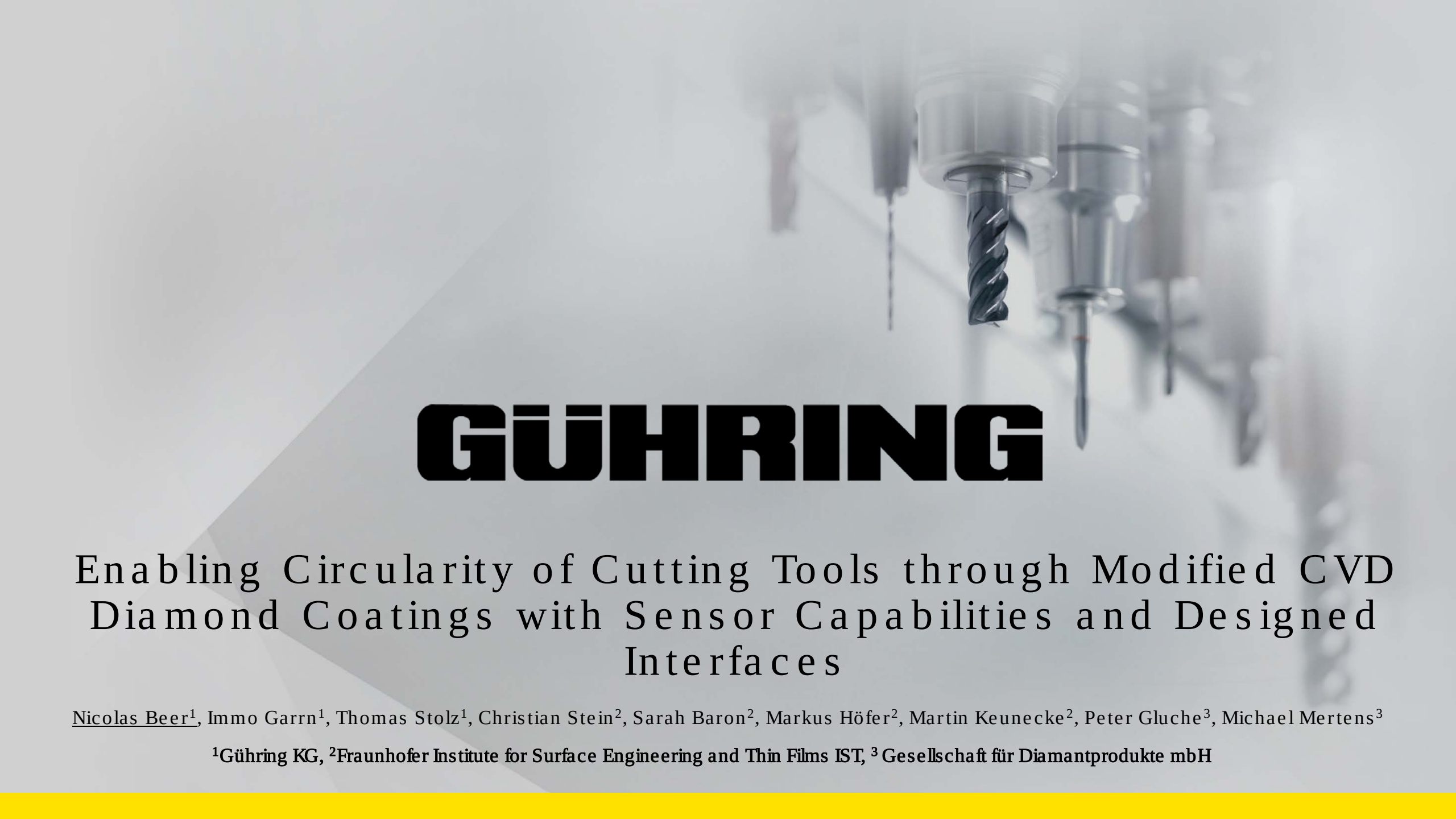
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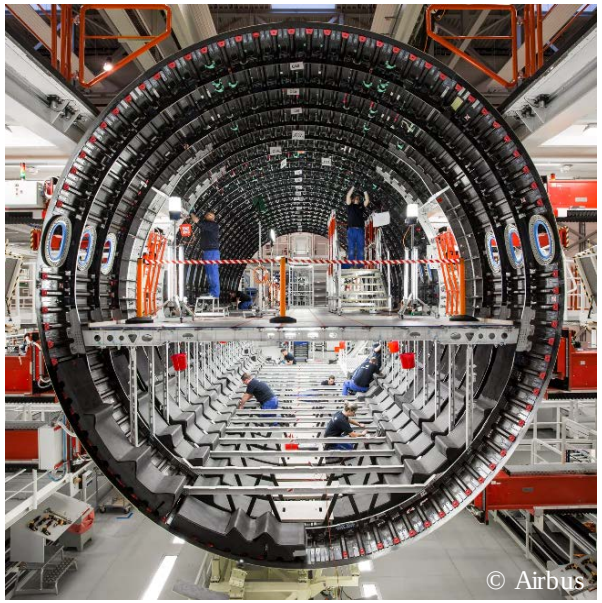
Enabling Circularity of Cutting Tools through Modified CVD Diamond Coatings with Sensor Capabilities and Designed Interfaces

Nicolas Beer[1], Immo Garrn[1], Thomas Stolz[1], Christian Stein[2], Sarah Baron[2], Markus Höfer[2], Martin Keunecke[2], Peter Gluche[3], Michael Mertens[3]

[1]Gühring KG, [2]Fraunhofer Institute for Surface Engineering and Thin Films IST, [3] Gesellschaft für Diamantprodukte mbH

Applications of Diamond Coated Tools

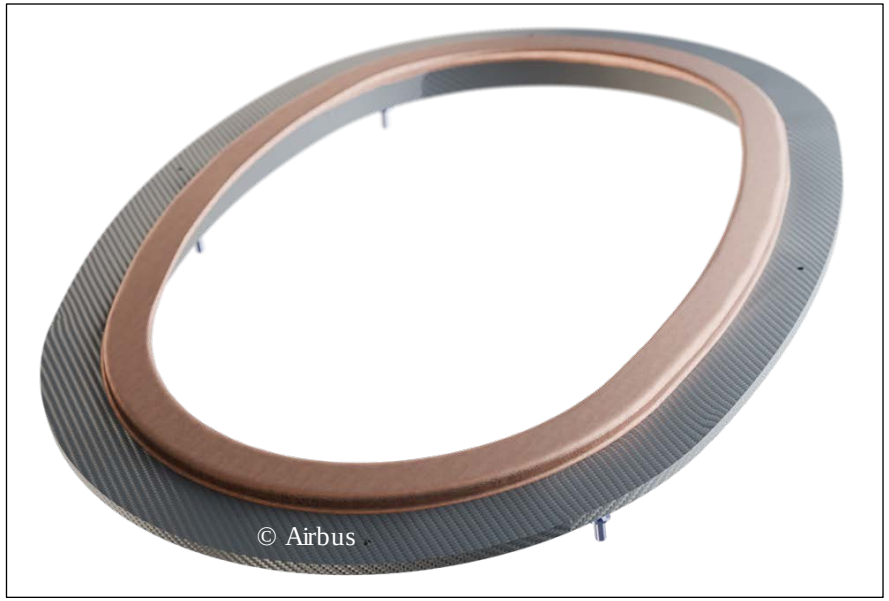
Fuselage structural assembly



Aircraft Rivet Joints



Aircraft A350 Carbon Window Frame





Mould & Die



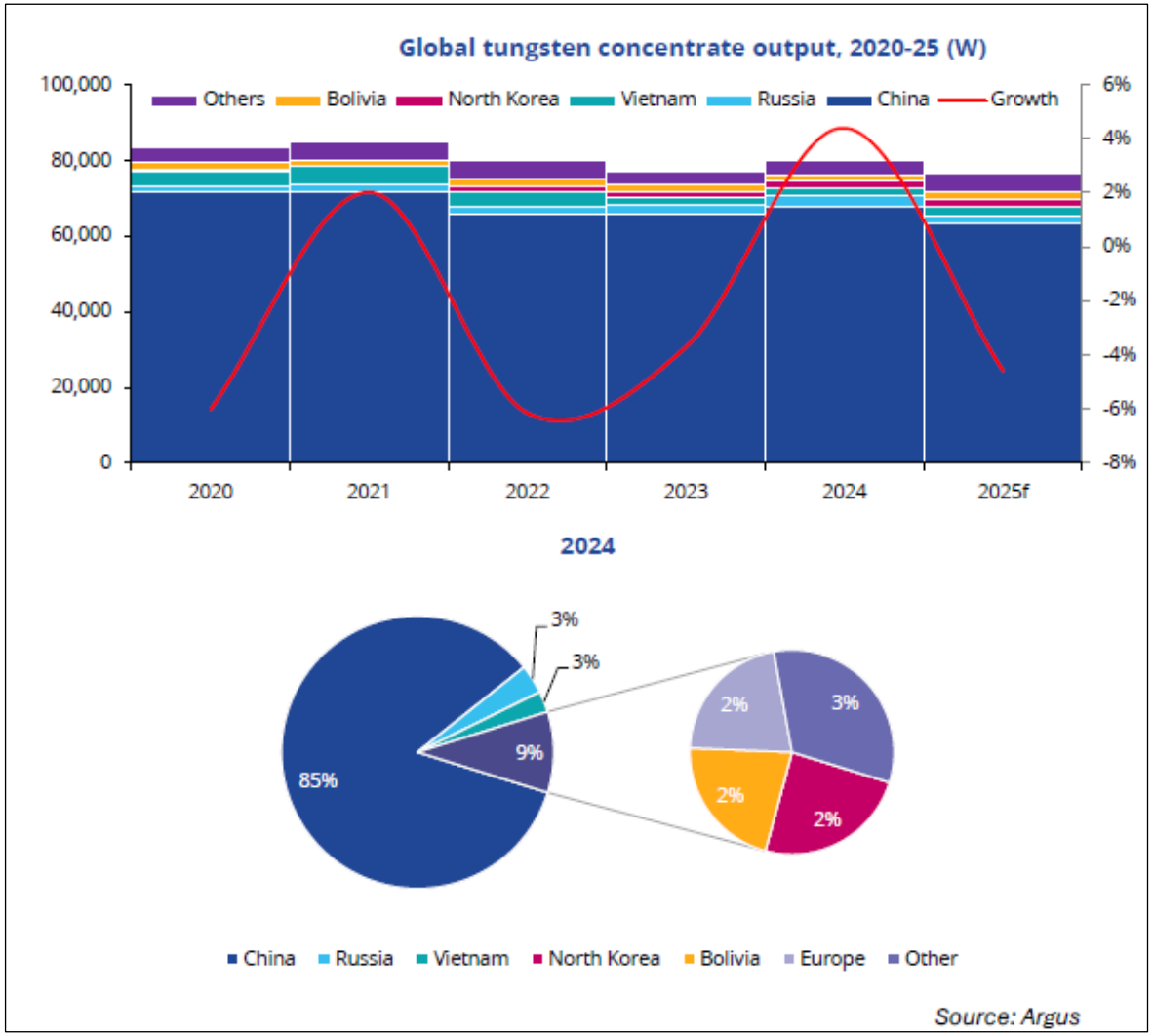
CFRP / Foam Sandwich

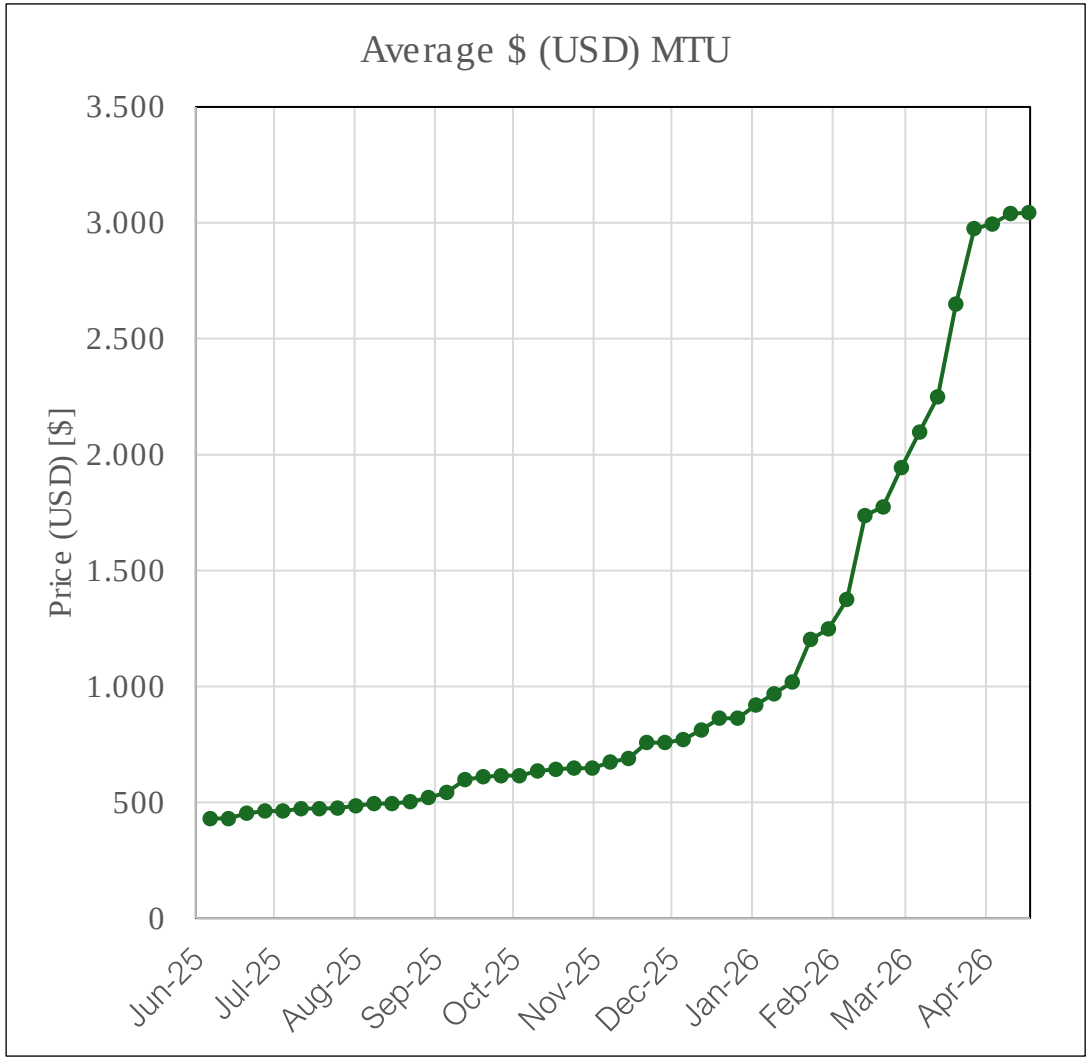


Carbon/Flax Hybrid multilayer Wood Stack

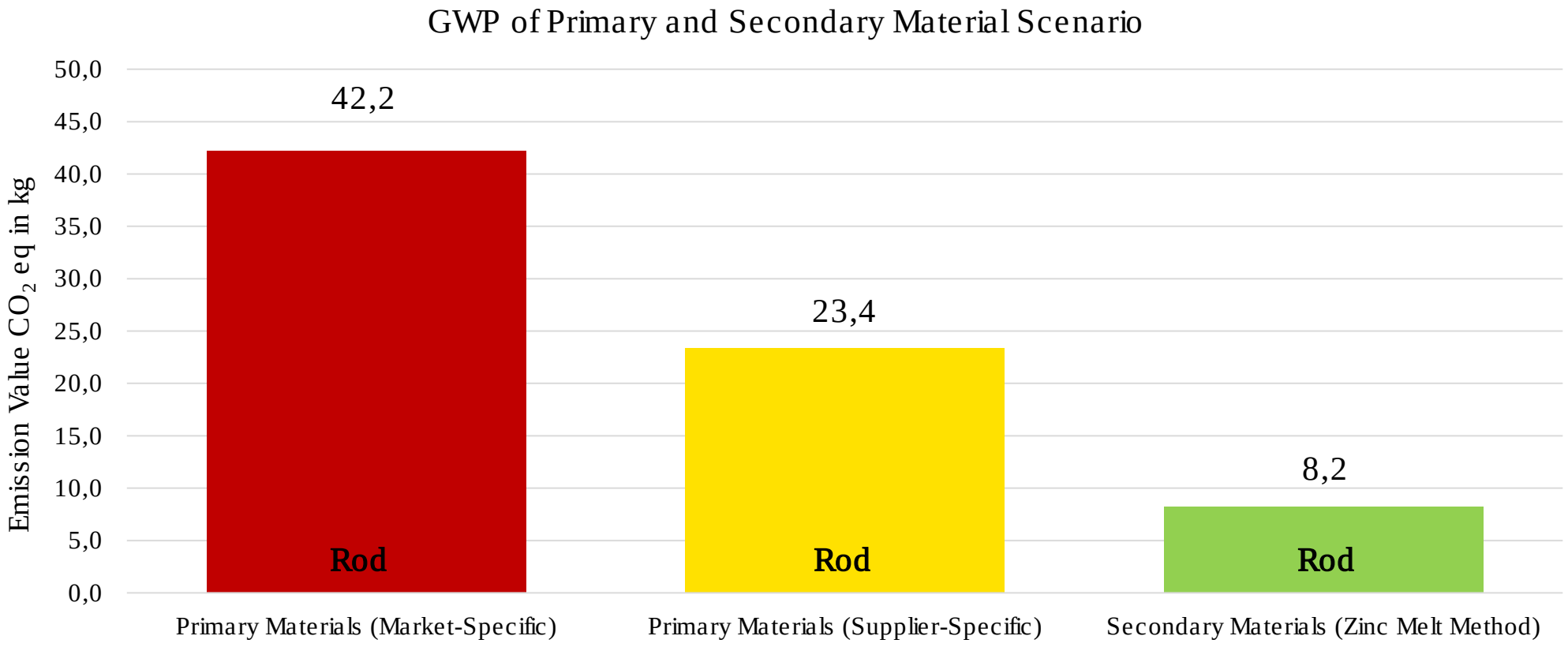


Tungsten Price



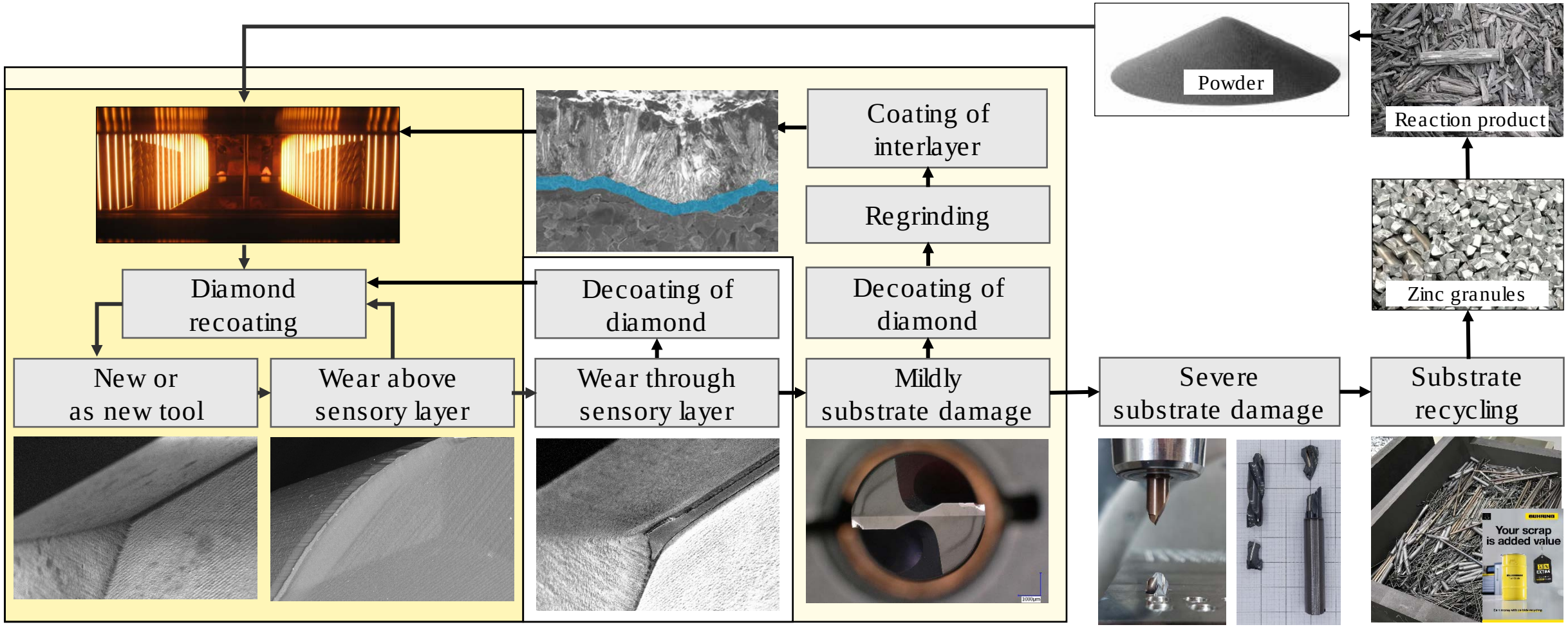


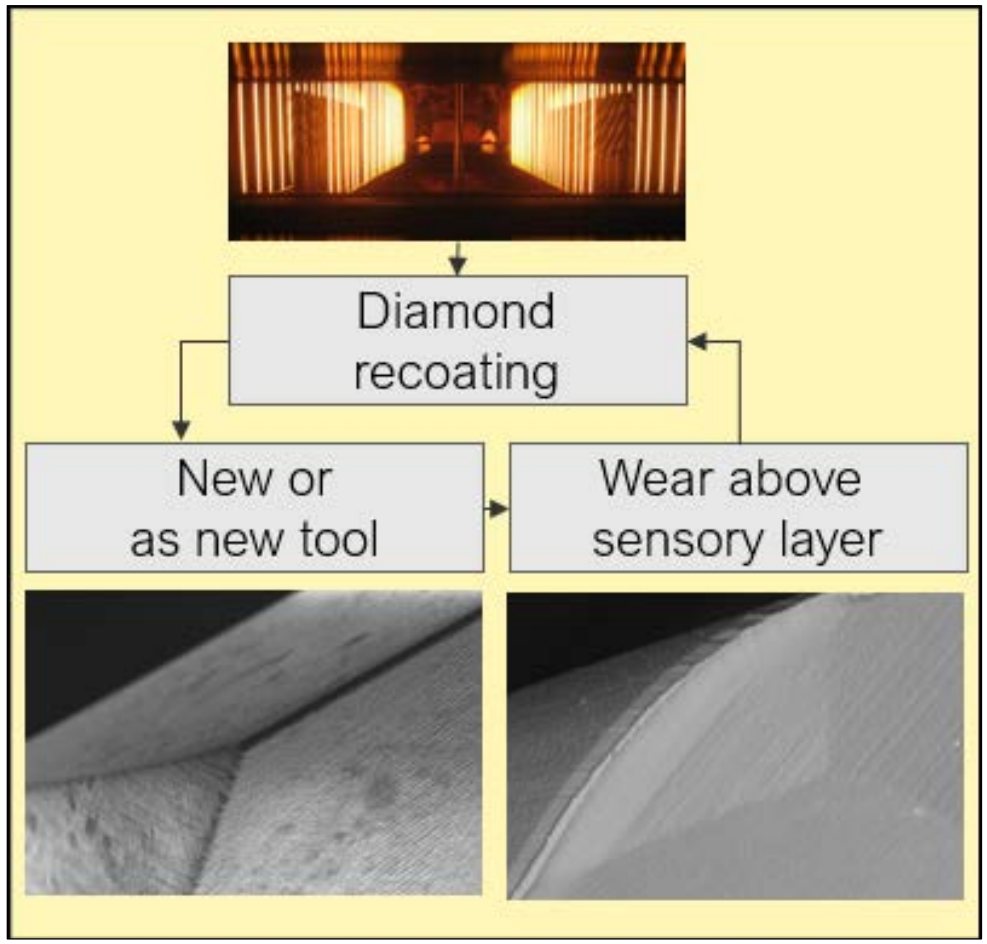
Comparative Analysis of CO_2 Emission Scenarios



Source:
Product Carbon Footprint Cemented Carbide Rod GC100S Primary Material vs. Secondary Material, INAS Institute, EDAG PS, Gühring KG 2025 (translated)

Circularity of Cutting Tools – Overview of Recondition Cycles



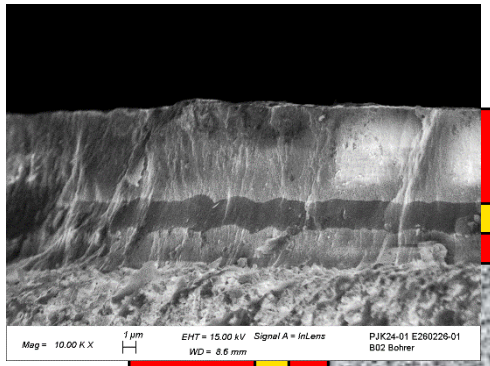


Method 1:

Modified CVD diamond coatings and the addition of conductive and non-conductive layers, transforming the coating into a **sensor system** to enable Circularity

Coating Concept

Idea:
Wear indication by heat-dependent resistance-measurement



Wear Protection Layer

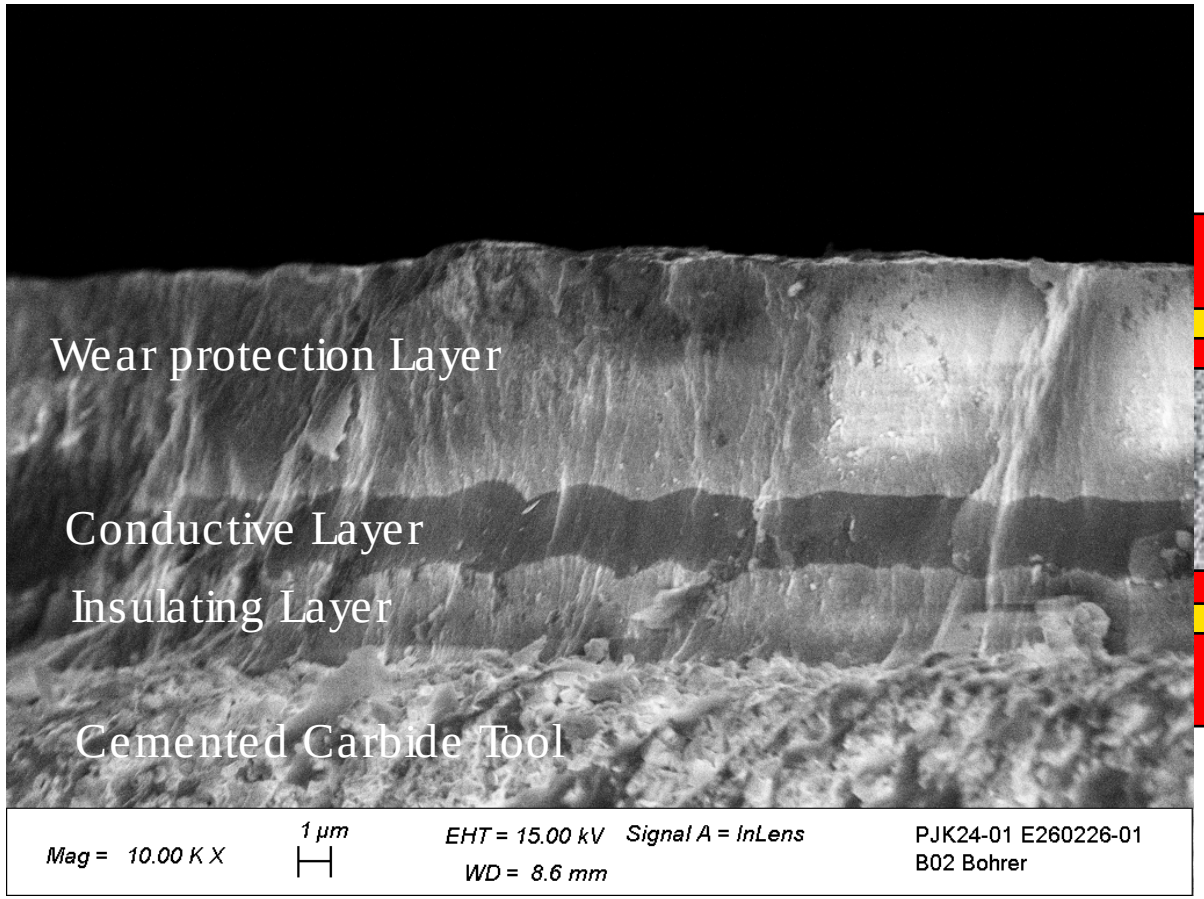
R,C

Cemented Carbide Tool

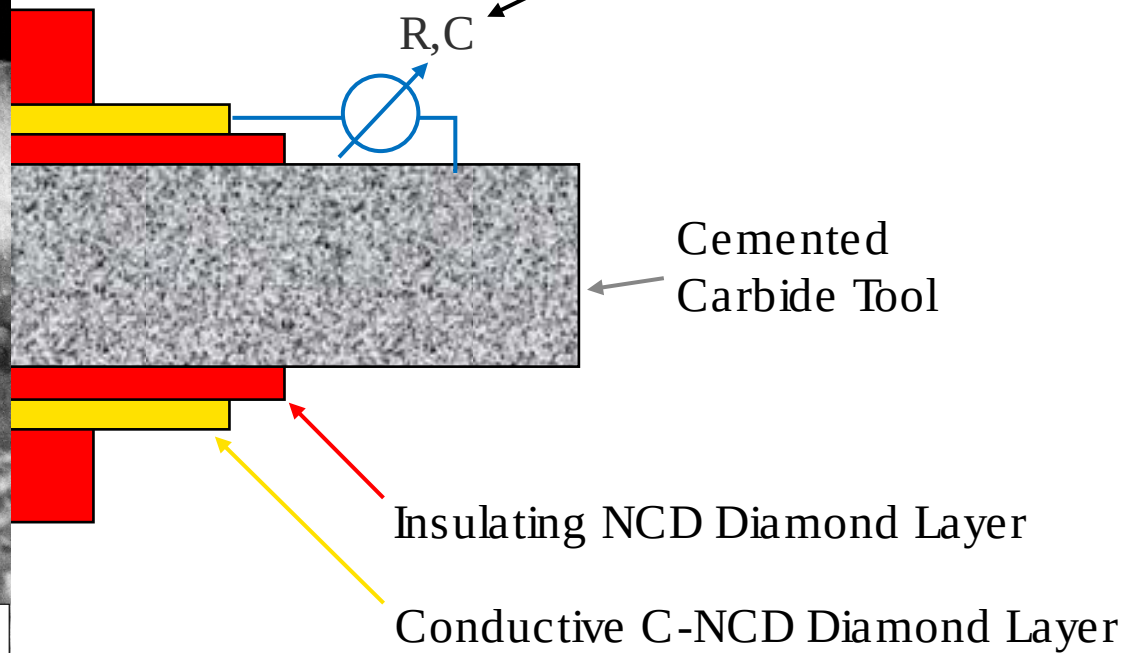
Insulating NCD Diamond Layer

Conductive C-NCD Diamond Layer

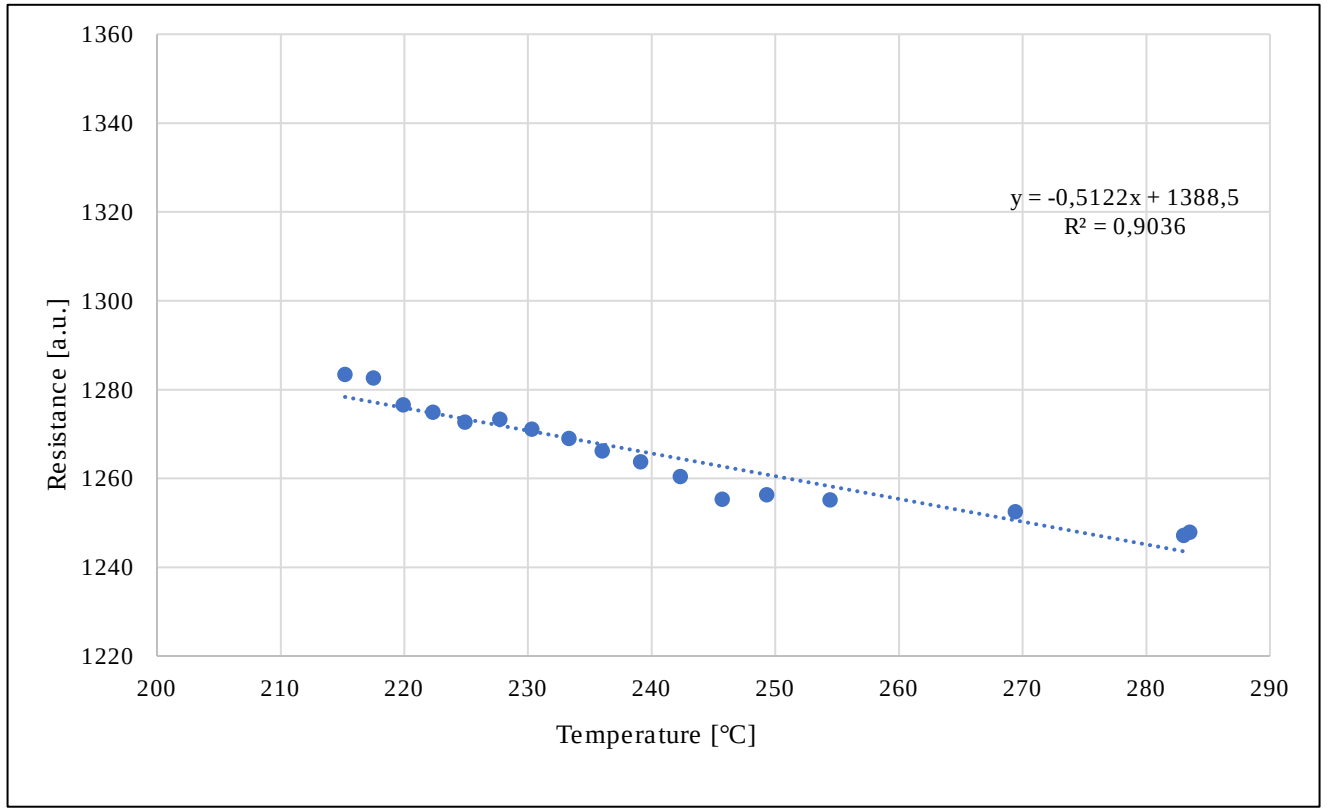
Coating Concept



Idea:
Wear indication by heat-dependent resistance-measurement

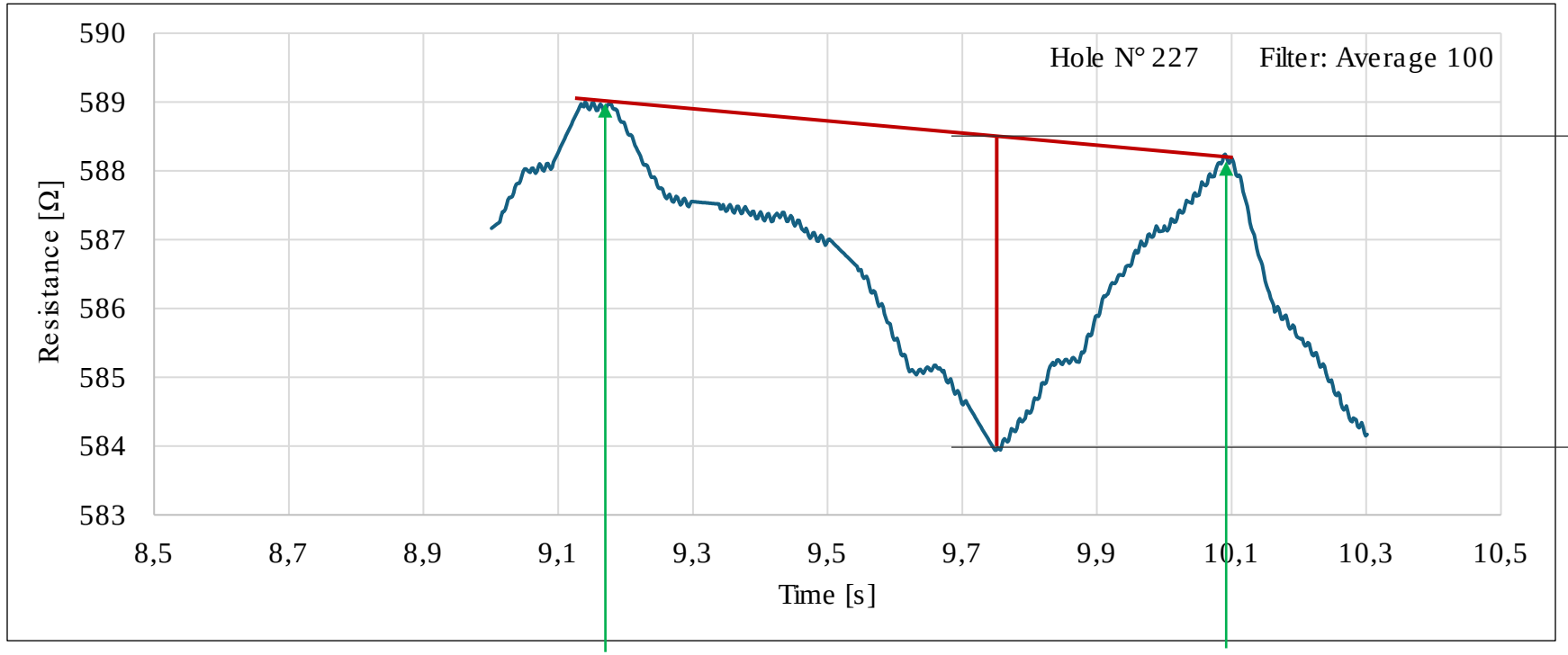


Temperature dependent Resistance Alteration



- The tool was uniformly heated, and its temperature was assessed by means of thermal imaging.
- During the subsequent cooling phase, an approximate correlation between electrical resistance and temperature could be established.
- The electrical resistance exhibits a temperature coefficient of approximately −0.041% K^{-1}.
- These results indicate that the resistance variation within this temperature range is sufficiently pronounced to be reliably detected by the measurement system.

Typical Decrease in Resistance during one Drilling Operation

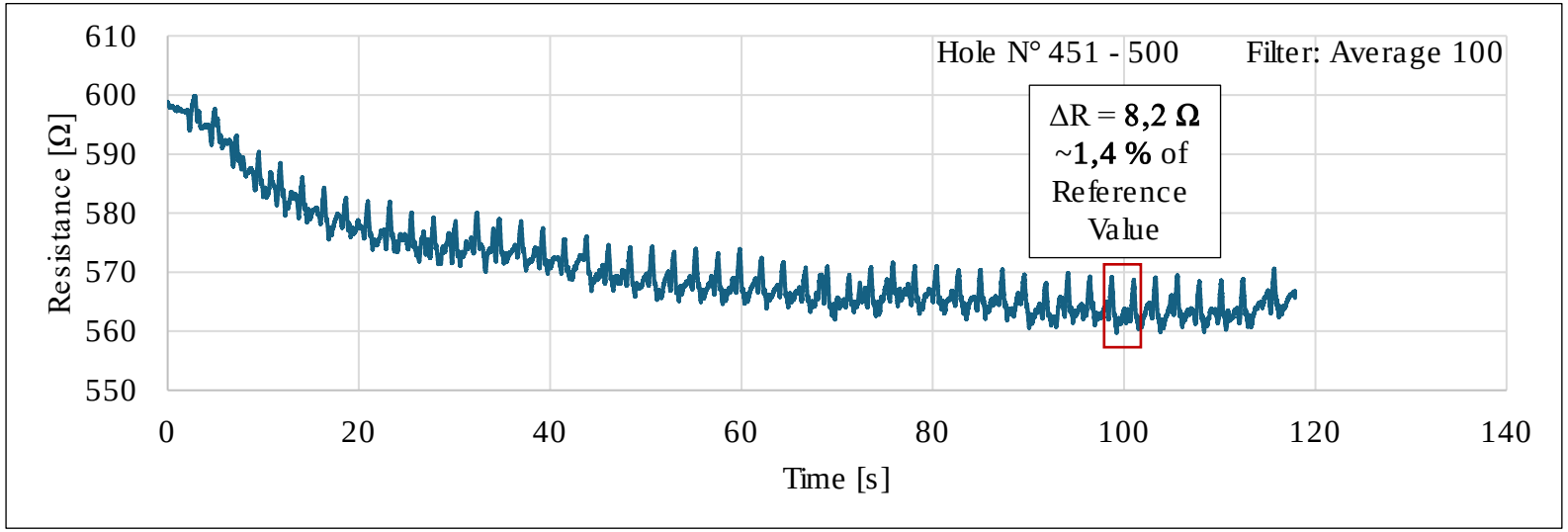


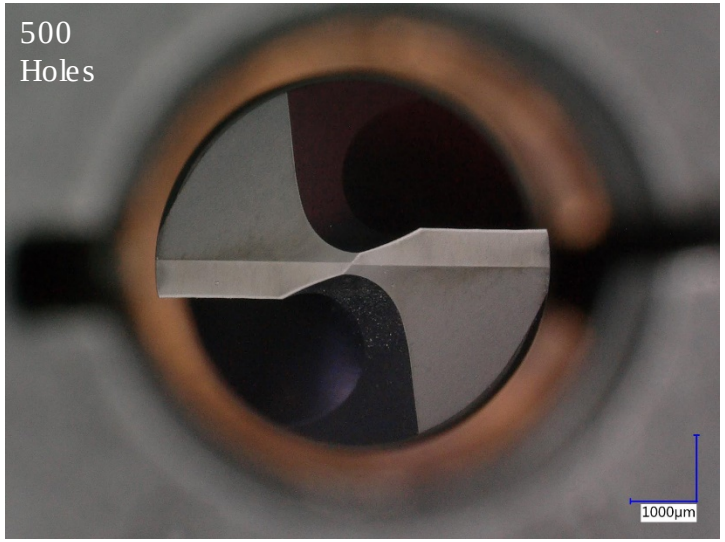
$\Delta R = 4{,}5\ \Omega$
~0,7 % of Reference Value

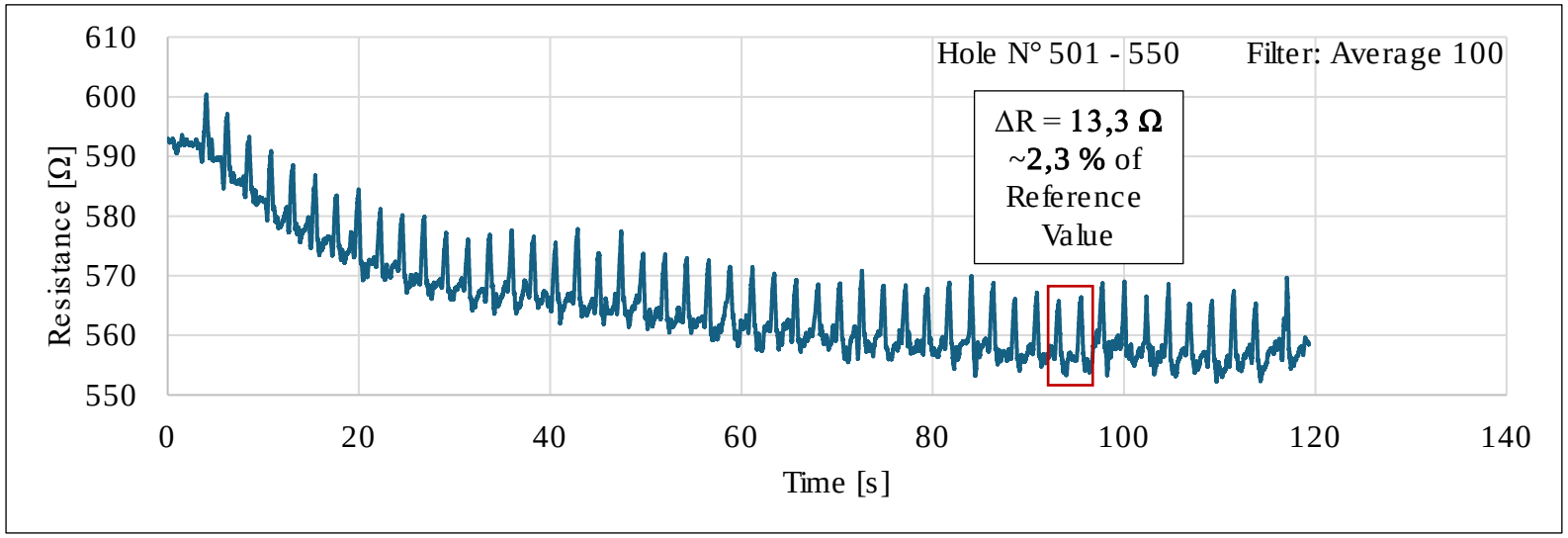
Start of Drilling Operation

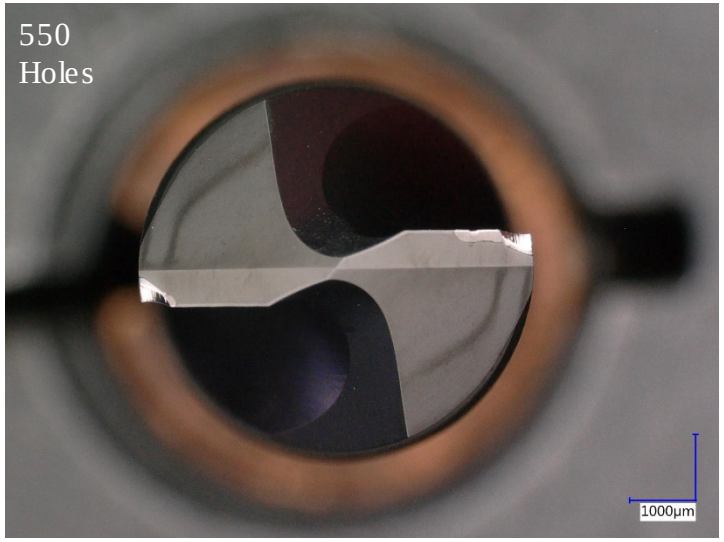
End of Drilling Operation

Progress of Resistance Variation during Tool Life

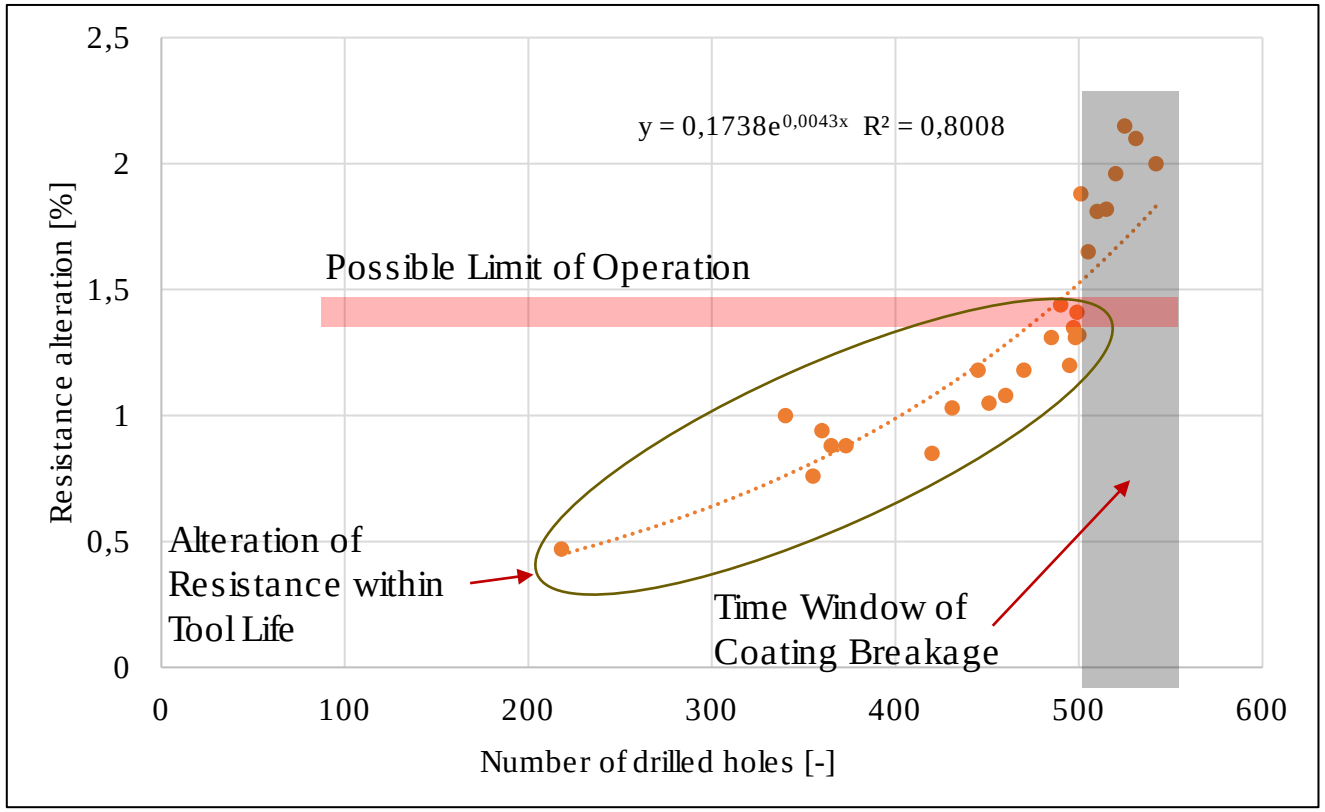






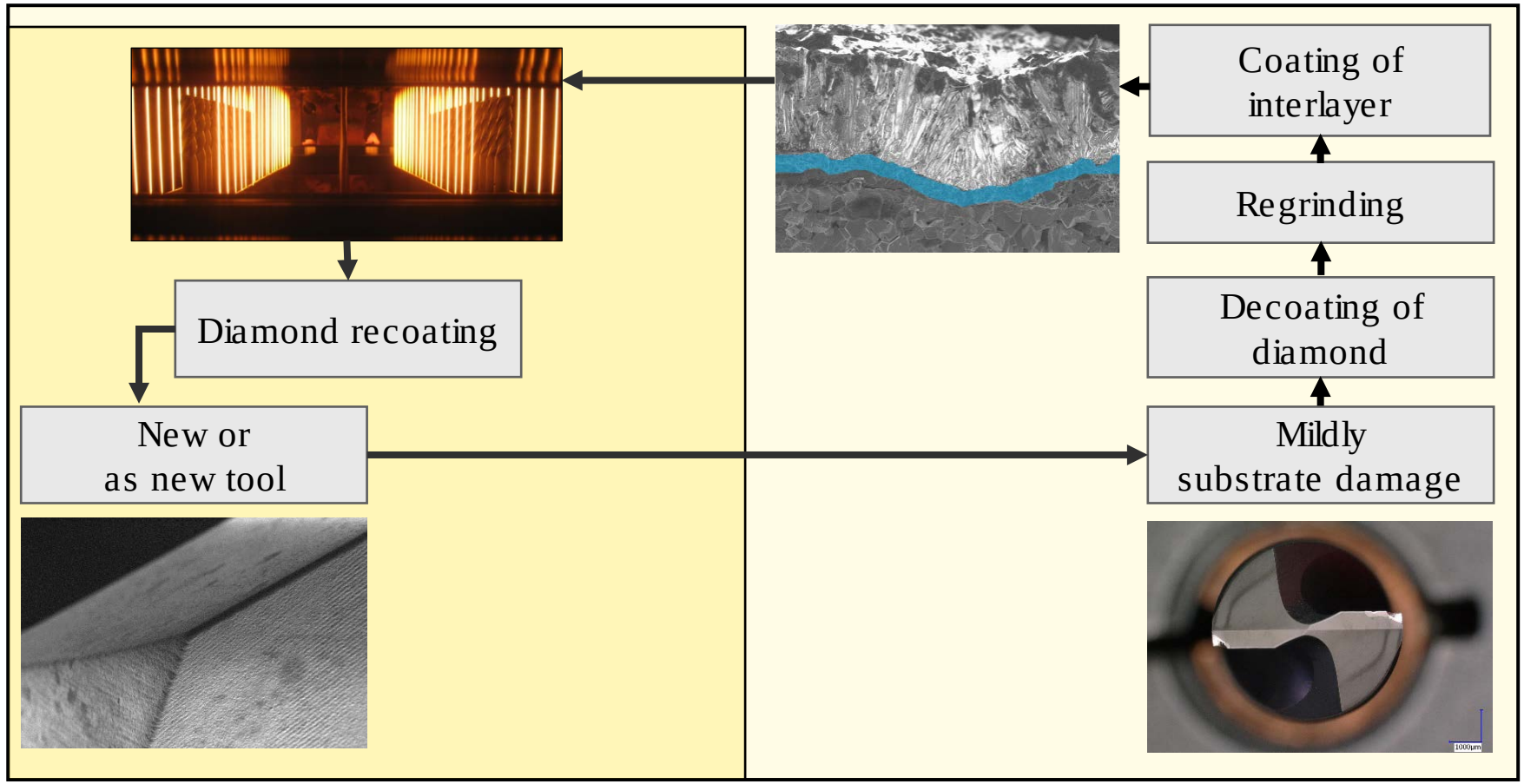


Resistance Alteration over Tool Life



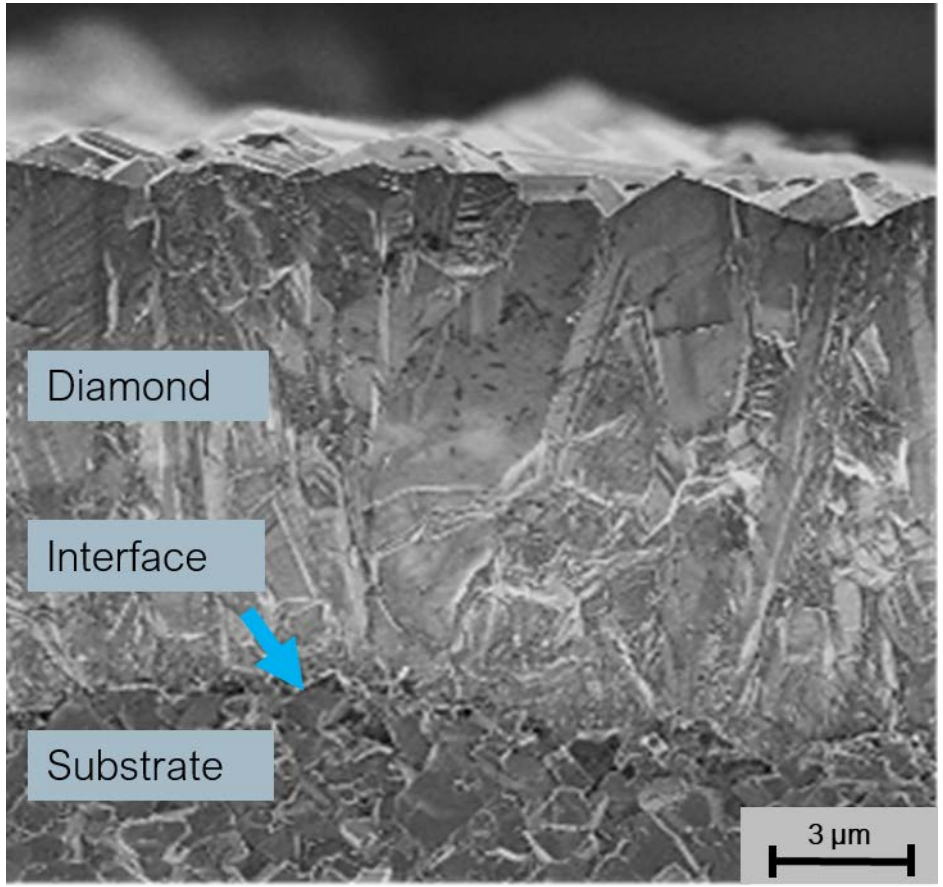
- Electrical resistance increases approximately exponentially with the number of drilling cycles.
- A clear coating failure point is not identifiable, but a strong increase after ~500 cycles may indicate failure.
- Process interruptions caused only minor variations.
- Comparable effects across different tools confirm the reproducibility of the observed behavior.

- Similar signal characteristics were observed in AlSi17Cu4, suggesting the trends are linked to both the application profile and the measurement system.



Method 2:

Designed Interfaces to enable Circularity



Microcrystalline diamond film on a substrate

Main objectives concerning a strong adhesion of CVD-diamond films on cemented carbide (WC-Co):

- Create a diffusion barrier against the harmful catalytic effect of cobalt while diamond film growth
- Enhance adhesion and enable highest wear resistance

Pre-Treatment of the near surface region!

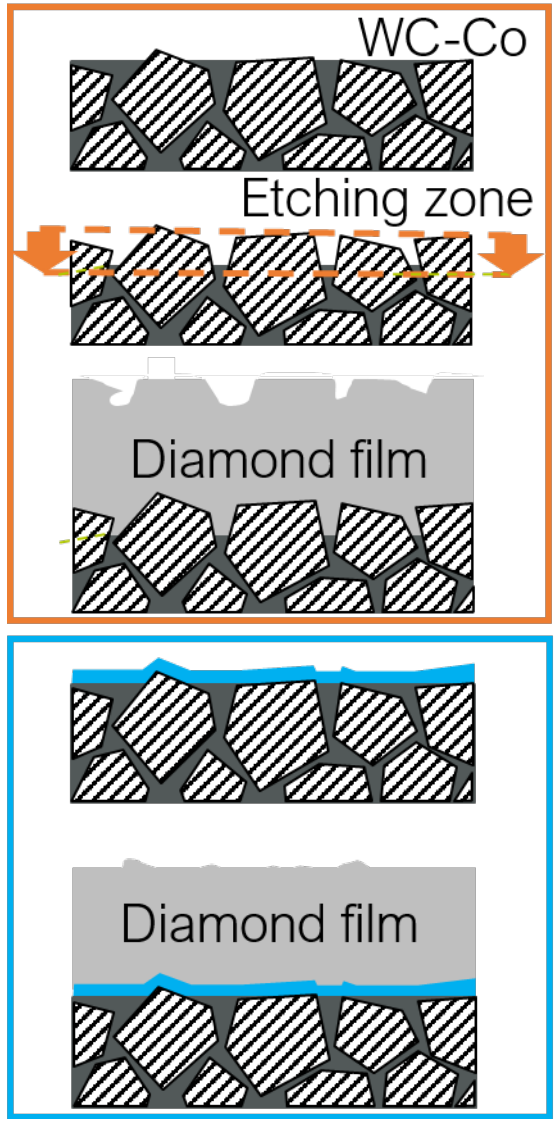
Pre-Treatment Methods

Standard method: Etching treatment of the near surface region

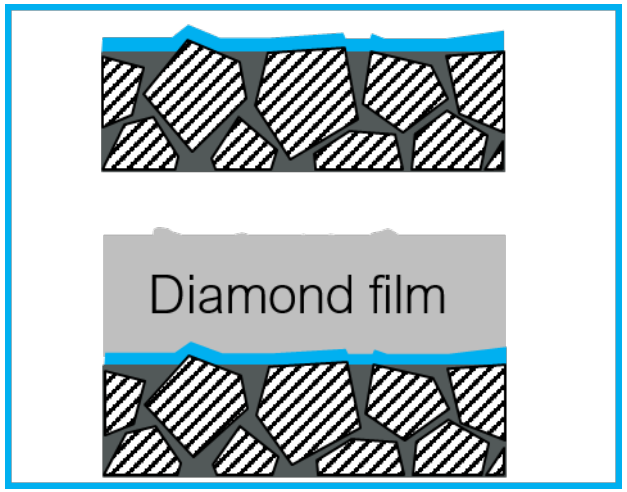
- Reduction of the cobalt binder in the near surface region
- Best results for WC-Co with binder contents around 6 wt%

Research and Development: Interlayers under the diamond film

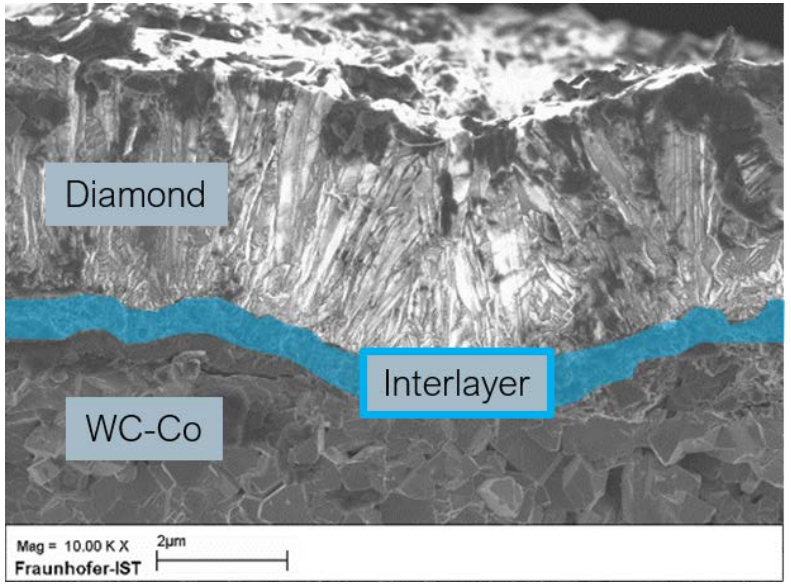
- Diffusion barrier against binder material
- High flexibility with regard to tool materials, for example with binder contents > 6 wt%
- Interlayers for example based on refractory metals, their carbides, nitrides or Si-based systems



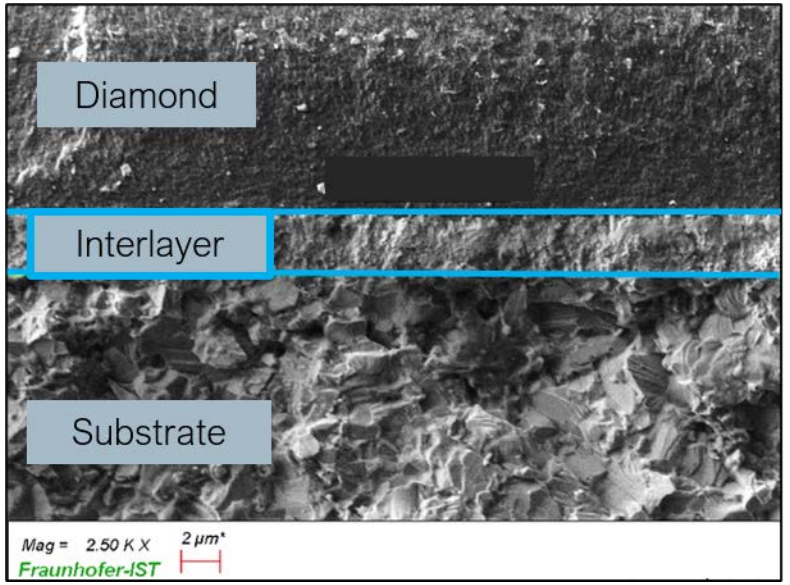
Research and development: Interlayers under the CVD-diamond film



Interlayer System, Shema



Interlayer System, Example 1



Interlayer System, Example 2

Aim:

- Replacing the chemically treated surface caused in etching pre-treatments and
- Enable restauration of coatable interfaces even after full wear by use of interlayers
- Enabling multiple recoating cycles

Research and development: Interlayers under the CVD-diamond film

Potential shown on more complex geometries:

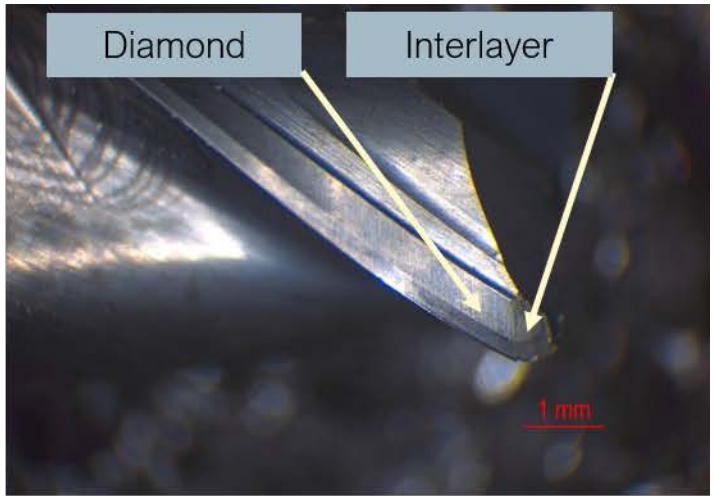
- Enable restauration of coatable interfaces even after full wear / delamination by use of interlayers
- Enabling multiple recoating cycles



Interlayer



Interlayer and CVD-diamond



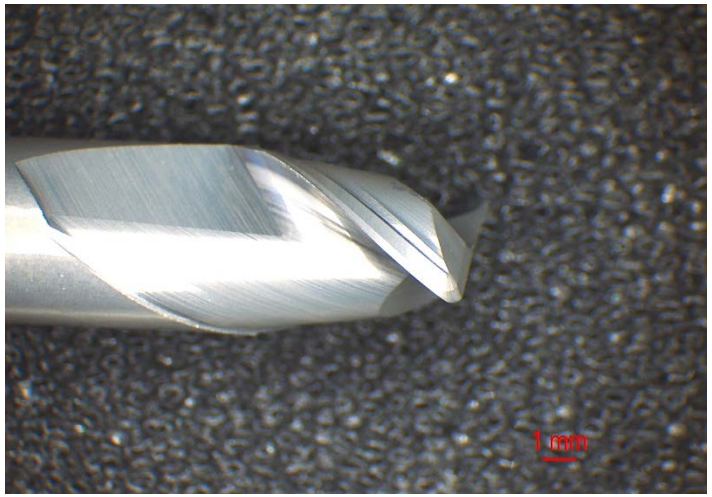
Worn / delaminated CVD-diamond, no intact interlayer

Decoating and recoating

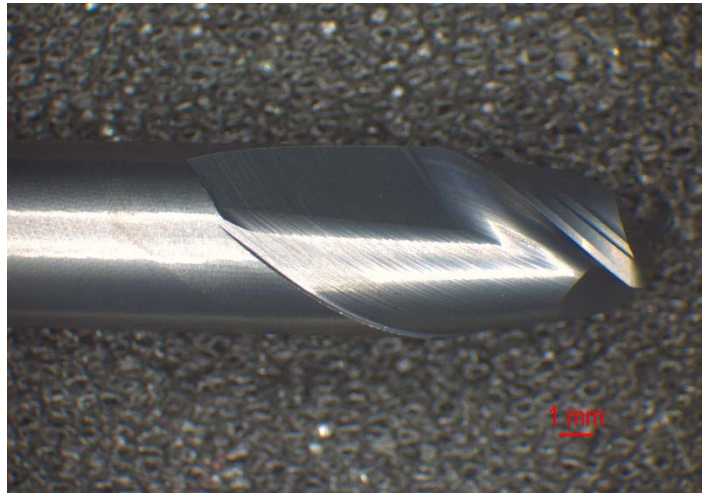
Research and development: Interlayers under the CVD-diamond film

Potential shown on more complex geometries:

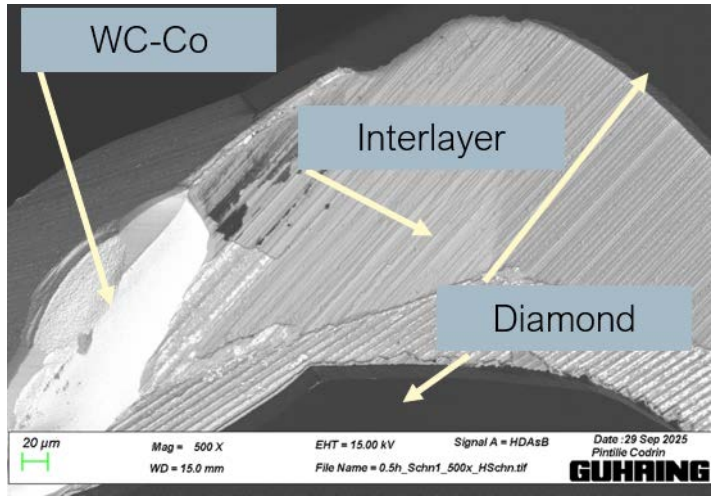
- Enable restauration of coatable interfaces even after full wear / delamination by use of interlayers
- Enabling multiple recoating cycles



Interlayer



Interlayer and CVD-diamond



Worn / delaminated CVD-diamond, no intact interlayer

Decoating and recoating

- ✓ **Diamond-coated WC-Co** cutting tools are commonly employed in **highly demanding cutting operations**
- ✓ To overcome their single-use status, an **enabling of circularity** is absolutely necessary, especially with regard to economic and social responsibilities concerning the use of Cobalt and Tungsten
- ✓ In this presentation, **two approaches of reconditioning diamond-coated cutting tools** were discussed:
  - ➢ Usage of modified CVD diamond-coatings as a sensor system and
  - ➢ Usage of interlayers underneath the diamond-coating as a barrier
- ✓ As shown there still exist **further questions** of research and development:
  - ➢ System complexity
  - ➢ Stability and reproducibility
  - ➢ Tool life and performance of reconditioned tools
  - ➢ Impact on social, ecological, and economic dependencies

- One part of the results was obtained within the scope of the joint research initiative "**DiTect**: Nanocrystalline diamond as a sensor layer for the detection of wear of coated, reusable cemented carbide cutting tools", funded by the German Federal Ministry of Education and Research.

  Funding code: 03XP0192

- Another part of the results was obtained within the framework of the collaborative research project "**FreeTools**: Substitution of the critical raw material cobalt in cemented carbide tools and improvement of resource efficiency through novel strategies for reconditioning and restoration", funded by the German Federal Ministry for Economic Affairs and Climate Action due to a resolution of the German Bundestag.

  Funding code: 03EI5031

SPONSORED BY THE
Federal Ministry of Education and Research

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

Thank you for your Attention
Questions?

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Universität Stuttgart



Increasing Sustainability and Resource Efficiency of Power Electronics Through Condition Monitoring and Predictive Control

Ingmar Kallfass, Diego Kuderna-Melgar, Valentyna Afanasenko, Dominik Koch

University of Stuttgart

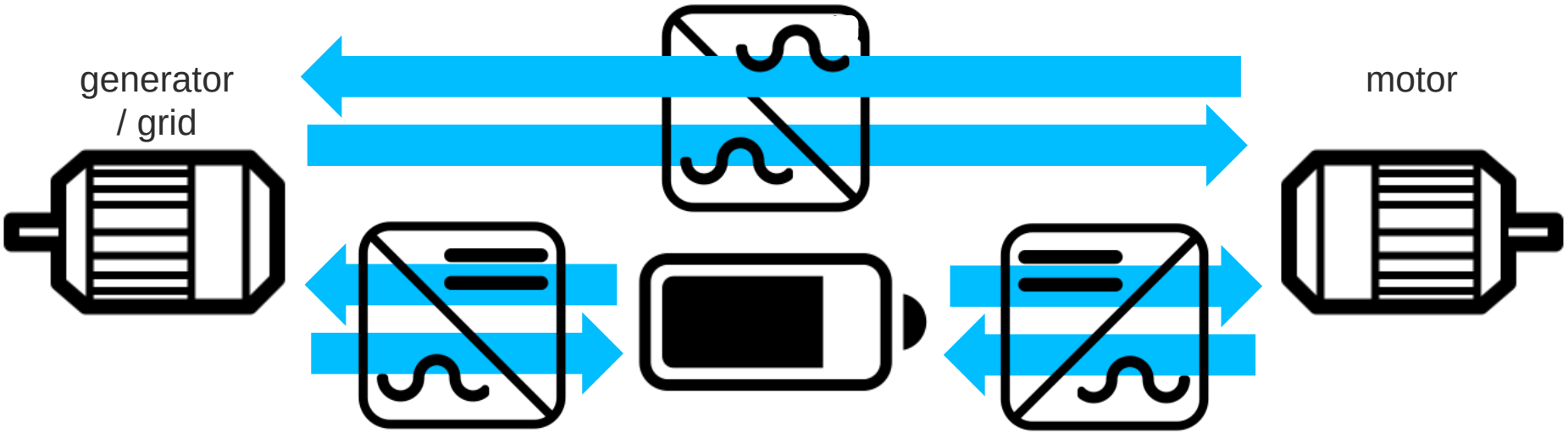
Conference on Circular Production Systems and Technologies 2026

University of Stuttgart
Germany

Institute of Robust Power Semiconductor Systems

Institut für Robuste Leistungshalbleitersysteme

Power Electronics as Key Functional Building Block of Electrified Systems

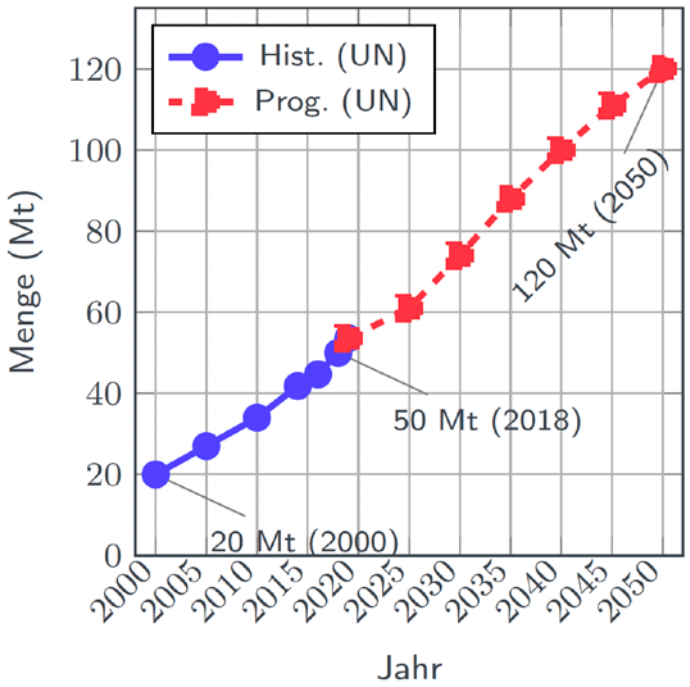


Requirements for the power-electronic sub-system



- ✓ Cost and energy-efficient
- ✓ Safe and reliable
- ✓ Low weight and volume
- ✓ Sustainable and ressource-efficient

Global Electronic Waste



Global Electronic Waste

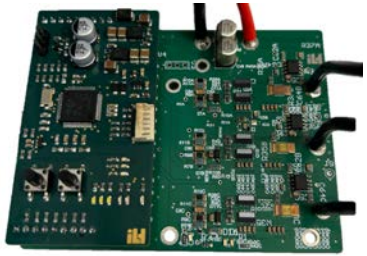
- 2021: 52 Mio. t
- 2030: 74 Mio. t
- 2050: 120 Mio. t
- Recycling: < 20%
- Material value 2019: 55 Mrd. EUR

New Requirements for (Power)Electronics

- Circular economy compatible design
- Minimization of critical raw materials
- Repairability, modularity, recyclability
- Life-cycle carbon footprint as design criterion

Sustainability in Power Electronics

CO_2 Reduction through Design for Sustainability, Condition Monitoring, Remaining Useful Lifetime Estimation and Predictive Control



- ✓ WBG materials (GaN, SiC) material and energy savings
- ✓ Modularity
- ✓ In-Circuit-Test

Design

- ✓ State-of-health monitoring (SoH)
- ✓ Remaining-useful-lifetime prediction (RuL)
- ✓ Predictive maintenance
- ✓ Predictive control

Operational Lifetime

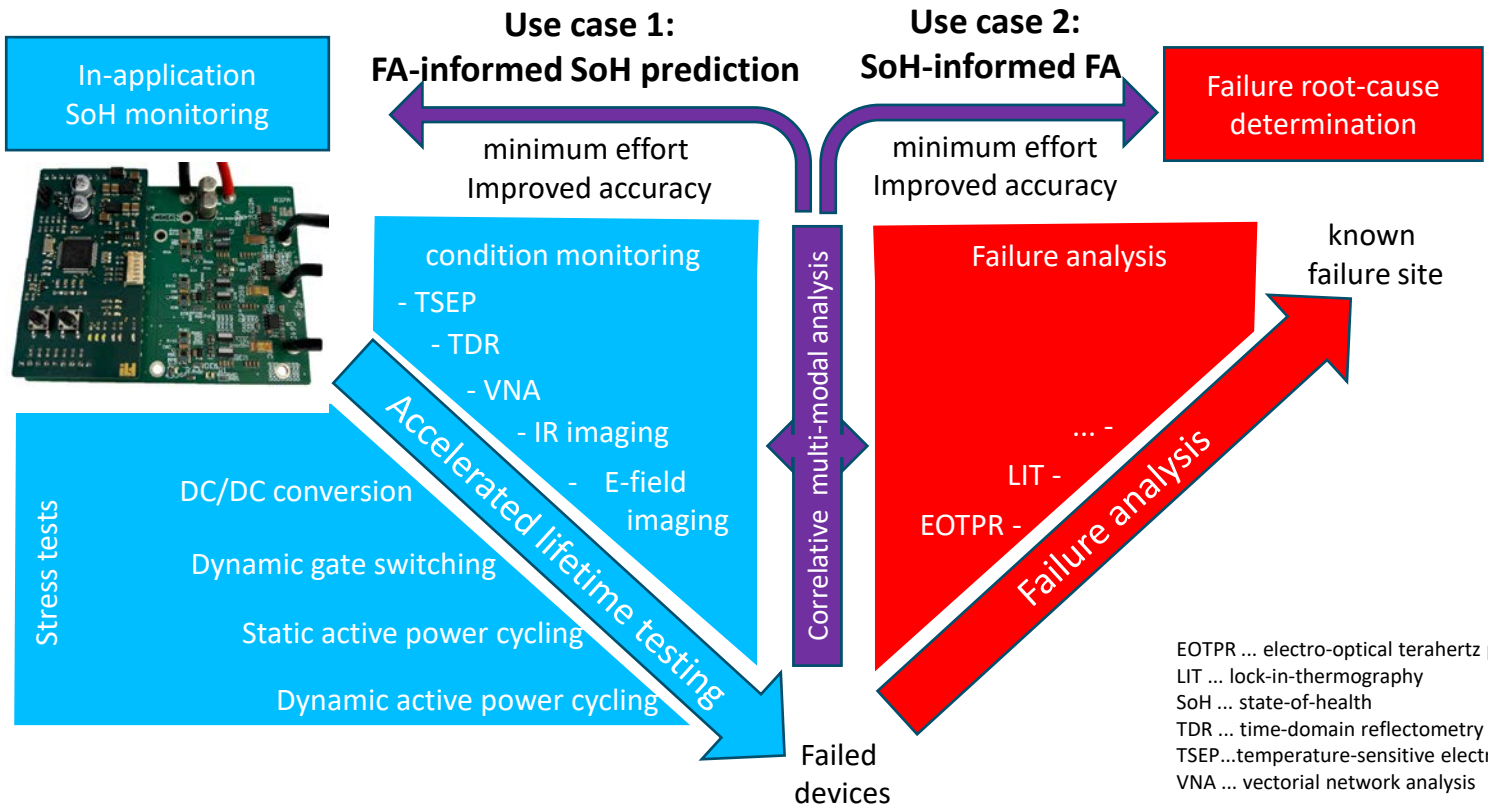
Accelerated Lifetime Testing

- ✓ Condition monitoring
- ✓ Root cause failure analysis (FA)

End-of-Life(?)

- ✓ Correlative FA
- ✓ Repair
- ✓ Refit
- ✓ Second Life

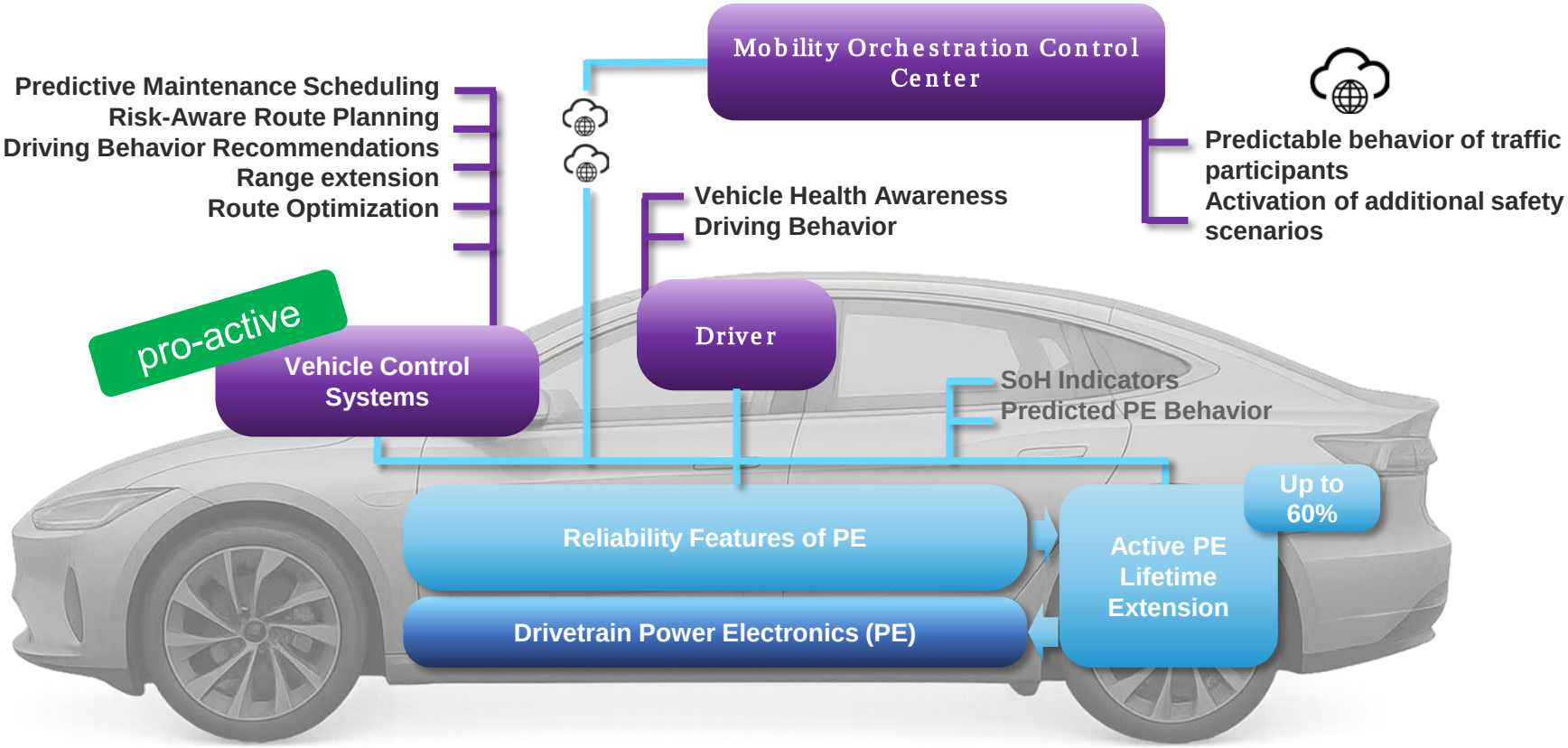
Correlative Failure Analysis: Use Cases



EOTPR ... electro-optical terahertz pulse reflectometry
LIT ... lock-in-thermography
SoH ... state-of-health
TDR ... time-domain reflectometry
TSEP...temperature-sensitive electrical parameter
VNA ... vectorial network analysis

Intelligent, Proactive Control of a Drive-Train Inverter

autotech. agil



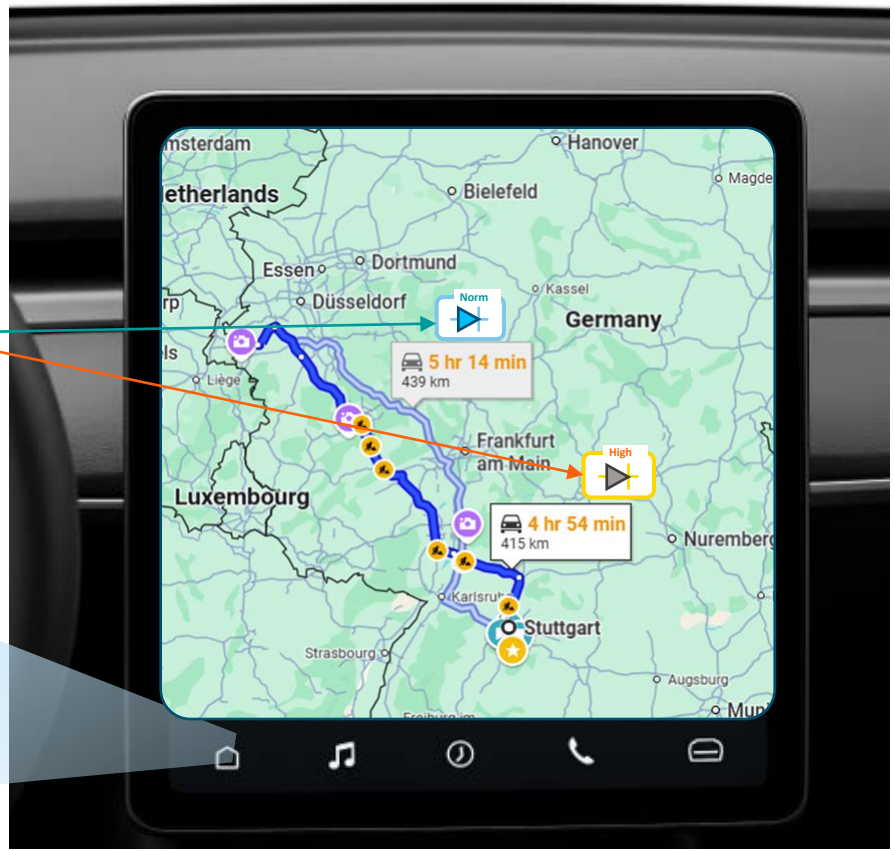
Route Planning with Health Indicators of Power Electronics

Application Example

Power Electronics Aging Factor for Enhanced Routing Decisions

Route Planning Menu

- Shortest route
- Scenic route
- E-REX ZF
- Efficient profile
- **Sustainable profile**
- Customized profile



Predictive Control for Lifetime Extension of Power Electronics

Application Example

Prediction of road conditions, converted into **electrical parameters** of the inverter



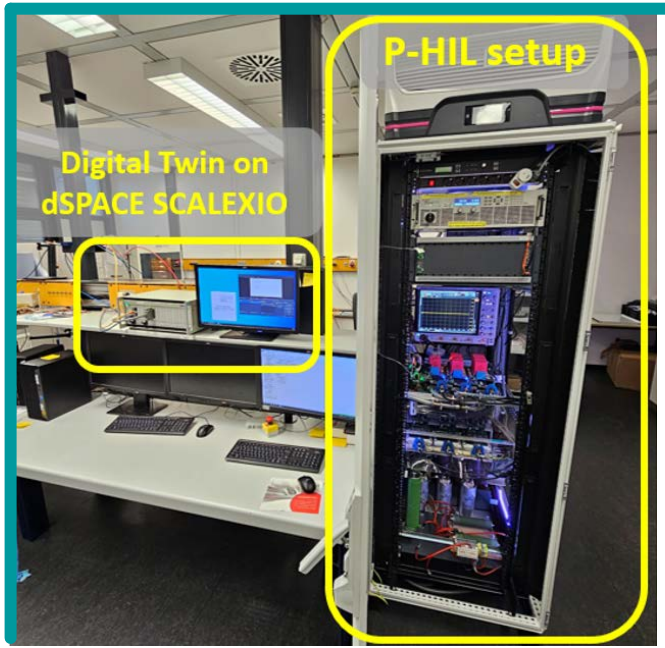
Digital twin of power electronics, predicting **junction temperature** profile of SiC MOSFET for 100 sec ahead

Smoothing algorithm calculating the optimal junction temperature profile of SiC MOSFET based on predictions to **extend the lifetime** of SiC MOSFETs

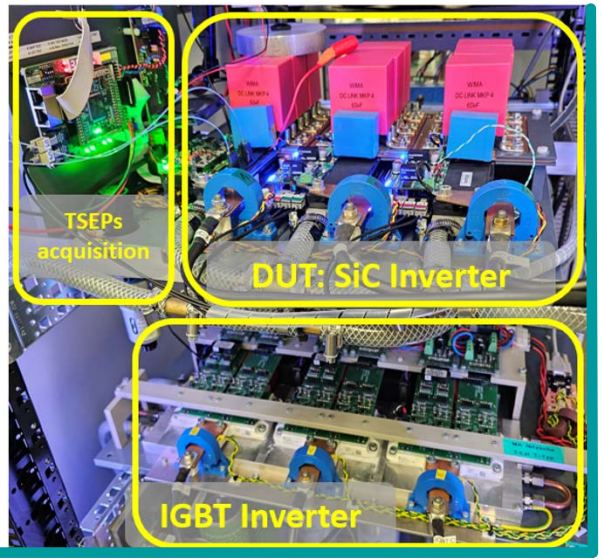
Loss controller managing losses in the inverter's SiC MOSFETs to implement the **optimal junction temperature** profile

The described predictive control operates directly at the driver level of the inverter's SiC MOSFETs and does not interfere with the main powertrain control

Features of Power-HIL Setup



- Providing inverter operating modes as in a vehicle powertrain
- Obtaining online Tj and TSEPs measurements for reliability studies
- Digital Twin Verification

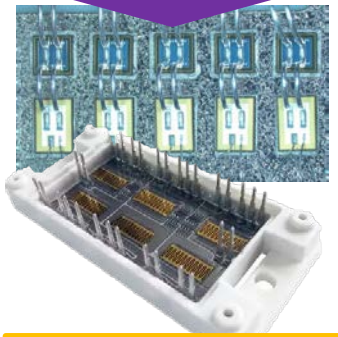


- Two back-to-back connected inverters:
- 50 kW SiC Inverter (DUT)
- 50 kW IGBT Inverter

Condition Monitoring of Power Semiconductor Devices and Modules

Motivation for Machine Learning

control & drivers



sensing & readout electronics

- Temperature sensor
- R_{th}
- TSEPs
  - R_{on}
  - V_{sd}
  - $V_{th,\ on/off}$
  - $t_{on/off}$
  - $I_{g,peak}$

parameter acquisition & data processing

- Degradation
- Temperature estimation
- Combined TSEPs sensor fusion

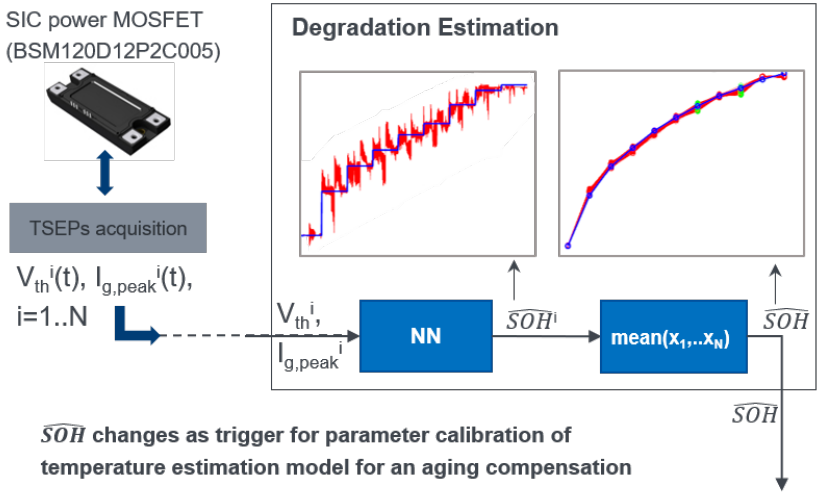
TSEPs carry information on temperature and degradation

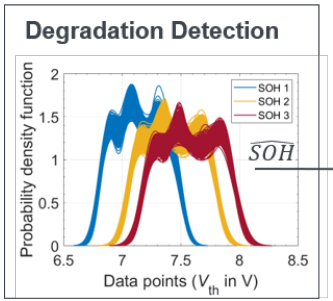
- are correlated
- have multiple dependencies (current, voltage, temperature)
- are degradation sensitive (DSEP)
- require frequent calibration

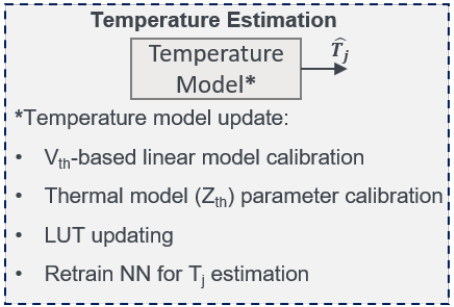
ML and AI

- can use raw or filtered data
- can make use of data augmentation
- can increase linearity, robustness, fidelity, ...
- can distinguish TSEP from DSEP

State-of-Health Estimation of Power Electronics





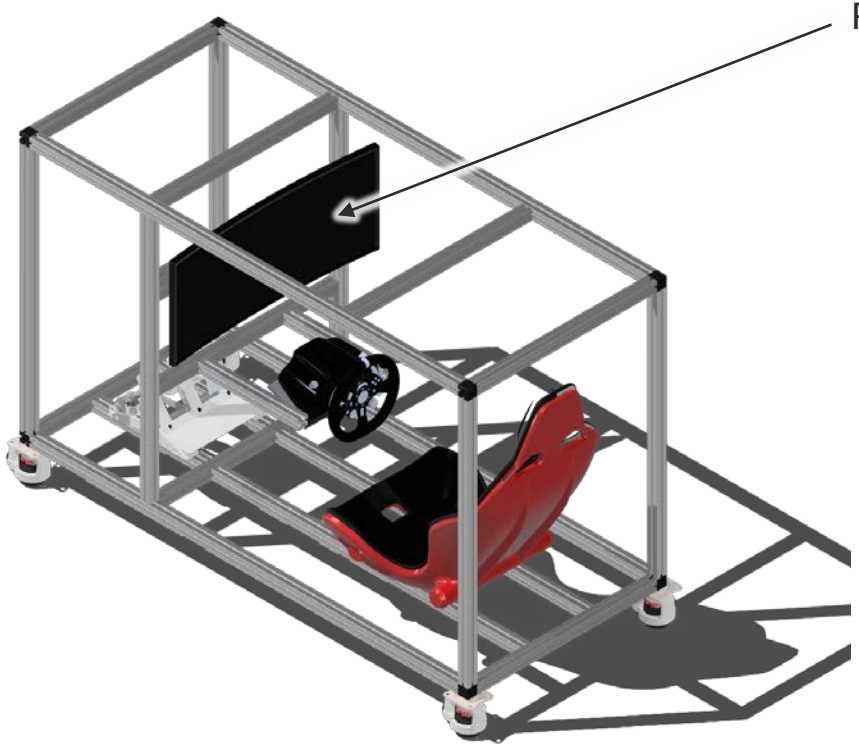


Determination of the State of the Health

- **Chip-level** degradation estimation based on a combination of the TSEPs sensor data
- Input: Measured TSEPs/DSEPs V_{th} and $I_{G,Peak}$
- Neural network for implementing a failure precursor-based estimation model → MAPE of 10.96±0.89%
- **Package-level** degradation state determination of a power module based on the junction temperature T_j
- Input: Temperature T_j
- Failure mechanism-based estimation model for PE bond wires (lifetime model)

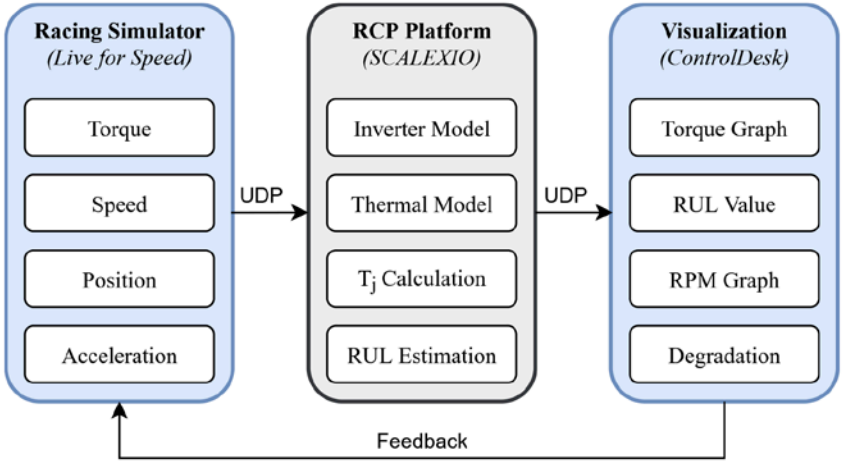
Coupled Real Time Driving Simulator

Online Connections



Real-time online connection to:

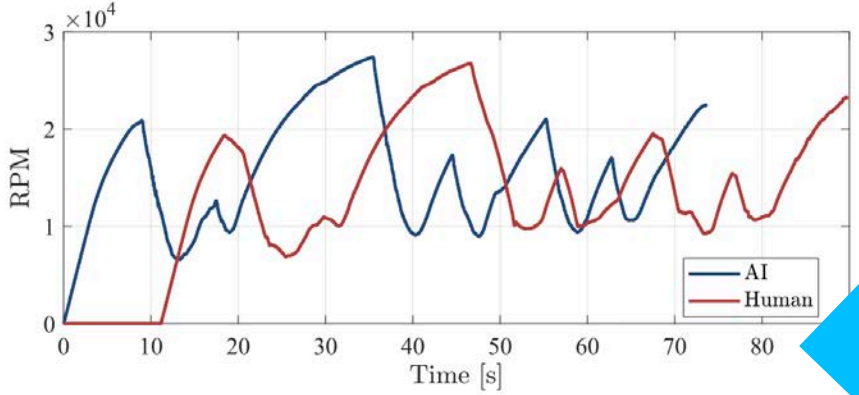
- Digital Twin
- 3-Phase Back to Back Converter



UDP ... User Datagram Protocol

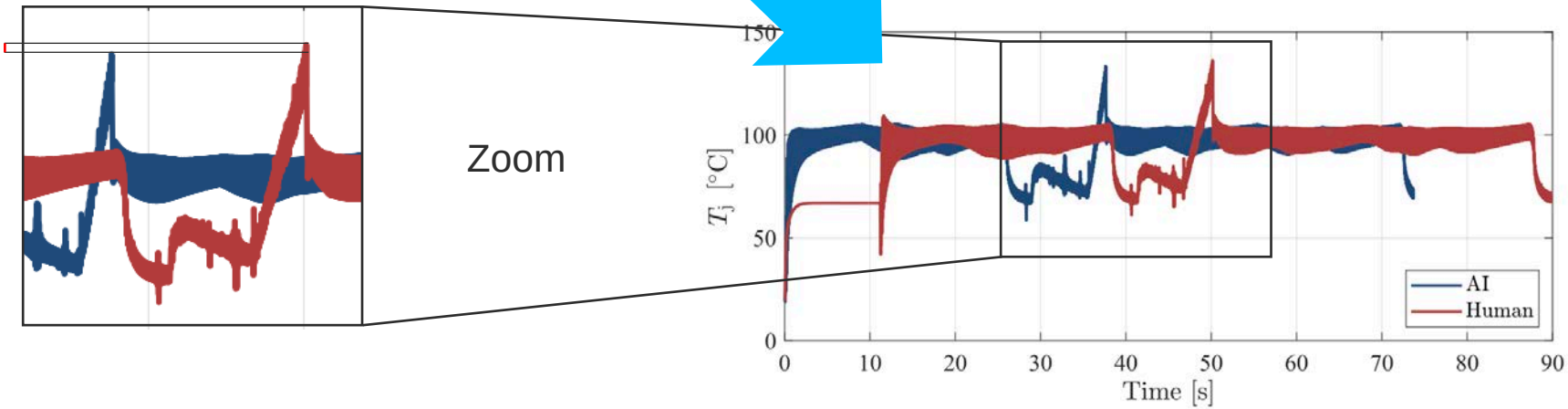
Coupled Real Time Driving Simulator

Temperature Profile



Driving Cycle translated into Junction Temperature

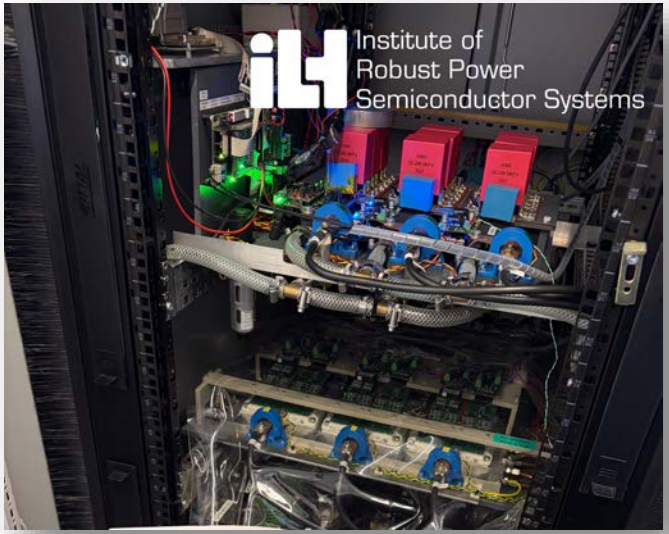
Less ΔT

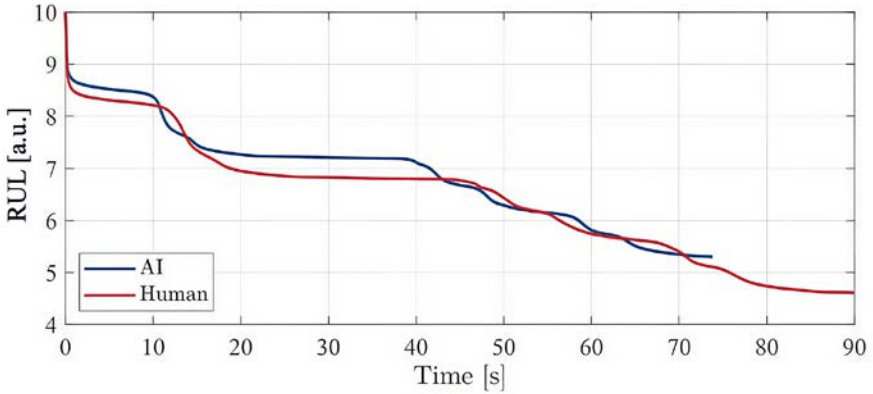


Coupled Real Time Driving Simulator

3 Phase Inverter

- Back to Back Inverter
- Motor Emulation





- Contiunous remaining useful lifetime (RuL) computation
- Different drive cycles → different degradation
- Applications: optimal route planning, lifetime-oriented predictive control

Conclusion

- Power electronics are a vital and integral component of every electrified system.
- Sustainability use case: Inline state-of-health monitoring of 50 kW three-phase inverter for remaining useful lifetime prediction and the intelligent predictive control
- Combination of data and model-based condition monitoring can be employed for increasing sustainability, resource efficiency and repairability of power electronic sub-systems.
- Inline condition monitoring of the most vulnerable components of power electronics not only opens up a pathway towards repairability and re-fitting, but also provides a key to the degradation-aware co-design of power electronics as part of a circular economy.

University of Stuttgart
Institute of Robust Power Semiconductor Systems

Thank You!



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CCPT
Conference on Circular Production Systems and Technologies
9th & 10th June 2026

At the frontier of product and production system: a perspective of crossovers between product reuse and reconfigurable manufacturing in the context of circular economy

Dr. Paul Stief, Dr.habil. Lazhar Homri

Arts et Metiers Institute of Technology, Université de Lorraine,
LCFC, 4 Rue Augustin Fresnel, Metz F- 57070, France

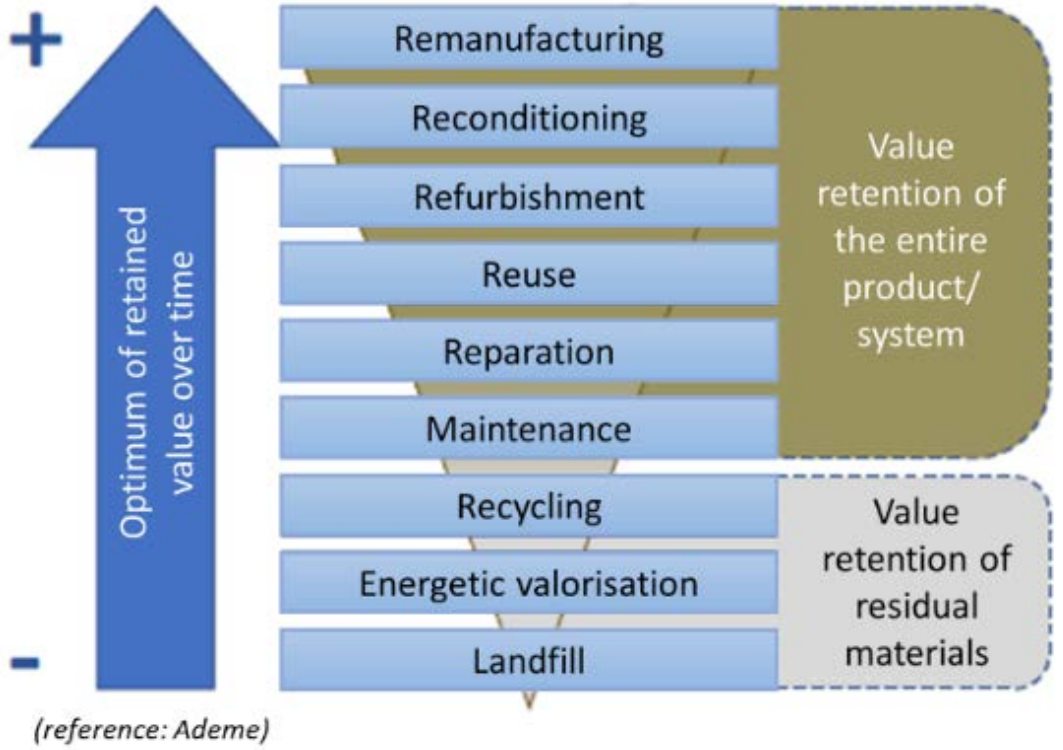
Context and Motivation

Circular strategies such as reuse, refurbishment and remanufacturing are no longer only sustainability questions, they are becoming strategic industrial capabilities

Timeline

- Industry 5.0: towards a sustainable, human centric and resilient European industry (perspective) – 2021
- Industry 5.0, a transformative vision for Europe: governing systemic transformations towards a sustainable industry (perspective) – 2022
- Framework for ensuring a secure and sustainable supply of critical raw materials (directive) – Avril, 2024
- Ecodesign requirements for sustainable products (directive) – Juin, 2024
- …





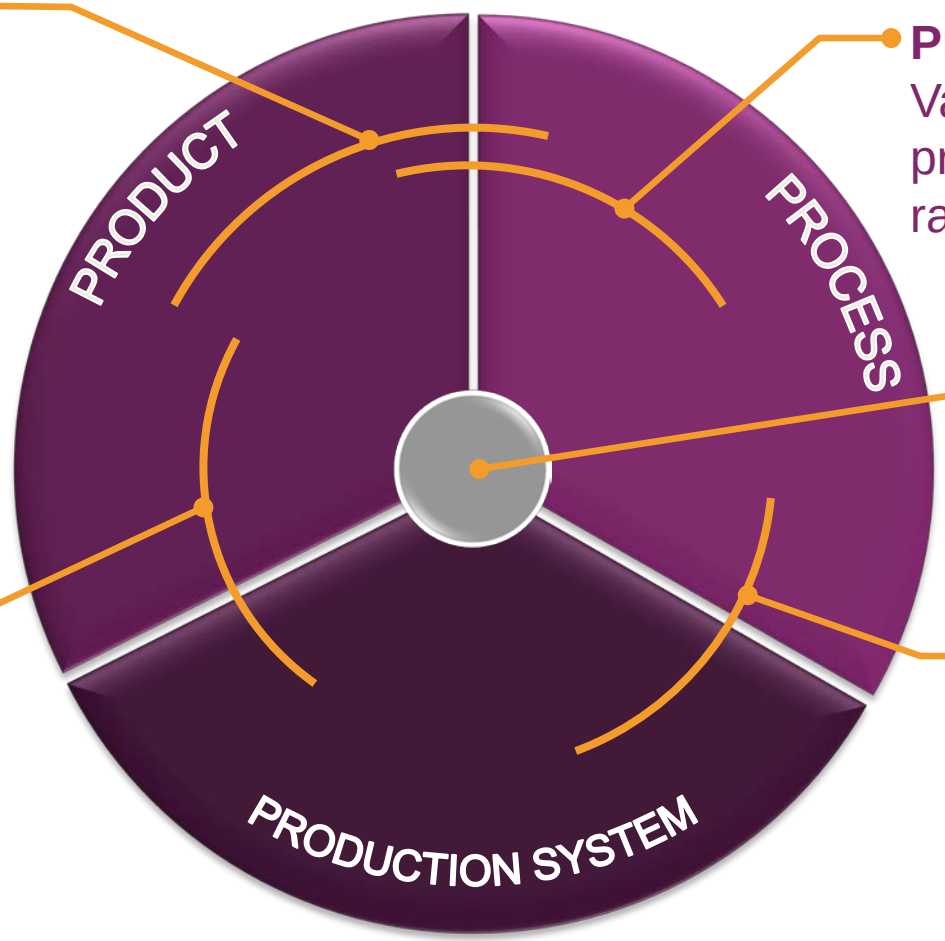
(reference: Ademe)

The Product-Process-Production System (PPPS) View

Circularity generates variability

Analysis and condition assessment
Determination of the most adapted R-Strategy and following processing steps

Process variety
Variability of cores and needed process steps induce a wide range of being kept available



CHALLENGE
Circularity of products: application of R-Strategies

Product variety and lot sizes
Ability of the production system to cope efficiently with various references in small lot sizes

Production planning and sequencing
Insertion of process variety into the production plan considering equipment and change-over times

Research Challenges in Current Literature

Existing research is fragmented

Current limitations:

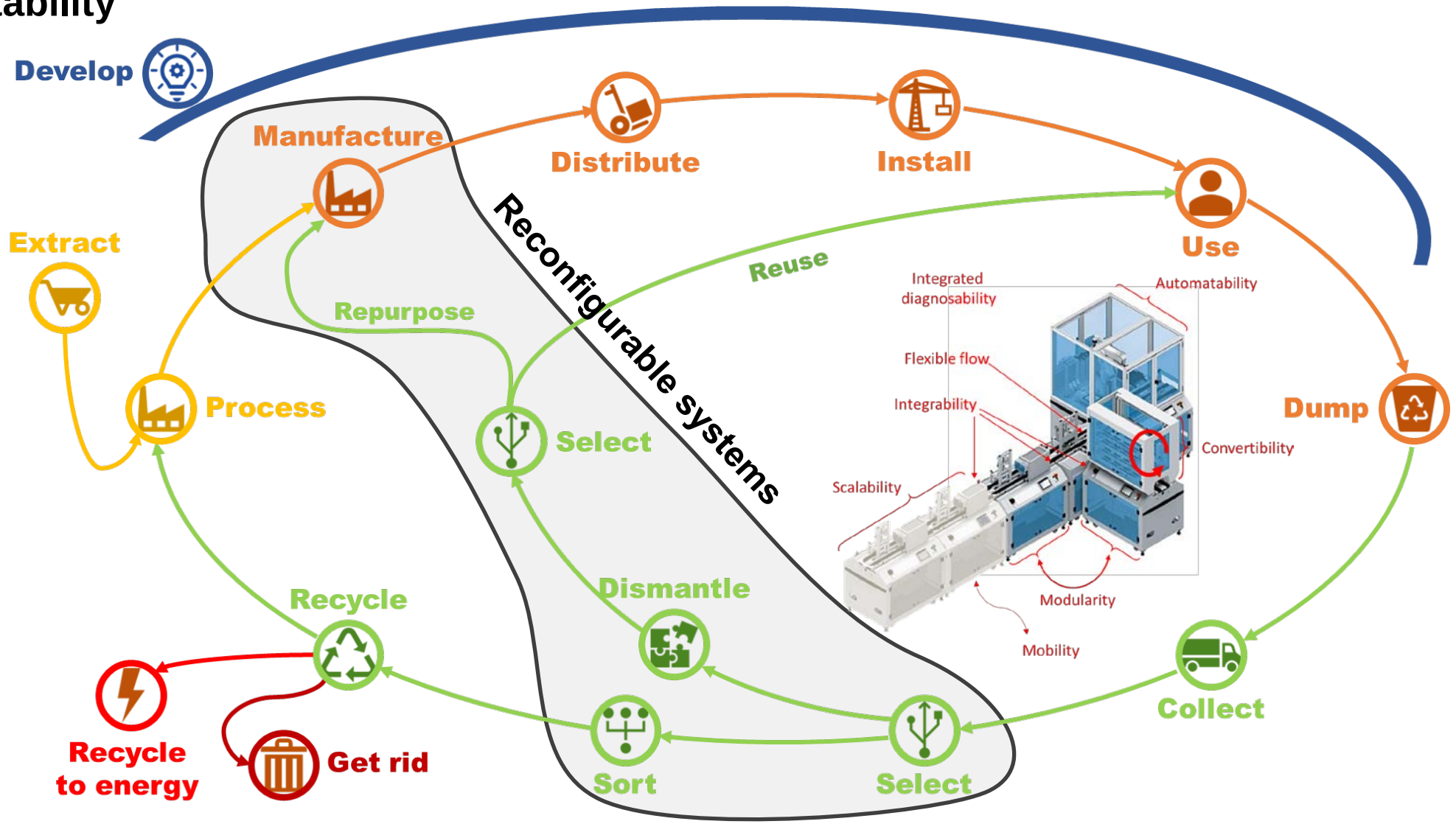
- Pairing decisions rarely consider RMS constraints
- Process planning remains weakly connected to component variability
- Production system design lacks detailed product-state information

Product	Process	Production System
Pairing	Process planning	RMS design
Tolerancing	Variety management	Reconfiguration
Condition assessment	Adaptive routing	Scalability

This fragmentation motivates the need for a unified PPPS framework linking product state assessment, pairing activities and RMS feasibility evaluation.

Reconfigurable Manufacturing System and Circularity

Circularity needs adaptable systems: RMS provide the technological foundation for that adaptability

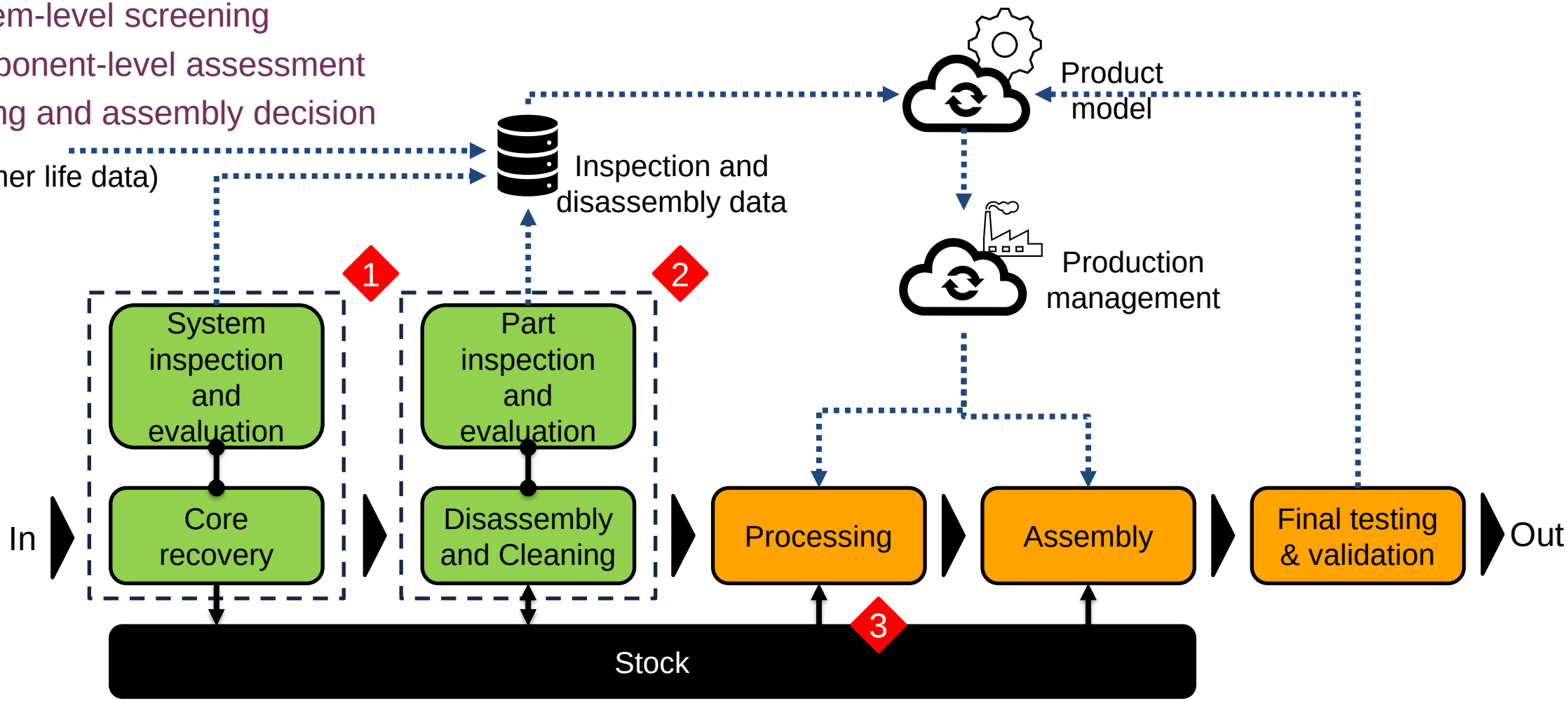


Proposed Framework

Decision-making progressively reduces uncertainty

3 major decision-making milestones:

- System-level screening
- Component-level assessment
- Pairing and assembly decision



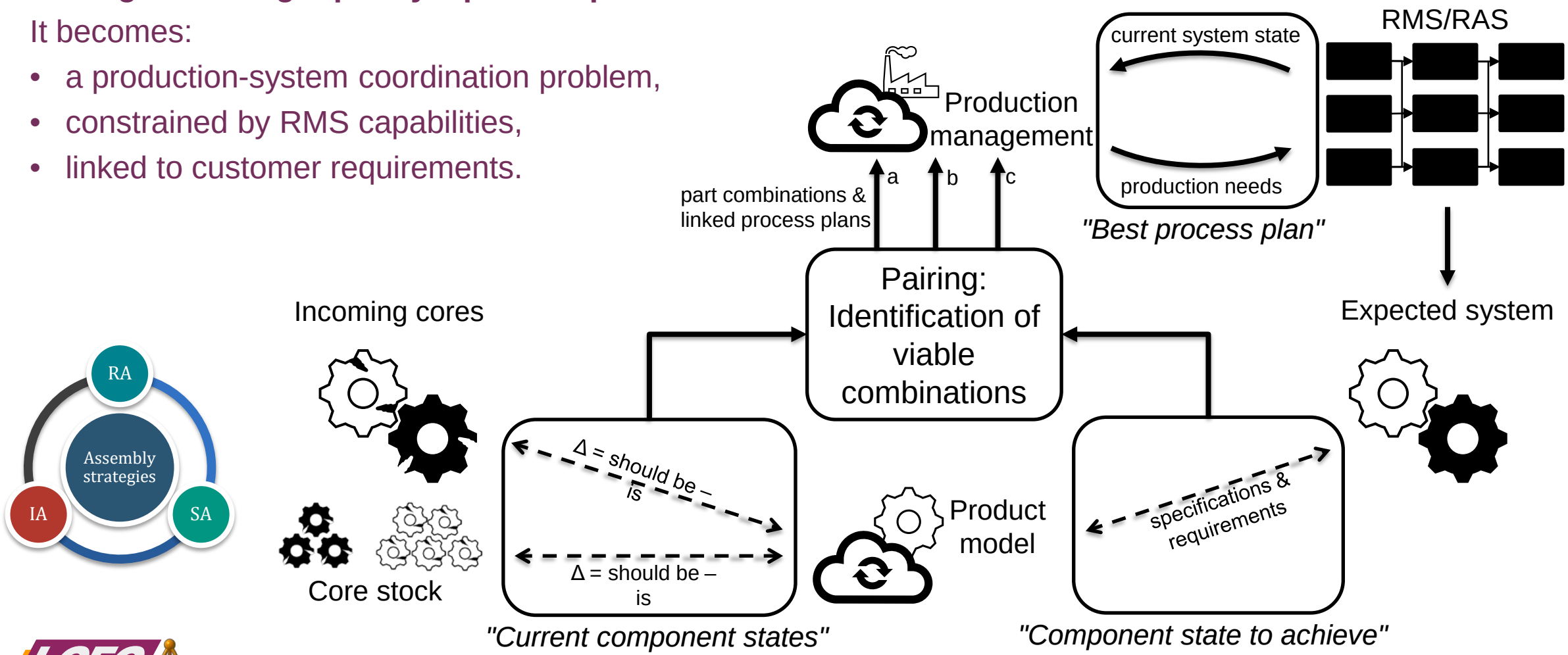
Proposed Framework

The optimal product pairing depends on the feasible production system configuration

Pairing is no longer purely a product problem.

It becomes:

- a production-system coordination problem,
- constrained by RMS capabilities,
- linked to customer requirements.



Outlook & Research Perspectives

Complexity needs development by research bricks

H2-TACTICS (LCFC/WBK) - Main research directions

- adaptive and dynamic tolerance allocation under manufacturing variability and simultaneous optimization of cost, quality and sustainability (energy and material consumption)
- integration of reuse/remanufacturing constraints for sustainability increasing
- pairing strategies based adaptive assembly for sustainable precision manufacturing.

The Franco-German GENIUS chair (Arts et Métiers - KIT) extends this vision at the full product lifecycle level through:

- advanced manufacturing, remanufacturing and recycling,
- optimization and reconfiguration of production systems,
- circular economy integration,
- Franco-German research and industrial transfer.

Conclusion

- Circularity creates coupled variability across products and systems
- RMS are key enablers for adaptive circular manufacturing
- Integrated PPPS decision-making is necessary
- Pairing evolves from a product-level optimization problem toward a system-level co-decision process

Circular manufacturing requires moving from isolated optimization toward systemic co-decision between products, processes, and production systems.

Thank you for your attention

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Université franco-allemande
Deutsch-Französische Hochschule

EUROMÉTROPOLE METZ

Moselle L'Eurodépartement

La Région Grand Est

H2-TACTICS:

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

anr agence nationale de la recherche



Any questions?

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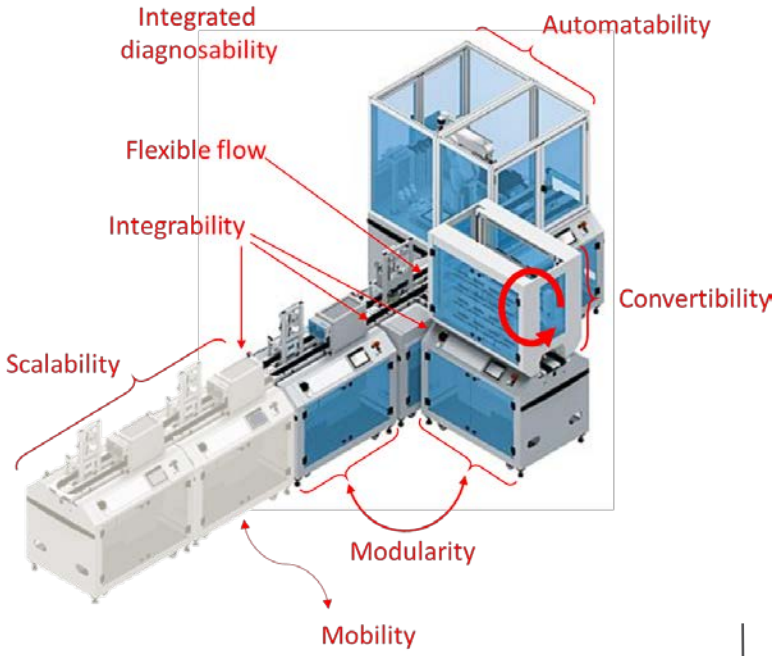
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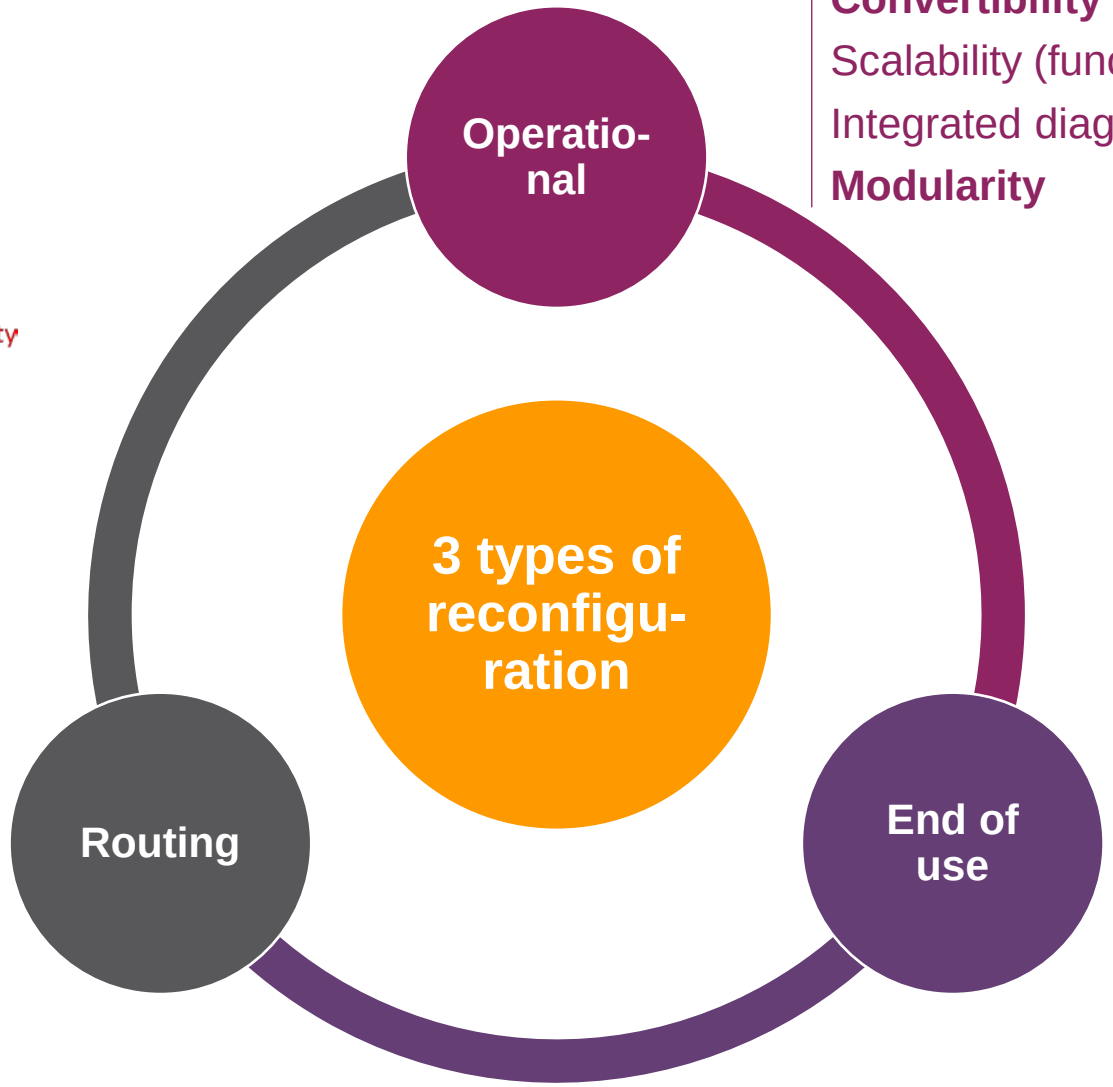
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Back-up

More details on RMS characteristics





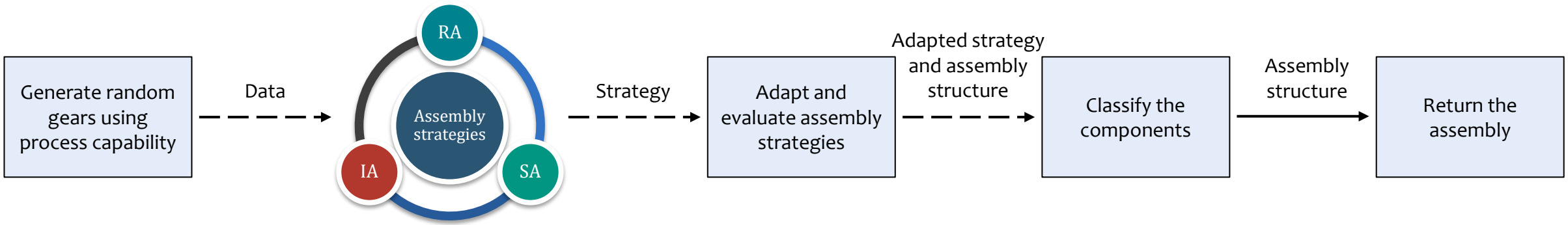
Convertibility
Scalability (functional)
Integrated diagnosability
Modularity

Flexible flow
Convertibility
Mobility
Integrated diagnosability
Modularity

Scalability (physical)
Automatability
Mobility
Convertibility
Integrability
Modularity

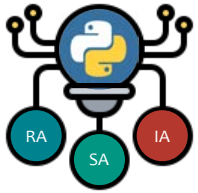
Adaptive assembly framework proposal

Question : What is the effect of incorporating adaptive assembly approaches on the enhancement of assembly quality within production?



RA = random assembly, IA = individual assembly, SA = selective assembly

Strategy selection and evaluation



A. ***Random pairing***

B. ***Individual pairing***

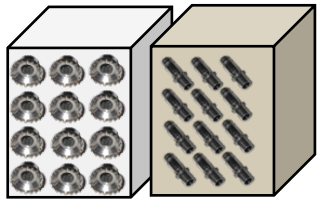
Global Optimum Quality Criteria (GOQC) algorithm - GOQC is an individual assembly scheme that evaluates all the combinations of the components and selects the pairs with the maximum quality level.

C. ***Selective pairing***

Batch selection - The batch selection divides the parts into several batches. Afterward, the batches will be paired concerning designer decision. The issue in this method is how should divide and on what bases ?

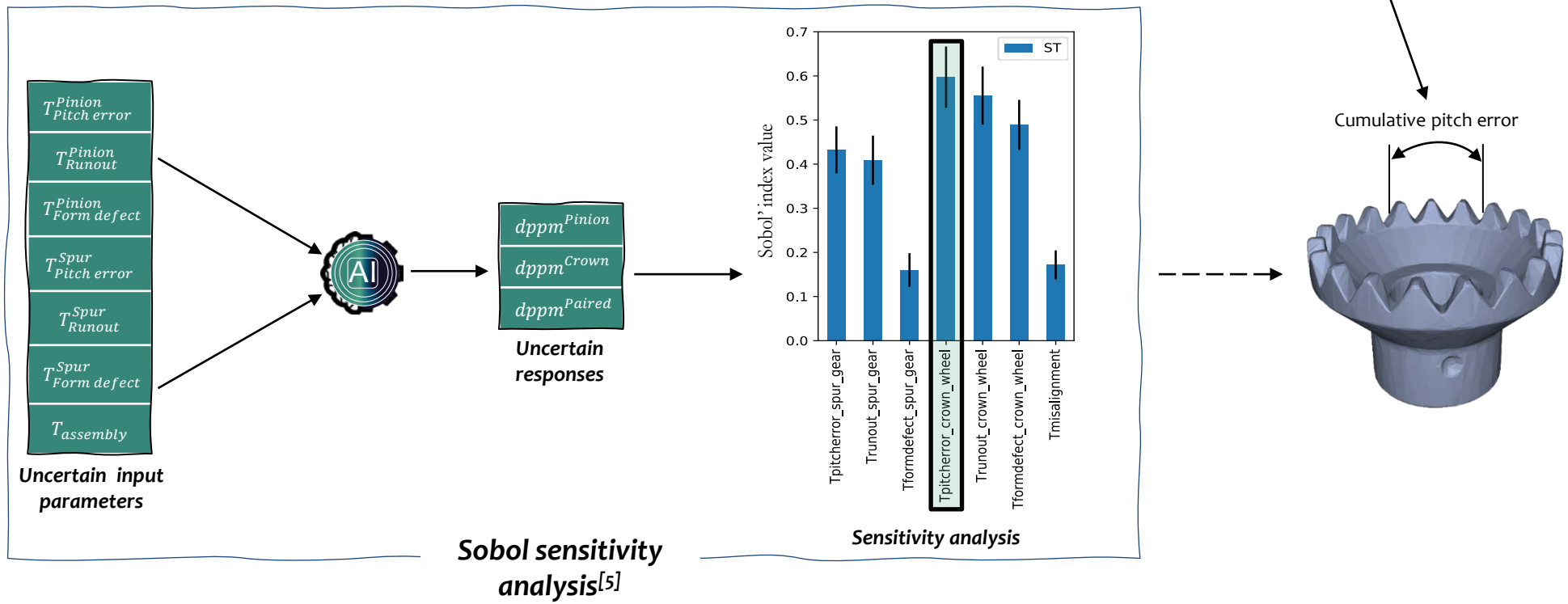
- Quality criterion mean maximization (QCMM) represents the **potential quality** of an assembly that targets **customer** satisfaction.
- Paired number maximization (PNM) illustrates **potential number of confirmed pairs which** the manufacturer's expectation of the production plan.
- Quality criterion inertia minimization (QCIM) measures spread around the mean value.
- MS1: Customer – manufacturer satisfaction
- MS2: Manufacturer – customer satisfaction

Selective assembly description



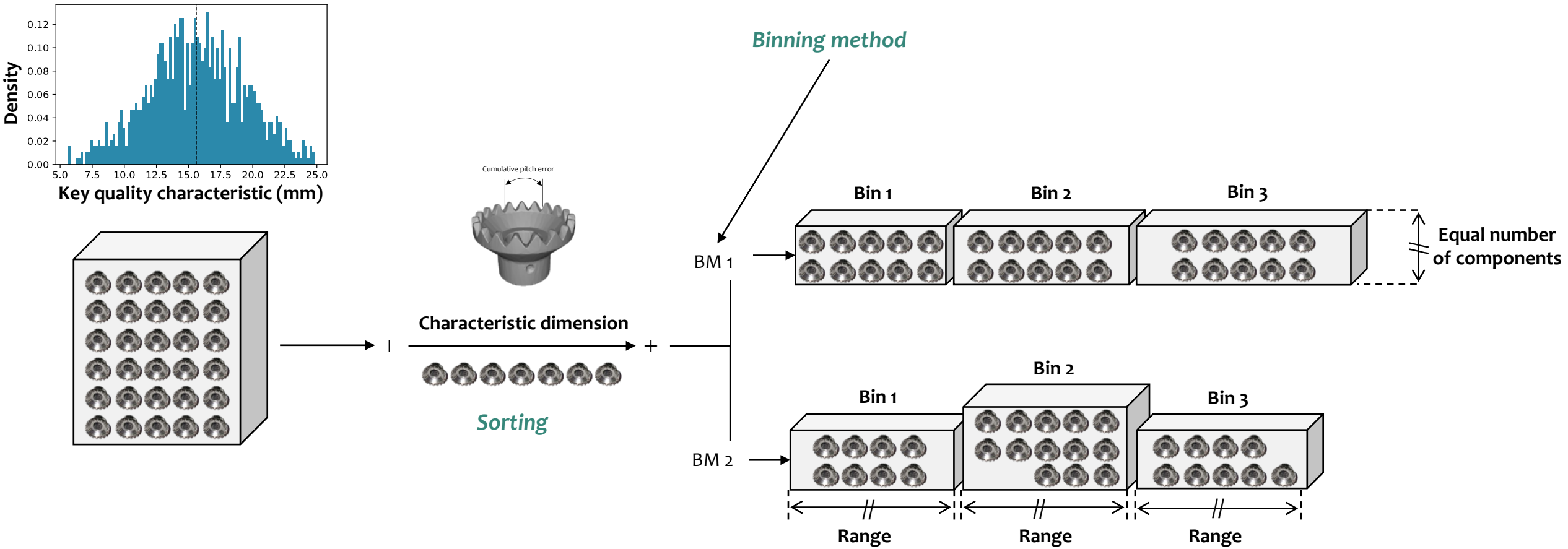
Batch selection - The batch selection divides the parts into several batches. Afterward, the batches will be paired concerning designer decision. The issue in this method is **how should divide** and on **what bases** ?

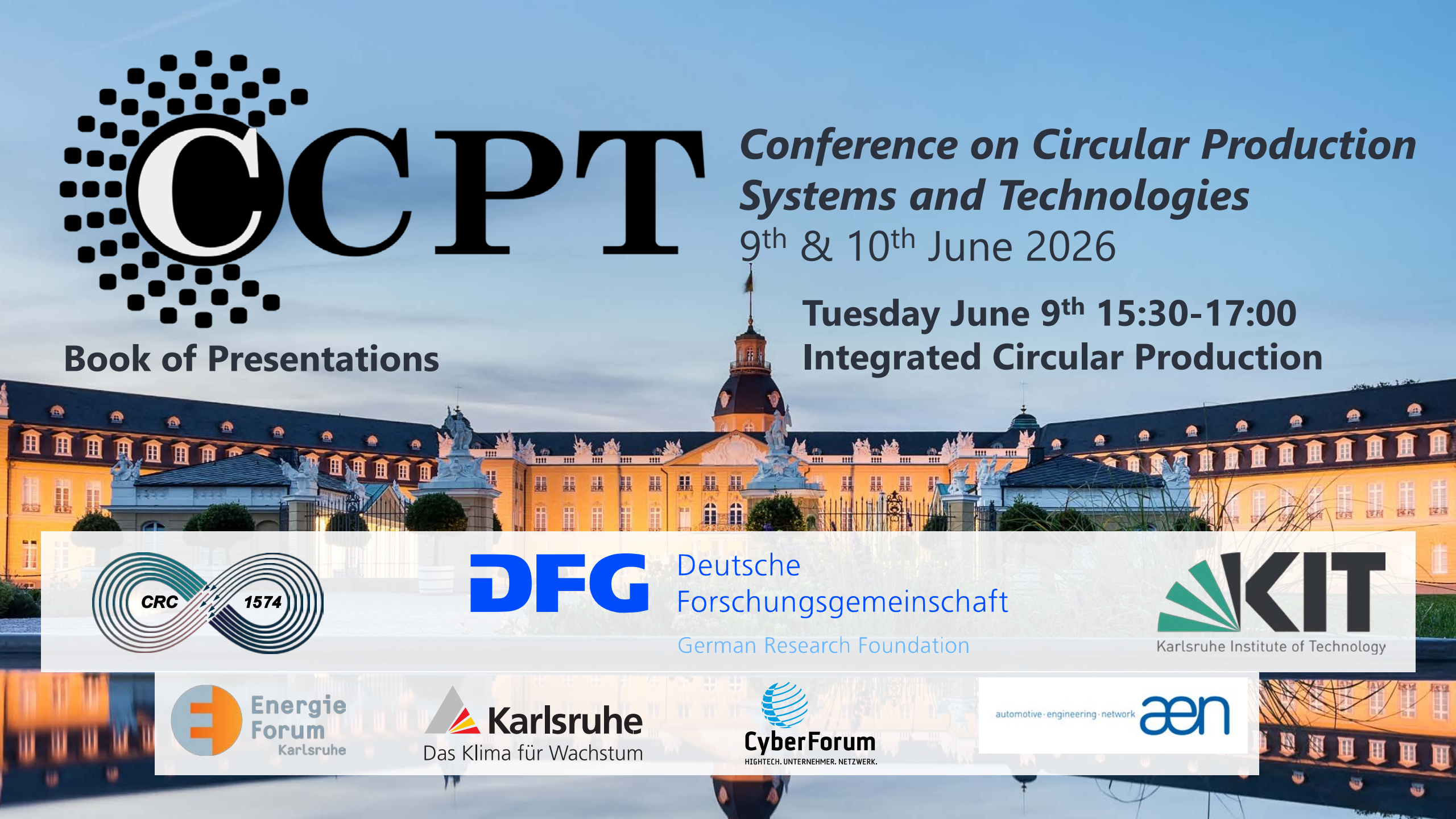
The characteristic to be measured and be categorized.



[5] Sobol, I. M., '. (1993). Sensitivity estimates for nonlinear mathematical models. *Math. Model. Comput. Exp, 1*(4), 407-414

Selective assembly: binning methods





CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Tuesday June 9th 15:30-17:00
Integrated Circular Production

CRC 1574

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

KIT Karlsruhe Institute of Technology

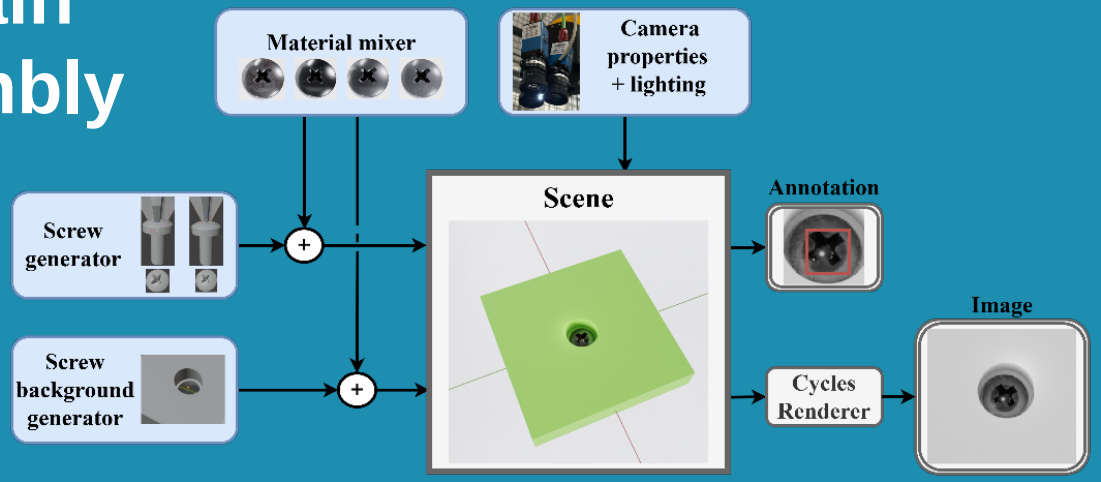
Energie Forum Karlsruhe

Karlsruhe Das Klima für Wachstum

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automotive · engineering · network aen

Synthetic Pre-training for Cross-Domain Fastener Detection in WEEE Disassembly



Re- & Demanufacturing Lab
Life Cycle Engineering (LCE) research group
Department of Mechanical Engineering
Campus Groep T Leuven
Faculty of Engineering Technology

Member of Flanders Make@KU Leuven Core Lab End 2 End Design Operations
Board member of KU Leuven Institute for Sustainable Minerals and Metal (SIM^2)

Ing. Anthonie Coopman

Prof. Dr. Jef Peeters

WEEE (waste of electronic and electrical equipment)

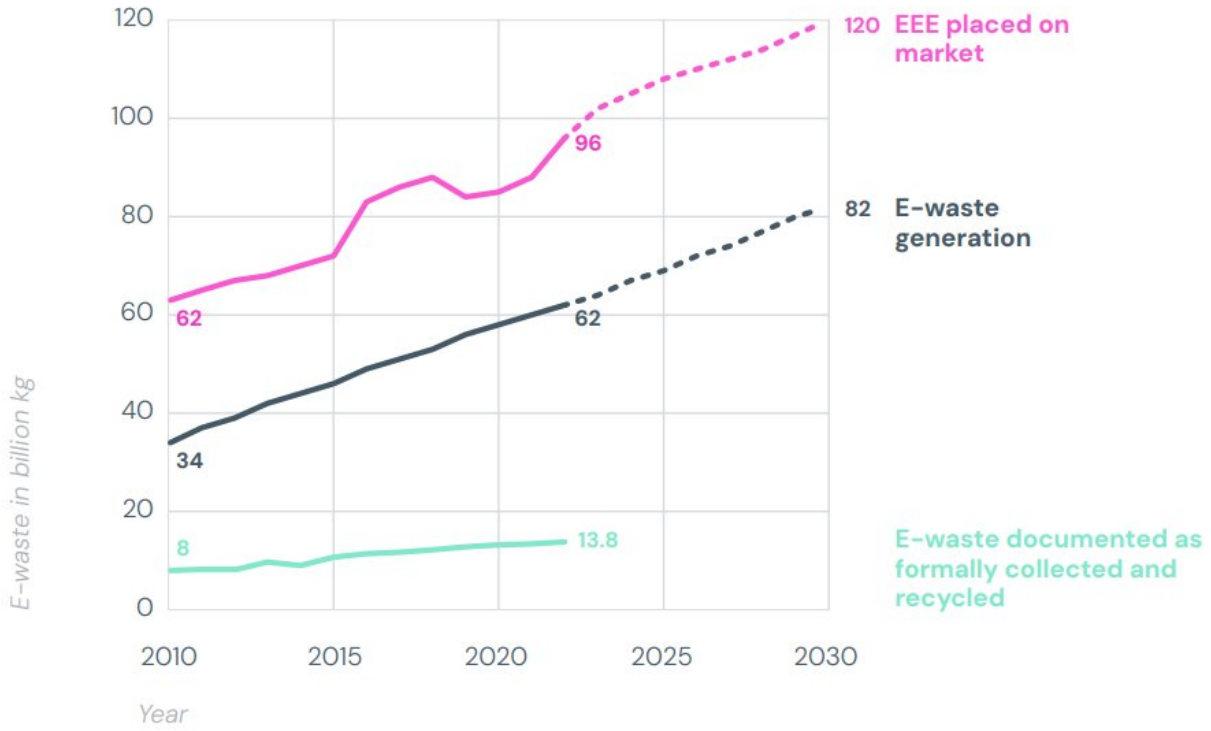
What is it?

- Waste stream
- Electronic appliances and devices
- Often battery-containing products
- Critical raw materials inside

→ Large variation in material composition
→ Large variation in sizes, shapes and sub-components

Why manage it?

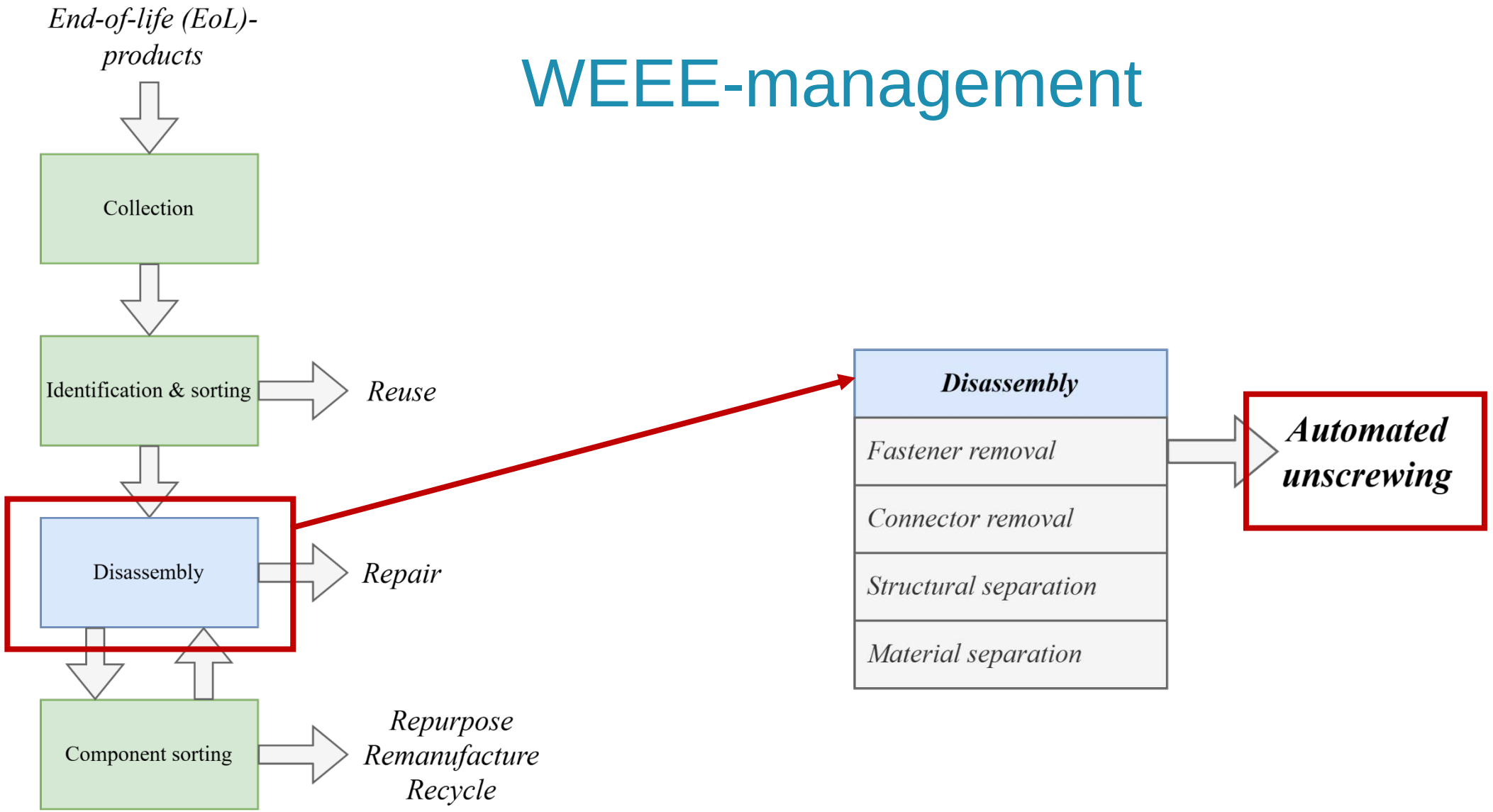
→ Avoid loss of precious materials
→ Toxic substances lead to health hazards
→ Environmental impact



[1] "The Global E-waste Monitor 2024," *E-Waste Monitor*. https://ewastemonitor.info/the-global-e-waste-monitor-2024/

KU LEUVEN LCE Re- & Demanufacturing Lab

WEEE-management



WEEE product variation



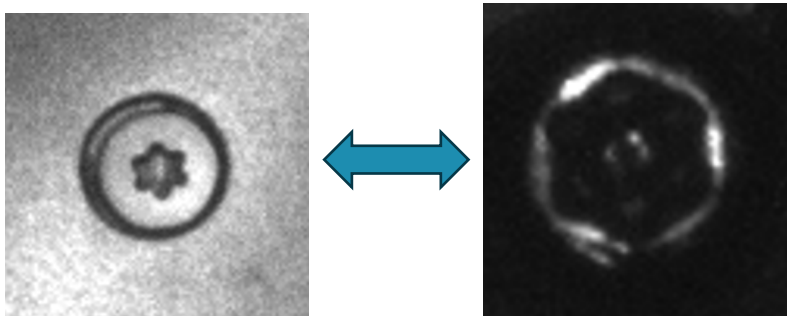




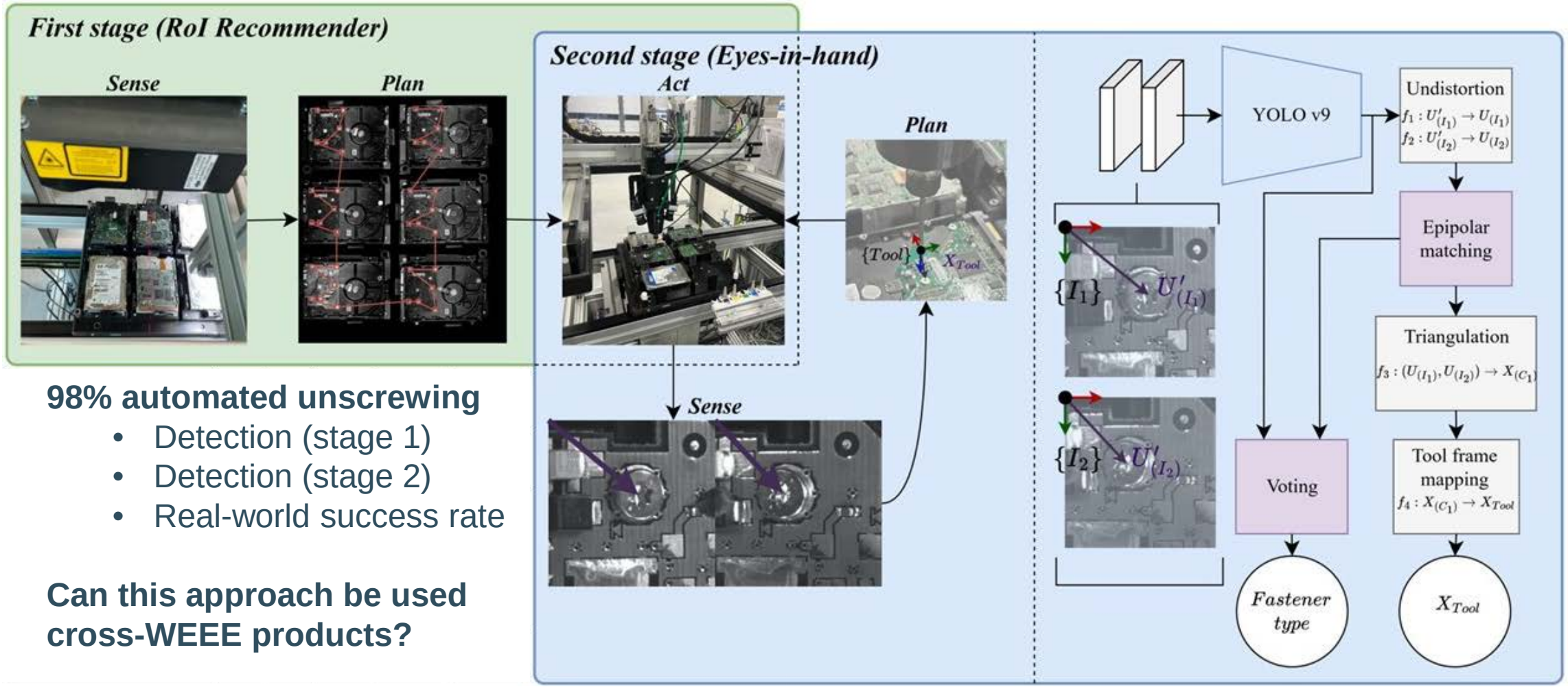




- **Variation of products** in WEEE
- Large part of the distribution
  - **Torx**
  - **Phillips**



Prior work (Eyes-in-hand autonomous robotic unscrewing)



98% automated unscrewing

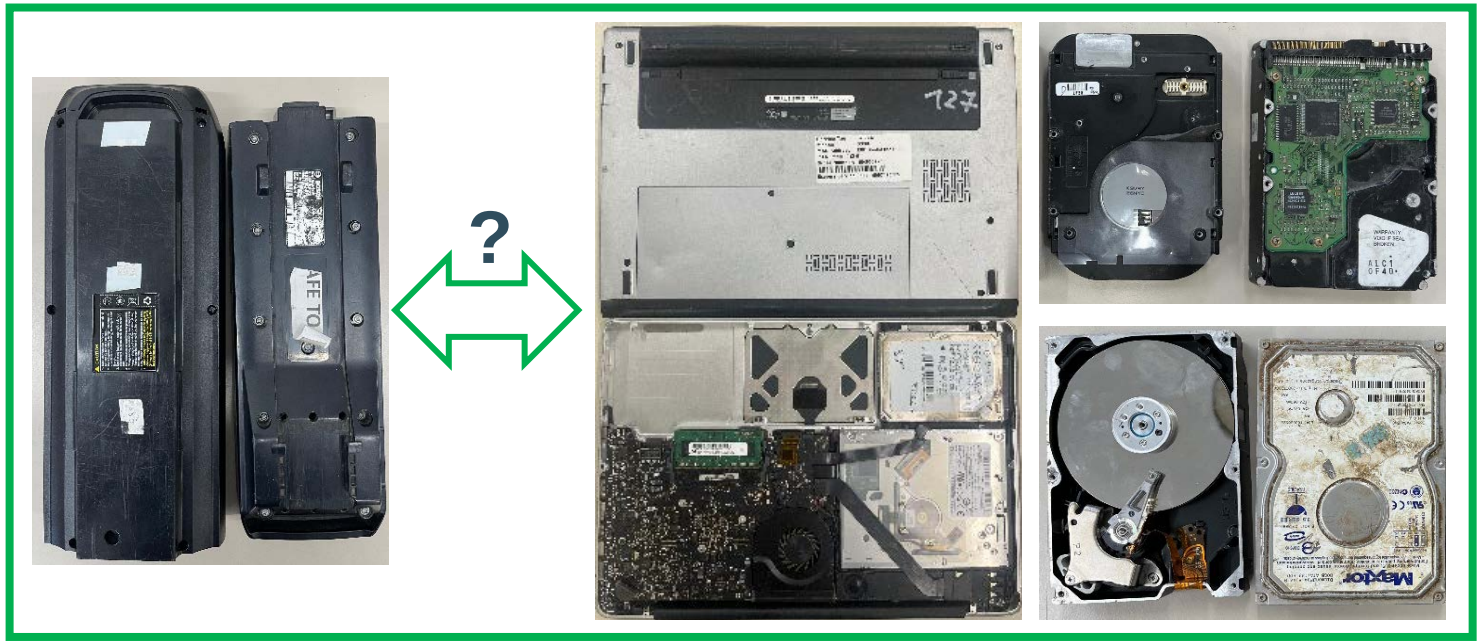
- Detection (stage 1)
- Detection (stage 2)
- Real-world success rate

Can this approach be used cross-WEEE products?

[2] A. Coopman, M. Piessens, J. Van Den Bosch, M. Vandersteegen, and J. R. Peeters, "A comparative study between a traditional coarse sense-plan-act system and a two-stage RoI recommender and Eyes-in-hand stereo system for robotized unscrewing of hard disk drives (HDDs)," in *2025 IEEE 21st International Conference on Automation Science and Engineering (CASE)*, IEEE, Aug. 2025, pp. 1539–1546. doi: 10.1109/CASE58245.2025.11163841

generalization for robotic unscrewing

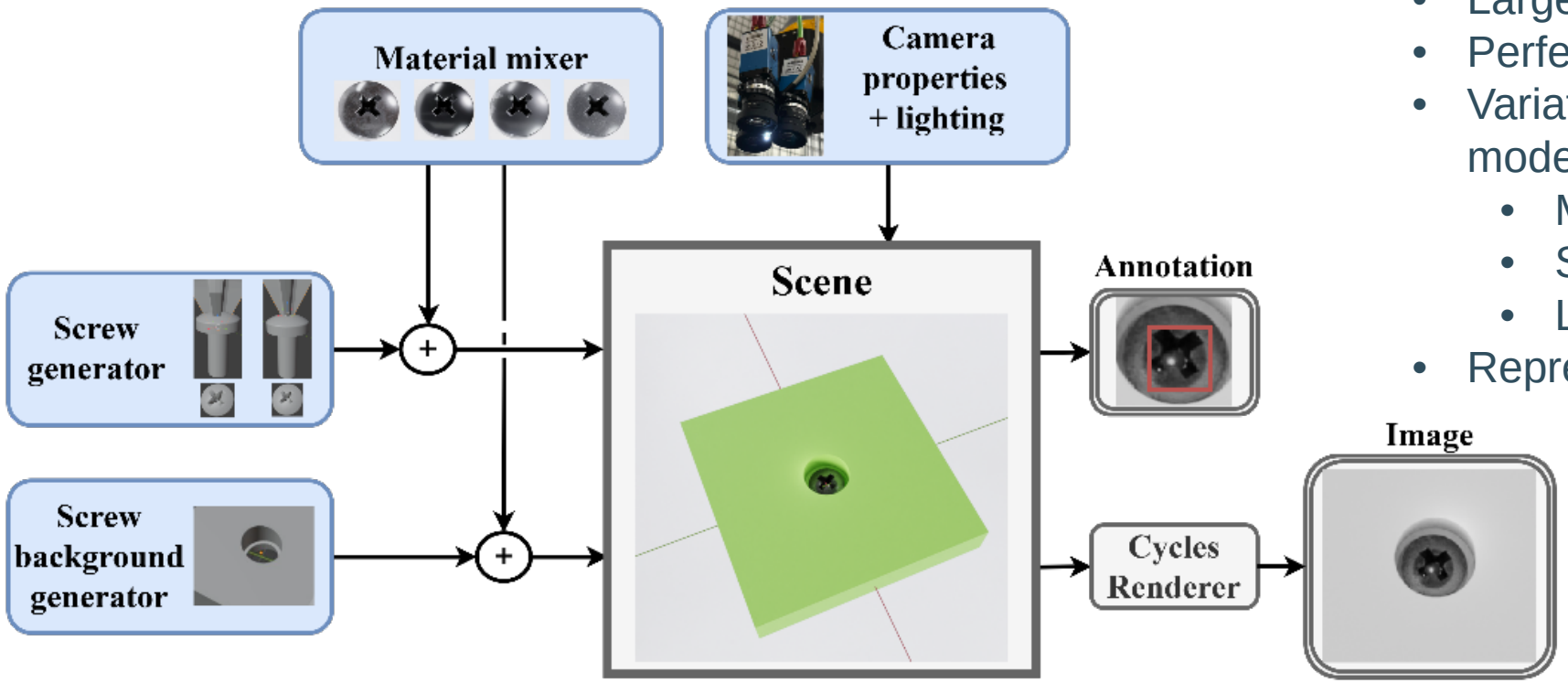
Eyes-in-hand system



How well do models **perform cross-domain?**

→ Can a Bike-battery trained model be used for unscrewing of hard disk drives (HDDs)?
→ Can synthetic data help in cross-domain performance?

Synthetic data challenges and pipeline

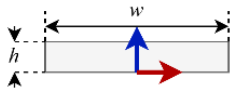


- Large dataset
- Perfect labels
- Variation through procedural modelling
  - Material properties (specularity)
  - Surface conditions
  - Lighting
- Representation of occluded holes

4592 randomized images generated

Synthetic screw generation

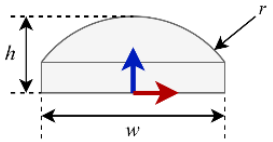
Flat Head



$$z = h$$

$$x \in \left[-\frac{w}{2.5}, \frac{w}{2.5}\right]$$

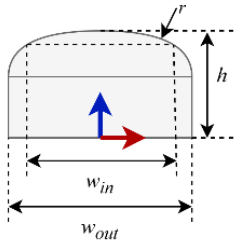
Raised Head



$$x^2 + (z - (h - r))^2 - r^2 = 0$$

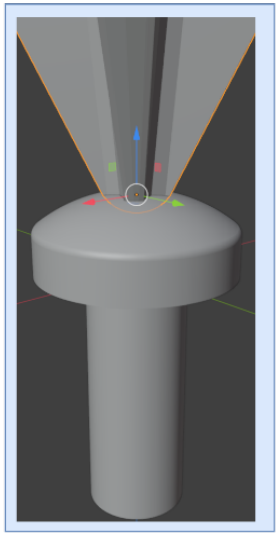
$$x \in \left[-\frac{w}{2.5}, \frac{w}{2.5}\right]$$

Pan Head



$$x^2 + (z - (h - r))^2 - r^2 = 0$$

$$x \in \left[-\frac{w_{in}}{2}, \frac{w_{in}}{2}\right]$$

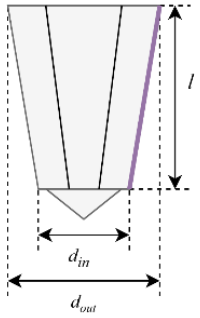


Torx Bit

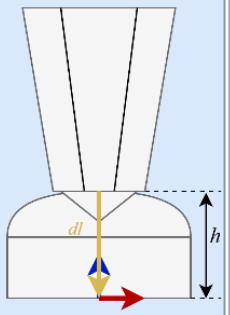


$$x = \frac{d_{out}}{2}$$

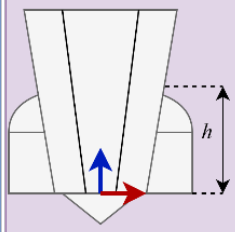
Phillips Bit



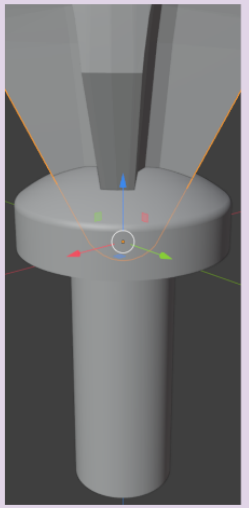
$$z = \frac{2l}{(d_{out} - d_{in})}x + d_l - \frac{ld_{in}}{(d_{out} - d_{in})}$$



$$d_l = h$$



$$d_l = 0$$

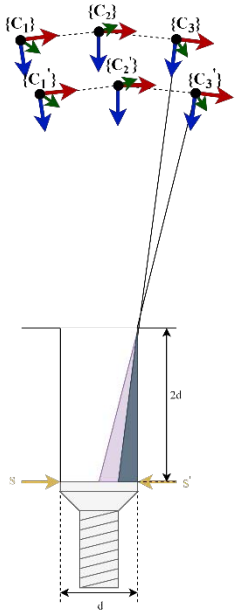


According to **ISO**:

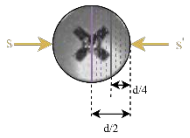
- 7045-7050
- 14581
- 14583

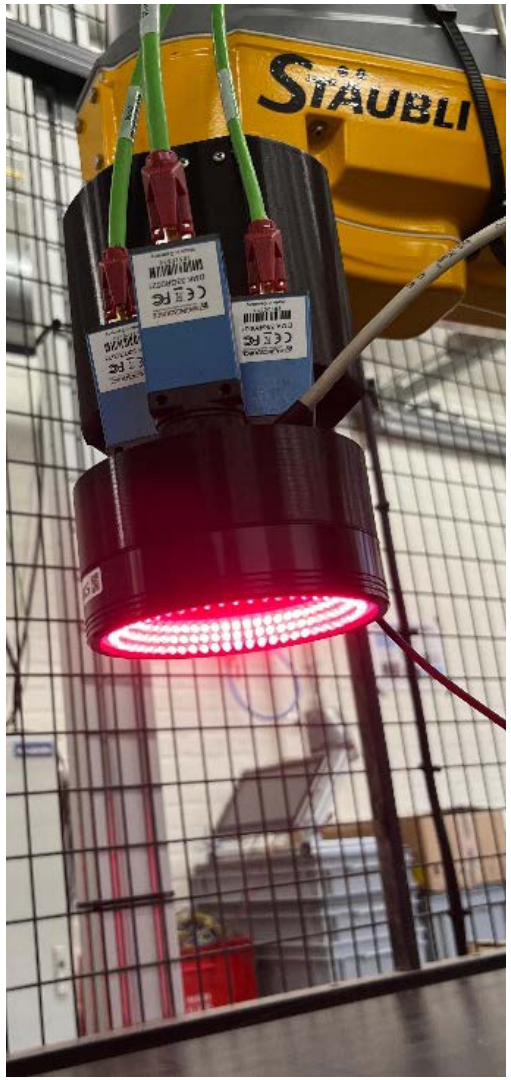
Real-world and synthetic datasets

- **3-camera setup** (Eyes-in-hand)
- **Deep recessed holes** (bike battery)
- Camera **settings**, aperture, focus and lighting are kept the same for all imaging









Real-world WEEE datasets





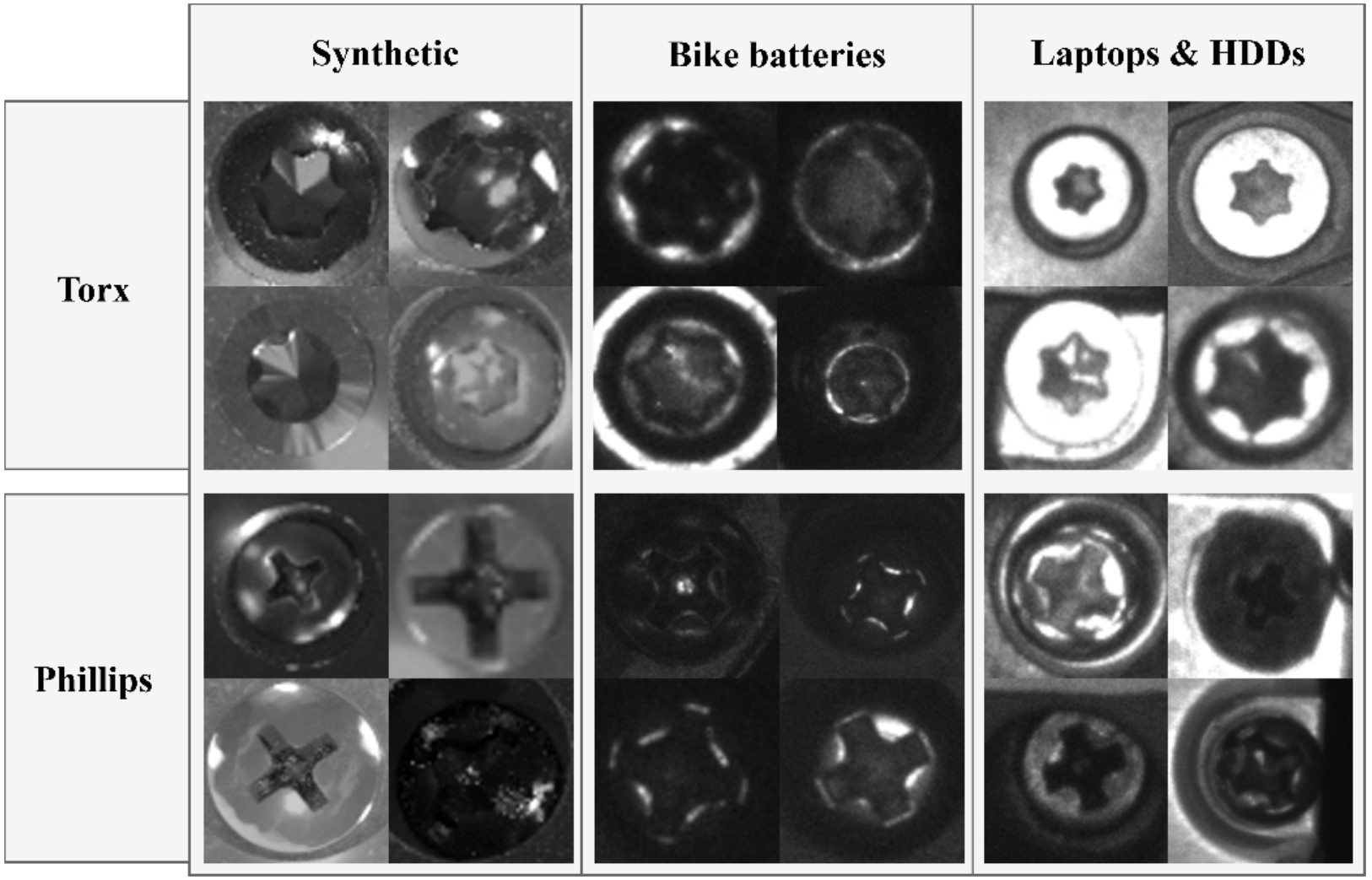


Bike battery dataset 309 images

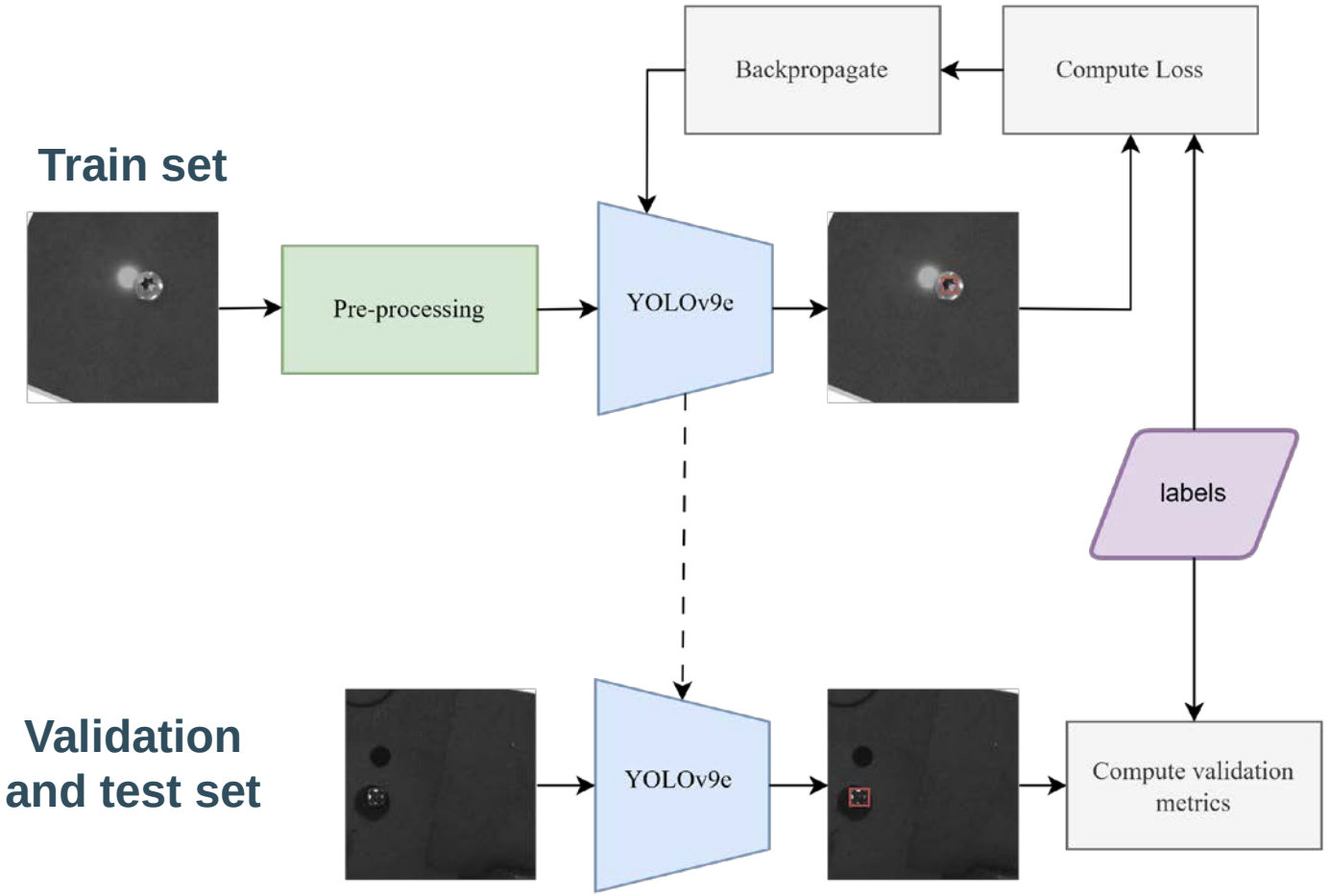
Laptop & HDD dataset 276 images

→ **70/15/15 train/val/test** split

Synthetic and real-world data examples



Experimental setup and evaluation

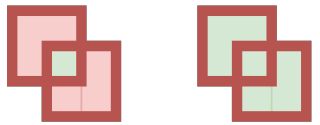


$$P = \frac{TP}{TP + Fp} \qquad R = \frac{TP}{TP + FN}$$

$$AP = \int_0^1 P(R)\, dR \Rightarrow mAP = \frac{1}{N}\sum_{i=1}^{N} AP_i$$

$$mAP50 \rightarrow IoU > 50\%\ for\ TP$$

Intersection Union



$$\frac{Intersection}{union} (= IoU)$$

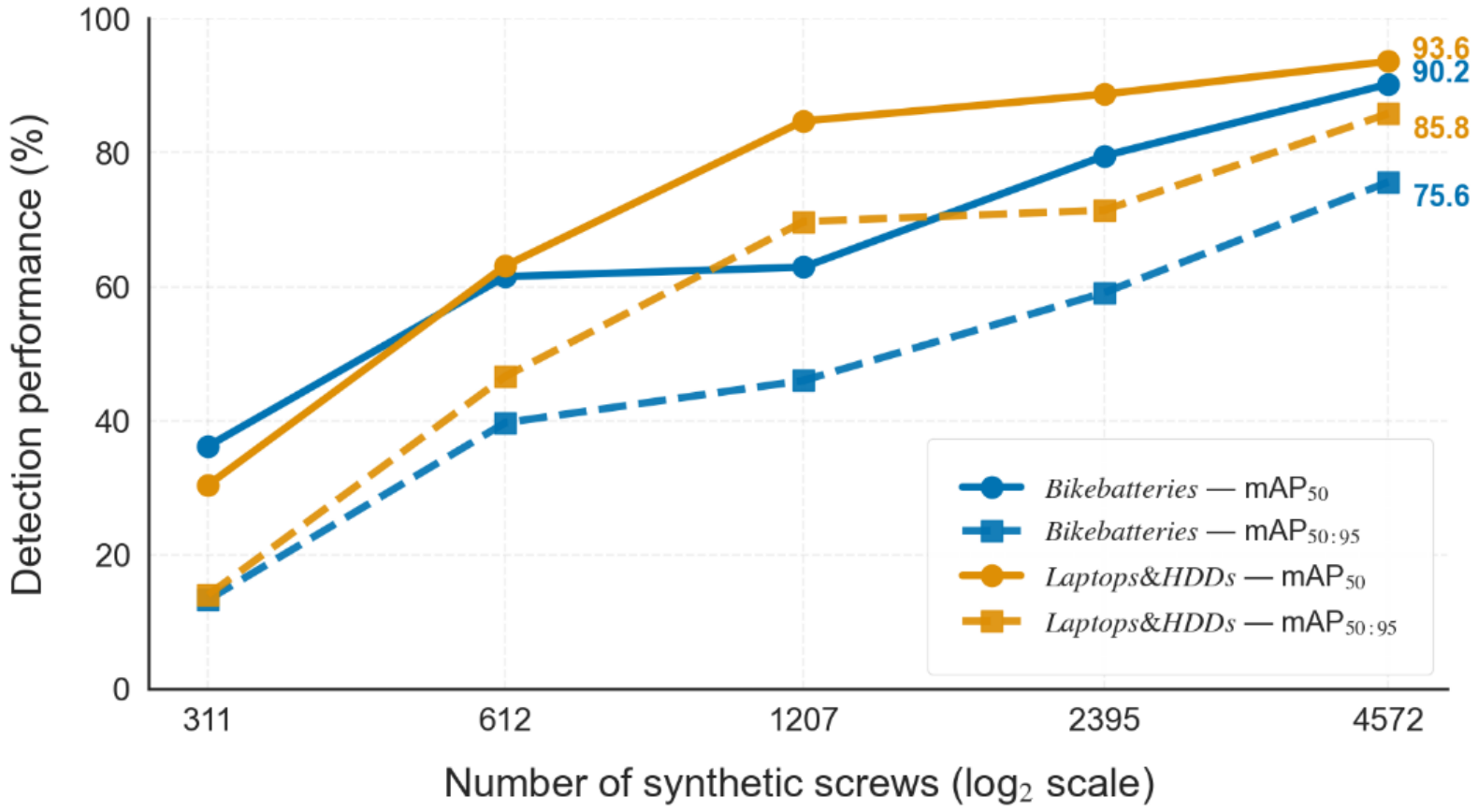
thresholding

Transfer learning: ***pre-training*** *a model on* ***generic data*** *and* ***fine-tuning*** *it on* ***task-specific data,*** *often includes freezing the initial layers.*

Faculty of Engineering Technology, Department of Mechanical Engineering,
Life Cycle Engineering (LCE) research group, De- and Remanufacturing Lab

KU LEUVEN LCE Re- & Demanufacturing Lab

Synthetic data generalizes and outperforms small real datasets!



- **Increasing dataset** size improves performance substantially
- **Larger datasets** should be tested to reach **convergence**
- Similar results for different products → **cross-domain generalization**

Cross-domain performance of synthetic and real-world data

Training set		Bike batteries – Test set		Laptops & HDDs – Test set	
Pre-train	**Fine-tune**	**mAP_{50} [%]**	**$mAP_{50:95}$ [%]**	**mAP_{50} [%]**	**$mAP_{50:95}$ [%]**
Bike batteries	/	87.4	41.7 ⇨	10.4	2.62
Laptops & HDDs	/	35.7	16 ⇦	87.1	61.4

- Solely real data in training set:
  → **good in-domain** performance
  → **poor out-of-domain** performance

Faculty of Engineering Technology, Department of Mechanical Engineering,
Life Cycle Engineering (LCE) research group, De- and Remanufacturing Lab

KU LEUVEN LCE Re- & Demanufacturing Lab

Cross-domain performance of synthetic and real-world data

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Synthetic (311)	/	39.8	18.3	34.3	15.8
Synthetic (4572)	/	90.2	75.6	93.6	85.8

- Solely synthetic data in training set:
  → **poor** performance for **small dataset** sizes
  → **consistent cross-domain**
  → **Large performance increase** by increasing **dataset size**
  → Large mAP50:90 compared to mAP50 = **good localization**

Cross-domain performance of synthetic and real-world data

Training set		Bike batteries – Test set		Laptops & HDDs – Test set	
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Synthetic (4572)	***Laptops &HDDs***	94.4	75.9 ⇦	**97.1**	**87**
Synthetic (4572)	***Bike batteries***	**95.7**	**78.6** ⇨	94.5	78.7

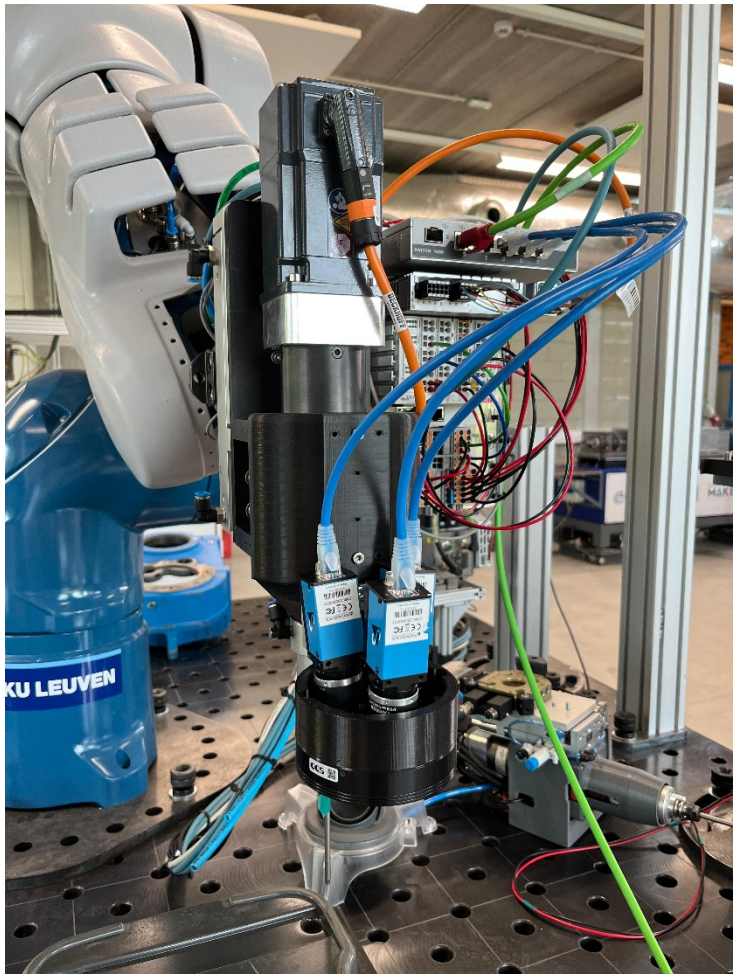
- Transfer learning approach:
  - → **Improvement** both **in-domain and cross-domain**
  - → **Localization** can be **affected** by **human annotation**

Conclusion & future work

- A **large number of high-quality synthetic data** can **compete** with models trained on solely **real-world data**.
- **Synthetic data** can play a **crucial role in the generalization** of screw detection by domain randomization.
- Real-world **waste stream-specific data** should be used to **fine-tune models** for **optimal performance**!

To be continued…

→ Screw pose estimation for angled products
→ Collision free motion-planning for cluttered environments
→ In-process data acquisition



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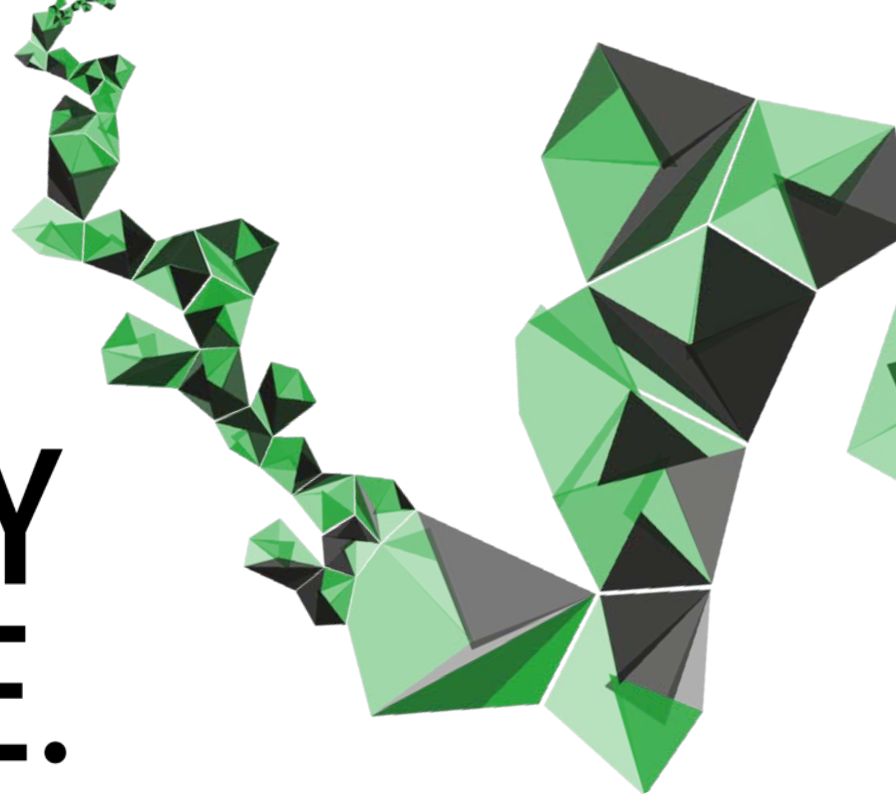


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Thank you for your attention!

Questions?

ENGINEERING TECHNOLOGY - DEPT. DESIGN, PRODUCTION AND MANAGEMENT
MANUFACTURING SYSTEM

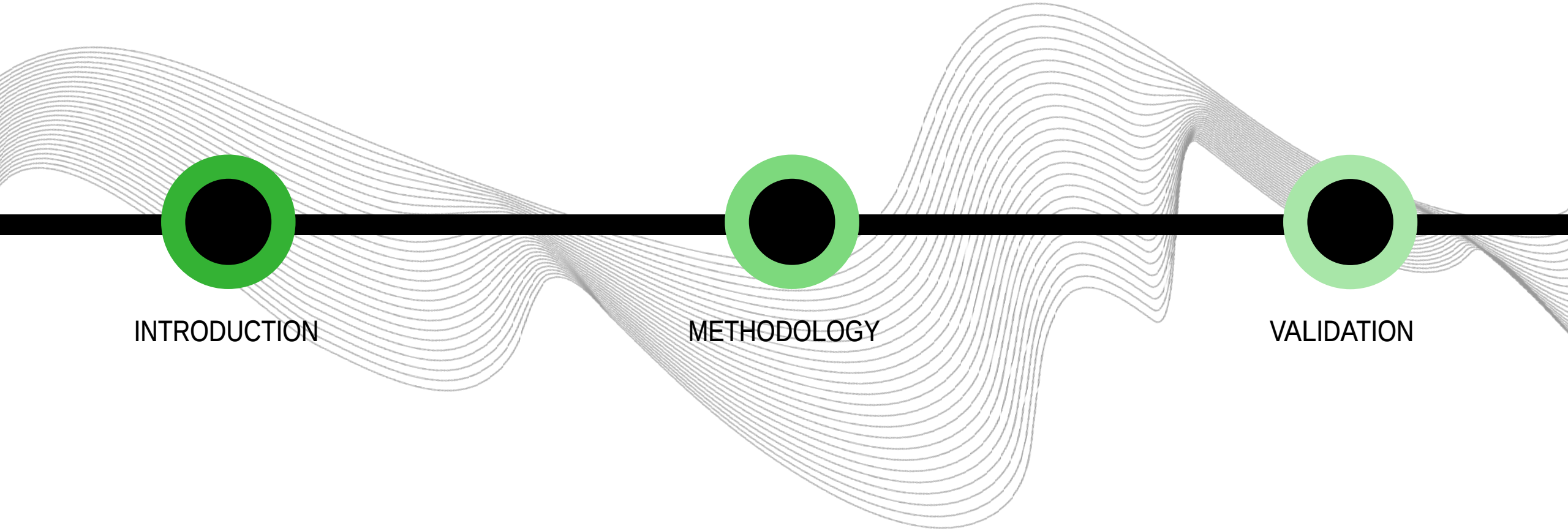


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HARMONISED TECHNOLOGY BLOCKS FOR BATTERY PACK RE-X SYSTEMS

SHUN YANG, JORGE FRANCISCO CABELLO OQUEÑA, NIRAJ CHAUHAN, HANS THIERY TJONG, SEBASTIAN THIEDE

IN THIS PRESENTATION:

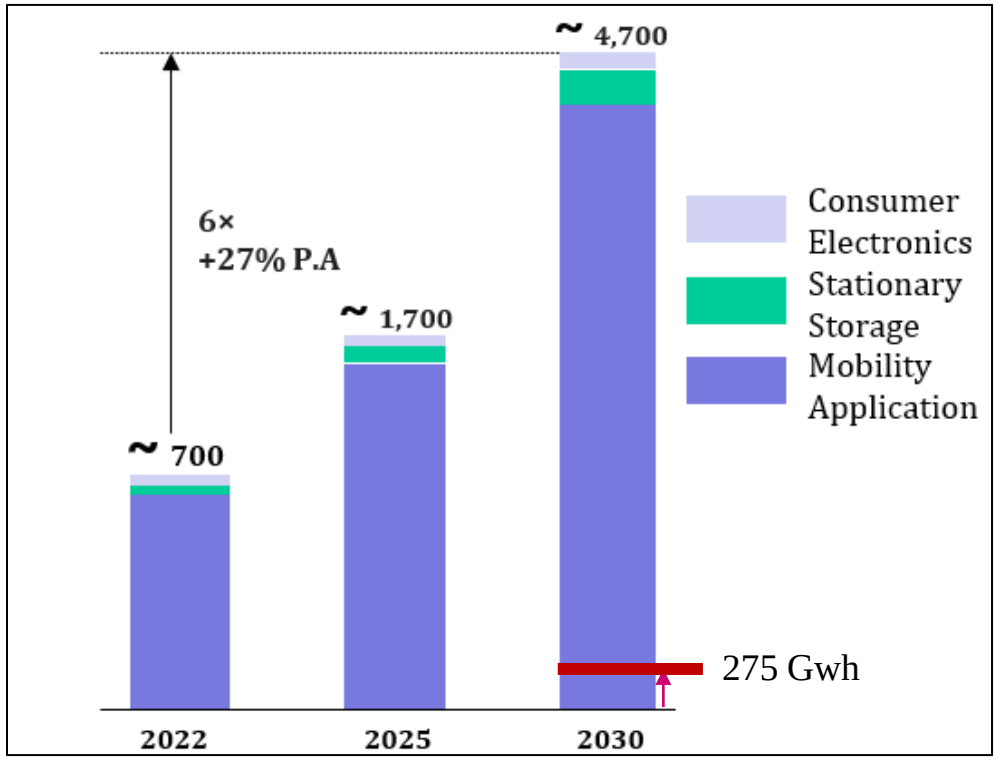


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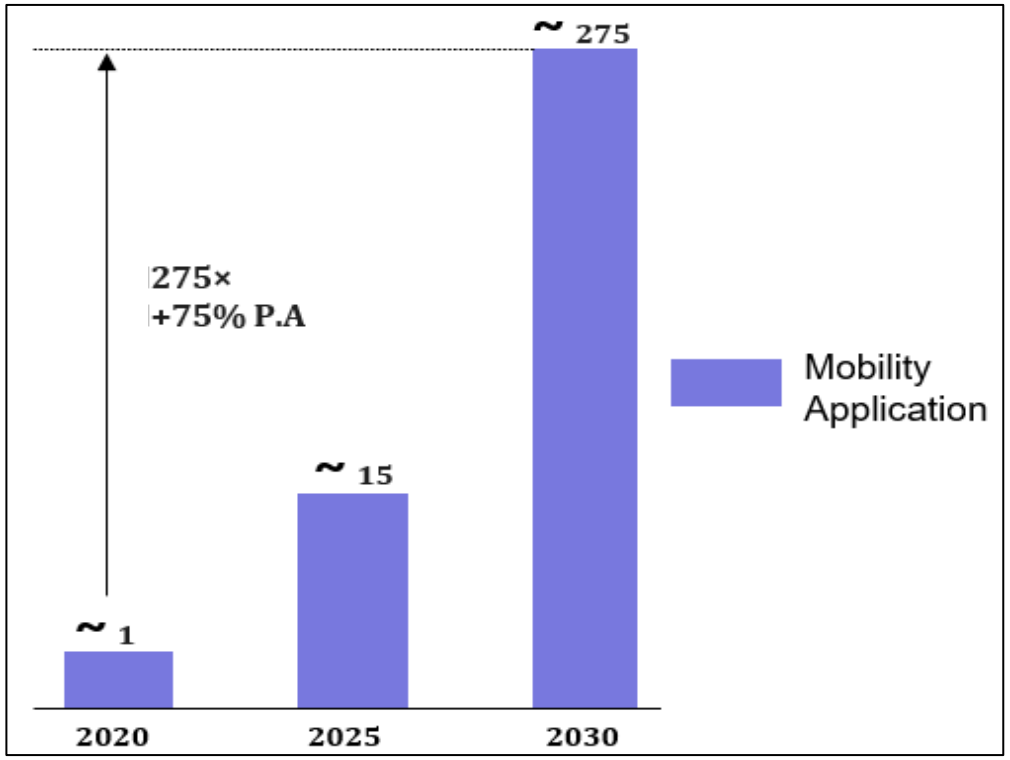
BACKGROUND & MOTIVATION

GROWING RETIRED BATTERY NEEDS EOFL MANAGEMENT

Global demands of Lithium-ion battery worldwide in (Gwh) by 2030



Expected retired Lithium-ion battery worldwide in (Gwh) by 2030



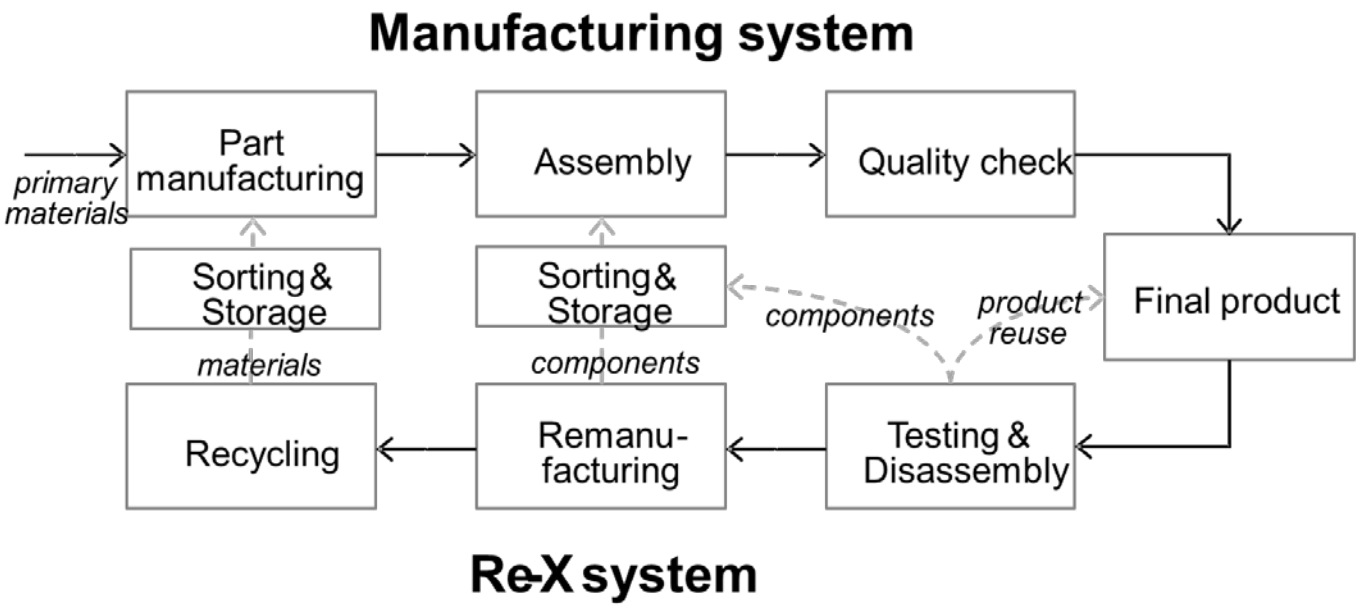
Growing retired battery number, makes efficient Re-X system development very crucial in this era.

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Source: Chauhan, N., Yang, S., & Thiede, S. (2025). Risk Assessment of Retired Lithium-Ion Battery Packs: FMEA and Pugh Matrix Integration.

CHALLENGES

EOFL IS BIG CHALLENGE IN MAKING RE-X DECISION





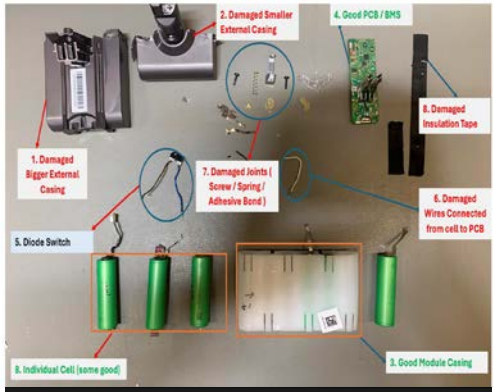
Safety Issues



Characterization



Disassembly uncertainty



Low material recovery

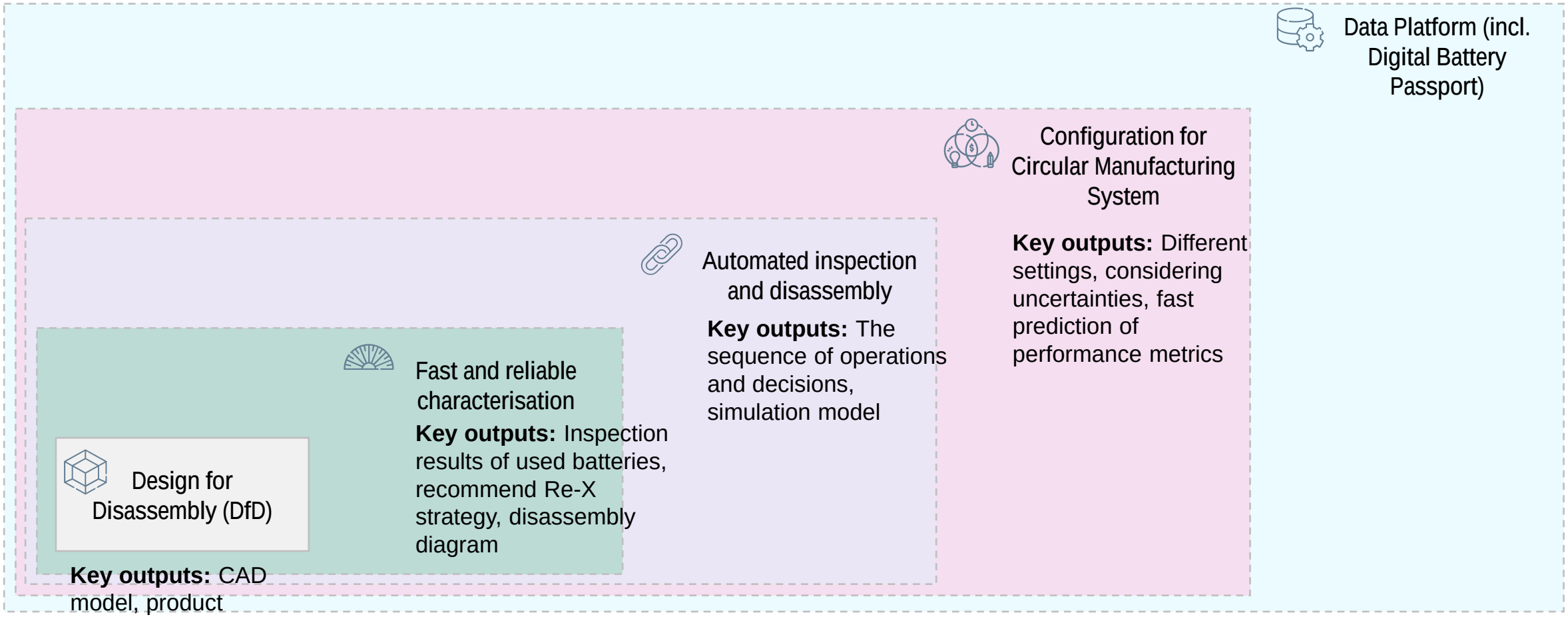
Unknown status of battery and uncertainty poses safety hazards and huge challenges for Re-X system.

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Source: Thiede, S., Yang, S., & Yazdi, P. G. (2024, April). Circular manufacturing systems in learning factories.

OVERVIEW METHODOLOGY

FUNCTION BLOCK ORIENTED BATTERY RE-X SYSTEM



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OVERVIEW METHODOLOGY

FUNCTION BLOCK ORIENTED BATTERY RE-X SYSTEM

	Function Block 1	Function Block 2	Function Block 3	Function Block 4
	Pd Prc	Prc	Prc Sys	Sys Plt
	Design for Disassembly (DfD)	Fast and reliable characterisation	Automated inspection and disassembly	Configuration for Circular Manufacturing System
Principles	• Easy for end-of-life separation • Accessibility of priority parts	• Identify the non-conforming batteries at the earliest opportunity	• Verify and validate system behavior virtually before physical deployment	• Flexible and scalable to analysis different scenarios with variant uncertainties
Technologies	• Gen AI • Fastening databases • Sensor technology	• Vision technology • Sensor technology • IoT	• Simulation • Digital twin • Virtual PLC	• Simulation • Machine learning
Methods	• DfD scoring • Life cycle cost • Cumulative Energy Demand	• DBP • Fuzzy FMEA • Multi-stage inspection	• DfD scoring • Life cycle cost • Cumulative Energy Demand	• Simulation based configuration • Auto code generation
Tools	• Hotspot Mapping Datasheet • LeanDfD	• DBP webtool • FMEA analysis sheet • OpenCV	• Visual component • TwinCAT • End-of-arm tooling	• Data analytics tool • Visual component • UI tool

Pd Product level
Prc Process level
Sys System level
Plt Platform level

DETAILED METHODOLOGY

INTERCONNECTION OF FUNCTION BLOCKS

Function Block 1

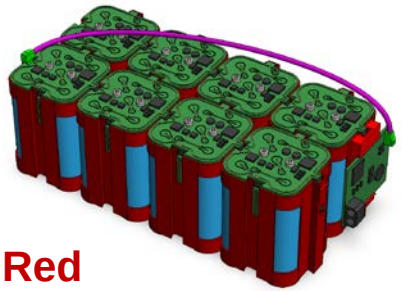
Pd Prc

Design for Disassembly (DfD)

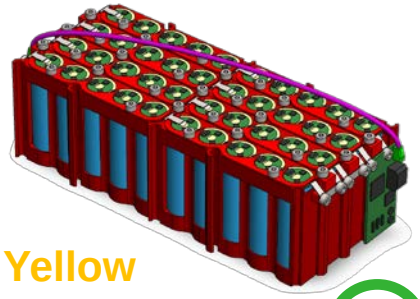
Function	Option 1	Option 2	Option 3
Terminal connection	Weld	Conductive adhesive	Spring
Mechanical connection	Bolt	Snap fit	Friction fit
Electrical connection	Spring	Standard connector	Bolt
Data connection	Standard connector	Spring	Wireless
BMS	Centralised	Distributed	Modular



Green concept



Red concept



Yellow concept

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DETAILED METHODOLOGY

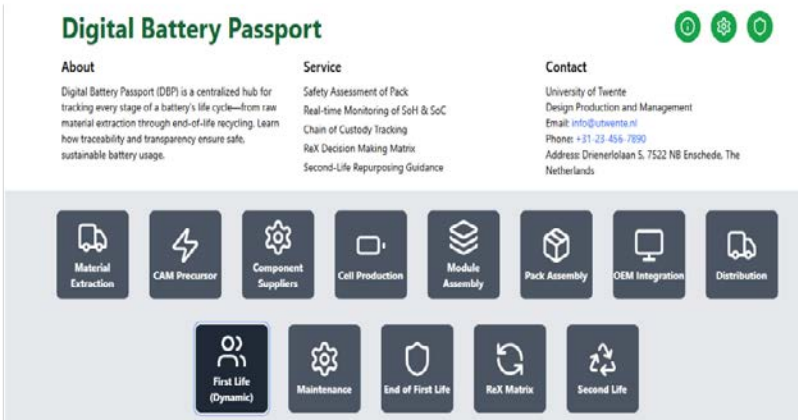
INTERCONNECTION OF FUNCTION BLOCKS

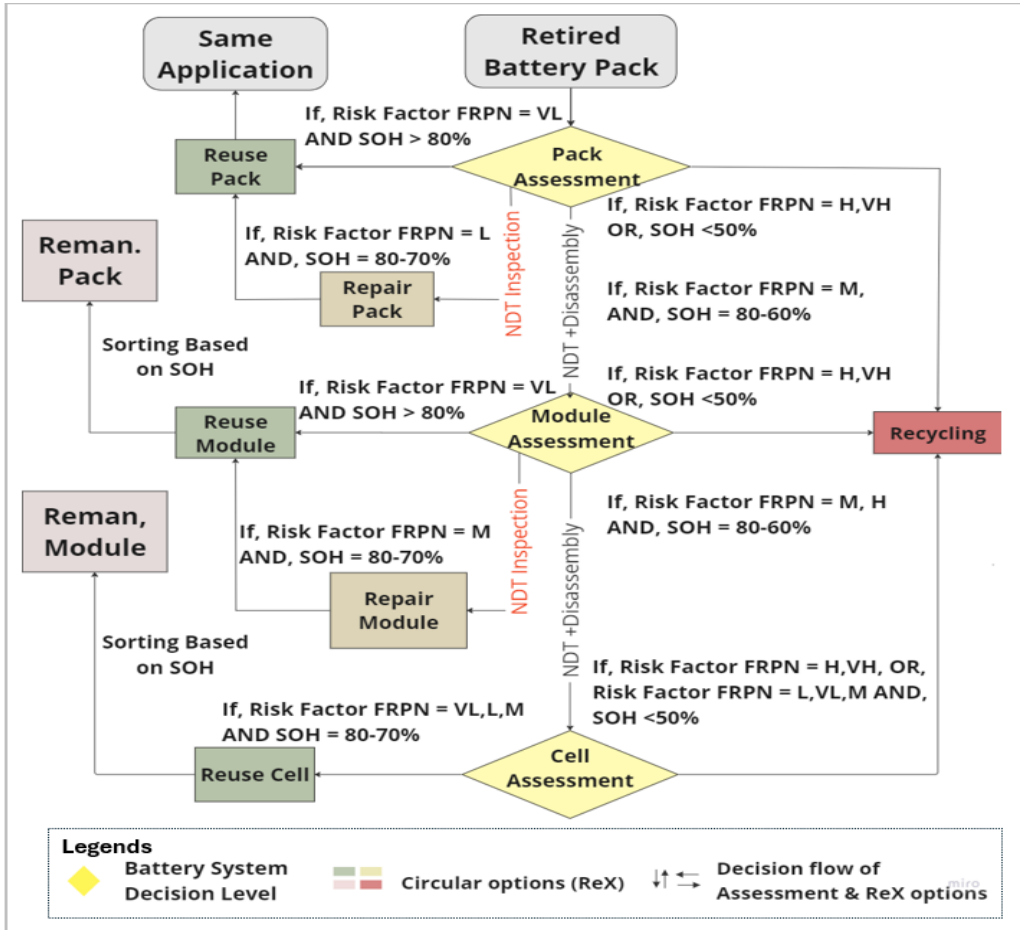
Function Block 2

Prc

Fast and reliable characterisation

Digital Battery Passport in Re-X Decision Model





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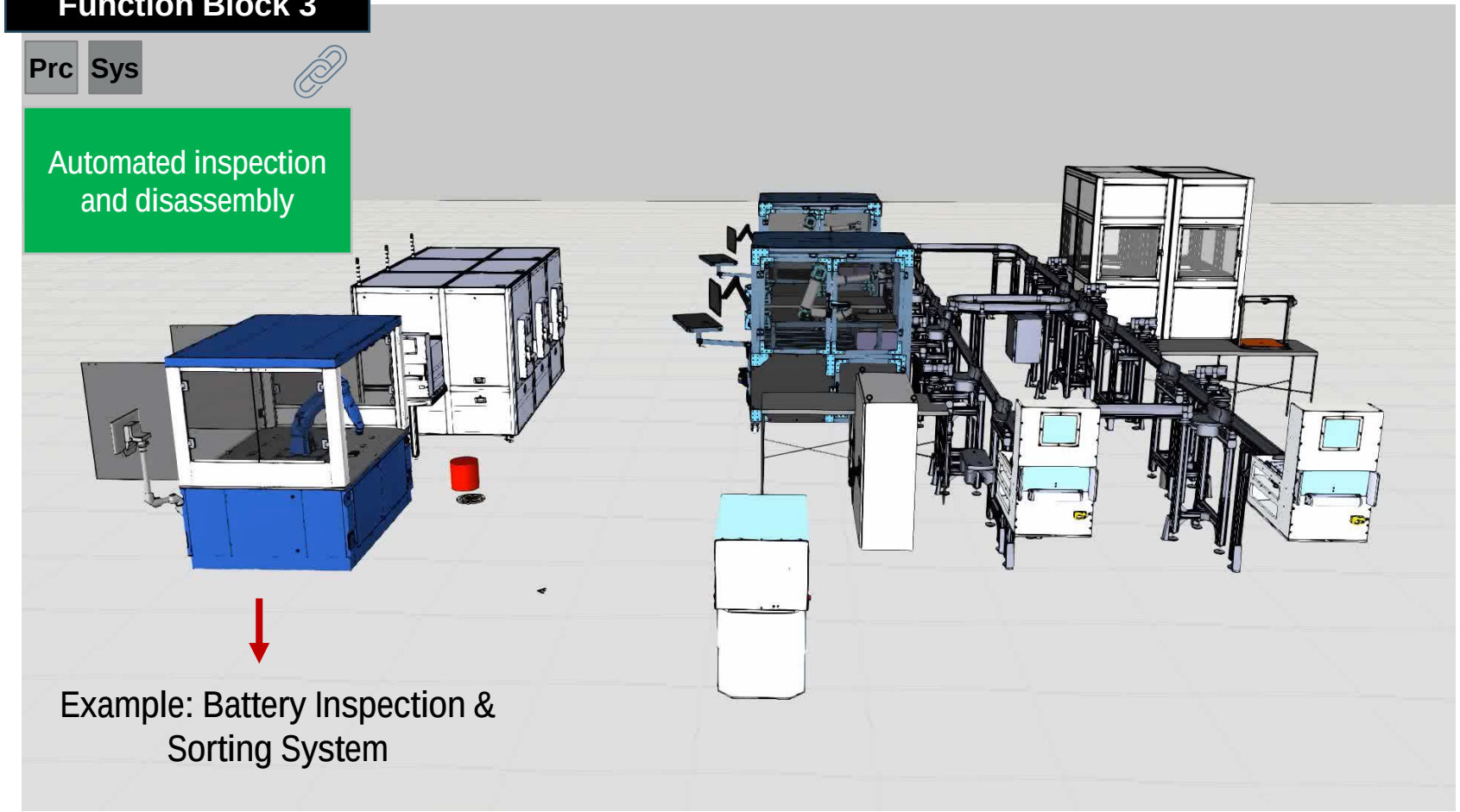
VALIDATION THROUGH DIGITAL PLATFORM

VIRTUAL COMMISSIONING FOR RE-X SYSTEM 1/2

Function Block 3

Prc Sys

Automated inspection and disassembly



Example: Battery Inspection & Sorting System

Phases of Development

(Inputs from design, system configurator, product req.)

Baseline Modelling

Building Pilot Line (Physical)

Digital Twining for Re-configuration, Optimization, Upgrade
(and live monitoring)

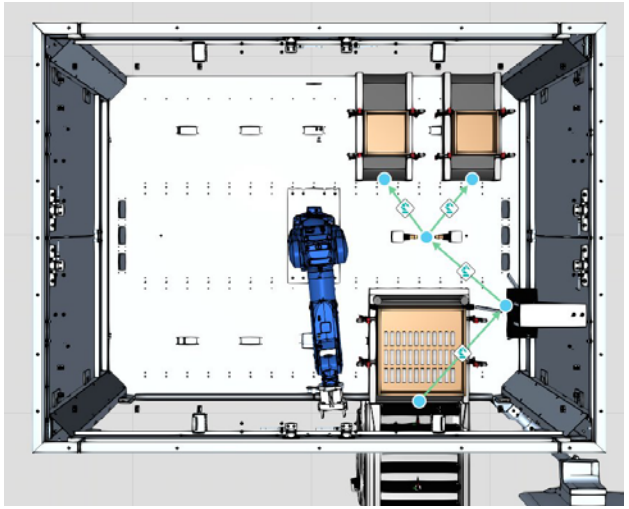
Digital twining current (baseline) configuration enable efficient planning, development, and iteration of designs

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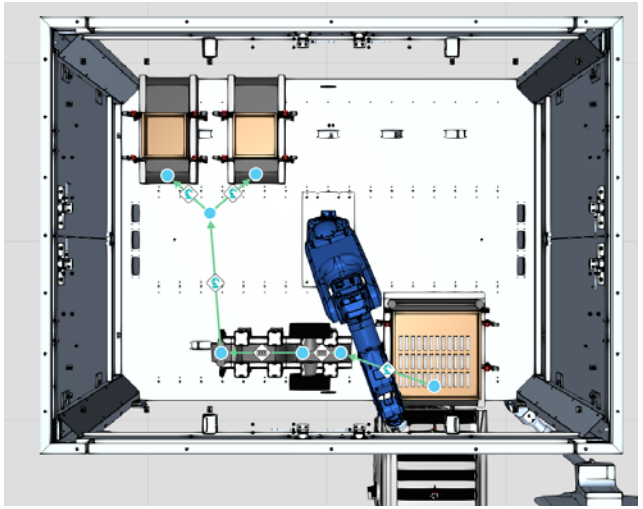
VALIDATION THROUGH DIGITAL PLATFORM

VIRTUAL COMMISSIONING FOR RE-X SYSTEM 2/2

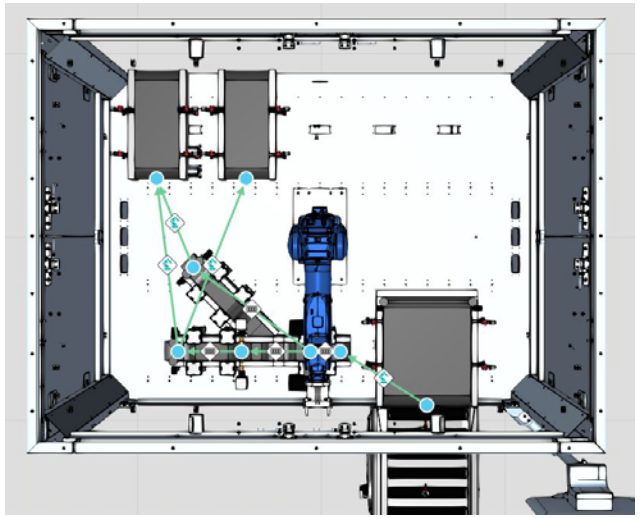
Layout 1 (Baseline)



Layout 2



Layout 3



‘Ideal’ simulation throughput higher ~30% than real physical setup



Criteria	*Layout 1*	*Layout 2*	*Layout 3*
Throughput	Low	Medium	Highest
Robot travel distance	Long	Medium	Shortest
Layout flexibility	High	Medium	Low
Expansion capability	Excellent	Limited	Limited
Maintenance accessibility	Good	Moderate	Moderate

Detailed analysis of different layouts and configurations could be done quickly without physical setup

VALIDATION OF CONFIGURATION PLATFORM

KEY CONCEPT OF CONFIGURATION PLATFORM

Function Block 4

Sys Plt

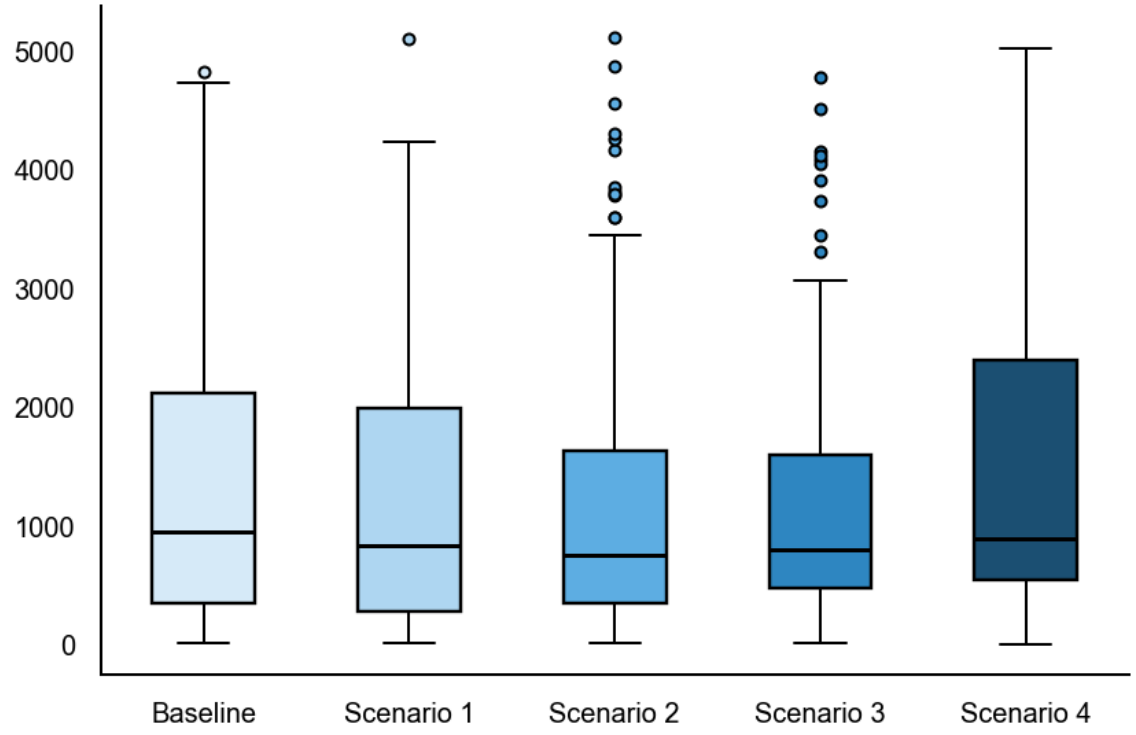


Configuration for Circular Manufacturing System

Parameters configuration

Scenario	Design #Process		Uncertainties	
	VS	OCV	Quality	Inspection accuracy
BL	1	1	VS: Bernoulli (p=0.8) OCV: Bernoulli (p=0.6)	VS: Normal (μ=95%)
1	1	2		
2	2	1		
3	2	2		
4	2	3		

Simulation and Results comparison



Key concept behind the configuration explains how is the mechanism of the configurator.

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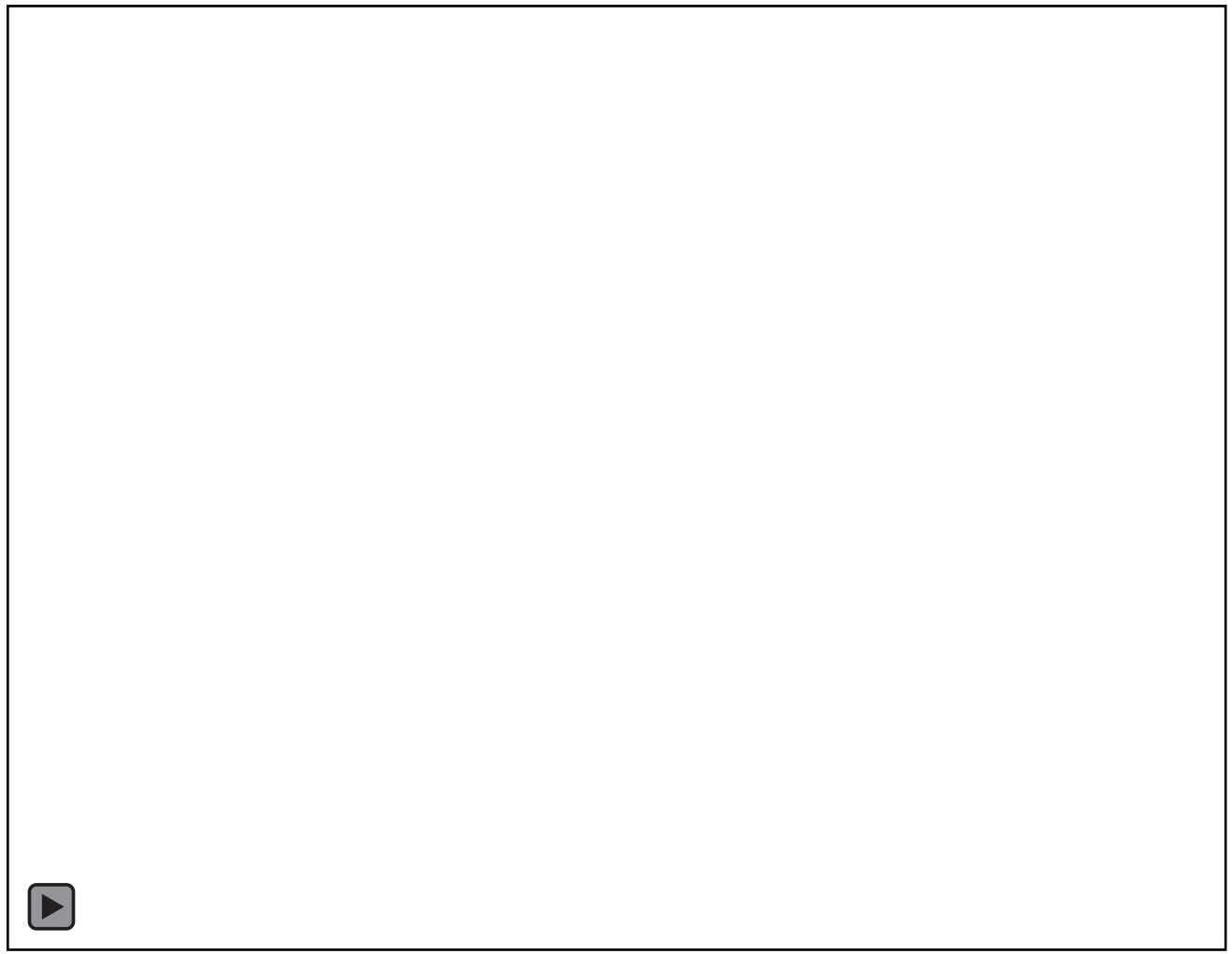
VALIDATION OF CONFIGURATION PLATFORM

EXAMPLE USE-CASE OF CONFIGURATION PLATFORM

Function Block 4

Sys **Plt**

Configuration for Circular Manufacturing System



Based on the concept, transferred to a user-friendly dashboard for implementation

SUMMARY

CONCLUSION & NEXT STEPS

- ✓ Stepwise inspection with historical data from digital battery passport helps early sorting of Re-X decision making, thus make the process more efficient and effective.
- ✓ Virtual commissioning not only enable the quick validation and analysis of the layout and configuration but also support iterative development in detail.
- ✓ Configuration platform can effectively support the evaluation and selection of alternative system configurations under uncertainty, enabling informed decision-making for the circular manufacturing systems.

- ❑ Testing the framework in a real factory through industrial piloting
- ❑ Linking all data across functional blocks to enable advanced analytics and dynamic optimisation
- ❑ The framework will also be extended to include further Re-X processes, such as the disassembly of battery packs and modules

THANK YOU FOR YOUR ATTENTION!





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UNIVERSITY OF TWENTE.

Conceptual foundation of the circular factory

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Doctoral student
(Circular factory)

SCAN ME

Funded by:

KK-stiftelsen

Co-authors:

Mats Jackson
Monica Bellgran

Background

Unsustainable Linear Production

- Industry relies on the “take–make–dispose” model.
- Leads to high resource use, waste, and environmental impact.
- Resource extraction ↑, waste expected to grow sharply (70% by 2050)



Global Shift Toward Circular Economy

- Driven by UN-SDGs translated into EU policies and customer demand for sustainable products
- CE Goal: retain valu[illegible]uce resour[illegible]educe [illegible]ronmental [illegible]

Factory: *Entity that host one or several production systems (Wiendahl et al., 2015)*



Problem formulation

Limits of Traditional Factories:

- Designed only for linear, stable production flows.
- Business models that do not promote takeback schemes
- Processes that cannot handle returned products due to uncertainties.
- Circular processes → complex, non-deterministic.

The need for factory design that:

- Integrates linear & circular processes.
- Retain value across multiple lifecycles
- With scalable & automated circular process
- With a robust system that manages uncertainties
- Embedding circularity principles into its production development.

Practical gap

State of the art……

- Circular processes in an isolated facility.
- Manual, mainly restricted to low-wage countries, where small batch production series.
- Reprocessed goods sold in secondary markets.
- Limited adoption, only 7.2% of reprocessed goods sales across key EU economic sectors in 2023.

Purpose/RQs



Build theoretical understanding of the circular factory concept.

RQ1: What gap exits in the current literature on the circular factory concept?

RQ2: What is a circular factory?

Conceptual approach

- Backward snowballing and theory-driven search using keywords.
- Literature screening
- Literature synthesis and analysis
- Organize findings into themes, patterns, or categories

Research Gap

Table 1: Factory circularity research stream

Research stream	References	Brief summary
Circular economy and resource loops systems	(Geissdoerfer et al., 2017; Kirchherr et al., 2017; Korhonen et al., 2018; Reike et al., 2018a; Stahel, 2016)	Broad system and policy level conceptualization of circular economy principles, resource loops, and value retention strategies.
Remanufacturing and value recovery operations	(Asif et al., 2012; Barquet et al., 2013; Tolio et al., 2017; Vijayaraghavan et al., 2013)	Focuses on demanufacturing, remanufacturing, and closed-loop production operations, while addressing reverse flows and uncertainties in product quality.
Manufacturing systems design, flexibility and reconfigurability	(Andersen et al., 2016; Asadi et al., 2019; Hassan et al., 2024; Jackson & Johansson, 2003).	investigates flexible, modular, and reconfigurable production systems that enable long system lifecycles and adaptation.
Product development and design for circularity.	(Bocken et al., 2016a; Franconi et al., 2022; Tusch et al., 2025)	Discusses circular design strategies, multi-generation products, and life-cycle-based design decision-making.
Circular Supply chain and business model	(Amir et al., 2023; Farooque et al., 2019; Geissdoerfer et al., 2018; Schroeder et al., 2019)	examines coordination of forward and reverse supply chains and circular business model innovation.
Digitalization, knowledge modelling, and control systems	(Bail et al., 2025; Roci et al., 2022; Thapa et al., 2025)	Exploration of digital twins, control architecture, and data-driven decision-making for resilient circular factories and processes.
Human, organizational, and social systems	(Bellgran & Säfsten, 2010; Horváth & Kemser, 2026; Slama et al., 2022)	addresses human-centered design, organizational structures, and social sustainability in production systems.
Circular facory vision & co-design	(Lanza, Deml, et al., 2024; May et al., 2023)	Integration of linear and circular production enabling perpetual product use and value retention; Product-Production-CoDesign

Production System Research
-Focused on throughput, efficiency, layout, automation, and control under stable assumptions.

Circular Economy Research
- circular supply chain management, remanufacturing, circular business models and circular product design.

Lack of theoretical and empirical conceptual definition of circular factories from a system perspective (production system & ecosystem)



What is a circular factory?

As a Production System host

Can process, reprocess, across multiple product and production system lifecycles with the aid of human and technological resources integrating linear and circular processes within shared system architectures.

As an Ecosystem actor

Coordinates material flows, information and value across multiple actors : customers, logistics partners, reverse logistics actors, service providers, and policy frameworks.

Definition: A circular factory is a facility within a broader ecosystem with one or more socio-technical circular production systems that integrates linear and circular processes, with capabilities required to create new and retain existing value across multiple product and production system lifecycles, to minimize raw materials usage, waste generation and environmental burden.

Five Main defining characteristics

1 **Socio-Technical System**

People, processes and technology are equally important

2 **Embedded within an Ecosystem**

Operational efficiency depends on business models, partners and value networks and regulatory standards.

3 **Integrated Linear and Circular Processes**

The production system integrates linear and circular processes rather than functioning separately

4 **Multi-Lifecycle Value Retention**

Product and production systems lifecycle can be prolonged, reconfigured or reused

5 **Resource & Environmental Orientation**

Consistent with broader circular economy and sustainable manufacturing goals

Conceptual framework

What does it mean in practice in the context of circular factory?

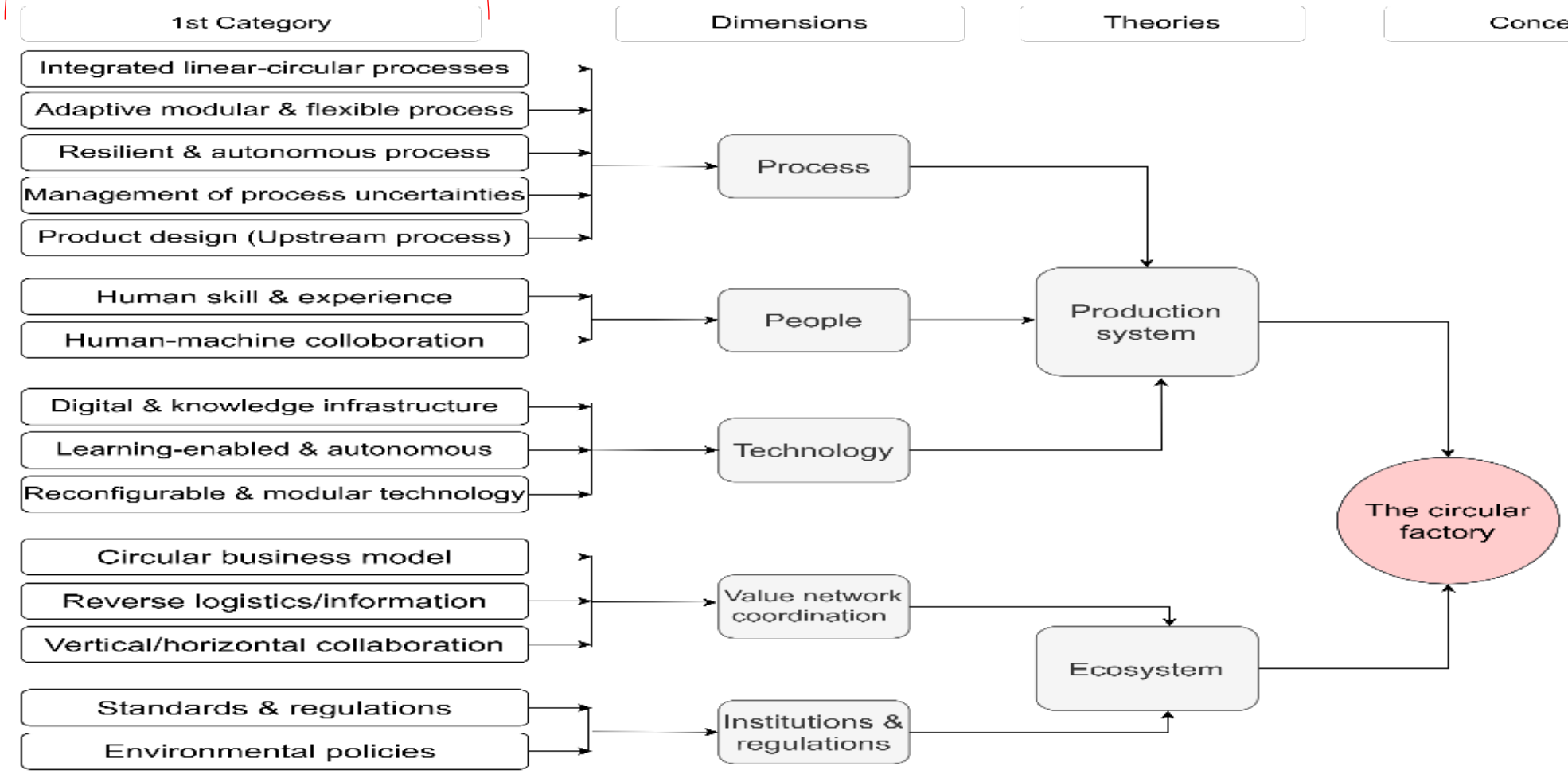


Figure 1: Conceptual framework with dimensions and key attributes for circular factory

Conclusions & Future Research Directions

Key Contributions

- The operational perspective
- The ecosystem Perspective

Future Research Agenda

- Empirical validation and comparative analysis with linear model.
- Identify and validate preconditions for circular factory development.
- Longitudinal and multi-case studies to capture dynamic evolution towards the circular factory to establish guidelines for circular factory design.

Mälardalens universitet

Thank you for your attention

Partial-to-Full Registration of Spatial Information Linked to Digital Product Passports for WEEE Disassembly

Niels Griffioen, Jef R. Peeters, Wim Dewulf

Department of Mechanical Engineering

KU Leuven Leuven,

Belgium

Current WEEE Treatment Limits High-Value Recovery

Current Dominant Approaches

- Manual dismantling
- Mechanical processing



Manual depollution



Shredding + mechanical separation

Circular Manufacturing

Selective component recovery

- Spare part reuse
- Remanufacturing
- Targeted CRM extraction

Autonomous demanufacturing:

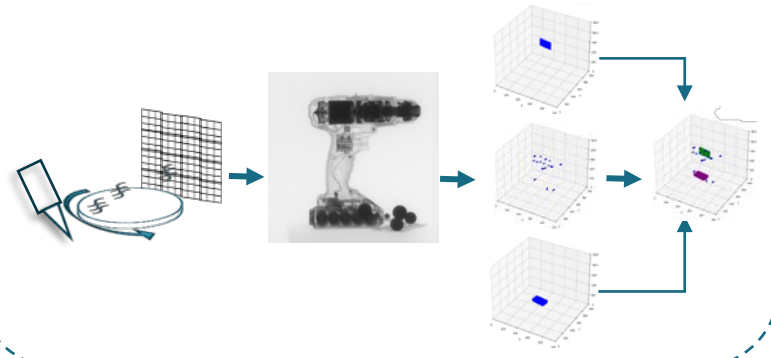
→ Requires precise spatial information

Asynchronous spatial-information enriched DPP

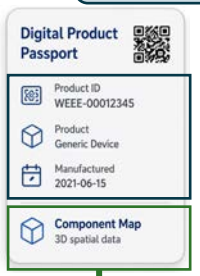
Asynchronous

Offline ⟷ In-process

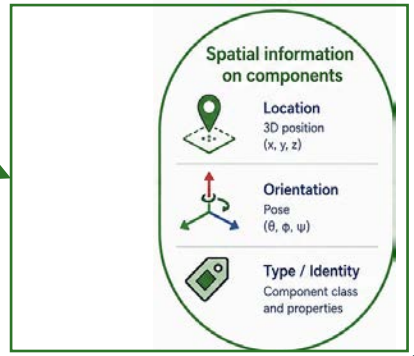
Collection [1][2]



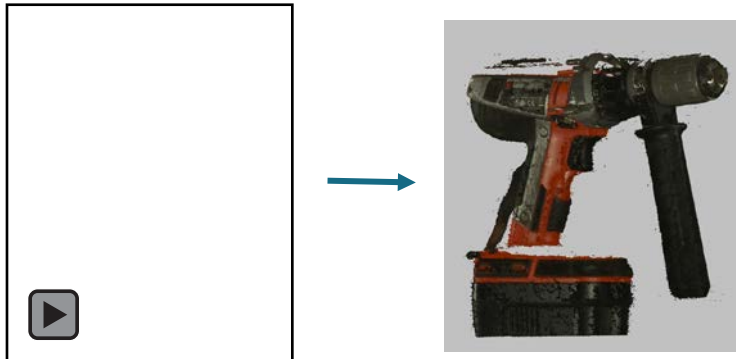
Storage*



Essential +
recommended
Enrichment



Use



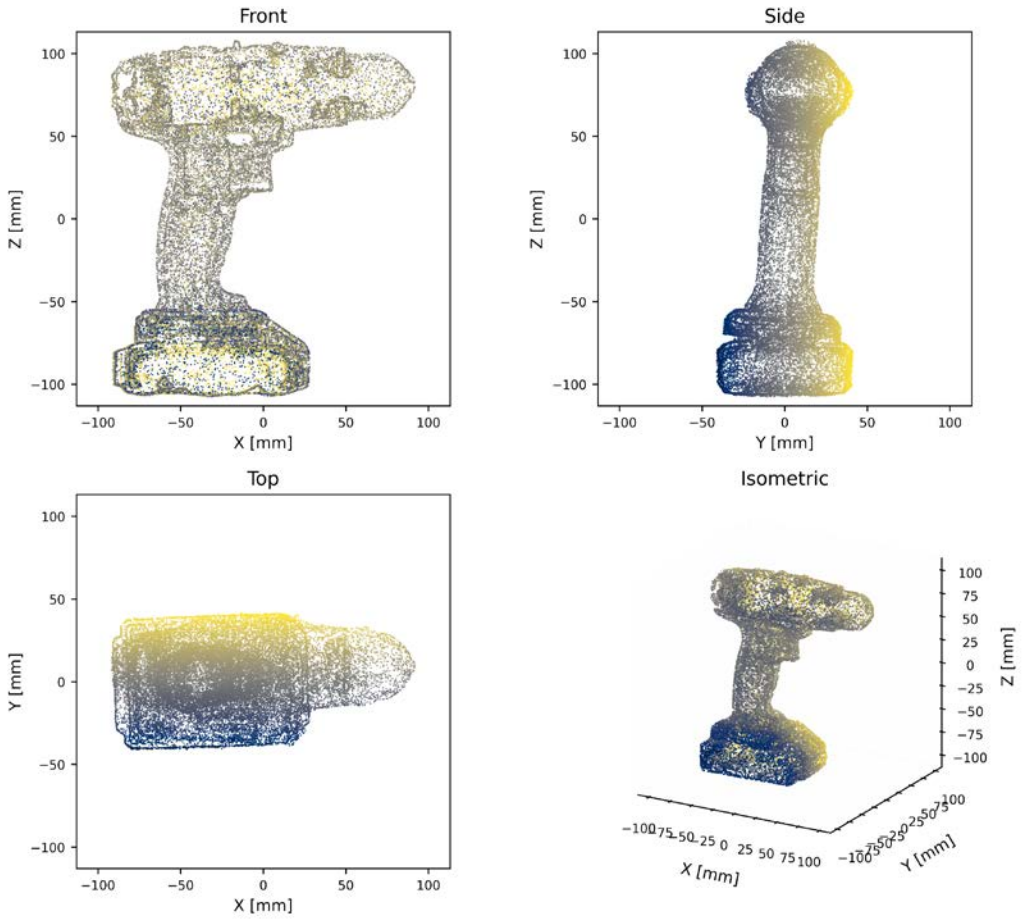
Alignment to live sensor data

*JRC methodology, March 2026

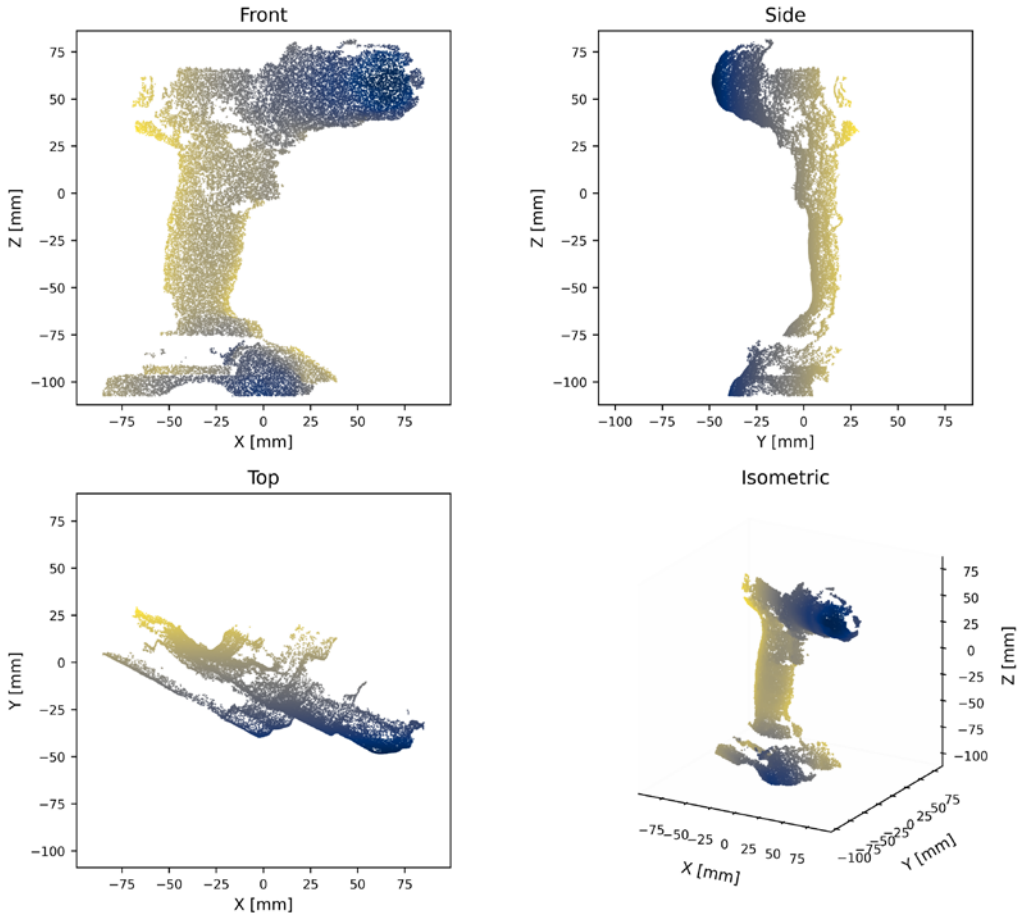
[1] N. Griffioen, A. Coopman, W. Sterkens, J. R. Peeters, and W. Dewulf, "Screw Localization Accuracy in CT-Based Predictions for De-Manufacturing," *Procedia CIRP*, vol. 140, pp. 563–568, Jan. 2026, doi: 10.1016/j.procir.2026.05.095.
[2] N. Griffioen, W. Sterkens, J. R. Peeters, and W. Dewulf, "Extending Digital Product Passports for EEE: Defining 3D Component Locations from X-ray Computed Tomography for Robotic Disassembly," *Manuscript submitted for publication*, 2026.

Partial-to-full registration problem

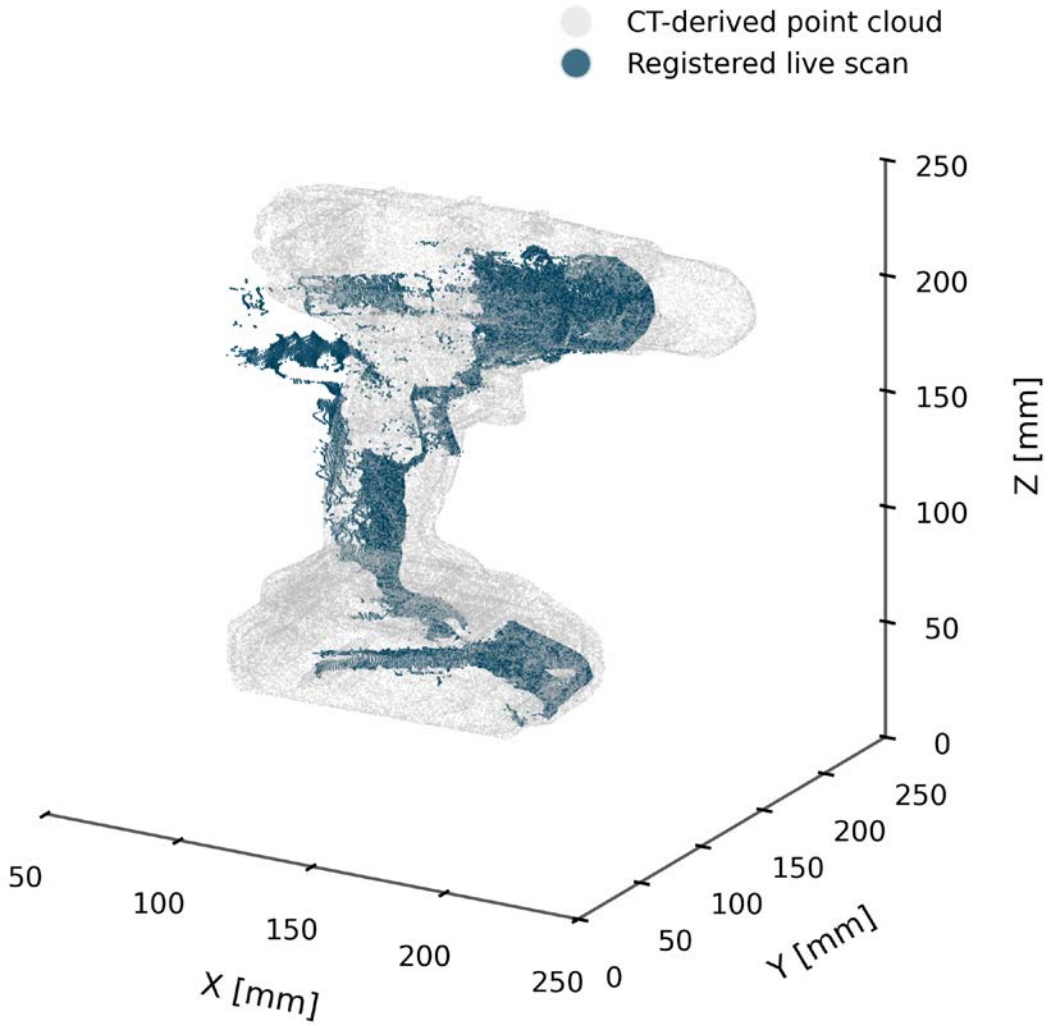
Offline: Full information



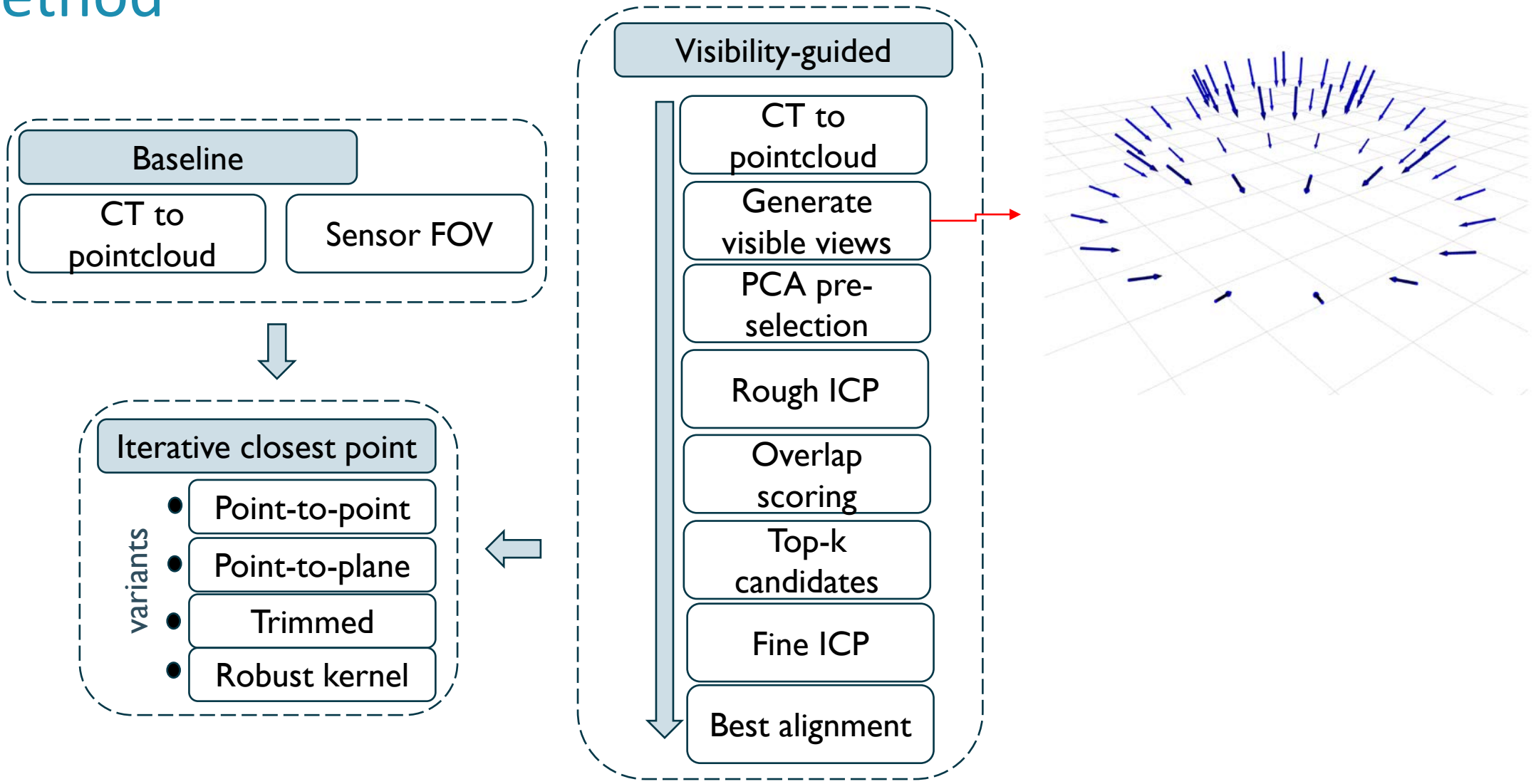
Live: FOV information



Direct partial-to-full registration



Method


Baseline
CT to pointcloud
Sensor FOV
Iterative closest point
variants
Point-to-point
Point-to-plane
Trimmed
Robust kernel
Visibility-guided
CT to pointcloud
Generate visible views
PCA pre-selection
Rough ICP
Overlap scoring
Top-k candidates
Fine ICP
Best alignment

Data

Case study

- 15 WEEE devices
- Complete XCT reference model
  - ❑ Outer shell converted to pointcloud
- Partial live observations
  - ❑ 20 line-of-sight pointcloud captures each

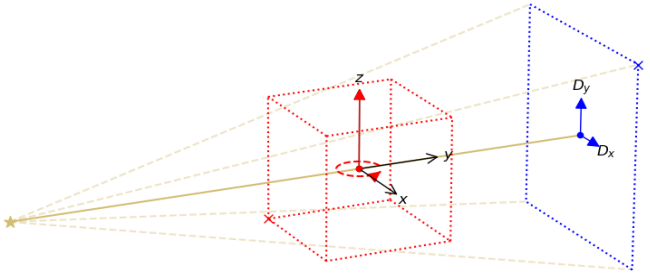
Data:

- Zivid 2+ mr60 structured-light camera
- Nikon XT H 450 industrial XCT system



a) Examples of WEEE devices





b) XCT system

Metrics

1 Fitness

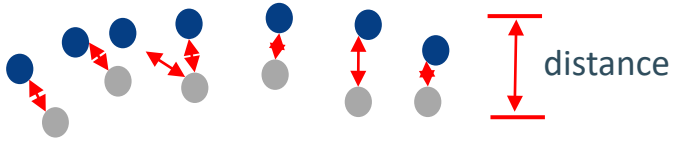
High fitness



Low fitness

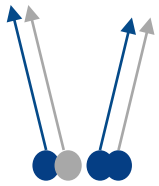


2 $d_{sym-med}$: Median symmetric distance

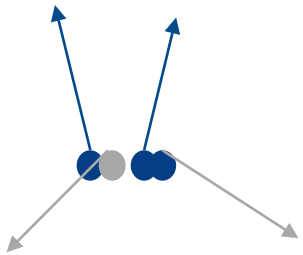


3 C_n: Normal consistency

High consistency

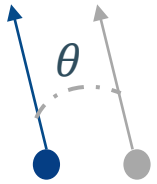


Low consistency

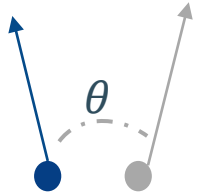


4 C_{angle}: Normal angle error

Low angle error

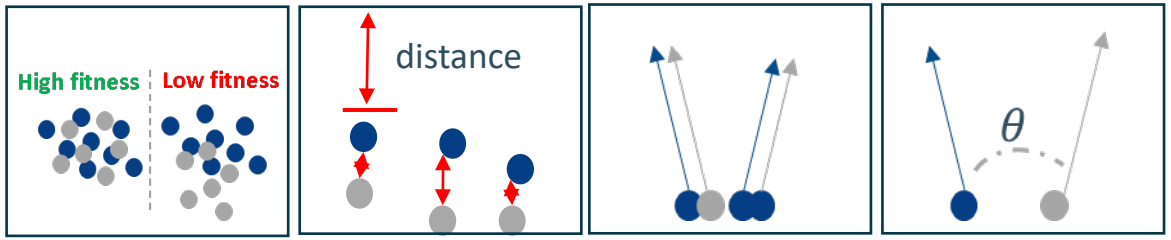


High angle error



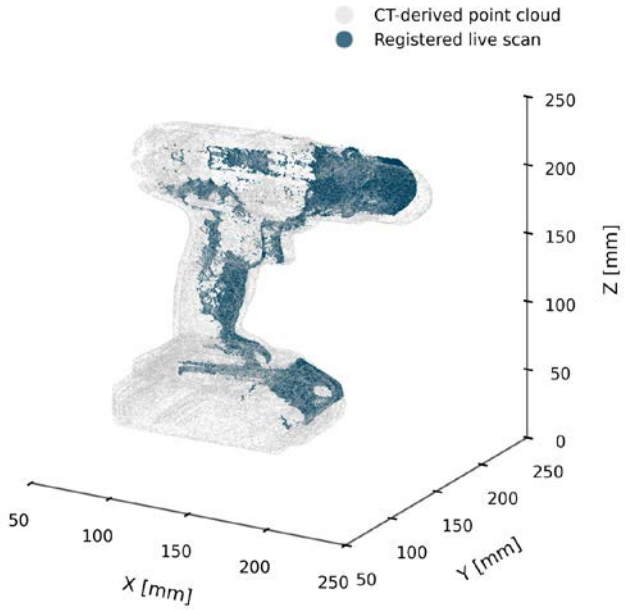
θ = angle between normals

Results

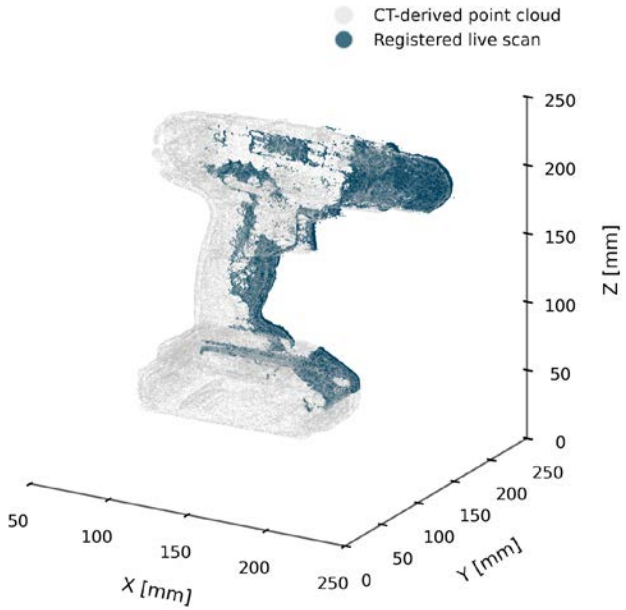


	Method	N	Time (s)	Fitness	$d_{sym-med}$	C_n	C_{angle}
Direct	Point-to-point ICP	300	1.1 ± 0.2	0.12 ± 0.09	16.32 ± 6.42	0.24 ± 0.25	48.97 ± 18.56
	Point-to-plane ICP	300	2.2 ± 0.6	0.16 ± 0.14	27.00 ± 78.69	0.32 ± 0.30	42.30 ± 20.73
	Trimmed ICP	300	0.3 ± 0.2	0.09 ± 0.07	20.89 ± 10.24	0.22 ± 0.26	53.32 ± 21.49
	Robust Kernel ICP	300	2.3 ± 0.6	0.16 ± 0.13	26.59 ± 70.66	0.32 ± 0.29	42.48 ± 20.36
Visibility-guided	Point-to-point ICP	300	2.3 ± 0.3	0.35 ± 0.19	8.10 ± 6.44	0.62 ± 0.28	24.11 ± 16.35
	Point-to-plane ICP	300	3.8 ± 1.1	0.34 ± 0.20	13.82 ± 35.70	0.69 ± 0.27	18.04 ± 11.16
	Trimmed ICP	300	2.1 ± 1.1	0.32 ± 0.18	8.71 ± 6.13	0.61 ± 0.28	24.24 ± 15.29
	Robust Kernel ICP	300	4.1 ± 1.0	0.34 ± 0.20	9.67 ± 12.94	0.67 ± 0.26	18.95 ± 11.05

Comparison



(a)
Direct registration



(b)
Visibility-guided registration

Conclusion

Findings:

- Direct ICP is sensitive to limited overlap
- Visibility guided registration reduces the mismatch

Key takeaway:

- Selecting the correct visible region using a computationally efficient pre-ICP step

Future work:

- Translate registration errors into robotic task errors.
- Larger and more diverse WEEE datasets
- Learned Feature-Based Global Registration methods
- Repetitive surfaces (without distinctive geometry)

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Re- & Demanufacturing Lab

Linkedin

Q&A

Contact details:
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Life Cycle Engineering team – Manufacturing Metrology team
Department of Mechanical Engineering
Faculty of Engineering Science & Technology

JRC methodology - 3 tiers of information



Institute for Machine Tools and Industrial Management (*iwb*)
TUM School of Engineering and Design
Technical University of Munich

Current challenges in remanufacturing operations

An expert-based study

Vincent Schröttle, Béla Goldbrunner, Lasse Streibel, Nora Reinbold, Christina Reuter

9th June, Karlsruhe

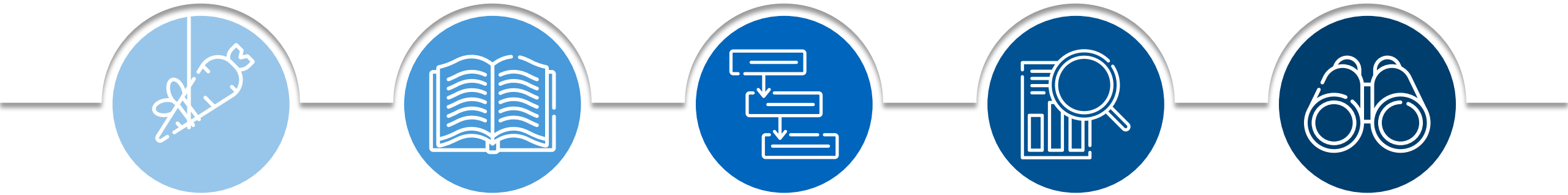
Conference on Circular Production Systems and Technologies (CCPT)



Institute for Machine Tools and Industrial Management (*iwb*)
TUM School of Engineering and Design
Technical University of Munich



Agenda



MOTIVATION

STATE OF THE ART

METHODOLOGY

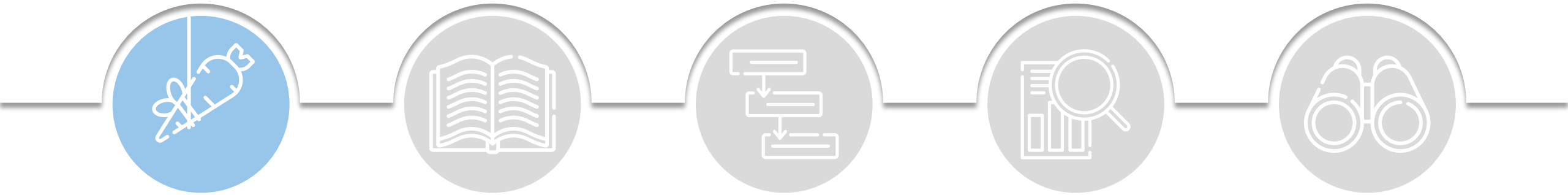
RESULTS

DISCUSSION AND OUTLOOK

Institute for Machine Tools and Industrial Management (*iwb*)
TUM School of Engineering and Design
Technical University of Munich



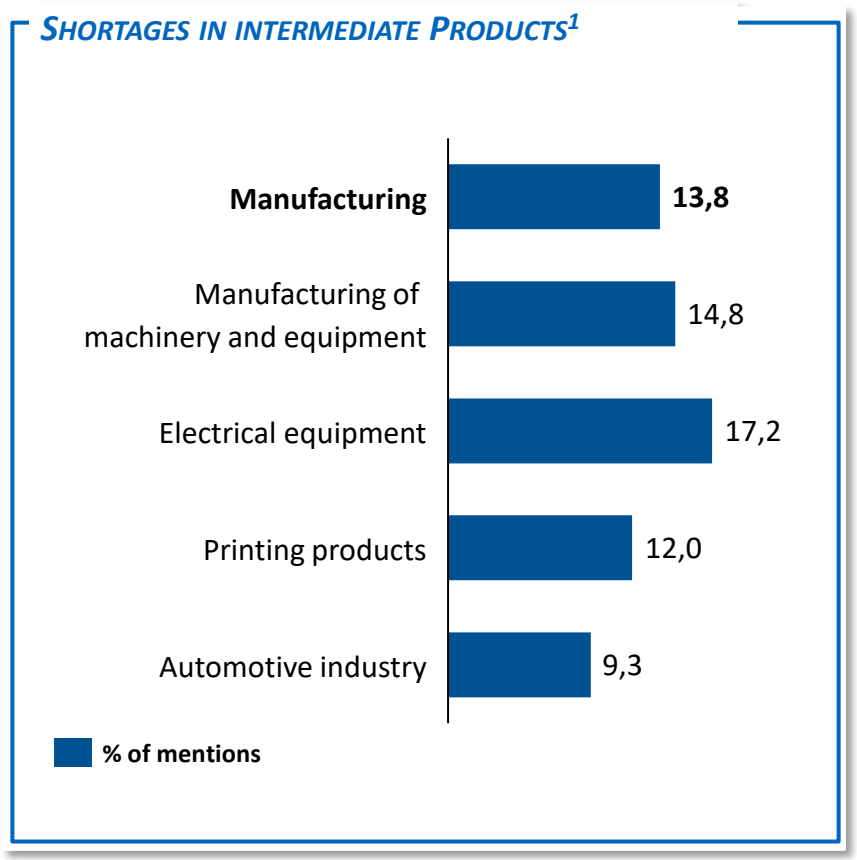
Agenda



MOTIVATION

Currently, German companies are facing severe material shortages for which remanufacturing is a solution.

Motivation

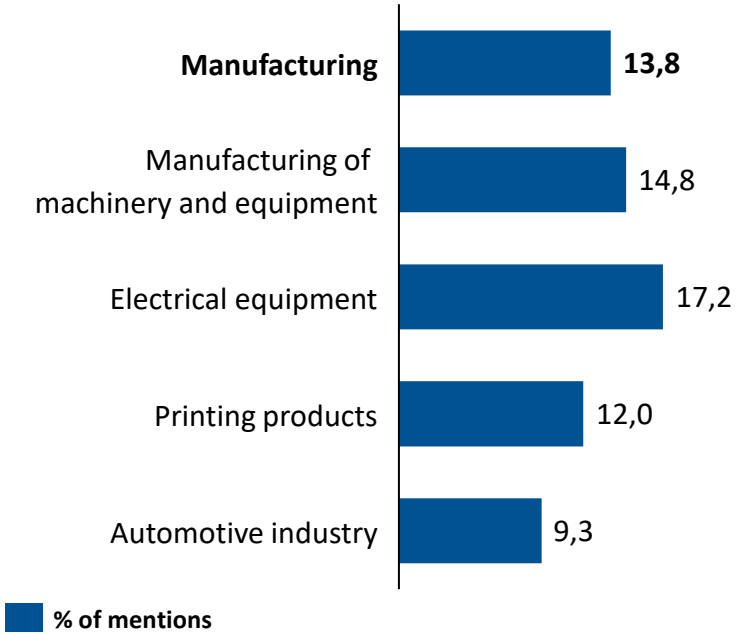


Currently, German companies are facing severe material shortages for which remanufacturing is a solution.



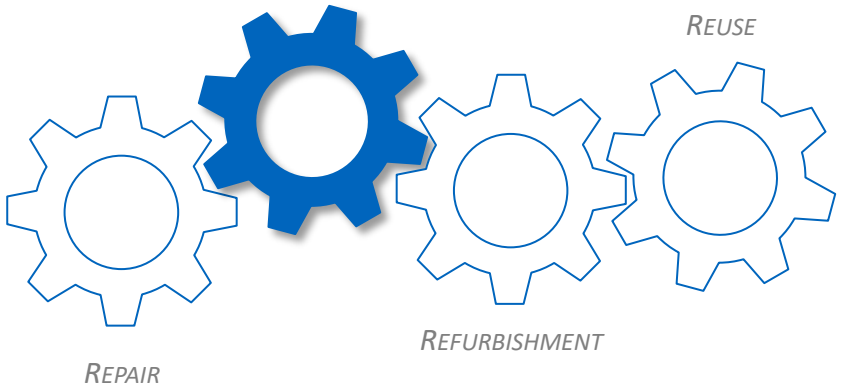
Motivation

SHORTAGES IN INTERMEDIATE PRODUCTS[1]



Circular approaches are needed in order to retain the high degree of value and material embedded into products during manufacturing[1]

REMANUFACTURING



CIRCULAR ECONOMY STRATEGIES

Remanufacturing aims at keeping products in use by restoring their quality and offers a multitude of potential benefits.



Motivation

Definition of Remanufacturing[1]

- Used products are utilized as inputs and brought back to a quality level meeting or exceeding the quality standards of a product made from virgin materials.
- typically involves a process consisting of disassembly, inspection, reprocessing and reassembly

Potential Benefits[2, 3]

- reduced dependency on raw / intermediate materials
- lower cost (e.g., for energy)
- minimized environmental impact

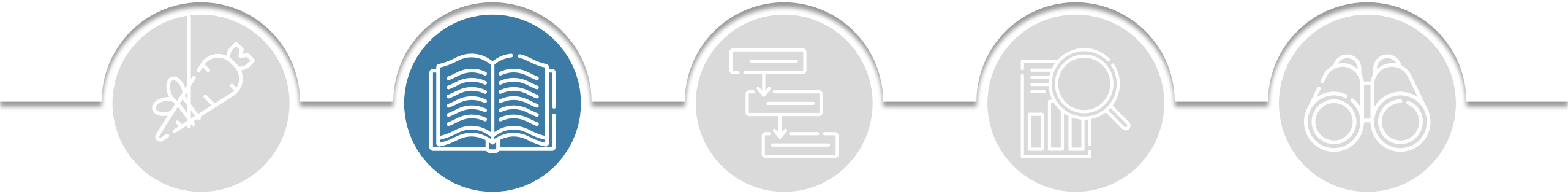
➢ **Estimated European remanufacturing market potential: EUR 100 billion by 2030[4] (from EUR 31 billion in 2025)**

The aforementioned growth will be partially driven by new market entrants, but also existing remanufacturers expanding their operations. To enable this, the challenges affecting existing remanufacturing operations must be identified.

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1 Kurilova-Palisaitiene et al. 2018
2 Steinhilper 1998
3 Paul et al. 2025
4 European Commission 2025

Agenda



STATE OF THE ART

In the literature, challenges are analyzed using systematic reviews and primary empirical studies, both of which are lacking operational depth.



State of the art concerning challenges in remanufacturing operations

Systematic Reviews

- Matsumoto et al. (2016) highlight the existence of both drivers and barriers for remanufacturing through a structured literature analysis.
- Gunasekara et al. (2018) identify barriers, like sourcing replacement parts or a lack of research in remanufacturing, and structure them according to the respective addressee responsible for providing solutions.

Primary empirical Studies

- Gunasekara et al. (2020) utilize semi-structured interviews to identify current issues in the Sri Lankan automotive remanufacturing industry.
- Govindan (2022) utilize interviews to identify barriers specifically connected to the blockchain technology in remanufacturing.
- Paul et al. (2025) validate pre-identified challenges in remanufacturing using interviews.
- Kurilova-Palisaitiene et al. (2018) and Mohamed Nasir et al. (2021) employ case studies to identify challenges.

Limitations

Findings derived from review-based evidence rather than primary shopfloor data raise questions about their practical validity.

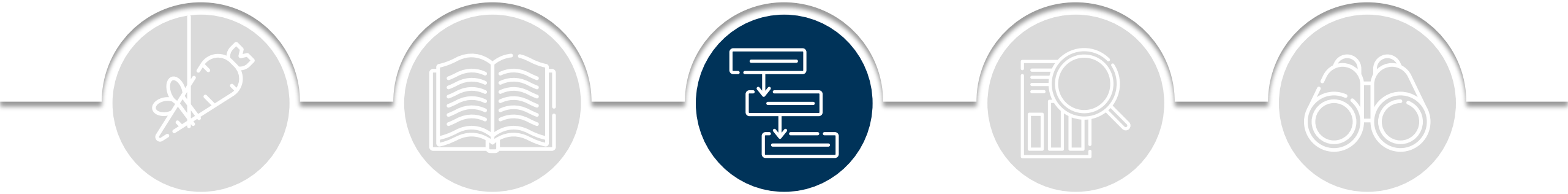
Empirical studies are small-scale or limited to specific areas of interest (regions, technologies).

Operational issues are still overlooked, potentially due to the scientific interest in remanufacturing only growing recently[1].

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1 Caterino et al. 2025

Agenda



METHODOLOGY

To address the research gap, expert interviews following the approach of Jäger and Reinecke (2009) are used.

Methodology based on Jäger and Reinecke (2009)

Filling the Research Gap

- Solution approach: discovering and understanding problems and challenges through the employment of experts[1]
- Method: expert interviews featuring a semi-structured interview guide offering the possibility to keep a certain level of comparability while simultaneously being able to adapt during the interview[1]

➢ **In this case, the experts act as proxies for their companies and their respective challenges.**

Methodology by Jäger and Reinecke (2009)

- Given the absence of clear and objective guidelines, a well-established methodological framework can enhance the reliability and validity of expert interviews by ensuring a systematic and transparent approach[2].

➢ **Jäger and Reinecke (2009) offer a comprehensive approach for designing and conducting expert interviews (see Fig. 1).**

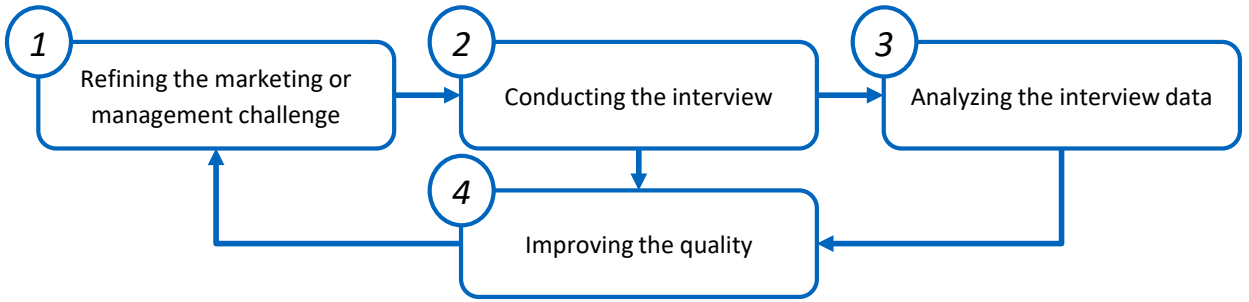


Fig. 1: Methodology steps (boxes) and their sequence (arrows)

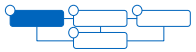
1 Jäger and Reinecke (2009) 2 Meuser and Nagel 2009

In a first step, the research problem is further clarified and used to select appropriate experts.



Methodology based on Jäger and Reinecke (2009) – Details

STEP 1: CLARIFYING THE RESEARCH PROBLEM



1. Literature shows a clear lack of analysis in the domain of operational challenges
2. As a result, the focus was primarily set on Germany with expert selection according to the research gap:
    1. Mandatory knowledge of operational processes
    2. Focus on key decision-makers
    3. Mandatory ongoing involvement in remanufacturing, either through in-house remanufacturing activities or through active participation in remanufacturing-related processes (e.g., consulting)

Experts were from diverse industry domains, representing a variety of remanufacturing processes.



Methodology based on Jäger and Reinecke (2009) – Details

Step 1: Clarifying the Research Problem



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Table 1: Overview of participating experts

No.	Job description	Company	Company domain
E1	Manager repair and reman. division	1	Industrial automation technology
E2	Team lead reman.	2	Automotive components
E3	Reman. plant manager	3	OEM industrial engines
E4	Product manager service	3	OEM industrial engines
E5	Project manager circularity	4	Construction equipment
E6	Manager energy solutions	5	OEM intralogistics battery solutions
E7	Head of operations planning reman. plant	6	OEM industrial engines
E8	Manager refurbishment operations	7	OEM intralogistics solutions
E9	Director business management and development with a focus on circularity	8	OEM printing solutions
E10	Senior consultant	9	Automotive / Circularity consulting
E11	Senior process engineer	10	OEM aerospace components
E12	CEO	11	Automotive and drivetrain component reman.
E13	Lead technical support department	11	Automotive and drivetrain component reman.
E14	Sales lead aftersales mobile hydraulics	12	OEM hydraulic components
E15	Manager repair and sustainability	13	Industrial automation technology
E16	CEO	14	Medical equipment reman.
E17	Reman. plant manager	15	Industrial automation technology
E18	Operations manager reman.	16	OEM automotive components
E19	Technology manager reman.	16	OEM automotive components

1 Jäger and Reinecke (2009) 2 Meuser and Nagel 2009

The interviews were conducted using a semi-structured interview guide that was pretested with academic experts.



Methodology based on Jäger and Reinecke (2009) – Details

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Step 2: Conducting the Interviews

- Questionnaire structured into three parts: data handling, general questions, and questions targeting challenge identification
- Pretesting with academic experts
- During interviewing, specific focus on avoiding unwanted bias, for example, by not asking suggestive questions[1]

1 Qu and Dumay 2011

Data analysis was done using two distinct methods to identify directly mentioned challenges and those only visible through comparison.



Methodology based on Jäger and Reinecke (2009) – Details

Step 1: Clarifying the Research Problem

1. Literature shows a clear lack of analysis in the domain of operational challenges
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Step 3 & 4: Data Analysis and Quality Improvement

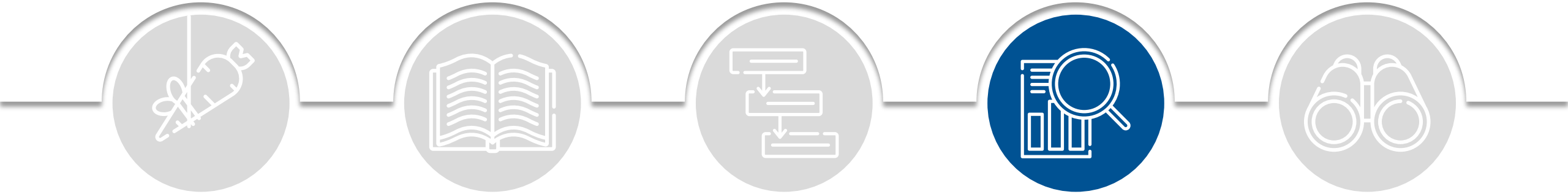
- 17 interviews were transcribed using the aTrain tool, 2 documented through manual note-taking
- Interview material was then anonymized and provisionally analyzed in order to identify any issues needing improvement
- **Final content analysis was done utilizing two separate methods:**

1 ***Structuring qualitative content analysis based on inductive categorization following Kuckartz (2014)***

2 ***Cross-case analysis reconstructing and comparing company-specific process configurations***

1 Qu and Dumay 2011

Agenda



RESULTS

In total, 30 distinct challenges were identified and subsequently clustered.



Results – Cluster overview

IN TOTAL EIGHT CHALLENGE CLUSTERS (CC) WITH A TOTAL OF 30 INDIVIDUAL CHALLENGES (C1 TO C30)

SIX CHALLENGE CLUSTERS WITH DIRECTLY MENTIONED CHALLENGES STEMMING FROM THE QUALITATIVE CONTENT ANALYSIS

TWO CHALLENGE CLUSTERS WITH CHALLENGES STEMMING FROM CROSS-CASE COMPARISON

Eight distinct clusters show the wide variety of challenges in the operational domain.

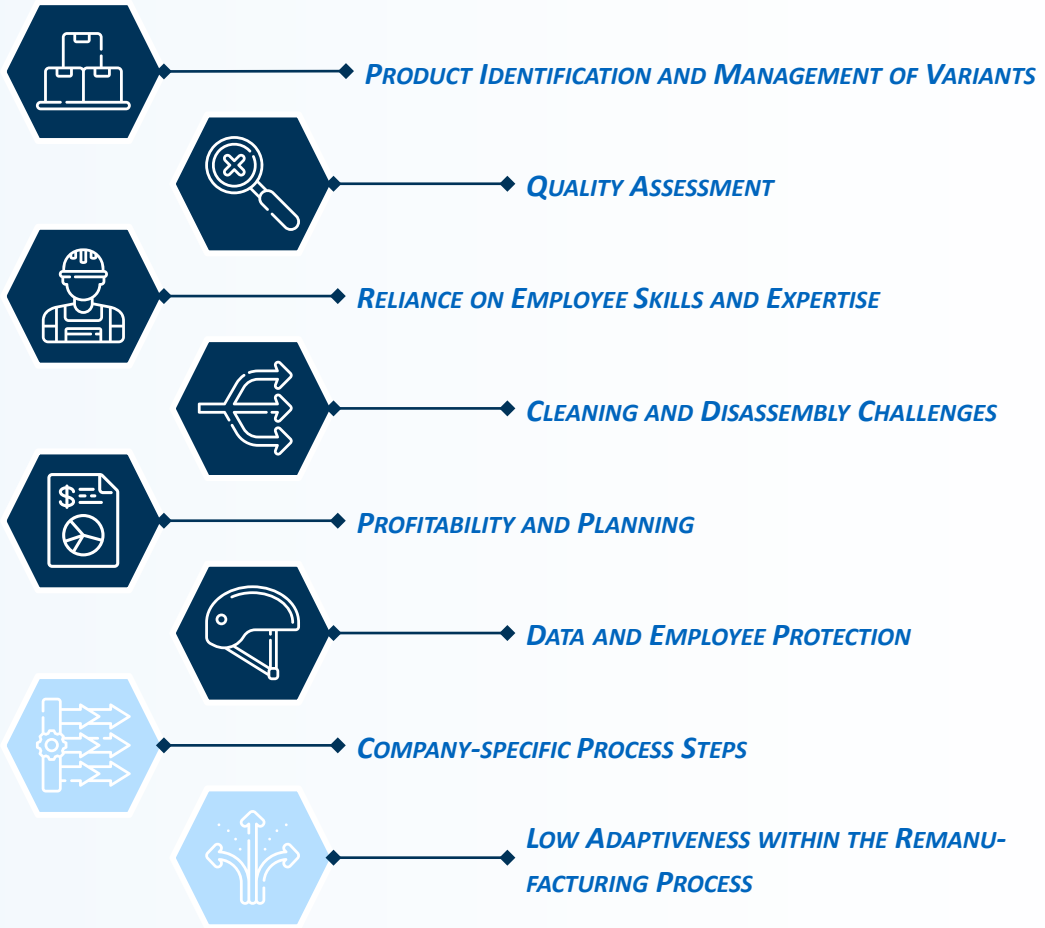


Results – Cluster overview

In total eight Challenge Clusters (CC) with a total of 30 individual Challenges (C1 to *C30*)

Six Challenge Clusters with directly mentioned challenges stemming from the qualitative content analysis

Two Challenge Clusters with Challenges stemming from cross-case comparison



Clusters CC1 and CC2 include challenges connected to product and variant management as well as quality assessment.



Results – Clusters CC1 and CC2

Product Identification and Management of Variants

- *C1* – Challenging initial identification due to missing identification plates or extensive cleaning necessary
- *C2* – Large number of potential variants (up to 400,000 in one case) complicating variant handling
- *C3* – Revisions to different parts of the same type requiring varying lines of action
- *C4* – Unauthorized and undocumented changes from customers introducing unknown parts

Quality Assessment

- *C5* - Manual inspection with only rudimentary tools, like reference pictures
- *C6* – Lack of objective and quantifiable measures to assess issues like scratches and discoloration
- *C7* – Determination of optimal inspection point to avoid unnecessary and irrecoverable effort
- *C8* – Challenging assessment of individual components due to physical and other interaction effects between components

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Challenge cluster derived from qualitative content analysis

Challenge cluster derived from process comparison

Clusters CC3 and CC4 demonstrate the importance of employees as well as process-related challenges, respectively.



Results – Clusters CC3 and CC4

Reliance on Employee Skills and Expertise

- *C9* – High variability of processes making automation challenging or impossible
- *C10* – High degree of discretionary power for the employee
- *C11* – Long training times due to a lack of support systems and training-on-the-job
- *C12* – Varying qualification levels due to unstructured training processes
- *C13* - Loss of knowledge due to retirement of experienced workers and low degree of knowledge formalization
- *C14* – Reluctance of skilled workers to join remanufacturing processes due to negative preconceptions

Cleaning and Disassembly Challenges

- *C15* – Core-specific issues changing necessary effort for individual disassembly
- *C16* – Unknown damages posing a risk for employees during disassembly
- *C17* – Lacking integration of disassembly during product design
- *C18* – Low degree of planning in cleaning
- *C19* – Unintended damages due to mishandling during disassembly and cleaning

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Challenge cluster derived from qualitative content analysis

Challenge cluster derived from process comparison

Clusters CC5 and CC6 include challenges associated with profitability and planning, as well as protection of data and employees.



Results – Clusters CC5 and CC6

Profitability and Planning

- *C20* – Low return numbers of individual variants complicating batching
- *C21* – Identification and selection of necessary replacement parts
- *C22* – High cost pressure along all operational processes due to customer willingness to pay or competition from new products

Data and Employee Protection

- *C23* – Sensitive or important data stored on the devices to be remanufactured
- C24 – Protection of employees to minimize risk to health and safety

Clusters CC7 and CC8 stem from cross-case comparison of remanufacturing processes.



Results – Clusters CC7 and CC8

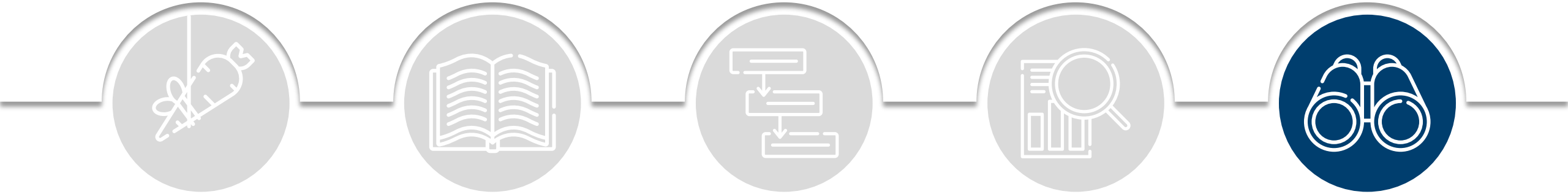
Company-specific Process Steps

- *C25* – Distinct process configurations within companies leading to different process requirements
- *C26* – External requirements like traceability due to certifications or regulation affecting process configurations
- *C27* – Varying structural integration of remanufacturing within the company as a whole

Low Adaptiveness within the Remanufacturing Process

- *C28* – Static support information not adapting to dynamic information or specific employee support needs
- C*29* – Reactive provisioning of information
- *C30* – Disregard for potentially important operational decision dimensions

Agenda



DISCUSSION AND OUTLOOK

This paper provides valuable insight into current remanufacturing operations, adding both detail and comprehensiveness to the literature.



Main limitations and directions of further research

THIS PAPER PROVIDES A COMPREHENSIVE AND UP-TO-DATE ANALYSIS OF OPERATIONAL CHALLENGES BY CONDUCTING EXPERT INTERVIEWS WITH A DIVERSE SET OF REMANUFACTURERS HIGHLIGHTING BOTH UNDERREPORTED ISSUES AS WELL AS ADDING OPERATIONAL DETAIL TO PARTIALLY KNOWN CHALLENGES

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Future research should focus on detailing operational challenges and developing solutions.



Main limitations and directions of further research

THIS PAPER PROVIDES A COMPREHENSIVE AND UP-TO-DATE ANALYSIS OF OPERATIONAL CHALLENGES BY CONDUCTING EXPERT INTERVIEWS WITH A DIVERSE SET OF REMANUFACTURERS HIGHLIGHTING BOTH UNDERREPORTED ISSUES AS WELL AS ADDING OPERATIONAL DETAIL TO PARTIALLY KNOWN CHALLENGES

THIS PAPER ONLY SERVES AS AN OVERVIEW OF CHALLENGES DUE TO THE TRADE-OFF BETWEEN INTERVIEW DEPTH AND LIMITING TIME BURDEN FOR THE PARTICIPANTS

MORE IN-DEPTH ANALYSIS OF OPERATIONAL ISSUES INCLUDING A BROADER SCOPE AND QUANTITATIVE INSIGHTS

ADRESSING THE CHALLENGES THROUGH STRUCTURED CONCEPTS TO SUPPORT ONGOING IMPROVEMENT OF EXISTING REMANUFACTURING PRACTICES

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Thank you for your attention!

I am looking forward to your questions.



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Assessing the Environmental Impact of a Circular Supply Chain: The Case of the Battery Cathode

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Transition to Electric Vehicles Challenges: Rising Demand + Raw Materials Scarcity

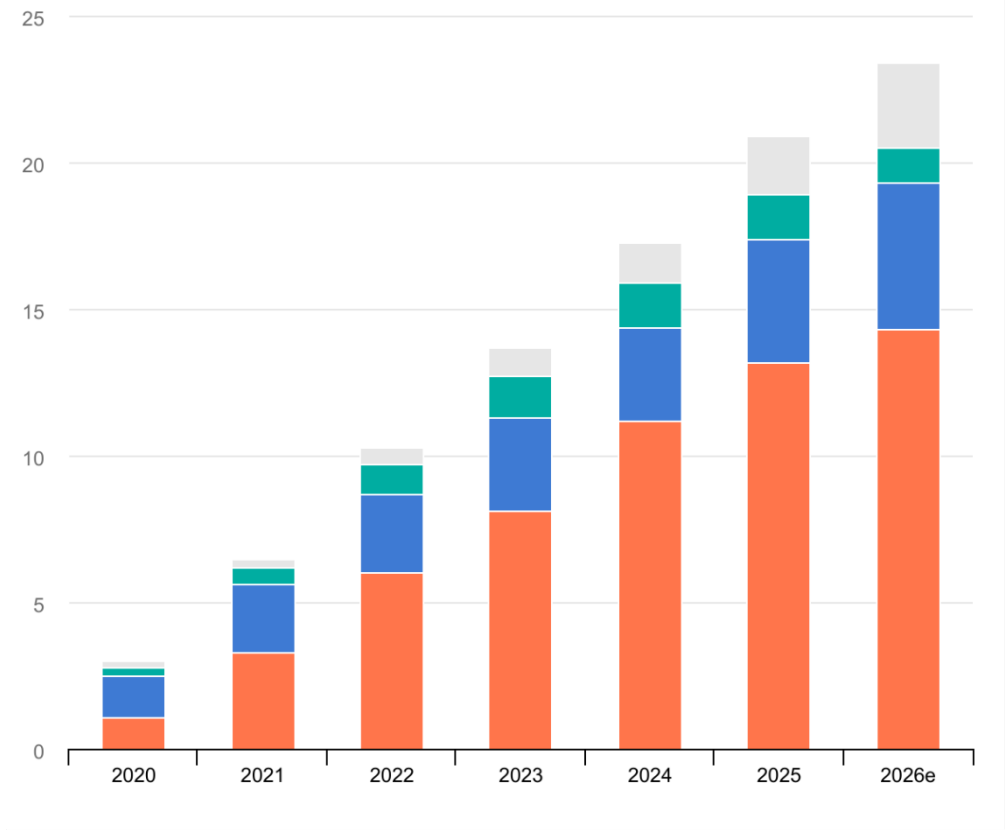


Figure: Global electric car sales (2020-2026) (IEA, *Global EV Outlook 2026)*

Demand Explosion: EV sales are driving a massive need for critical metals (85% Lithium demand comes from EVB)(IEA, *Global EV Outlook 2024).*

New Dependency: Shifting from fossil fuels creates a new reliance on scarce, geographically concentrated materials.

Supply Bottleneck: Supply will struggle to keep pace (it takes 10 to 17 years to open a new mine)(IEA, *The Role of Critical Minerals in Clean Energy Transitions* 2021).

EVB Circular Supply Chain (CSC)

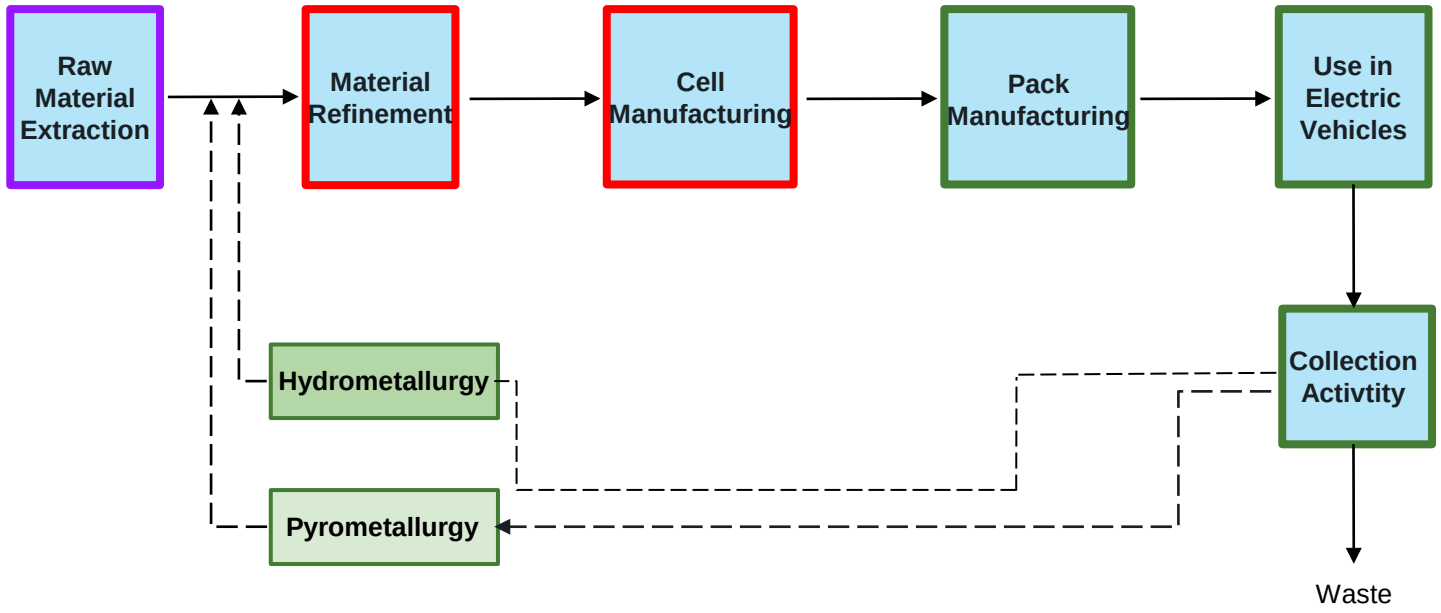


Figure: EVBs circular supply chain model

European Targets

(European Union, Regulation (EU) 2023)

Mandatory minimum recycled content for EV batteries placed on the market.

2031	
Cobalt	16%
Nickel	6%
Lithium	6%
Lead	85%

2036	
Cobalt	26%
Nickel	15%
Lithium	12%
Lead	85%

State of the Art and Research Question

Life cycle assessment widely used tool to quantify the environmental impacts.

State of the art

- **Cradle-to-gate assessments of battery manufacturing.**
- **End-of-life LCA: Recycling loop comparison.**
- **Closed loop system with avoided burden.**

Research Gap

Effective reintegration of recovered materials into the battery supply chain is rarely explicit

Research questions

RQ1: How can the environmental impact of a circular supply chain for EV batteries be assessed using a Life Cycle Assessment approach?

RQ2: How do hydrometallurgical and pyrometallurgical recycling scenarios affect the environmental performance of the battery cathode supply chain over time?

LCA Methodology

Relying Matrix-based LCA data structure (Heijungs and Suh, 2002)
In accordance with ISO 14040 and ISO 14044.

Life cycle assessment steps:

Goal and scope: defing system boundry and functionnal unit

Life cycle inventory: collecting and quantifying all system's inputs and outputs

Impact assessment (LCIA): assess environmental impact of defined system

Interpretation: analyzes the results

Matrix A

$$\begin{array}{c} \\ p \end{array} \begin{array}{c} q \\ \begin{bmatrix} + & \cdots & 0 \\ \vdots & - & \vdots \\ 0 & \cdots & + \end{bmatrix} \end{array}$$

p: flows

q: processes

$g = B.s$

$h = C.g$

Matrix B
Characterization
Matrix C

$$\begin{array}{c} \\ r \end{array} \begin{array}{c} q \\ \begin{bmatrix} + & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & r+ \\ & \cdots & \\ \vdots & & \vdots \\ & \cdots & \end{bmatrix} \end{array}$$

- consumption
+ production

r: environmental flows

Vector f
demand

$$\begin{array}{c} \\ p \end{array} \begin{bmatrix} \\ \vdots \\ \\ \end{bmatrix}$$

Scaling vector

$s = A^{-1}.f$

k: impact categories

$h = C.s$

LCA Methodology for CSC

Expanding matrices A and B and vector f.

Adding activities and related flows.

matrice A: linear system

	q1	q2	q3
p1	1	−1	0
p2	0	1	−1
p3	0	0	1

matrice A: ciruclar system

	q1	q2	q3	Collection	Recycling
p1	1	−1	0	0	0
p2	0	1	−1	0	0
p3	0	0	1	0	0
Collected product	0	0	0	1	0
Recycling product	−1	0	0	0	1

Case Study: Application to cathode NMC811

Functional unit: 1kg of cathode NMC811 (Dai,2019).

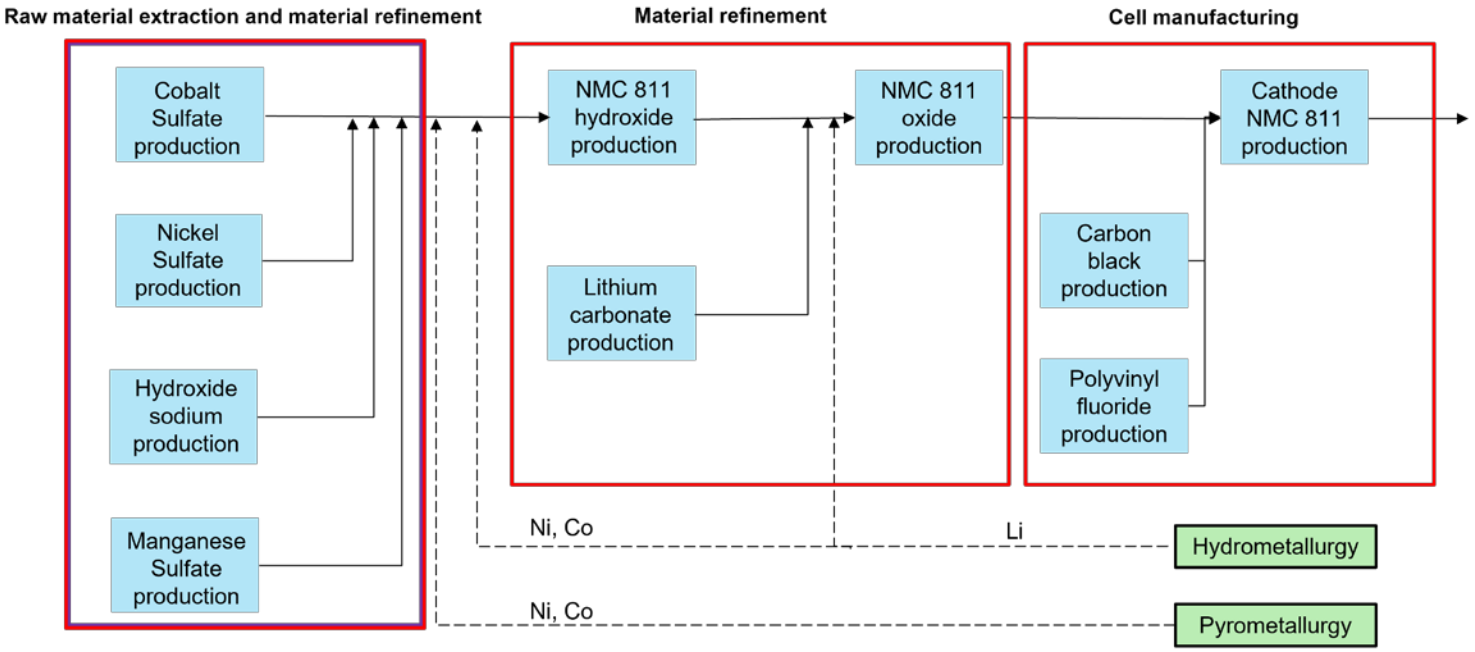


Figure: Cathode NMC811 circular supply chain model.

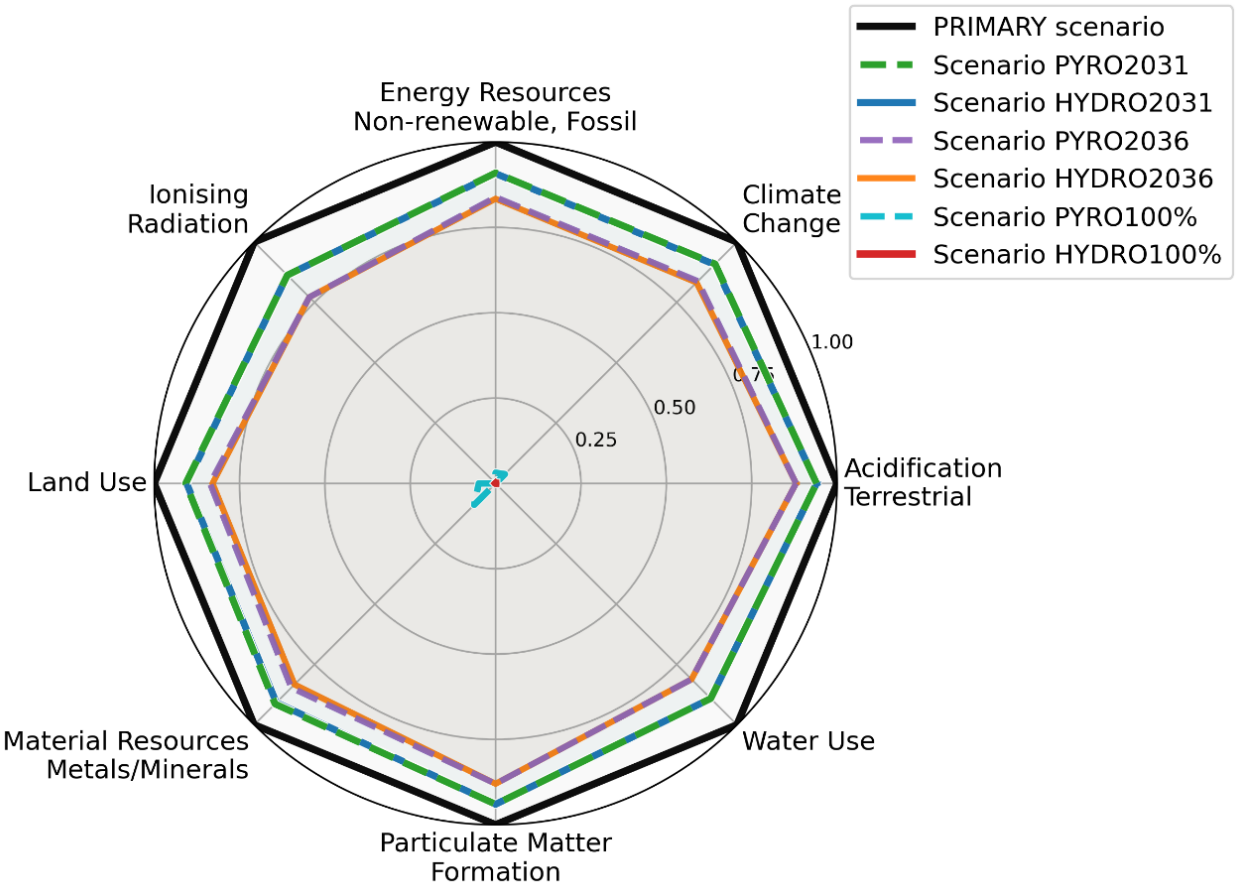
Table: Compared Scenarios

European Union, Regulation (EU) 2023

Scenario	Recycled content targets
PRIMARY	0% recycled content
HYDRO2031	EU2031: Co 16%, Li 6%, Ni 6%
PYRO2031	EU2031: Co 16%, Li 6%, Ni 6%
HYDRO2036	EU2031: Co 26%, Li 12%, Ni 15%
PYRO2036	EU2031: Co 26%, Li 12%, Ni 15%
HYDRO100%	Co 100%, Li 100%, Ni 100%
PYRO100%	Co 100%, Ni 100%

Inventory Data: Econinvent 3.9.1
Characterization Method: ReCiPe Midpoint 2016

Main Results



2031 targets: 5.5 - 10.7% impact reduction compared to PRIMARY scenario

2036 targets: 10.1 - 18.5% impact reduction compared to PRIMARY scenario

100% targets: 58 - 99% impact reduction compared to PRIMARY scenario

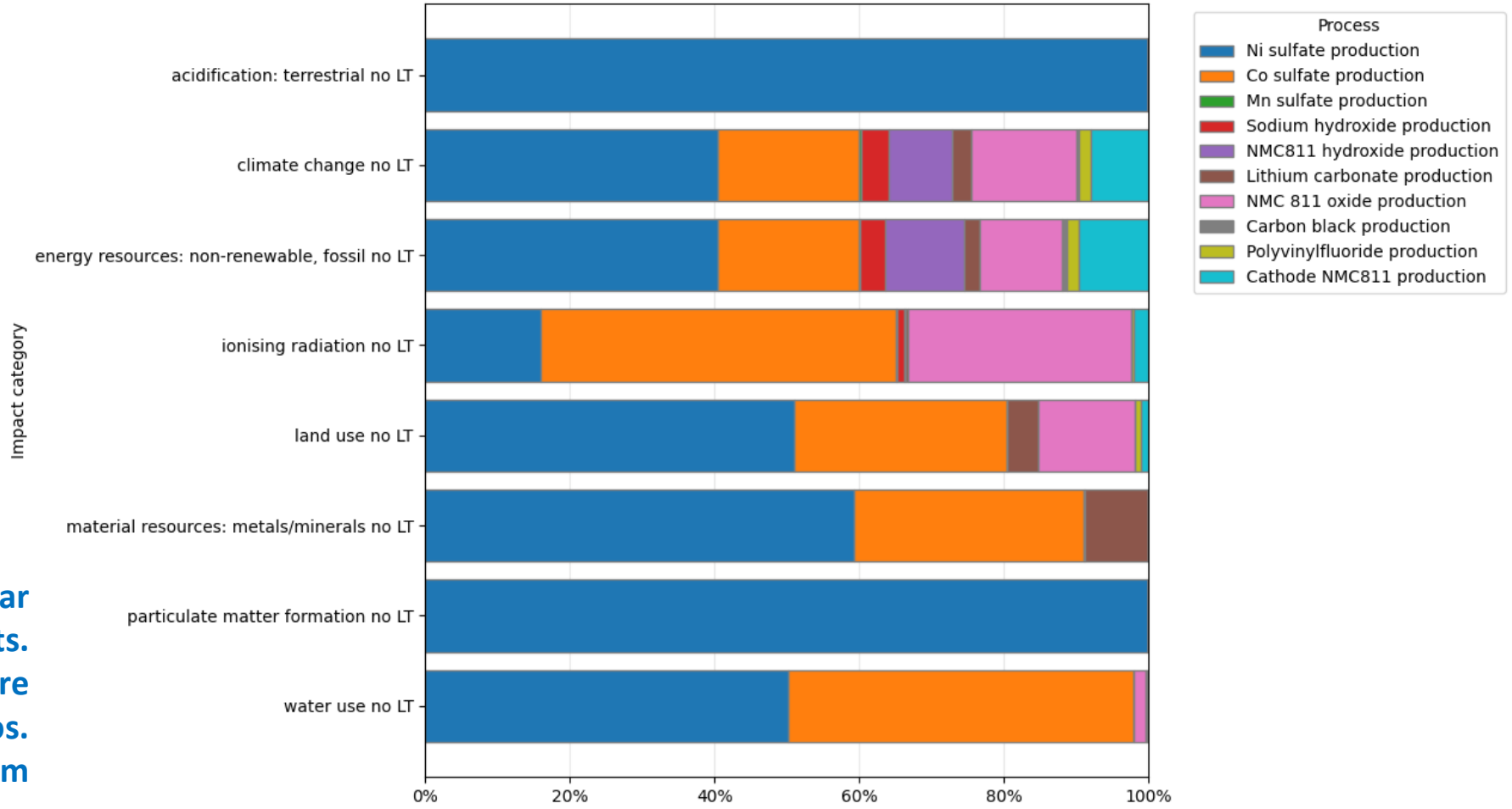
Figure: Normalized environmental impact comparison of the assessed scenarios

Main Results

Hydrometallurgical loop recyling impacts

≈

Pyrometallurgical loop recyling impacts



-Most impact categories are similar for the 2031 and 2036 targets.
-The differences are more pronounced for the 100% scenarios.
-The key difference is lithium recovery.

Figure: Process contribution to the selected environmental impacts in the PRIMARY scenario

Conclusion and Perspective

- Regarding the Research Question RQ1, this study shows how a life cycle assessment framework can be adapted to explicitly model and integrate material feedback loops.
- With respect to the Research Question RQ2, this modelling structure makes it possible to compare alternative configurations and to examine how recycled-content levels and recycling technologies influence environmental impacts.
- Extend the approach to additional circular strategies, battery components, chemistries, and prospective return-flow scenarios.

Thank you !

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Impacts

Impact category	Primary scenario	Scenario H2031	Scenario P2031	Scenario H2036	Scenario P2036	Scenario H100%	Scenario P100%
acidification: terrestrial no LT	0.6654	0.6255	0.6255	0.5856	0.5856	0.0003	0.0003
climate change no LT	19.6291	18.5276	18.5549	17.6444	17.7126	7.796	8.2503
ecotoxicity: freshwater no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ecotoxicity: marine no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ecotoxicity: terrestrial no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
energy resources: non-renewable	6.2106	5.86	5.8672	5.579	5.5968	2.4078	2.5264
eutrophication: freshwater no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
eutrophication: marine no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
human toxicity: carcinogenic no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
human toxicity: non-carcinogenic no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ionising radiation no LT	0.2726	0.2487	0.2487	0.2329	0.2329	0.0987	0.0988
land use no LT	0.3269	0.3007	0.3016	0.28	0.282	0.052	0.0655
material resources: metals/minerals no LT	3.587	3.2589	3.2779	2.9892	3.0369	0.0078	0.3252
ozone depletion no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
particulate matter formation no LT	0.1929	0.1814	0.1814	0.1698	0.1698	0.0	0.0
photochemical oxidant formation: human health no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
photochemical oxidant formation: terrestrial ecosystems no LT	0.0	0.0	0.0	0.0	0.0	0.0	0.0
water use no LT	1.5688	1.4015	1.4015	1.2793	1.2793	0.0325	0.0323

Primary scenario Matrix A

	Ni sulfate production	Co sulfate production	Mn sulfate production	Sodium hydroxide production	NMC811 hydroxide production	Lithium carbonate production	NMC 811 oxide production	Carbon black production	Polyvinylfluoride production	Cathode NMC811 production
Cathode	0	0	0	0	0	0	0	0	0	1
Poly	0	0	0	0	0	0	0	0	1	-0,0250
Carbon black	0	0	0	0	0	0	0	1	0	-0,0250
NMC oxide	0	0	0	0	0	0	1	0	0	-0,95
Lithium	0	0	0	0	0	1	-0,2460	0	0	0
NMC hydro	0	0	0	0	1	0,0000	-0,9490	0	0	0
Sodium	0	0	0	1	-0,8538	0,0000	0,0000	0,0000	0,0000	0,0000
Manganese	0	0	1	0	-0,15692	0	0	0	0	0
Cobalt	0	1	0	0	-0,16107	0	0,0000	0	0	0
Nickel	1	0	0	0	-1,2865	0	0,0000	0	0	0

Scenario H2031 matrix A

Flow	Ni sulfate production	Co sulfate production	Mn sulfate production	Sodium hydroxide production	NMC811 hydroxide production	Lithium carbonate production	NMC 811 oxide production	Carbon black production	Polyvinylfluoride production	Cathode NMC811 production	Hydromettalurgy Ni recyling	Hydromettalurgy Co recyling	Hydromettalurgy Li recyling
Cathode	0	0	0	0	0	0	0	0	0	1	0	0	0
Poly	0	0	0	0	0	0	0	0	1	-0,0250	0	0	0
Carbon black	0	0	0	0	0	0	0	1	0	-0,0250	0	0	0
NMC oxide	0	0	0	0	0	0	1	0	0	-0,95	0	0	0
Recycled Li	0	0	0	0	0	0	-0,01476	0	0	0	0	0	0,0221867
Lithium	0	0	0	0	0	1	-0,2312	0	0	0	0	0	0
NMC hydro	0	0	0	0	1	0,0000	-0,9490	0	0	0	0	0	0
Sodium	0	0	0	1	-0,8538	0,0000	0,0000	0,0000	0,0000	0,0000	0	0	0
Manganese	0	0	1	0	-0,15692	0	0	0	0	0	0	0	0
Recycked Co	0	0	0	0	0,0257712	0	0	0	0	0	0	0,01884038	0
Cobalt	0	1	0	0	-0,1353	0	0,0000	0	0	0	0	0	0
Recycled Ni	0	0	0	0	-0,07719	0	0	0	0	0	0,15011348	0	0
Nickel	1	0	0	0	-1,2093	0	0,0000	0	0	0	0	0	0

Primary scenario Matrix B

flow	unit	Ni sulfate production	Co sulfate production	Mn sulfate production	Sodium hydroxide production	NMC811 hydroxide production	Lithium carbonate production	NMC 811 oxide production	Carbon black production	Polyvinylfluoride production	Cathode NMC811 production
Carbon dioxide, fossil	kilogram	1,184406495	4,899939438	0,101158379	0	0	0,46472405	0,055310394	0	0,553645632	0,005383364
Heat, waste	megajoule	0,309308407	1,479907968	0	0	0	0,102556652	0,018486368	0	0,281981151	0,001121914
Hydrogen	kilogram	0	0,410169282	0	0	0	0	0	0	0	0
Water	cubic meter	0,678355427	4,910433836	0	0	0	0	0,025041761	0	0,165689282	0,003044677
Radon-222	kilo Becquerel	656,4317547	4263,696992	44,06851832	93,16589869	6,854326044	66,55894277	1011,731941	11,444184	696,4361715	67,82957425
Carbon dioxide, fossil	kilogram	4,261882201	10,25707589	0,468914401	0,955065219	0,557005708	0,844420398	2,35380394	0,425803438	9,694494883	0,558401822
Carbon dioxide, from soil	kilogram	0	0,139353473	0	0	0	0	0	0	0	0
Carbon dioxide, non-fossil	kilogram	0	0,101285518	0	0	0	0	0,10849376	0	0	0,006584346
Carbon-14	kilo Becquerel	0	0,571222394	0	0	0	0	0,03860847	0	0	0,002343098
Heat, waste	megajoule	0	0,225187082	0	0	0	0,111624699	0	0	0	0
Hydrogen-3, Tritium	kilo Becquerel	0,213573406	1,509178617	0	0	0	0	0,283388222	0	0,12380539	0,017198464
Niobium-95	kilo Becquerel	0	0,201505136	0	0	0	0	0	0	0	0
Noble gases, radioactive, unspecified	kilo Becquerel	706,0966967	5118,342265	11,8805564	25,00987126	1,562386553	17,55735108	216,4908097	3,398175055	197,9704122	14,64786189
Radon-222	kilo Becquerel	18,35980542	118,9926007	1,234186244	2,608240775	0,202570639	1,869927461	28,21147424	0,348436032	19,53213589	1,899766771
Water	cubic meter	0	0,260457649	0	0	0	0	0,000195623	0	0	0
Xenon-133	kilo Becquerel	0,730523646	4,729993354	0	0	0	0	0,45603246	0	0,681498302	0,029056005
Xenon-135	kilo Becquerel	0,213603095	1,340201292	0	0	0	0	0,137131261	0	0,224980363	0,008322319
Carbon dioxide, fossil	kilogram	1,0456215	9,195917766	0	0	1,360233609	0,621692117	0,147568667	1,379225422	1,992787989	0,989334289
Carbon dioxide, non-fossil	kilogram	0,186947521	0,896558707	0	0	0	0,172717804	0,172462036	0	0,262866898	0,012317761
Heat, waste	megajoule	0,829345639	4,784488577	0,11563042	0,113045808	1,790934601	0,210099431	0,722371411	0	2,369412965	1,337426457

Matrice C

impact_category	1 - Carbon dioxide, fossil | kilogram | air |	2 - Heat, waste | megajoule | air |	3 - Hydrogen | kilogram | air |	4 - Water | cubic meter | air |	5 - Radon-222 | kilo Becquerel | air | low population density, long-term	6 - Carbon dioxide, fossil | kilogram |	7 - Carbon dioxide, from soil	8 - Carbon dioxide, non-fossil | kilogram | air |	9 - Carbon-14 | kilo Becquerel | air |	10 - Heat, waste | megajoule | air |	11 - Hydrogen-3, Tritium | kilo Becquerel | air |	12 - Niobium-95 | kilo Becquerel | air |
acidification: terrestrial no LT	0	0	0	0	0	0	0	0	0	0	0	0
climate change no LT	1	0	0	0	0	1	1	1	0	0	0	0
ecotoxicity: freshwater no LT	0	0	0	0	0	0	0	0	0	0	0	0
ecotoxicity: marine no LT	0	0	0	0	0	0	0	0	0	0	0	0
ecotoxicity: terrestrial no LT	0	0	0	0	0	0	0	0	0	0	0	0
energy resources: non-renewable, fossil no LT	0	0	0	0	0	0	0	0	0	0	0	0
eutrophication: freshwater no LT	0	0	0	0	0	0	0	0	0	0	0	0
eutrophication: marine no LT	0	0	0	0	0	0	0	0	0	0	0	0
human toxicity: carcinogenic no LT	0	0	0	0	0	0	0	0	0	0	0	0
human toxicity: non-carcinogenic no LT	0	0	0	0	0	0	0	0	0	0	0	0
ionising radiation no LT	0	0	0	0	0	0	0	0	1,15	0	0,000856	0
land use no LT	0	0	0	0	0	0	0	0	0	0	0	0
material resources: metals/minerals no LT	0	0	0	0	0	0	0	0	0	0	0	0
ozone depletion no LT	0	0	0	0	0	0	0	0	0	0	0	0
particulate matter formation no LT	0	0	0	0	0	0	0	0	0	0	0	0
photochemical oxidant formation: human health no LT	0	0	0	0	0	0	0	0	0	0	0	0
photochemical oxidant formation: terrestrial ecosystems no LT	0	0	0	0	0	0	0	0	0	0	0	0
water use no LT	0	0	0	1	0	0	0	0	0	0	0	0

Vector f

Primary scenario

	Demand
Cathode	1
Poly	0
Carbon black	0
NMC oxide	0
Lithium	0
NMC hydro	0
Sodium	0
Manganese	0
Cobalt	0
Nickel	0

Hydro scenario

	Demand
Cathode	1
Poly	0
Carbon black	0
NMC oxide	0
Recycled Li	0
Lithium	0
NMC hydro	0
Sodium	0
Manganese	0
Recycked Co	0
Cobalt	0
Recycled Ni	0
Nickel	0

Lithium scenario

	Demand
Cathode	1
Poly	0
Carbon black	0
NMC oxide	0
Lithium	0
NMC hydro	0
Sodium	0
Manganese	0
Recycked Co	0
Cobalt	0
Recycled Ni	0
Nickel	0

Conference Dinner

At the ZKM, 18:00

Exhibition: The Story that never Ends



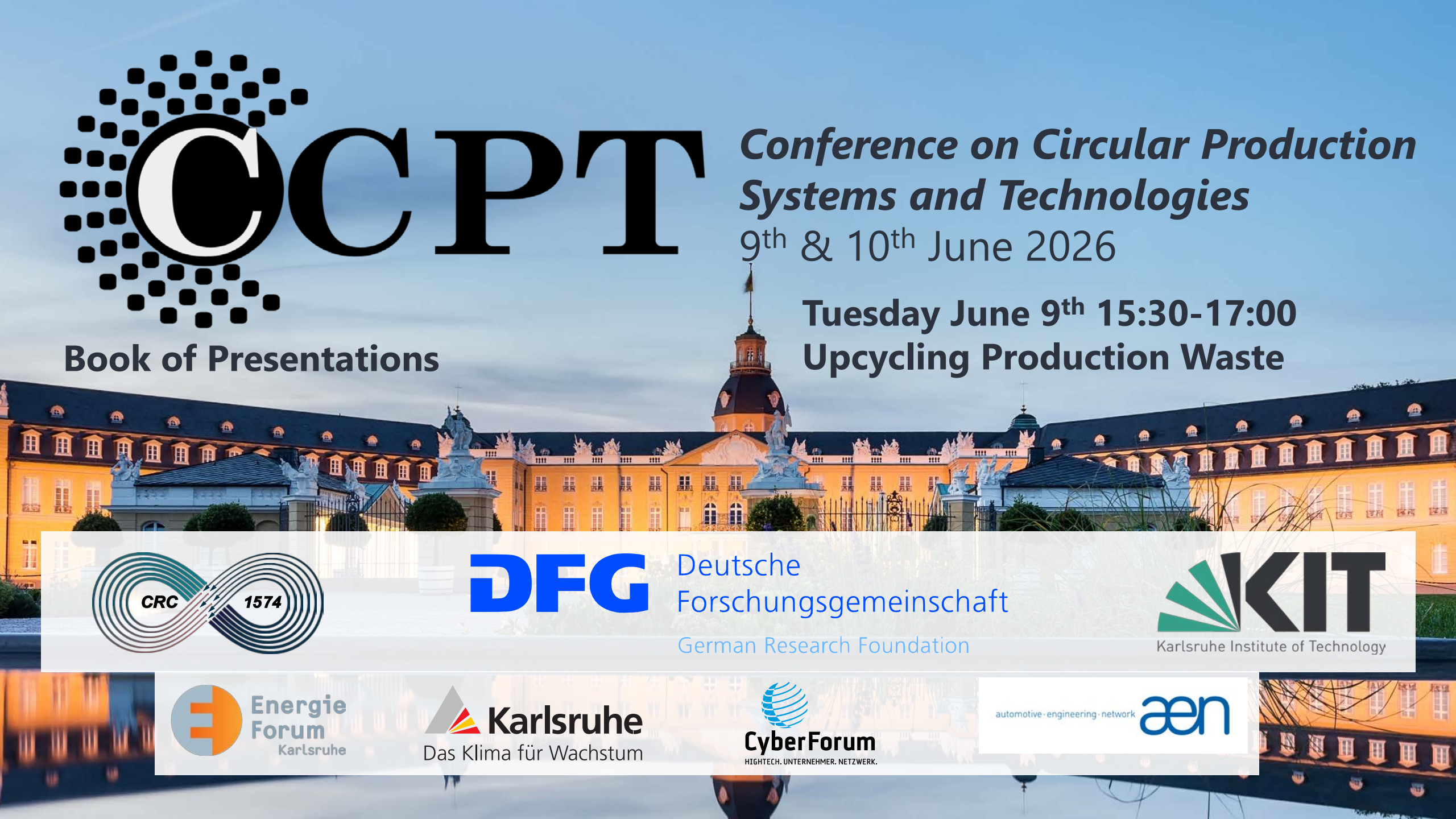
By Tram: Tram 2 to ***ZKM*** (Tram Ticket included)
By Car: ZKM car park via **Südendstraße 44**

CCPT

SFB 1574

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

KIT Karlsruhe Institute of Technology



CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Tuesday June 9th 15:30-17:00
Upcycling Production Waste

CRC 1574

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

KIT Karlsruhe Institute of Technology

Energie Forum Karlsruhe

Karlsruhe Das Klima für Wachstum

CyberForum HIGHTECH. UNTERNEHMER. NETZWERK.

automotive · engineering · network aen

A Multi-Parameter Rotating Drum Approach for High-Sensitivity Flowability Analysis of Recycled Metal Powders

Marius Hoffmann, Martin Bonenberger, Marvin Rothmeier, Luca Thober, Frederik Zanger, Michael Wahl, Roman Kirsch

Presented by: Marius Hoffmann

09.06.2026

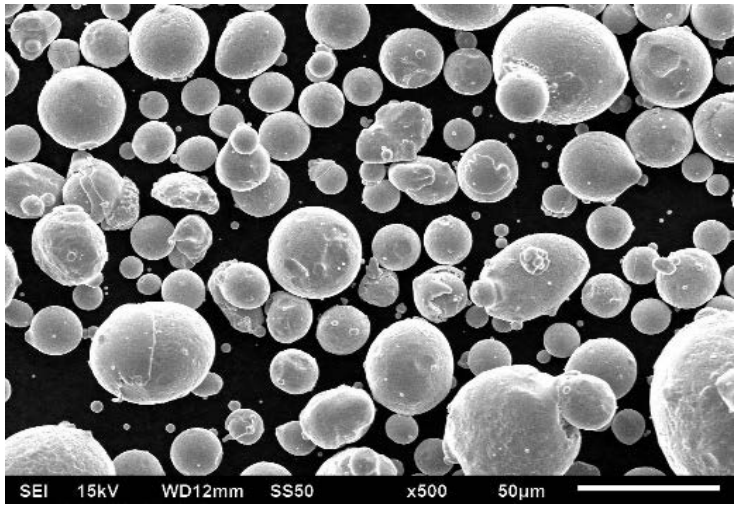
Recycled 316L Metal Powder Produced by VIGA

- Vacuum Induction Gas Atomization at Umwelt-Campus Birkenfeld
- Three batches of 316L stainless steel powder
- Fractionation by dry sieving to 20–63 µm

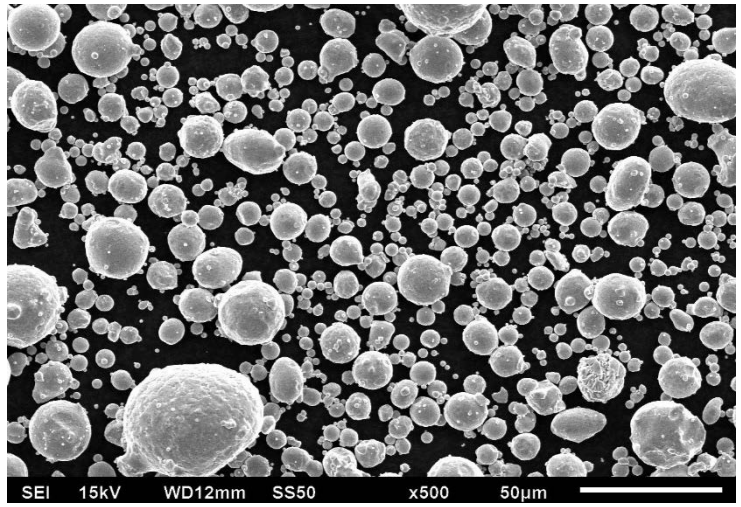




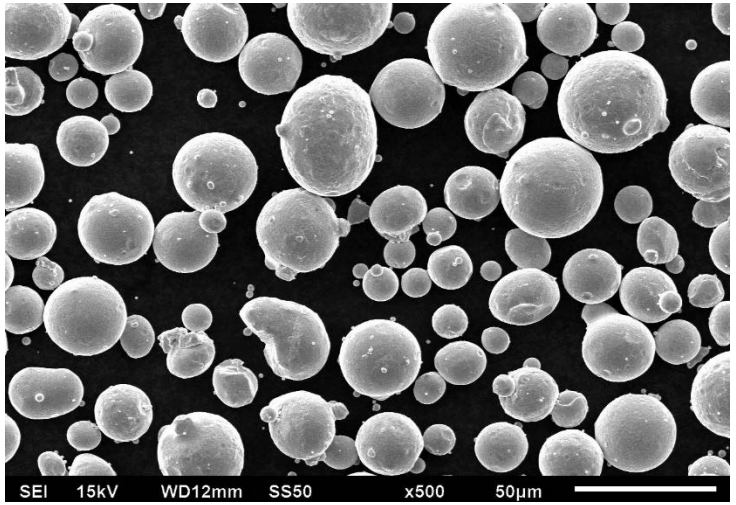
Scanning Electron Microskope



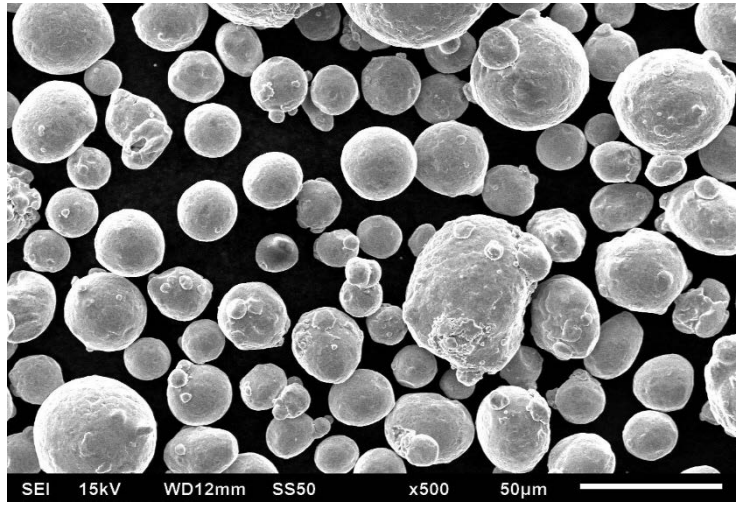
26001
Sive
Fraction
20-63 µm



26002
Sive
Fraction
20-63 µm

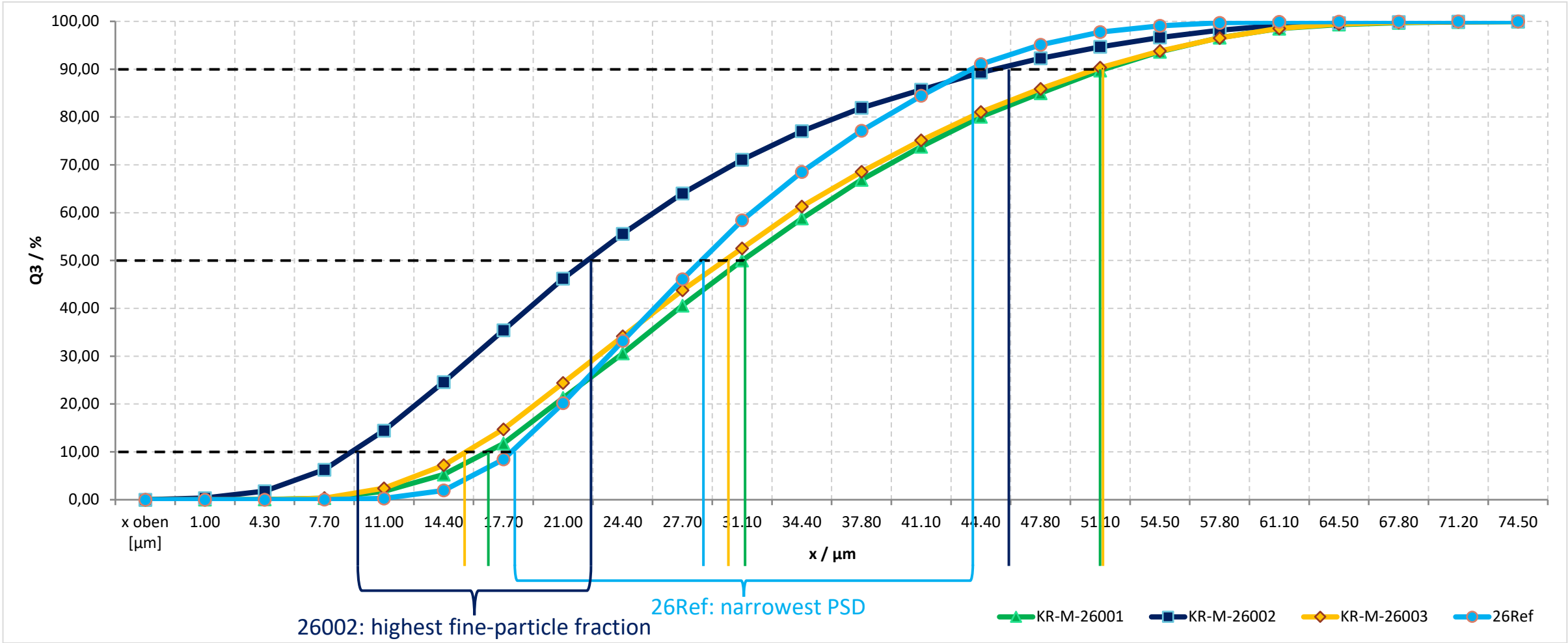


26003
Sive
Fraction
20-63 µm



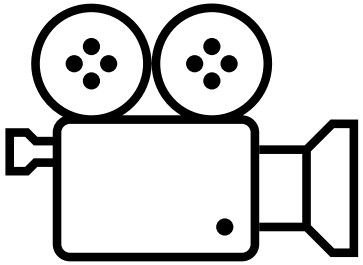
26Ref
com-ercial
20-53 µm

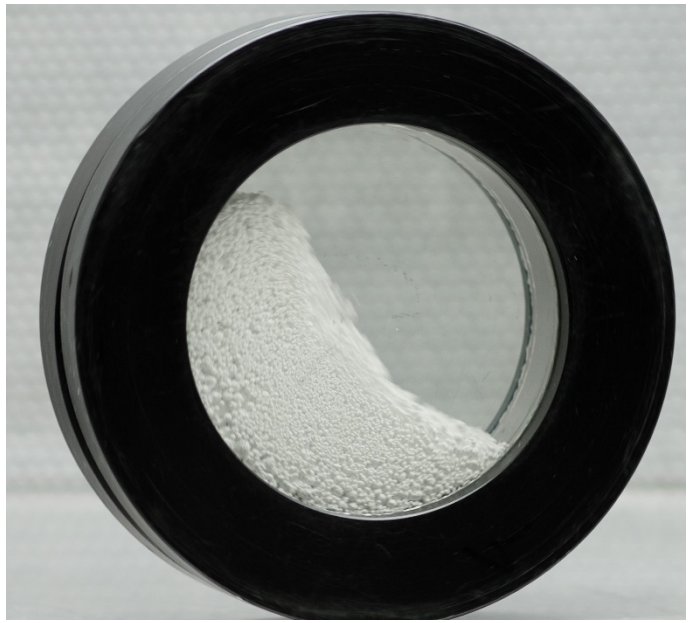
Particle Size Distribution

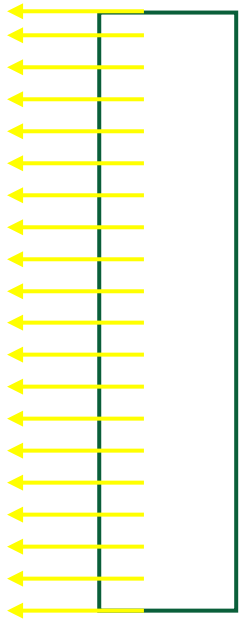


CZS Center KRAFt: **K**reislaufwirtschaft und **R**essourceneffizienz mittels **A**dditiver **F**ertigungs**t**echnologien

Rotating Drum Analysis









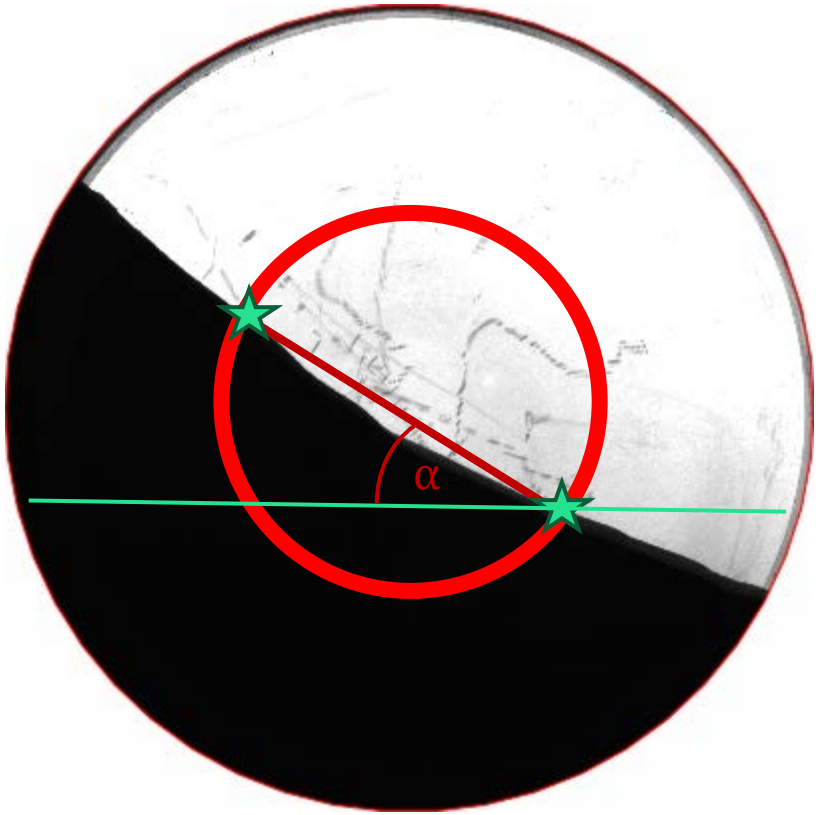
Camera

Rotating drum with sample

LED-Screen

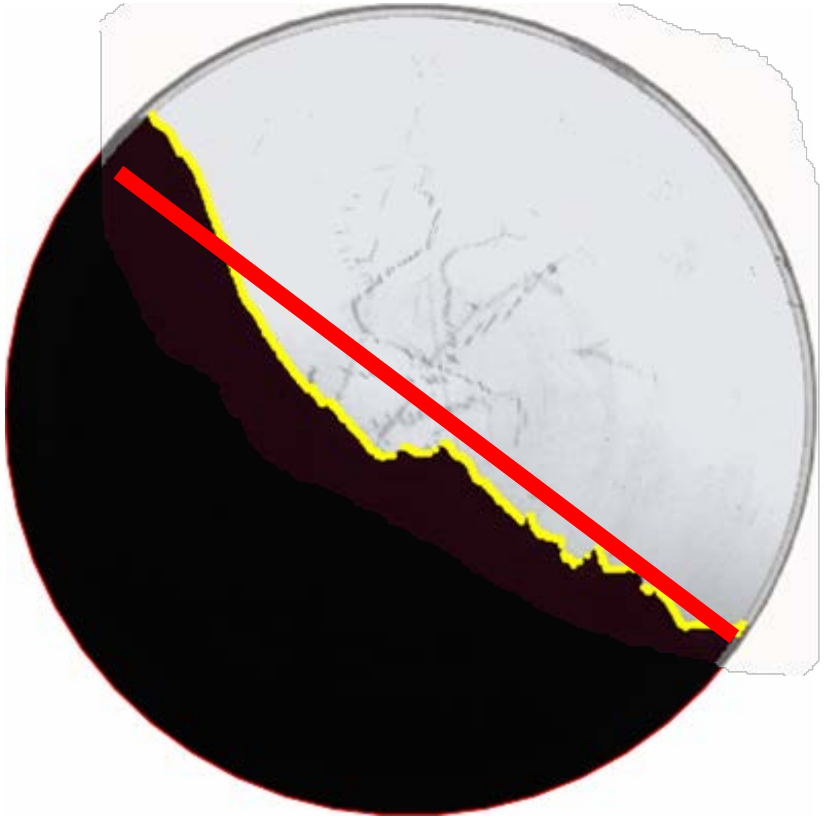
Dynamic Angle of Repose

- Single Frame Analysis
- Set Region of Interest
- Identify
  - (X|Y) top
  - (X|Y) bottom
- Calculate
  - $\alpha = \arctan\left(\frac{y_{top} - y_{bottom}}{x_{top} - x_{bottom}}\right)$
- The mean of all angles are the dynamic anlge of repose



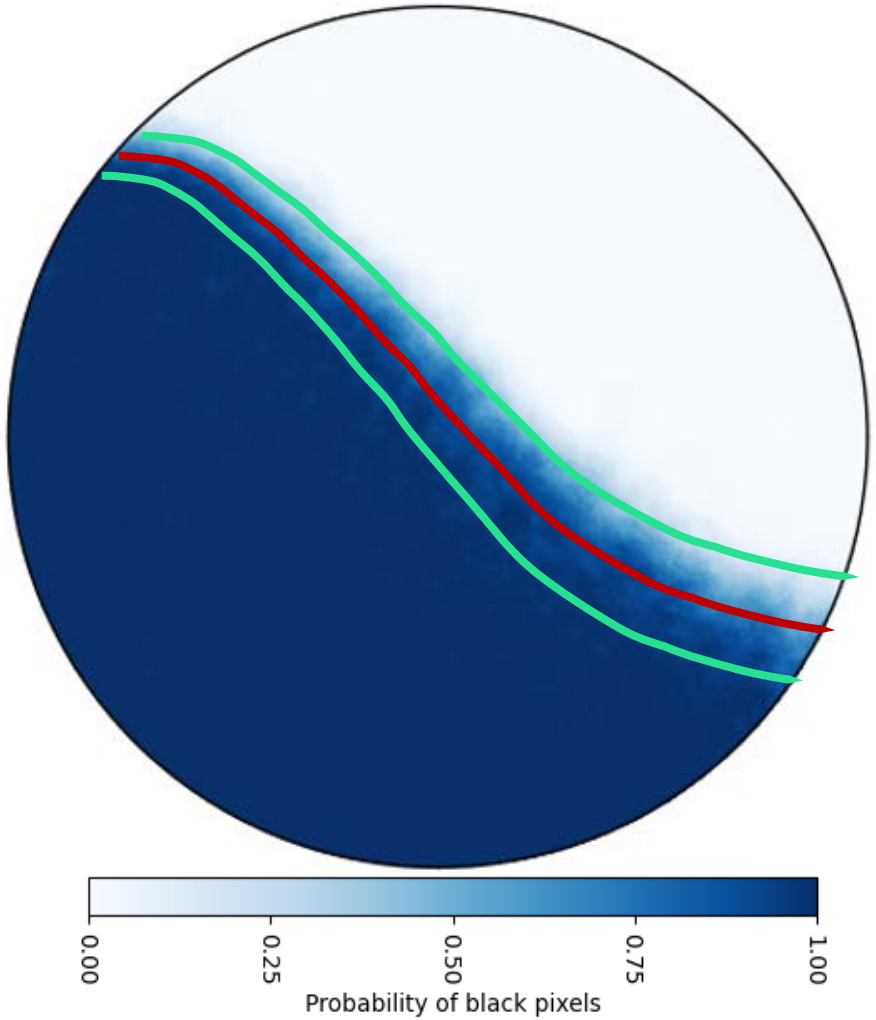
Roughness index

- Single Frame analysis
- Calculate the number of pixel of the interface
- Calculate the number of pixel of the minimum interface
- $\mathrm{RI}_i = \frac{\mathrm{Interface}_i\,[\mathrm{px}]}{\mathrm{Interface}_{\mathrm{min}}[\mathrm{px}]}$
- The mean of all RI_i are the Roughness index



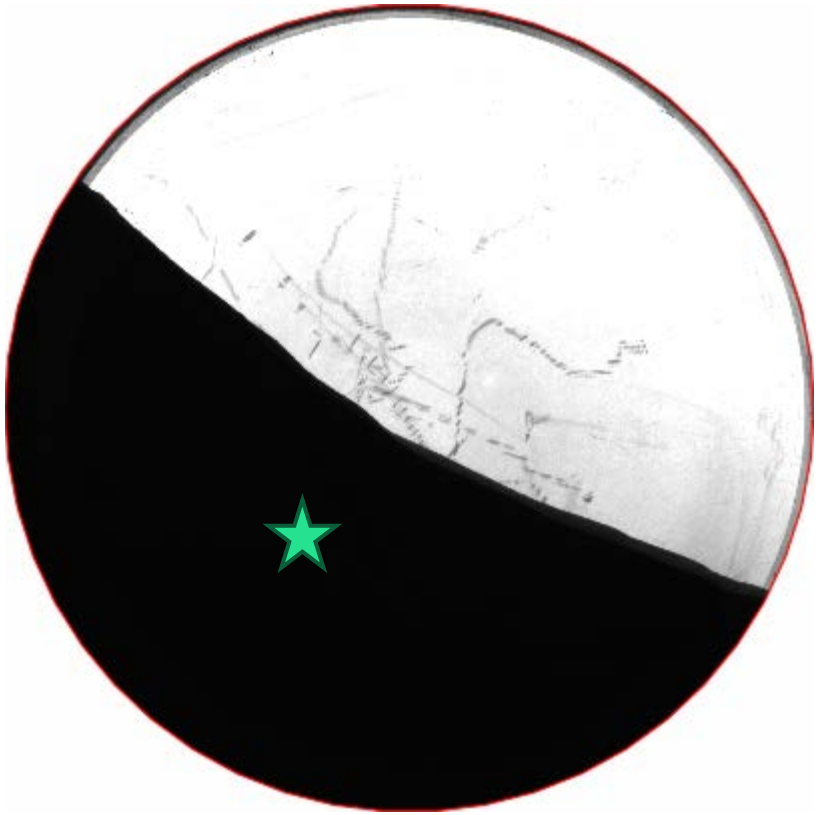
Cohesive index

- Image Stac analysis
- Caculate the mean Y-Position for every collum x
- Caculate the standard deviation for every Frame in the stac
  - $\sigma(x) = \sqrt{\frac{\sum_{i=1}^{N}(\bar{y}(x) - y_i(x))^2}{N}}$
- The mean of all standard deviations are the Cohesive index



Avalanche Energy

- Image Stac analysis
- Caculate the mean Y-Position of all black pixel
- Calculate the spezific potentional energy in every frame
  - $\Delta E = E_t - E_{t-1}$

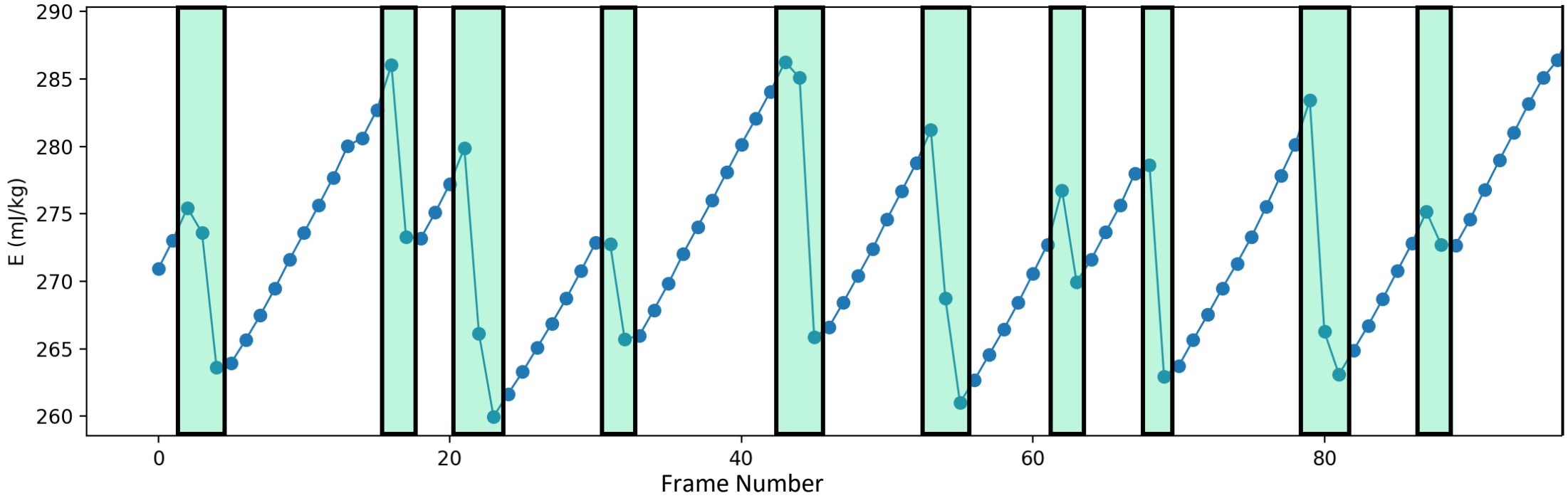


Avalanche Energy

Plotting the time-discrete potential energy

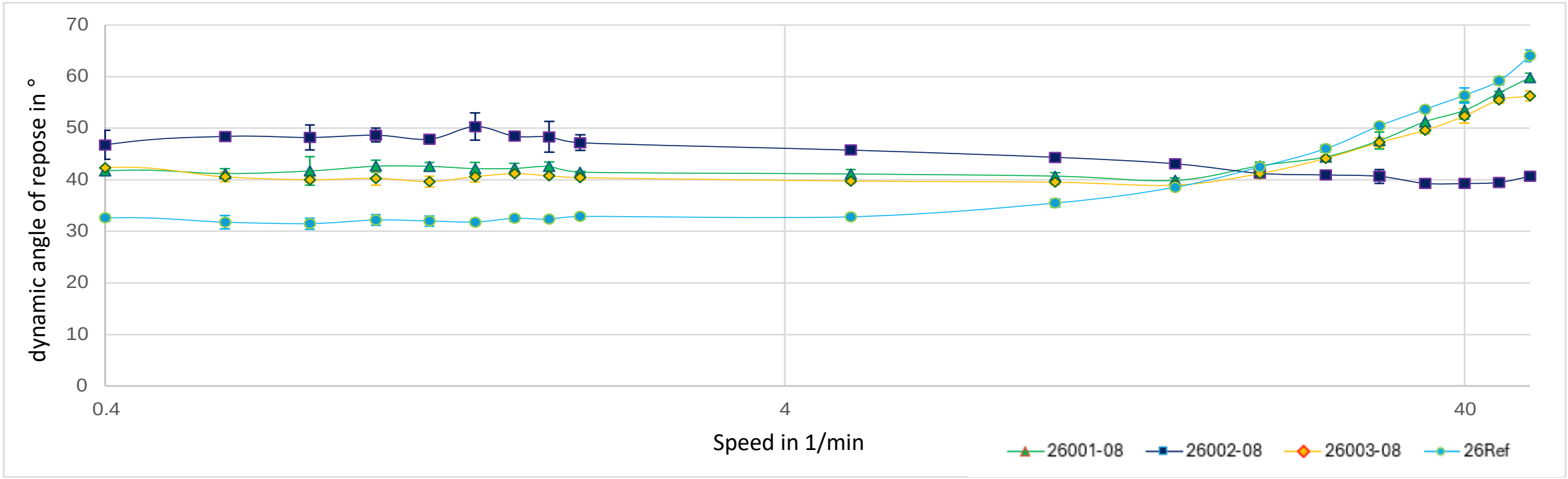
Indentify Avalanche Events and calculate ΔE

The mean of all ΔE are the Avalanche Energy



Dynamic Angle of Repose

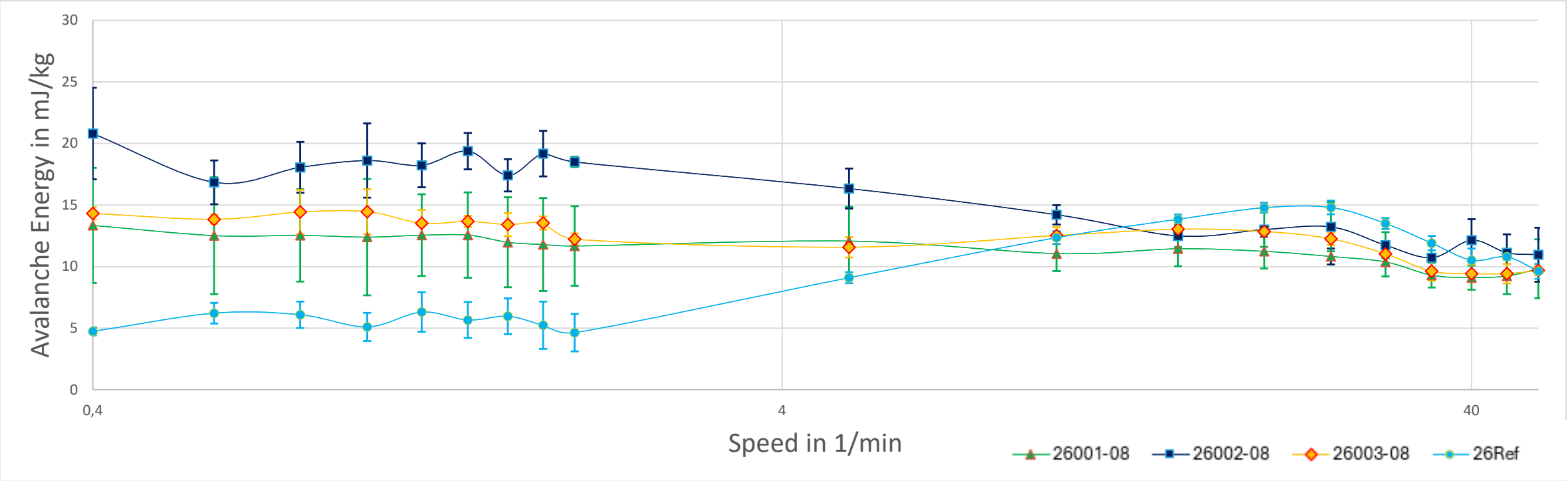
- Low-speed regime (≤ 2 rpm)
  - Clear powder-specific differences
  - 26002 shows the highest angle
  - 26001 and 26003 behave similarly
- High-speed regime (>2 rpm)
  - 26001, 26003 and 26Ref incraease and converge
  - 26002 slightly decreases
  - Flow bahavior become speed-dependent



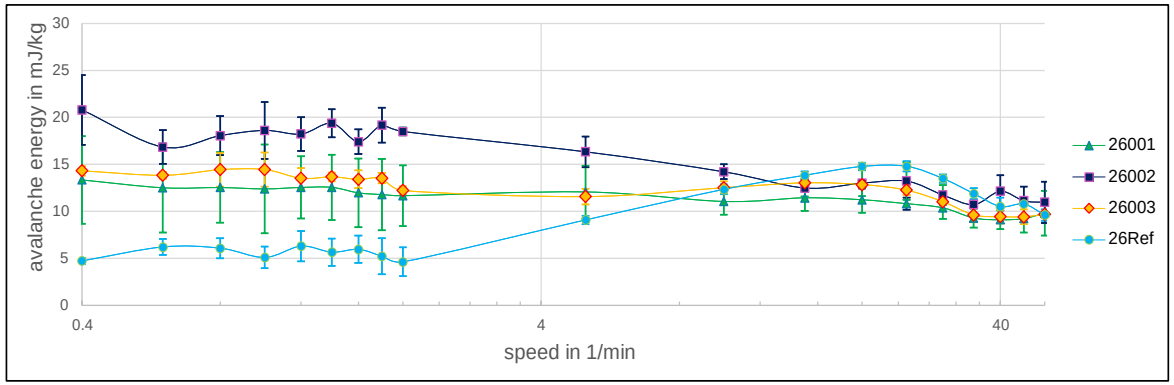
CZS Center KRAFt: **K**reislaufwirtschaft und **R**essourceneffizienz mittels **A**dditiver **F**ertigungs**t**echnologien

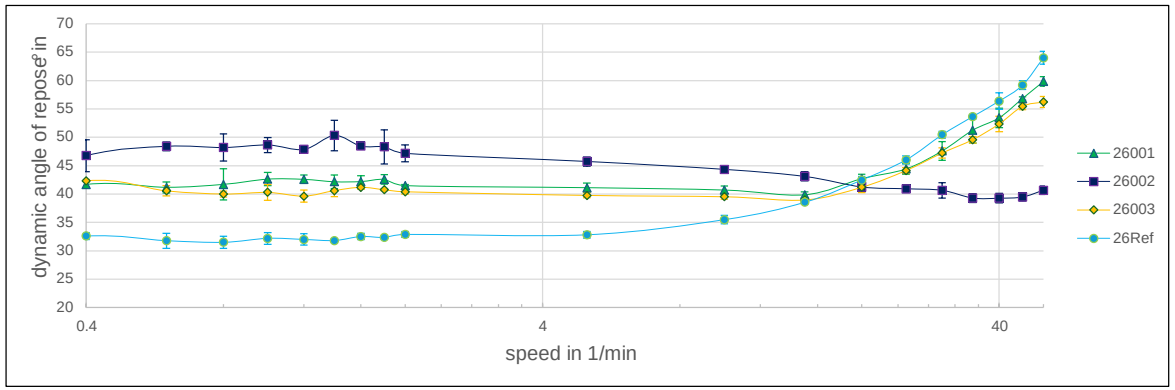
Avalanche Energy

- Low-speed regime (≤ 2 rpm)
  - Clear powder-specific differences
  - 26002 shows the highest avalanche energy
  - 26Ref shows the lowest avalanche energy
  - 26001 and 26003 show intermediate values
- High-speed regime (>2 rpm)
  - 26002 decreases with increasing speed
  - 26Ref increases strongly
  - 26001 and 26003 remain relatively stable
  - Powder ranking changes at higher speeds



Regime-Dependent Correlation Analysis





Low-Speed Regime (≤ 2 rpm)	Dynamic Angle of Repose	Cohesive Index	Roughness Index	Avalanche Energy
Dynamic Angle of Repose	1			
Cohesive Index	0.256	1		
Roughness Index	0.493	0.707	1	
Avalanche Energy	-0.198	0.313	-0.051	1

Low-Speed Regime: Parameters are only weakly to moderately correlated → complementary information

High-Speed Regime	Dynamic Angle of Repose	Cohesive Index	Roughness Index	Avalanche Energy
dynamic angle of repose	1			
Cohesive Index	-0.546	1		
Roughness Index	-0,774	0,933	1	
Avalanche Energy	0,877	-0,620	-0,803	1

High-Speed Regime: Stronger correlations occur → regime-dependent parameter coupling

Conclusion

Dynamic angle of reponse
Mean flow resistance

Roughness index
Interface irregularity

Robust flowability characterisation by combining four comlementary discriptors

Cohesive index
Temporal surface fluctuation

Avalanche energy
Energy release during flow events

No single parameter fully describes powder flowability the combined approach provides a more robust and sensitive characterization.

Carl Zeiss Stiftung

Umwelt-Campus Birkenfeld | HOCHSCHULE TRIER



Questions?

Contact: m.hoffmann@umwelt-campus.de

Karlsruhe Institute of Technology

Institute of Production Science

Sintering Simulation in Binder Jetting: A Leverage towards the Industrialization of Upcycling of HSS Production Waste

Conference on Circular Production Systems and Technologies – CCPT 2026

Marvin Dornick, Milan Konrad, Frederik Zanger | 09.06.2026



Motivation

Why HSS tools, how to produce them and what could AM enable?

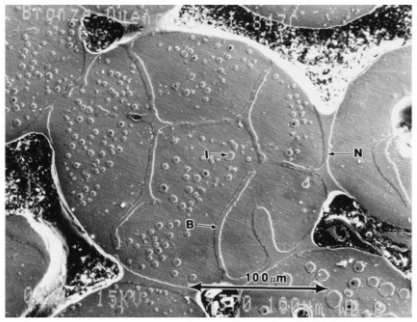


[1]

Examples of HSS cutting tools

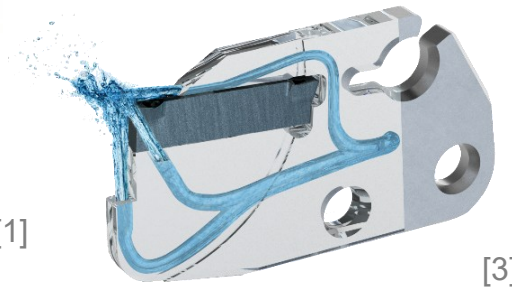
- High-speed steels (HSS) are conventionally manufactured via powder metallurgy (PM) and are used due to high warm hardness and toughness

- Super-solidus-liquid-phase sintering allows high densification



[2]

Liquid phase formation at grain boundaries and within



[3]

Cooling channel integration

- Additive manufacturing may enable new applications due to design freedom or for optimization through functional integration enhancing durability or performance

[1] Richconn Technology Co., Limited, [2] R.M.German 1997 [3] Rosswag GmbH

Motivation

Why BJT challenges are worth solving!

Binder Jetting (BJT) is suitable for **economical shaping** of small to large parts even in **higher quantities** and for broad **variety** of **materials**

The challenge is optimizing the sintering process for BJT to achieve high densities:

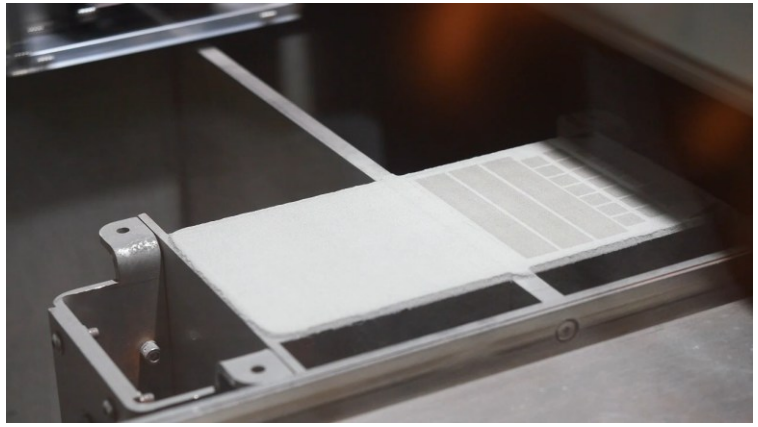


GREEN PART
Green part **density** of BJT parts are **significantly lower** (< **65%**, instead of 80-90%).

MULTIPLE INFLUENCES
Complex **interaction** with **liquid phase**, **substrate** and **gravity**.

PROCESS INHOMOGENITY
Several **anisotropic** effects due to the AM **process** are induced.

COMPLEX GEOMETRIES
Complex shapes with varying wall **thicknesses**.



BJT process with powder reservoir (left) and print bed (right)



HSS-BJT cutting tool demonstrators

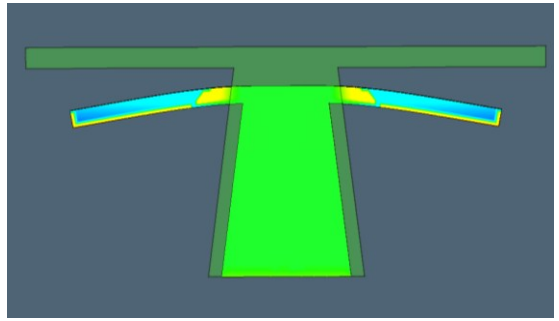
Motivation

Distortion – inevitable, but manageable?

Distortion leads to either **defect** or increased **costly post-processing** reducing economic and ecological **sustainability**

- **Sintering** is the **most energy consuming** step at the end of the AM-production chain
- High demand for sintering simulation for **distortion compensation** to benefit from **BJT** advantages
- Input parameters often include **costly equipment** and sometimes **lengthy experiments**
- **Transfer** from measurements **to sintering infrastructure** and application onto **novel** unsteady **material** (for re- and **upcycling**) is complicated due to **complexity**

Approach to estimate a **material model** to use **existing** PM **infrastructure** to enable **BJT** manufacturing of **HSS** tools for **fast** industrial **adaptation**



Distortion simulation in Simufact Additive

Materials & Methods

Sintering software and input parameters

Sintering Simulation Software
Simufact Additive (HEXAGON)

- Macroscopic approach (**phenomenological**, continuum mechanical → **FEA**-based)
- Marc 2025.1 advanced non-linear multi-physics solver
- Sintering boundary conditions according to Skorohod-Olevsky Visco-Plastic Sintering model

Sintering Simulation
Input Parameters

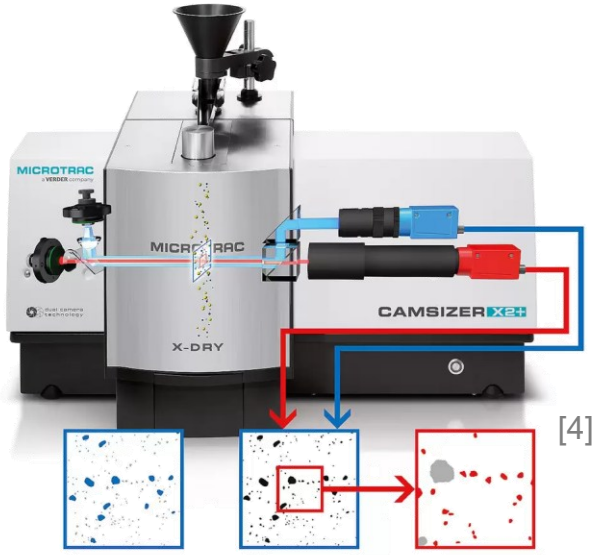
- Powder median particle size D_{50}
- Powder original grain size
- Green part density
- Static friction coefficient
- Desired sintering profile
- Viscosity profile
- Shrinkage profile

Microtrac Retsch GmbH
Microtrac Retsch GmbH

Materials & Methods

Determination of input parameters

Sintering Simulation **Input Parameters**	Input Parameters **Determination methods**
▪ Powder median particle size D_{50} ▪ Powder original grain size ▪ Green part density ▪ Static friction coefficient ▪ Desired sintering profile ▪ Viscosity profile ▪ Shrinkage profile	▪ Dynamic image analysis



[4]

Working principle of dynamic image analysis

[4] Microtrac Retsch GmbH

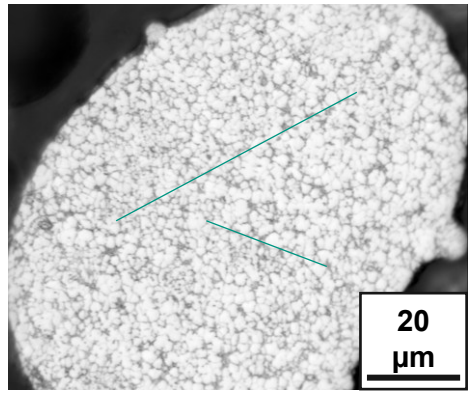
Materials & Methods

Determination of input parameters

Sintering Simulation **Input Parameters**	Input Parameters **Determination methods**
▪ Powder median particle size D_{50}	▪ Dynamic image analysis
▪ Powder original grain size	▪ Metallographic microscopy and counting intersections
▪ Green part density	
▪ Static friction coefficient	
▪ Desired sintering profile	
▪ Viscosity profile	
▪ Shrinkage profile	



Embedded powder in epoxy resin

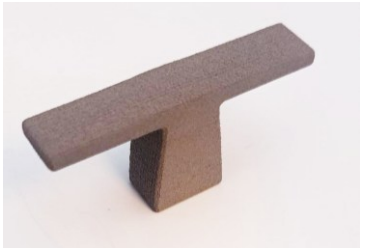


Metallographic micrograph with 1000x magnification and exemplary measurement lines

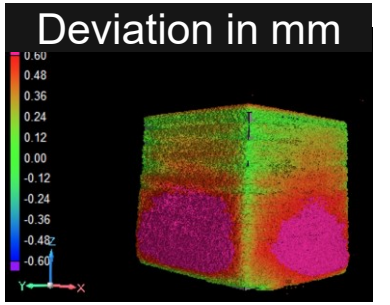
Materials & Methods

Determination of input parameters

Sintering Simulation **Input Parameters**	Input Parameters **Determination methods**
▪ Powder median particle size D_{50}	▪ Dynamic image analysis
▪ Powder original grain size	▪ Metallographic microscopy and counting intersections
▪ Green part density	▪ CT scans and precision weighting
▪ Static friction coefficient	
▪ Desired sintering profile	
▪ Viscosity profile	
▪ Shrinkage profile	



Double cantilever green part



Computer tomograph of cubic green part and colored geometrical deviation from desired geometry



[5]

High precision laboratory scale

[5] Mettler Toledo GmbH

Materials & Methods

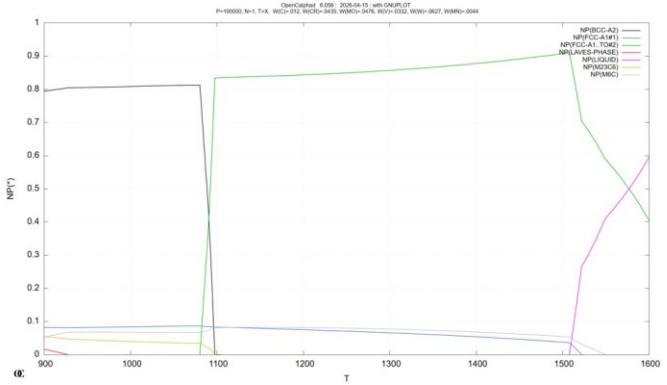
Determination of input parameters

Sintering Simulation **Input Parameters**	Input Parameters **Determination methods**
▪ Powder median particle size D_{50}	▪ Dynamic image analysis
▪ Powder original grain size	▪ Metallographic microscopy and counting intersections
▪ Green part density	▪ CT scans and precision weighting
▪ Static friction coefficient	▪ Literature research
▪ Desired sintering profile	
▪ Viscosity profile	
▪ Shrinkage profile	

Materials & Methods

Determination of input parameters

Sintering Simulation **Input Parameters**	Input Parameters **Determination methods**
▪ Powder median particle size D_{50}	▪ Dynamic image analysis
▪ Powder original grain size	▪ Metallographic microscopy and counting intersections
▪ Green part density	▪ CT scans and precision weighting
▪ Static friction coefficient	▪ Literature research
▪ Desired sintering profile	▪ Analysis of phase diagram (via OpenCalphad)
▪ Viscosity profile	
▪ Shrinkage profile	

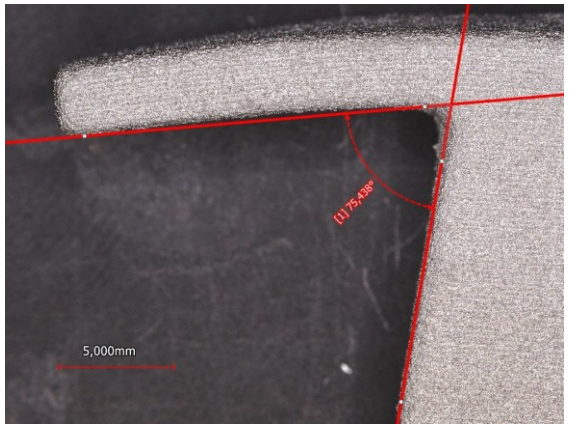


Phase diagram for M3-HSS composition created using OpenCalphad)

Materials & Methods

Determination of input parameters

Sintering Simulation **Input Parameters**	Input Parameters **Determination methods**
▪ Powder median particle size D_{50}	▪ Dynamic image analysis
▪ Powder original grain size	▪ Metallographic microscopy and counting intersections
▪ Green part density	▪ CT scans and precision weighting
▪ Static friction coefficient	▪ Literature research
▪ Desired sintering profile	▪ Analysis of phase diagram (via OpenCalphad)
▪ Viscosity profile	▪ Sintering double-cantilever parts at 1210, 1230, 1250 °C and fitting pre-existing temperature depended curves
▪ Shrinkage profile	



Macrograph of sintered double cantilever part with measured angle to estimate deformation

Materials & Methods

Determination of input parameters

Sintering Simulation **Input Parameters**	Input Parameters **Determination methods**
▪ Powder median particle size D_{50}	▪ Dynamic image analysis
▪ Powder original grain size	▪ Metallographic microscopy and counting intersections
▪ Green part density	▪ CT scans and precision weighting
▪ Static friction coefficient	▪ Literature research
▪ Desired sintering profile	▪ Analysis of phase diagram (via OpenCalphad)
▪ Viscosity profile	▪ Sintering double-cantilever parts at 1210, 1230, 1250 °C and fitting pre-existing temperature depended curves
▪ Shrinkage profile	▪ sintering cubic specimens at 1210, 1230, 1250 °C, CT scans and analysis

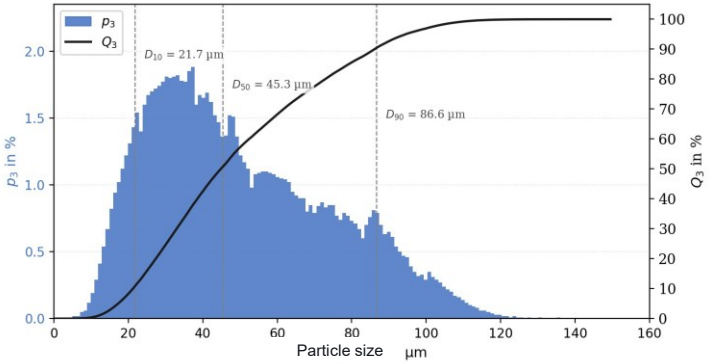


Sintered cubic specimens in holder prepared for CT scanning

Results

Determination of input parameters

Sinter **Input**	**Det**	Input Parameters **Measurements & Determination**
Powder median partic	▪ Dynamic image a	▪ D_{50} = 45.3 µm
Powder original grain	▪ Metallographic m intersections	
Green part density	▪ CT scans and pre	
Static friction coefficie	▪ Literature researc	
Desired sintering profi	▪ Analysis of phase	
Viscosity profile	▪ Sintering double- 1230, 1250 °C ar temperature depe	
Shrinkage profile	▪ sintering cubic sp 1250 °C, CT scar	

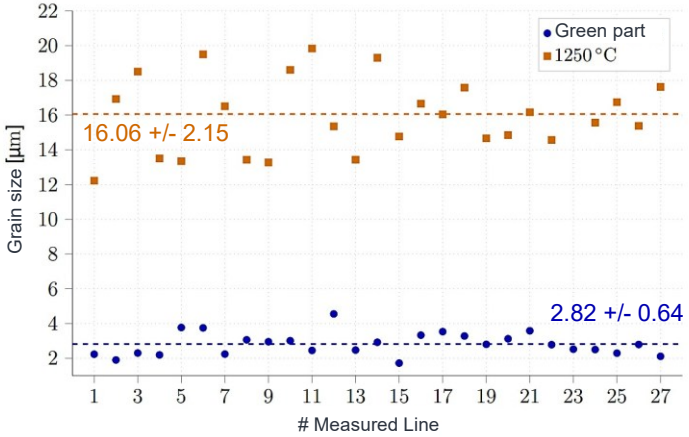


Particle size distribution (Ferret's diameter) as relative p_3 and accumulated Q_3 fraction

Results

Determination of input parameters

Sinter **Input**	**Det**	Input Parameters **Measurements & Determination**
Powder median partic	▪ Dynamic image a	▪ D_{50} = 45.3 µm
Powder original grain	▪ Metallographic m intersections	▪ Average grain size D_{grain}= 2.82 (+/- 0.64) µm
Green part density	▪ CT scans and pre	
Static friction coefficie	▪ Literature researc	
Desired sintering profi	▪ Analysis of phase	
Viscosity profile	▪ Sintering double- 1230, 1250 °C ar temperature depe	
Shrinkage profile	▪ sintering cubic sp 1250 °C, CT scar	

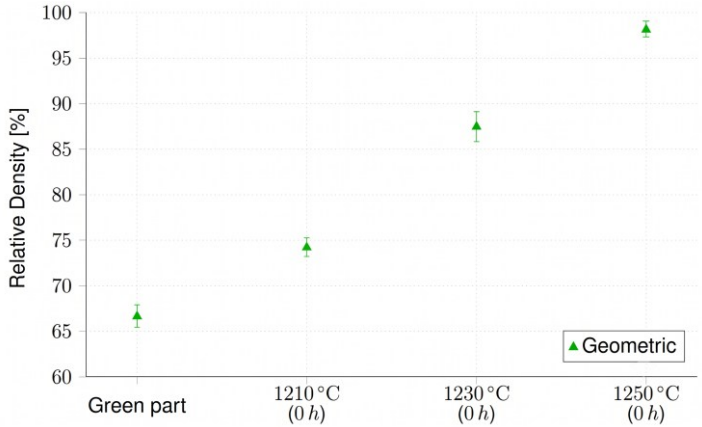


Individual measurements of the line intercept method for the powder material and the samples sintered at 1250 °C. The dashed lines indicate the respective mean values.

Results

Determination of input parameters

Sinter **Input**	**Det**	Input Parameters **Measurements & Determination**
Powder median partic	▪ Dynamic image a	▪ D_{50} = 45.3 µm
Powder original grain	▪ Metallographic m intersections	▪ Average grain size D_{grain}= 2.82 (+/- 0.64) µm
Green part density	▪ CT scans and pre	▪ m_{avg}= 6.6 g, V_{avg}=1224 mm³, $\rho_{avg,rel}$= 66.6%
Static friction coefficie	▪ Literature researc	
Desired sintering profi	▪ Analysis of phase	
Viscosity profile	▪ Sintering double- 1230, 1250 °C ar temperature depe	
Shrinkage profile	▪ sintering cubic sp 1250 °C, CT scar	



Development of sintered relative density in cubic specimens

Results

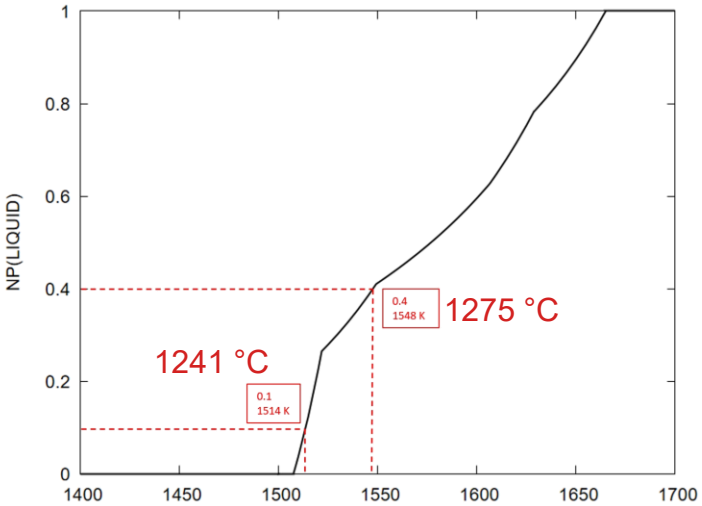
Determination of input parameters

Sinter **Input**	**Det**	Input Parameters **Measurements & Determination**
Powder median partic	▪ Dynamic image a	▪ D_{50} = 45.3 µm
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Green part density	▪ CT scans and pre	▪ m_{avg}= 6.6 g, V_{avg}=1224 mm³, $\rho_{avg,rel}$= 66.6%
Static friction coefficie	▪ Literature researc	▪ 0.33 [-] (Software documentation/manual)
Desired sintering profi	▪ Analysis of phase	
Viscosity profile	▪ Sintering double- 1230, 1250 °C ar temperature depe	
Shrinkage profile	▪ sintering cubic sp 1250 °C, CT scar	

Results

Determination of input parameters

Sinter **Input**	**Det**	Input Parameters **Measurements & Determination**
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Powder original grain	▪ Metallographic m intersections	▪ Average grain size D_{grain}= 2.82 (+/- 0.64) µm
Green part density	▪ CT scans and pre	▪ m_{avg}= 6.6 g, V_{avg}=1224 mm³, $\rho_{avg,rel}$= 66.6%
Static friction coefficie	▪ Literature researc	▪ 0.33 [-] (Software documentation/manual)
Desired sintering profi	▪ Analysis of phase	▪ 1241-1275 (as N-atmosphere 1230, 1210) °C
Viscosity profile	▪ Sintering double- 1230, 1250 °C ar temperature depe	
Shrinkage profile	▪ sintering cubic sp 1250 °C, CT scar	

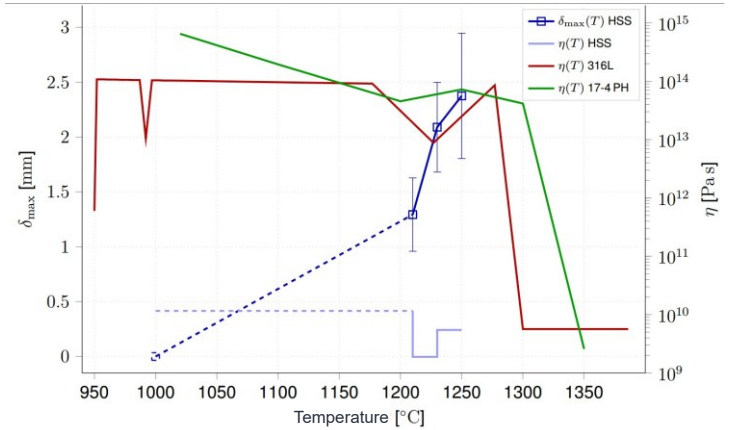


Mole fraction of the liquid phase of the used M3-HSS as a function of temperature. The optimal sintering range is marked by red dashed lines.

Results

Determination of input parameters

Sinter **Input**	**Det**	Input Parameters **Measurements & Determination**
Powder median partic	▪ Dynamic image a	▪ D_{50} = 45.3 µm
Powder original grain	▪ Metallographic m intersections	▪ Average grain size D_{grain}= 2.82 (+/- 0.64) µm
Green part density	▪ CT scans and pre	▪ m_{avg}= 6.6 g, V_{avg}=1224 mm³, $\rho_{avg,rel}$= 66.6%
Static friction coefficie	▪ Literature researc	▪ 0.33 [-] (Software documentation/manual)
Desired sintering profi	▪ Analysis of phase	▪ 1241-1275 (as N-atmosphere 1230, 1210) °C
Viscosity profile	▪ Sintering double- 1230, 1250 °C ar temperature depe	▪ $\delta_{max,1210}$= 1.3 mm, $\delta_{max,1230}$= 2.1 mm, $\delta_{max,1250}$= 2.4 mm → η_{1210}= 11.2 GPa s, η_{1230}= 2.1 GPa s, η_{1250}= 5.4 GPa s
Shrinkage profile	▪ sintering cubic sp 1250 °C, CT scar	

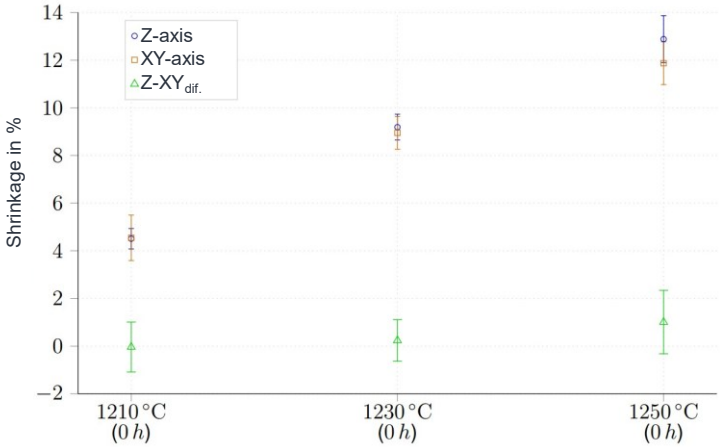


Maximum deflection δ_{max} of the bending beams and calculated viscosity η(T) of the HSS and reference material models in Simufact Additive as a function of sintering temperature.

Results

Determination of input parameters

Sinter **Input**	**Det**	Input Parameters **Measurements & Determination**
Powder median partic	▪ Dynamic image a	▪ D_{50} = 45.3 µm
Powder original grain	▪ Metallographic m intersections	▪ Average grain size D_{grain}= 2.82 (+/- 0.64) µm
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Shrinkage profile	▪ sintering cubic sp 1250 °C, CT scar	▪ $\Delta l_{avg,xy,1210}$= 4.7% $\Delta l_{avg,xy,1230}$= 9% $\Delta l_{avg,xy,1250}$= 11.9% → $\Delta l_{avg,z,1210}$= 4.7%, $\Delta l_{avg,z,1230}$= 9.2%, $\Delta l_{avg,z,1250}$= 12.8%



Shrinkage of the cubic samples in the Z- and X/Y-directions and their difference.

Discussion

Approach to estimate a **material model** to use **existing** PM **infrastructure** to enable **BJT** manufacturing of **HSS** tools for **fast** industrial **adaptation**

Fast and efficient approach was found

NEXT STEPS:

- Transfer to recycled material waste
- Use **dilatometry** for **vacuum** atmosphere

Thank you!



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CCPT Conference on Circular Production Systems and Technologies
9th & 10th June 2026

SFB 1574

KIT Karlsruher Institut für Technologie

Circular Production of Electrical Machine Stators via Upcycling of Manufacturing Scrap into Active Electromagnetic Components

Mojgan ZARE[1], Adrian SCHÄFER[2], Marco SPETH[1], Nejila PARSPOUR[2], & Mathias LIEWALD[1]

DBU



iew

IFU

Universität Stuttgart

[1]Institute for Metal Forming Technology (IFU), University of Stuttgart
[2]Institute of Electrical Energy Conversion (iew), University of Stuttgart

Agenda

- **Motivation**
- New Recycling Route
- Electromagnetic measurement
- Environmental Benefit: CO_2 Reduction
- Outlook and Future Works

Motivation

Conventional Production Method

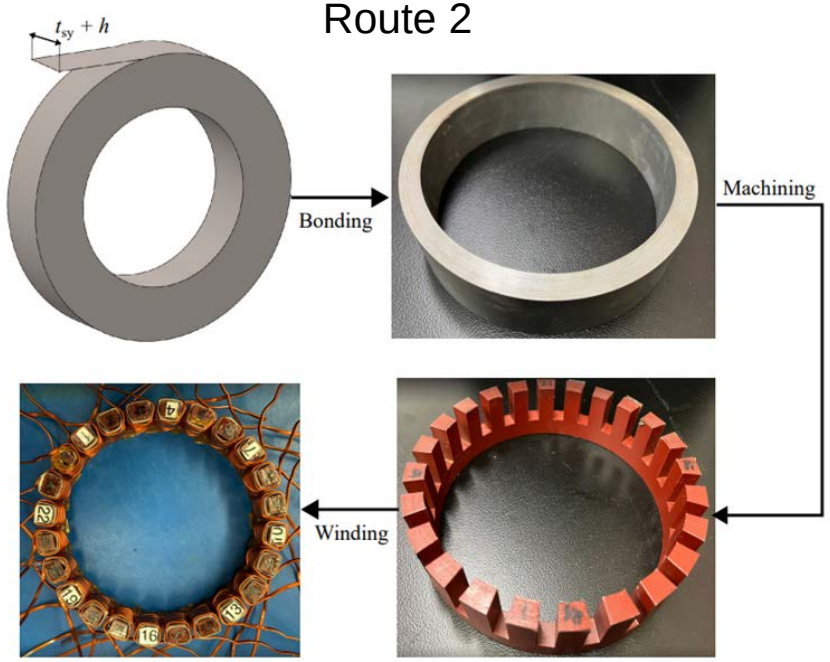
Electrical steel lamination

Route 1



Quelle: https://vacuumschmelze.de

Route 2



Quelle: Nishanth et al., 2023

SMC Powder Metallurgy



Quelle: IEW

Purpose

Developing a new process route for producing an active material by recycling decommissioned electrical machines as well as for the scraps generated during the production of new laminations

Agenda

- Motivation
- **New Recycling Route**
- Electromagnetic measurement
- Environmental Benefit: CO_2 Reduction
- Outlook and Future Works

New Process Route

Steel Scrap Used Parts



Closed-Loop Recycling Process for Electrical Steel

Shredding



Size Sorting



Insulation



Compaction

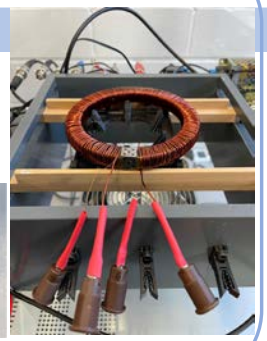


Green Compacts



Electromagnetic Charactrization

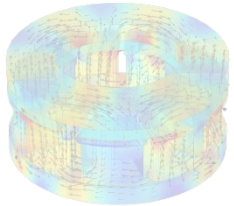




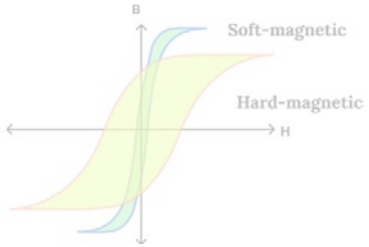
CCMC Product



New material for 3D flux properties



3D - Eddy current inhibition



New recycling route excluding melting

Various applications



New Process Route

Shredding Process

STIEFELMAYER lasertechnik









Single Shaft Machine WLK4









Granulator

New Process Route

Insulation & Compaction

Non-Insulated chips	Phosphated Mn-Ph Phosphated Zn-Ph

Fine



Medium

Coarse



ZWEZ Functional Coatings for Metal

Hydraulic press with a maximum force of 1600 kN



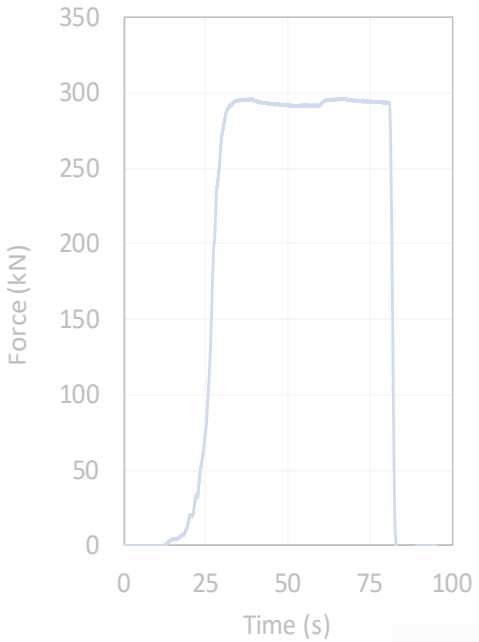
ISO-POX® HP 89/7
Electrical epoxy resin
Zinc stearate/
Molykote



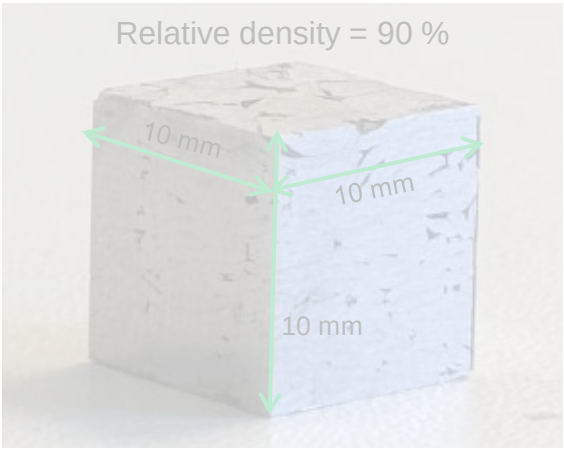
Test Condition Variants

Density measurement (Geometric method DIN EN ISO 2738)

Max. Compaction Force: 300 kN
(Max. Pressure: 1000 MPa)



Cut by ATM Brilliant 250 Cutter



A sample with Mn-Ph insulation (4–6 µm), using1 wt.% of epoxy resin & without external lubrication

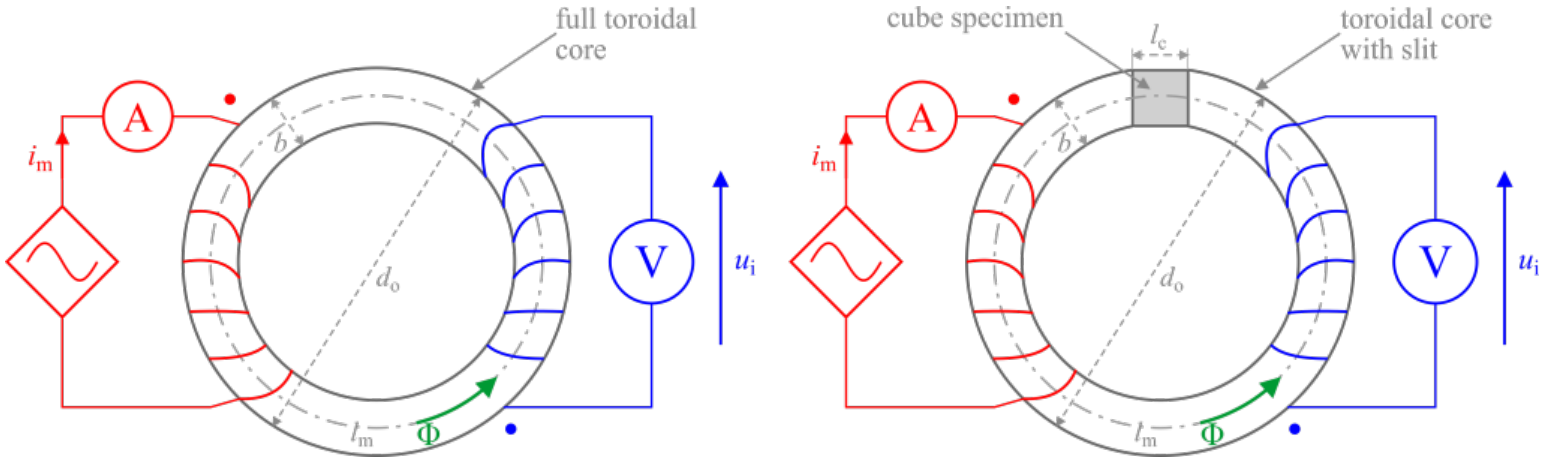
Electromagnetic Characterization

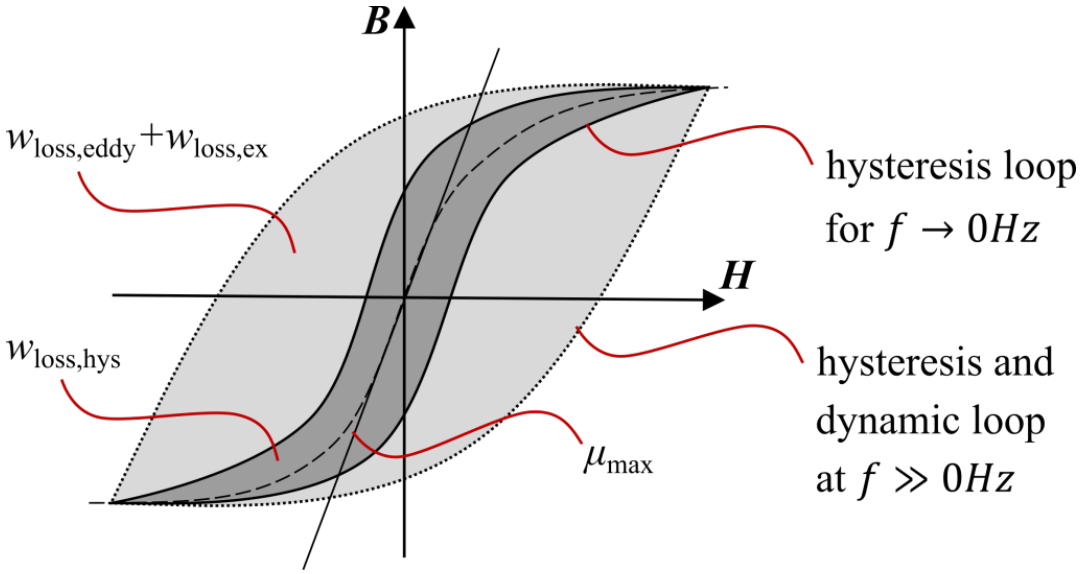
Agenda

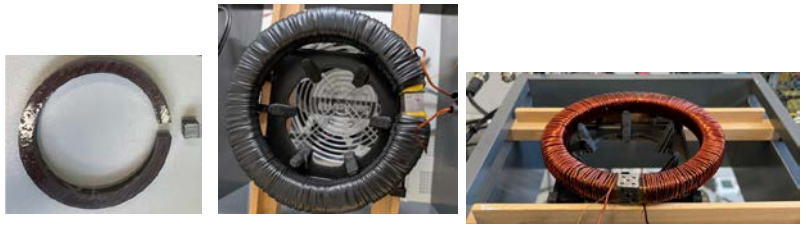
- Motivation
- New Recycling Route
- **Electromagnetic measurement**
- Environmental Benefit: CO_2 Reduction
- Outlook and Future Works

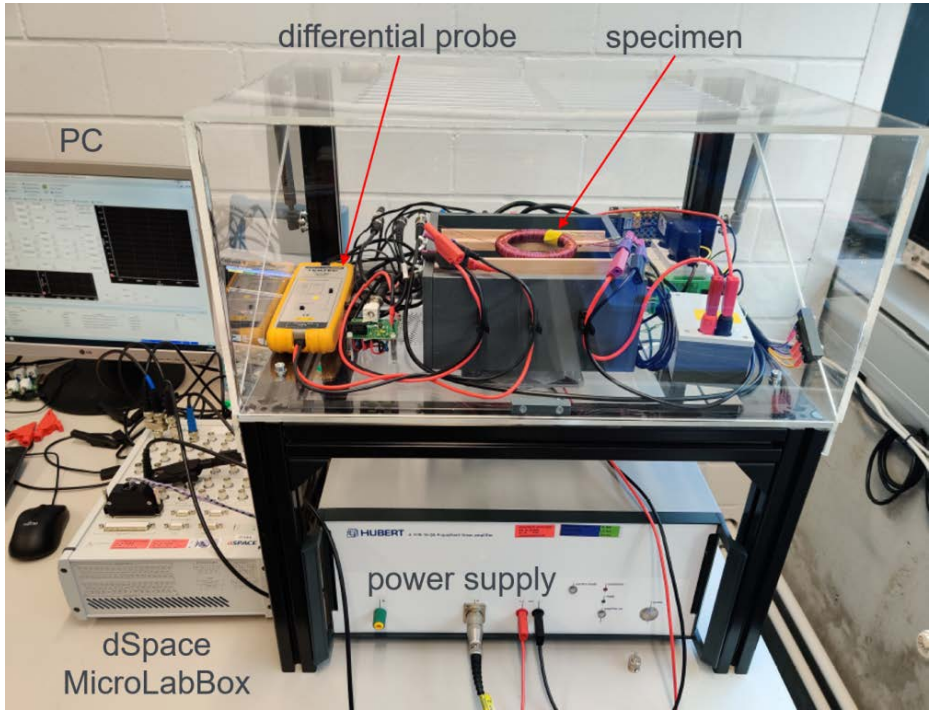
Electromagnetic measurement

Measurement Concept





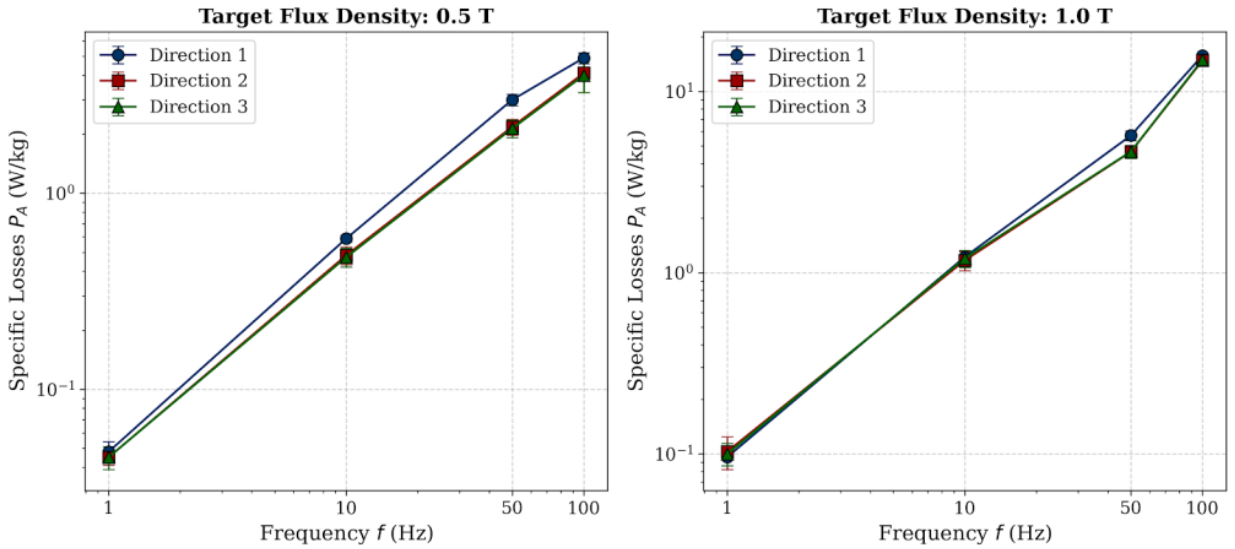




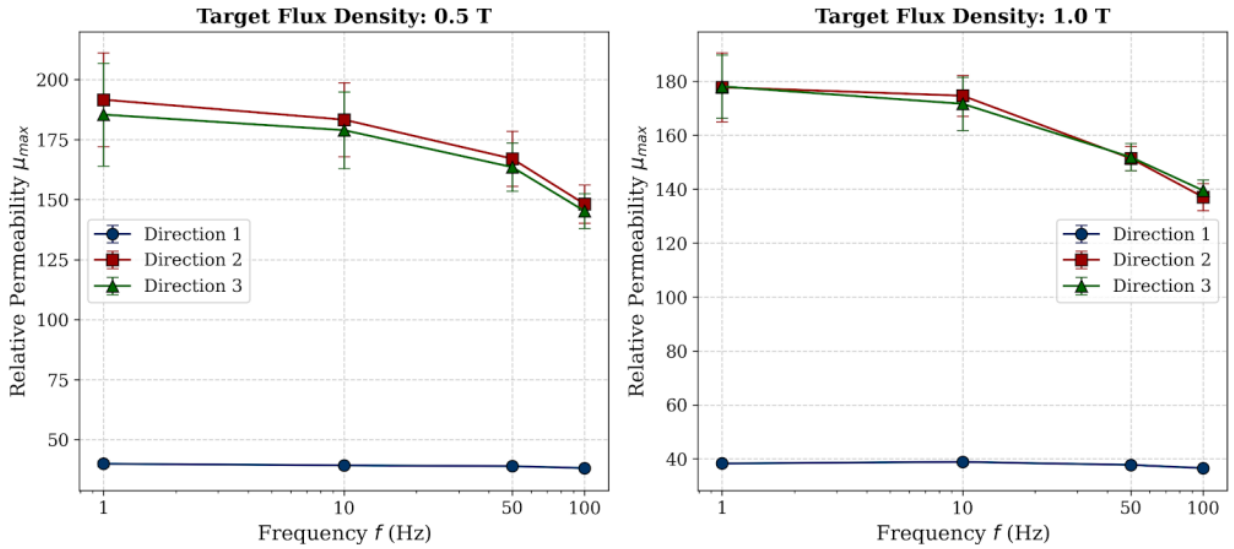
Test bench setup for the electromagnetic measurements of toroidal cores and combined toroidal core with inserted cubes

Electromagnetic measurement

Specific losses of the CCMC material



Maximum relative permeability



- Upcycled CCMC achieved electromagnetic properties comparable to conventional SMC materials.
- CCMC produced entirely from manufacturing scrap.
- A circular manufacturing concept for future electrical machines is validated.
- Anisotropy can be exploited as a design advantage for 3D magnetic flux applications.

Agenda

- Motivation
- New Recycling Route
- Electromagnetic measurement
- **Environmental Benefit: CO_2 Reduction**
- Outlook and Future Works

Environmental Benefit: CO_2 Reduction Estimation

Conventional & New route Comparison

Process step	gCO_2/kg
CONVENTIONAL ROUTE	
EAF melting + casting	256.7
Hot rolling	118.3
Cold rolling	77.8
Sheets coating	n.q.*
TOTAL — Conventional (lower bound)	452.8
CCMC UPCYCLING ROUTE	
Shredding	30.0
Insulation of chips	n.q.*
Chip compaction	41.0
TOTAL — CCMC	71.0
CO_2 saving — CCMC vs. conventional (no anneal)	84 %

➢ Conventional recycling route
(melting → casting → rolling)

➢ CCMC route
(shredding → insulation → compaction)

Only process steps with independently published energy data were included.
Missing data (e.g., Mn-phosphating) were excluded symmetrically from both routes.

- New recycling eliminates energy intensive melting and rolling operations.
- CCMC provides a significantly more sustainable route for manufacturing active electromagnetic components from electrical steel scrap.

Agenda

- Motivation
- New Recycling Route
- Electromagnetic measurement
- Environmental Benefit: CO_2 Reduction
- **Outlook and Future Works**

Outlook and Future Works

- Direct compaction of cubic specimens with a developed die with different chip size under various test condition
  > Higher compaction pressures and densities (>95%)

- Validation with industrial scrap from end of life machines

Tools stress Investigation

eesy-DieOpt Vers. 3.10

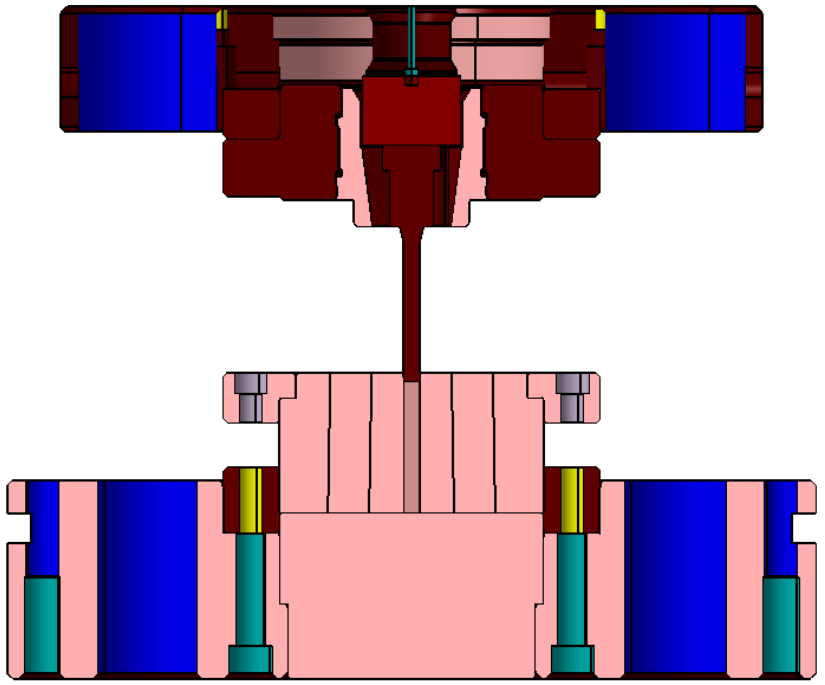
Container

Segmented Die

Shrink Ring

DEFORM
Design Environment for FORMing

Tools Manufacturing

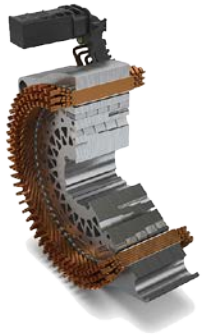


Outlook and Future Works

- Electromagnetic characterization of optimized CCMC materials for different cubic samples

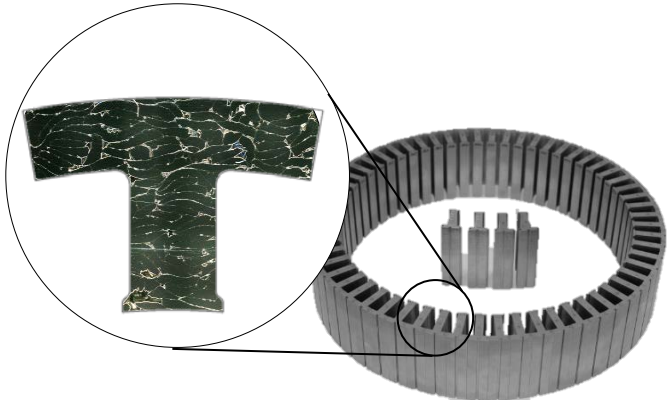
➢ Extending To Real-world Applications







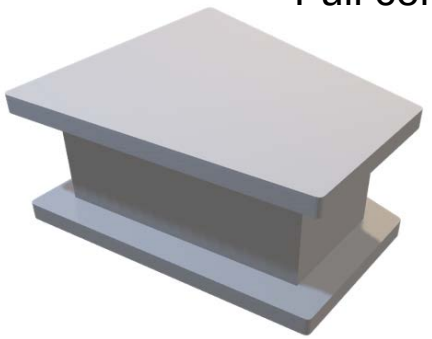
Quelle: Schaeffler



Quelle: swd-technology.com

➢ CCMC Stator segment in axial flux machine

Full complexity



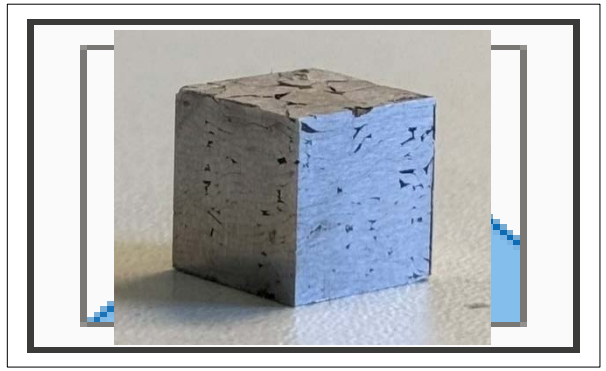


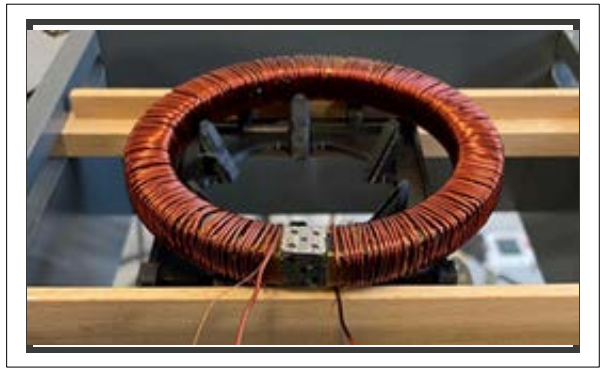
Trapezoidal prism

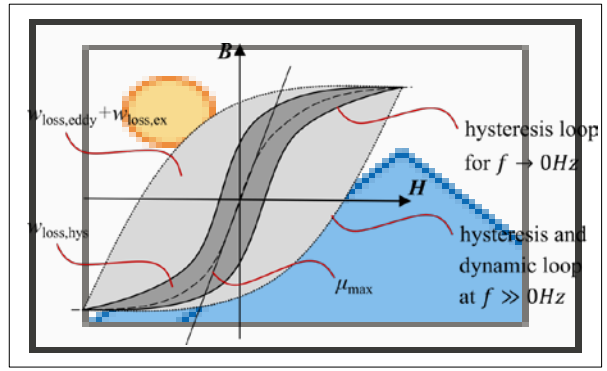












Thank you for your attention

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Spare slides

Hysteresis Loop Extraction

For the extraction of the hysteresis loop of the cubic CCMC sample Ampère's circuital law is utilized which states that in the measurement setup, the total measured magnetic voltage is the sum of the drops across the ring and the cube

$$N_{1,meas} \cdot i_{1,meas}(t) = H_{meas}(t) \cdot l_m = H_{ring}(t) \cdot l_{ring} + H_{cube}(t) \cdot l_{cube}.$$

While the left side of this equation is known by measuring the excitation current $i_{1,meas}$, the H_{ring} on the right side must be derived by the Ampère's law of the reference setup

$$N_{1,ref} \cdot i_{1,ref}(t) = H_{ref}(t) \cdot l_m.$$

Since the toroidal core consists of the same material in both setups when transformed to the B-domain the B-H-trajectories are the same.

$$H_{ring}(B) = H_{ref}(B)$$

Therefore, the hysteresis loop of the cube is calculated by

$$H_{cube}(B) = \frac{H_{meas}(B) \cdot l_m - H_{ref}(B) \cdot l_{ring}}{l_c}$$

$$H_{cube}(B) = \frac{N_{1,meas} \cdot i_{1,meas}(B) - N_{1,ref} \cdot i_{1,ref}(B) \cdot \frac{l_{ring}}{l_m}}{l_c}$$

With the hysteresis loop of the cube the gravimetric loss energy density per cycle is calculated as

$$w_{c,grav} = \rho \oint H_{cube}(B)\, \mathrm{d}B$$

yielding the gravimetric loss power density $p_{c,grav} = w_{c,grav} \cdot f$.

The maximum relative permeability is determined from the H-centered hysteresis curve

$$H_{cube,avg}(B) = \frac{H_{c,falling}(B) + H_{c,rising}(B)}{2}$$

by calculating the gradient of the steepest secant

$$\mu_{max} = \max\left(\frac{\mu_0 \cdot H_{cube,avg}(B)}{B}\right).$$

Spare slides

Conventional Route

Process Step	Calculation	gCO_2/kg
EAF melting + casting	Sector data	256.7
Hot rolling	(0.117×410) + (0.350×201)	118.3
Cold rolling	(0.175×410) + (0.030×201)	77.8
Strip coating + final anneal	No data — excluded	n.q.
Total		**452.8**

References:

Emission factors: UBA 2023; UBA 2022

EAF + rolling energy: Schlemme et al. 2019

Shredder power: WEIMA WLK 4 datasheet

Compaction energy: Herlan, IFU Stuttgart 1989

CCMC Route

Process Step	Calculation	gCO_2/kg
Shredding (WLK 4, 22 kW, ~300 kg/h)	(22÷300)×410	30.0
Mn-Ph insulation	No data — excluded	n.q.
Chip compaction (0.100 kWh/kg)	0.100×410	41.0
Total		**71.0**

KU LEUVEN

Environmental Performance of a Chip-Based Recycling Route for Ti6Al4V Additive Manufacturing Feedstock

Pooya Hosseini, Simon Kettelmann, Berend Denkena, Brent Hendrickx, Joost R. Duflou

Outline

- Why Titanium Matters
- Waste Paradox
- Chip-to-Powder as an Alternative
- Environmental Performance
- What This Means Going Forward



Machining Chips

Titanium: Strategic… but Fragile

Titanium is a future metal

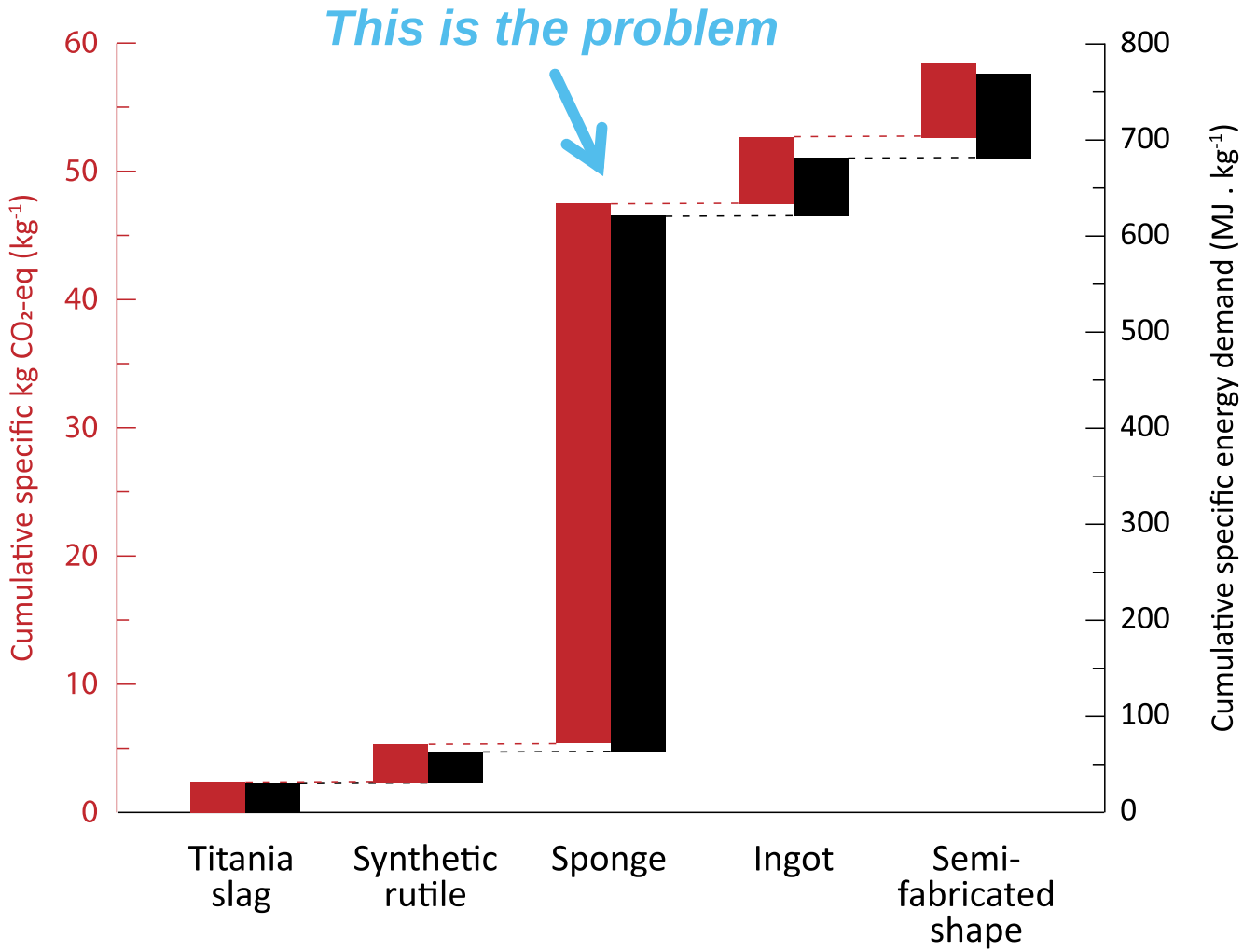
- High strength-to-weight ratio
- Aerospace backbone

But… extremely costly

- Energy-intensive sponge production

Europe is exposed

- Limited EU sponge supply
- 60% import dependence



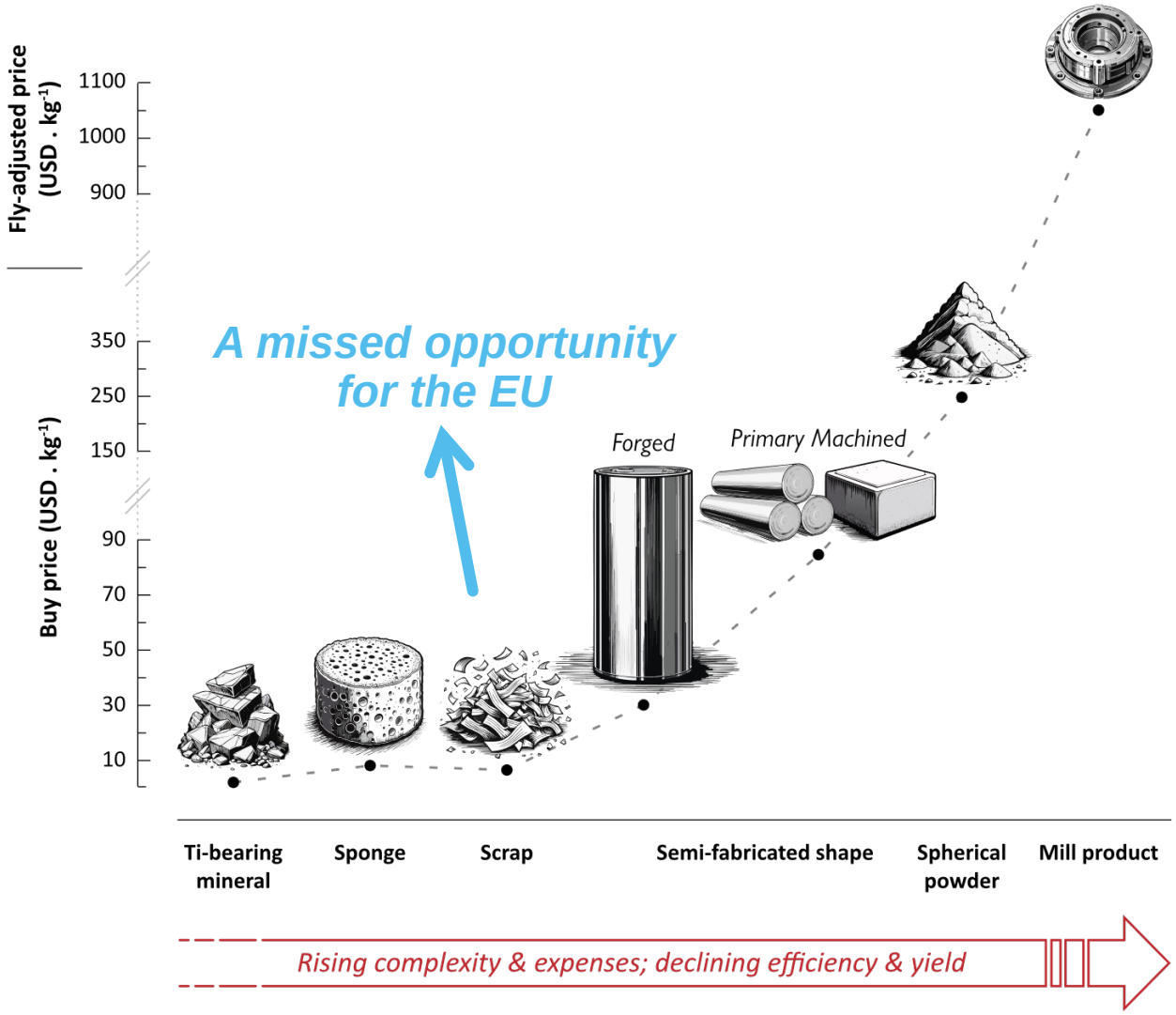
A System That Wastes Value

Machining inefficiency

- Up to 90% → chips
- ~250 kt scrap/year

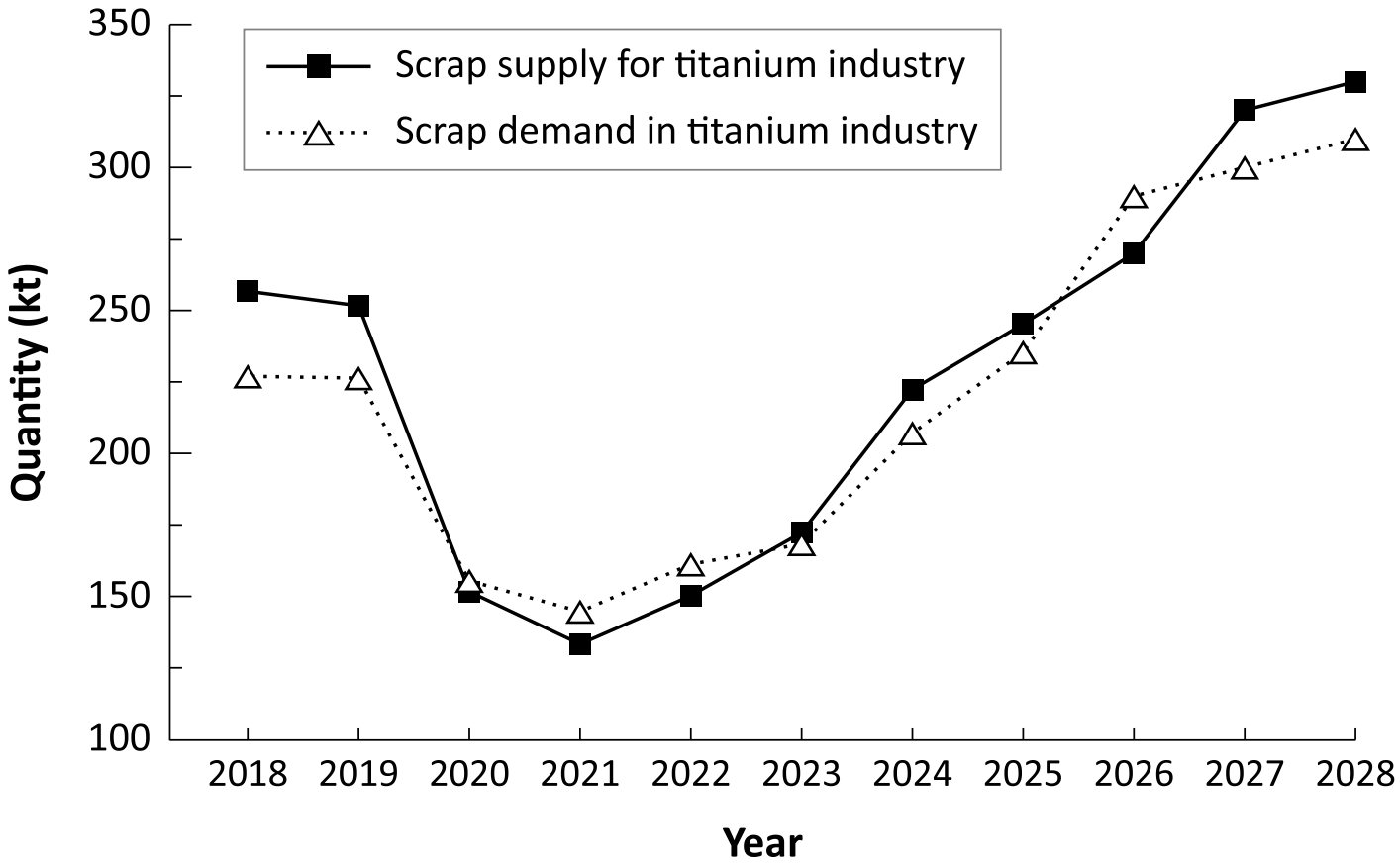
Recycling today?

- Remelt + dilute with sponge
- Oxygen & contamination issues



A Growing Scrap Stream Seeking Value

- Scrap **availability** remains **substantial**
- Supply and demand **continue to expand**
- **Higher-value** routes needed **beyond remelting**



'Recycling Ti6Al4V Machining Chips into Powder for Aerospace Additive Manufacturing: Environmental Impacts and Market Dynamics,' Hosseini, et al., 2026

Solid-state Recycling







Mining + Feedstock

Manufacturing

Product

Waste

Disposal

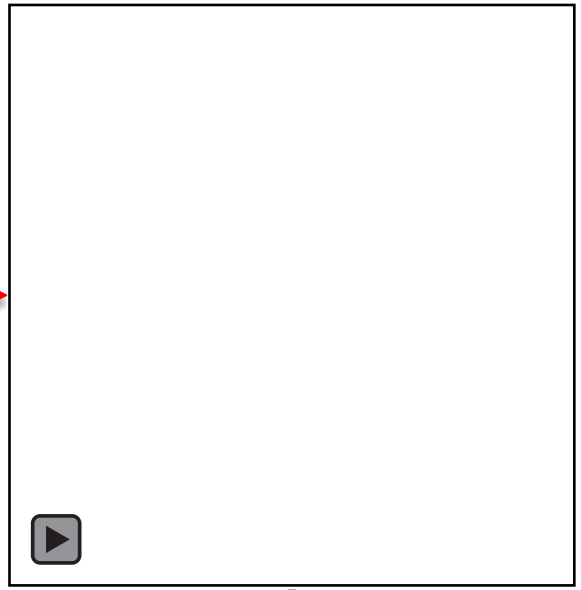
Intermediate Processing

Mining + Feedstock

Manufacturing

Product

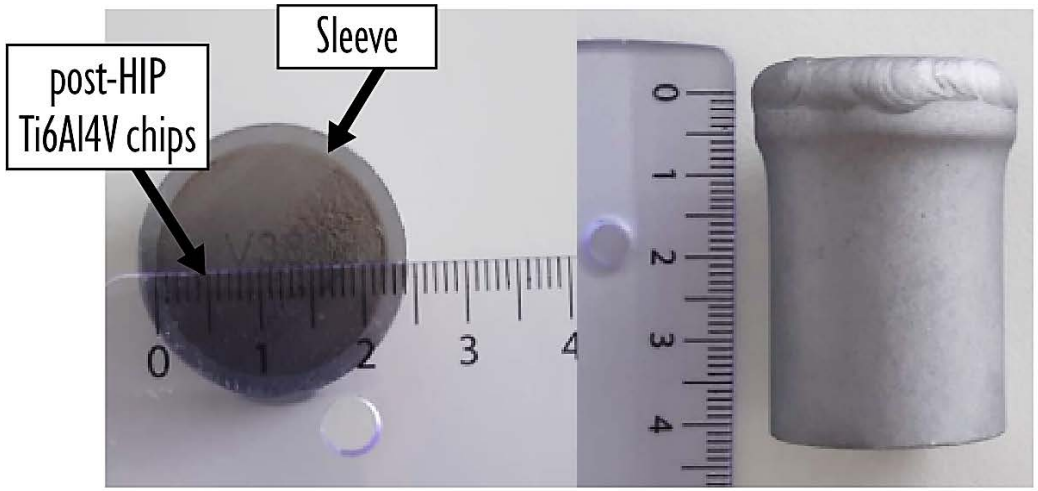
Waste

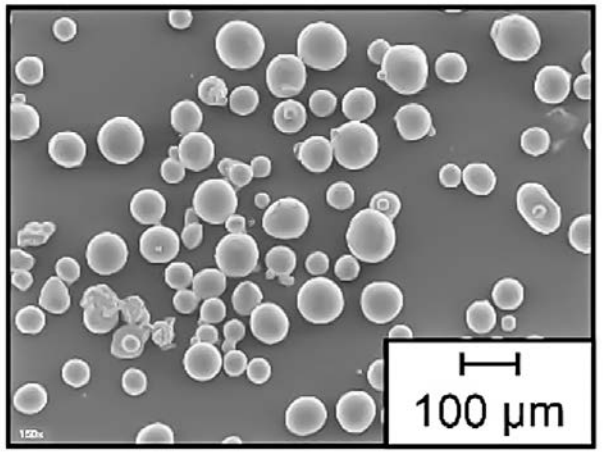


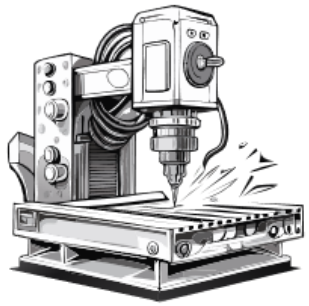


Equal Channel Angular Pressing *(Meltless Process)*

Chip-to-Powder Process







CNC Machining of Ti6Al4V Block



Ti6Al4V Machining Chips

Meltless Consolidation & Hot Isostatic Pressing



Ti6Al4V Fully-Dense Atomization Electrode

Electrode Induction Melting Inert Gas Atomization



Ti6Al4V Spherical Powder

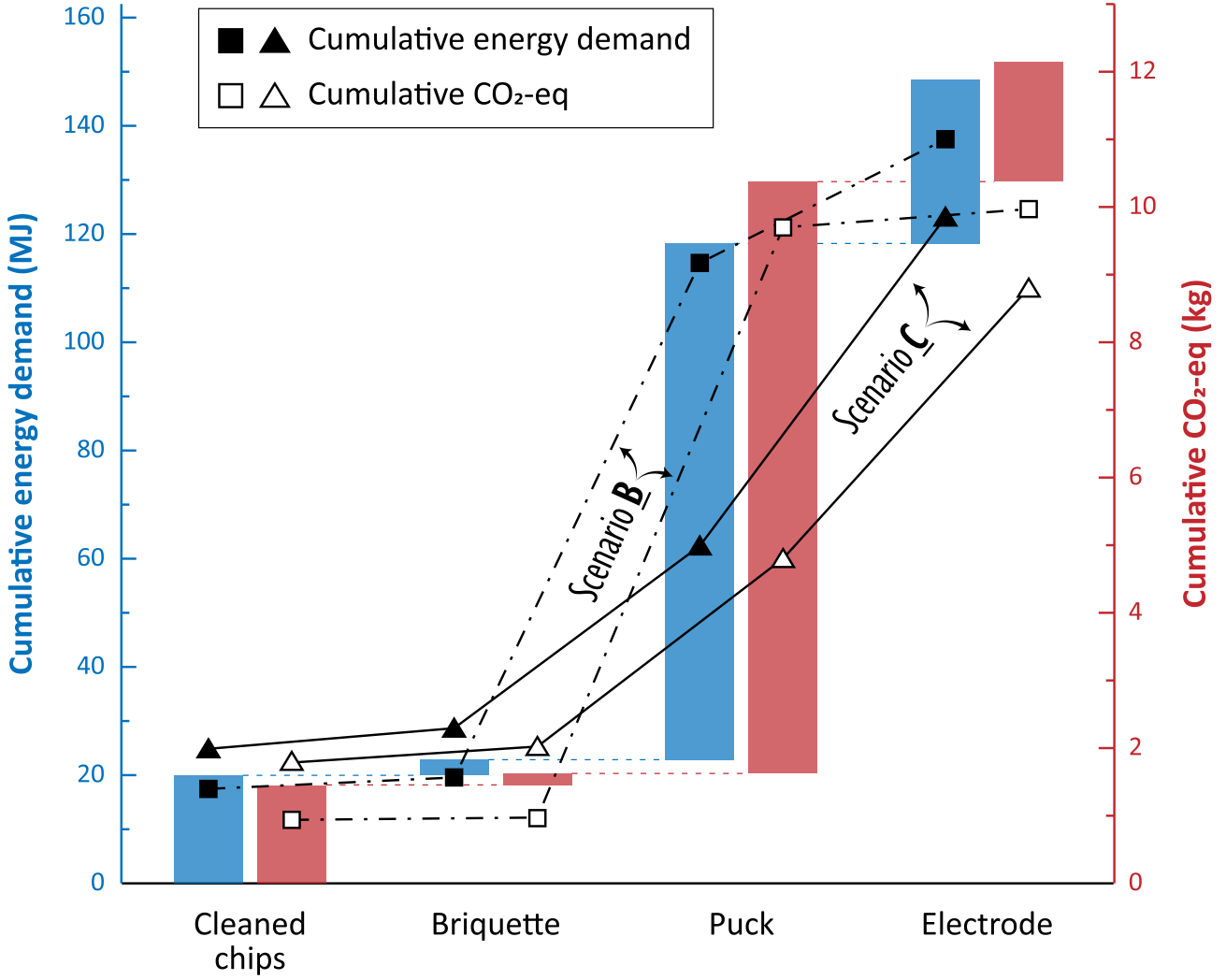
'Recycling of Ti-6Al-4V chips for closed-loop manufacturing,' Denkena, et al., 2024

Where Does the Impact Come From?

- **Scenario A** (***blue*** & ***red*** bars)
  Developed Ti6Al4V chips-to-powder recycling

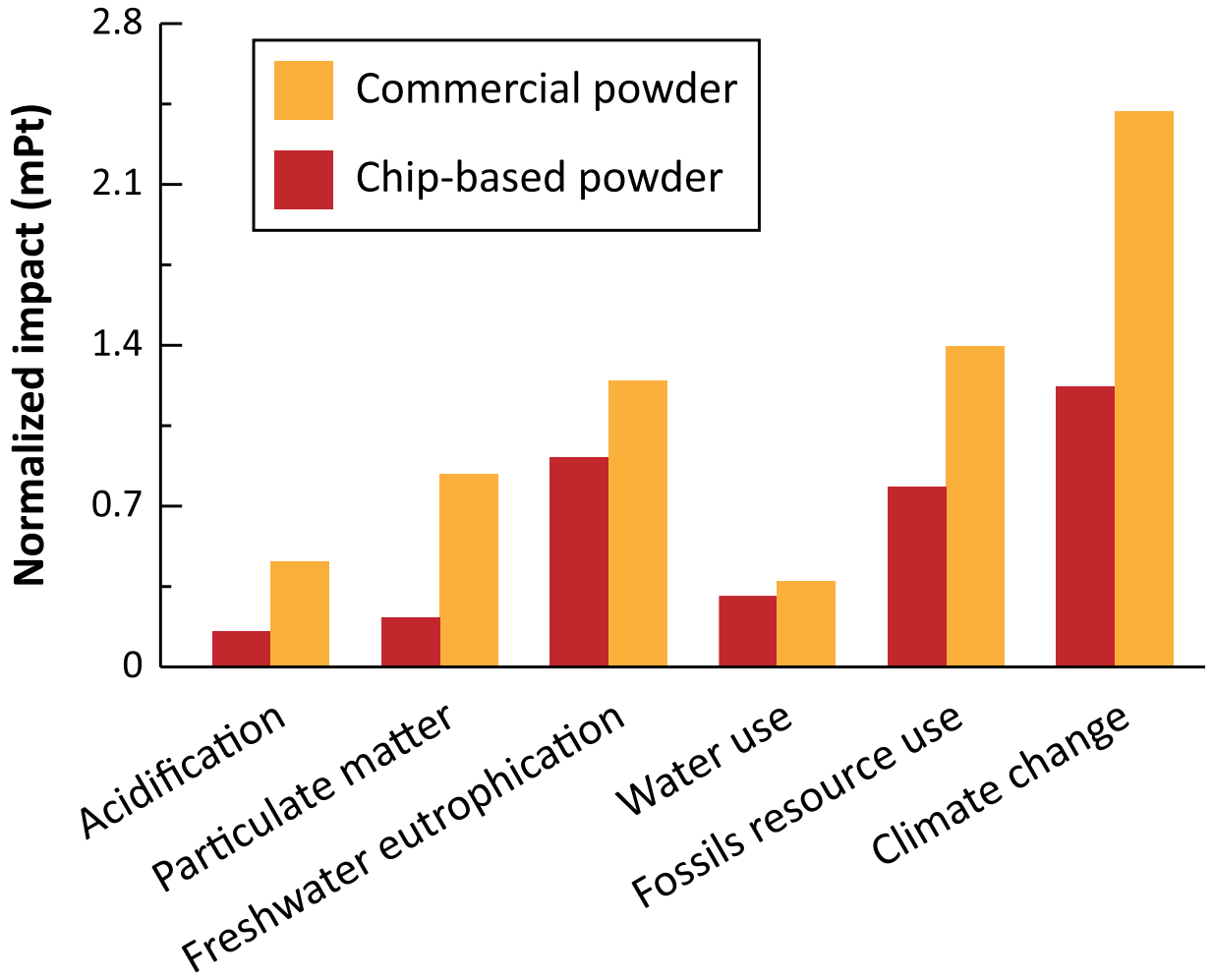
- **Scenario B**
  Scenario A with green electricity & local supply chain (5x higher renewable share vs Scenario A)

- **Scenario C**
  Scenario A with stainless steel sleeve (304) replacing Ti6Al4V sleeve



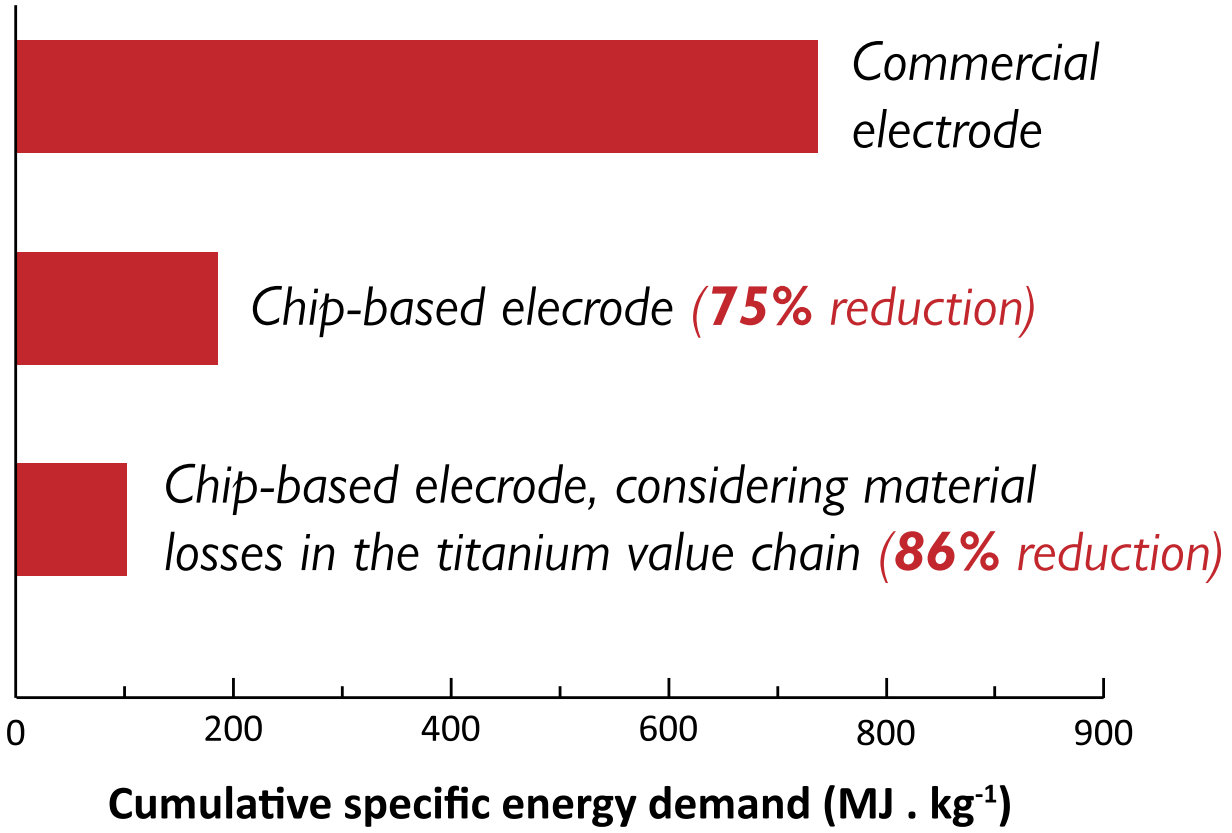
Less Impact, Same Powder

- **Benefits** extend **beyond climate change**
- No **burden shifting** between **categories**
- **Circular** feedstock with **aerospace-grade potential**



Material Losses Drive Energy Demand

- Value-chain **losses dominate** the real **burden**
- **Chip-to-powder** route bypasses **sponge dependency**
- **Biggest** gain comes **before atomization**



Conclusion & Outlook

- **Titanium chips** are an **underutilized strategic** resource
- **Chip-to-powder** recycling **bypasses sponge-intensive** production
- Environmental **benefits arise** primarily from **avoiding upstream** material **losses**
- Up to **86% reduction** in cumulative **energy demand**
- **Future work:** scale-up, industrial implementation, and broader valorization pathways

Landfills **are monuments** *to* ***linear*** *thinking!*

KU LEUVEN

Correlations between material properties of commercially available PETG filaments for MEX-TRB/P additive manufacturing

Nick Schneider, Marius Hoffmann, Kai Scherer, Roman Kirsch, Michael Wahl

Presented by: Nick Schneider

09.06.2026

1. Challenge and Objective

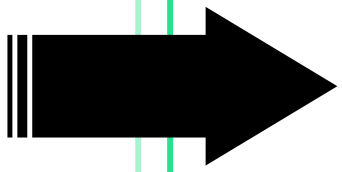
Challenge:

- **MEX-TRB/P** is the primary additive manufacturing process for **thermoplastic polymers**.
- The use of **recyclates**, particularly from **post-consumer waste**, is growing in importance.
- Polymers of **unknown origin** require **material characterization**, which is often complex and time-consuming.

1. Challenge and Objective

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Objective:

1. Challenge and Objective

Challenge:

- **MEX-TRB/P** is the primary additive manufacturing process for **thermoplastic polymers**.
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- Polymers of **unknown origin** require **material characterization**, which is often complex and time-consuming.

Objective:

- **Material characterization** of different **filament** grades within one **polymer type** using additively manufactured specimens.
- Identification of useful **correlations** between material properties.
- **Reduction** of the characterization steps required for an **initial material assessment**.

2. Material

Requirements for material selection:

- ! Established use in additive manufacturing
- ! No additional additives
- ! High grade variability
- ! Uniform filament diameter

Implementation:

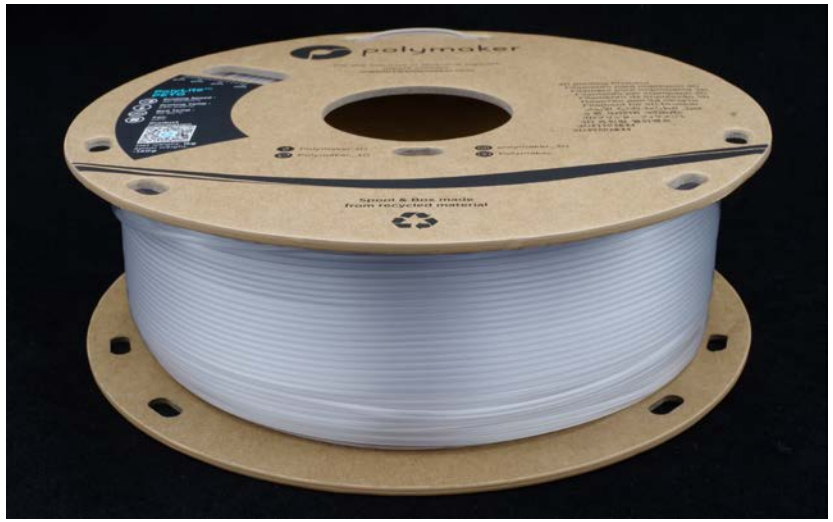
- ☑ **PETG** (Polyethylene Terephthalate Glycol)
- ☑ **Natural** (colorless)
- ☑ **9** grades (**5** manufacturers)
- ☑ **Ø 1.75 mm**

2. Material

Selected Filament Types:

Grade	Manufacturer	Identifier
PolyLite PETG	Polymaker	A
Prusament PETG	Prusa Polymers a.s.	B
HDglass	FormFutura B.V.	C
ReForm – rPET[a]	FormFutura B.V.	D
EasyFil ePETG	FormFutura B.V.	E
Fiberlogy EASY PET-G	Fiberlab S.A.	F
Extrudr PETG	FD3D GmbH	G
Extrudr XPETG REC	FD3D GmbH	H
PolyCore PETG-1000[b]	Polymaker	I

[a] Produced from waste generated during the extrusion of PETG grade C
[b] Supplied in granule form and extruded into filament in-house.



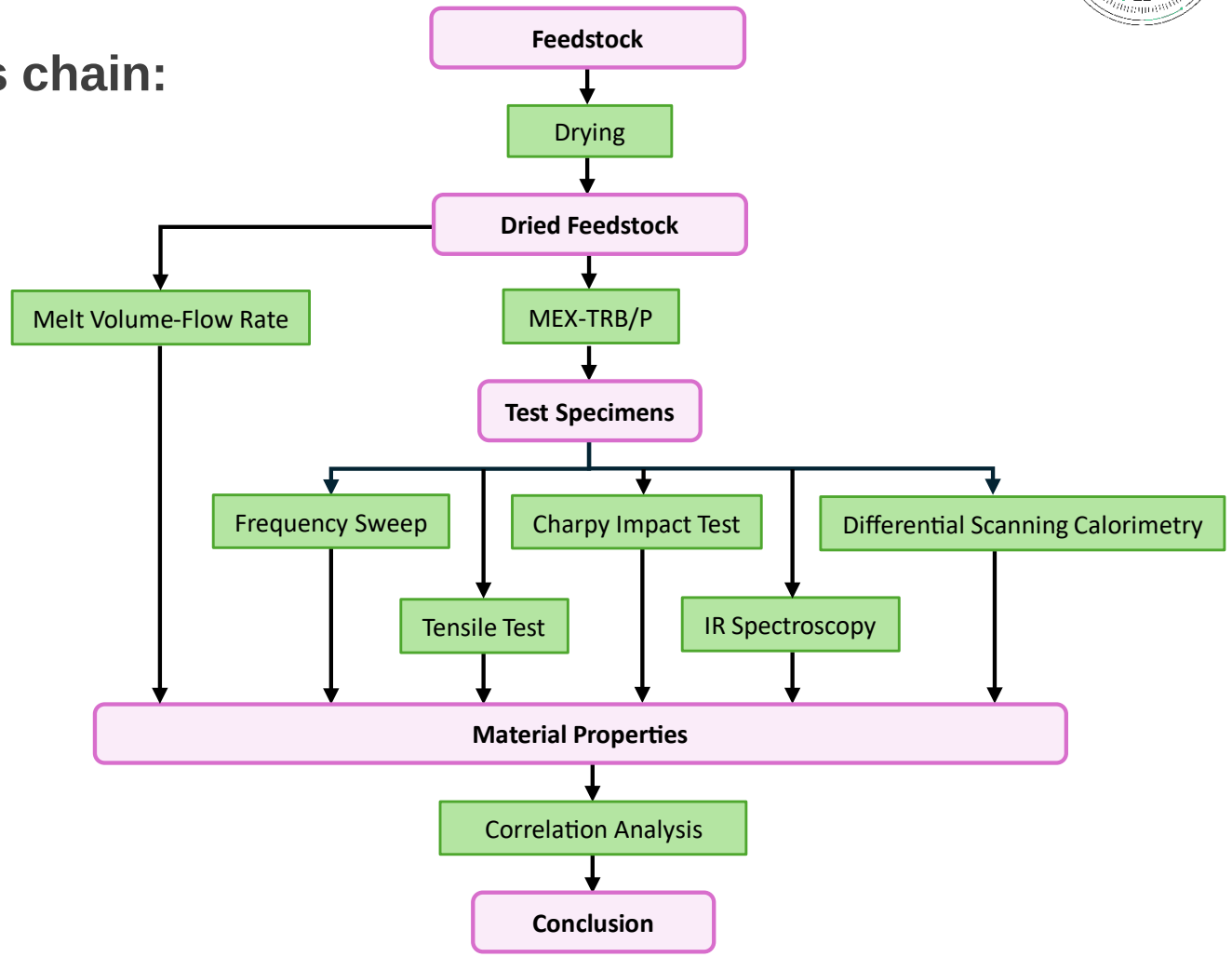
PolyLite PETG (Polymaker, Changshu, China)

virgin filament
recycled filament

3. Methodological approach

Requirements for the analysis process chain:

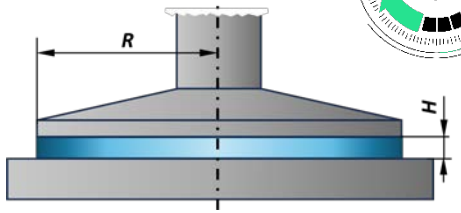
- **Uniform** material handling and analysis
- Broad coverage of material characteristics, including **mechanical**, **rheological**, **thermal**, and **chemical-structural properties**

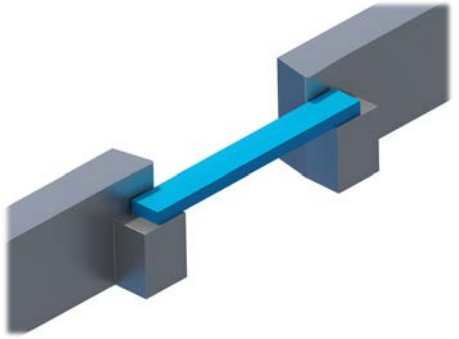


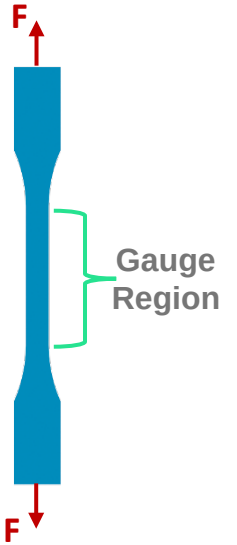
3. Methodological approach

Characterization methods:

- **Mechanical properties**
  - 01 Tensile Test
  - 02 Charpy Impact Test
- **Rheological properties**
  - 03 Frequency Sweep (Rheological Analysis)
  - 04 Melt Volume–Flow Rate (MVR)
- **Thermal properties**
  - 05 Differential Scanning Calorimetry (DSC)
- **Chemical–structural properties**
  - 06 Infrared Spectroscopy (ATR)







CZS Center KRAFt: **K**reislaufwirtschaft und **R**essourceneffizienz mittels **A**dditiver **F**ertigungs**t**echnologien

3. Methodological approach

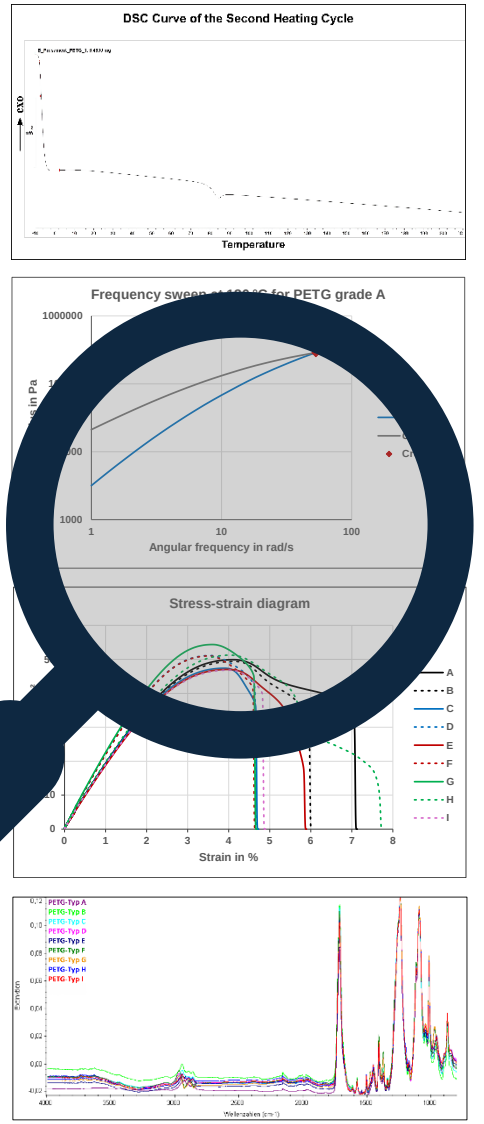
Determined material properties:

- Tensile modulus E_t
- Tensile strength σ_m
- Elongation at tensile strength ε_m
- Charpy impact strength a_{cU}
- Crossover modulus G_c
- Crossover angular frequency ω_c
- Glass transition temperature T_g
- Melt Volume-Flow Rate **MVR**
- Wavenumbers of local IR peaks

3. Methodological approach

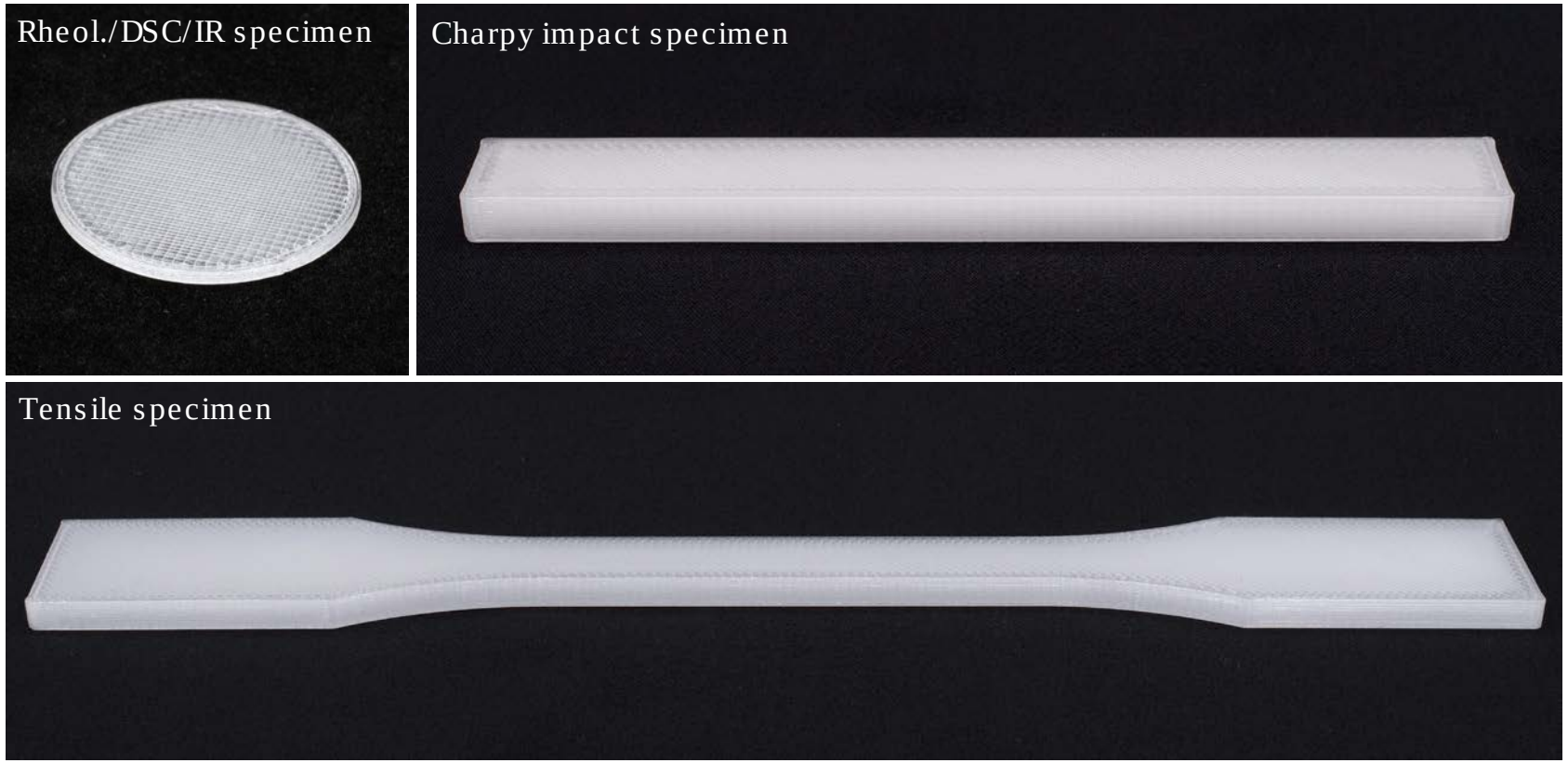
Correlation Analysis:

- **Cross-method** comparison of characteristic values
- Assessment of **linear relationships**
- **Pearson correlation coefficient *r*** as quality criterion



4. MEX-TRB/P

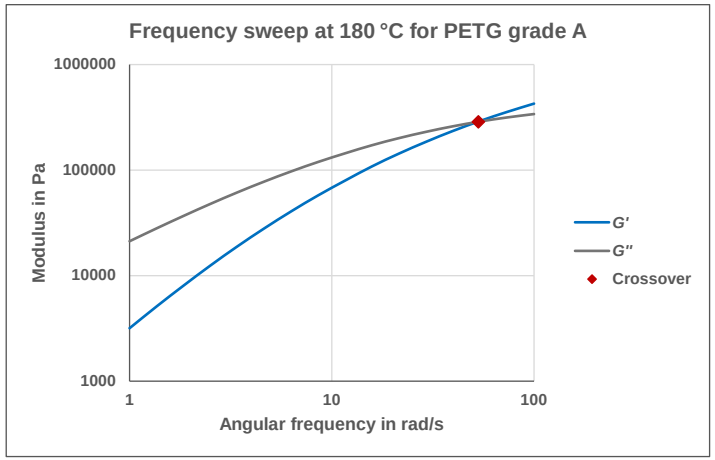
Test specimens:

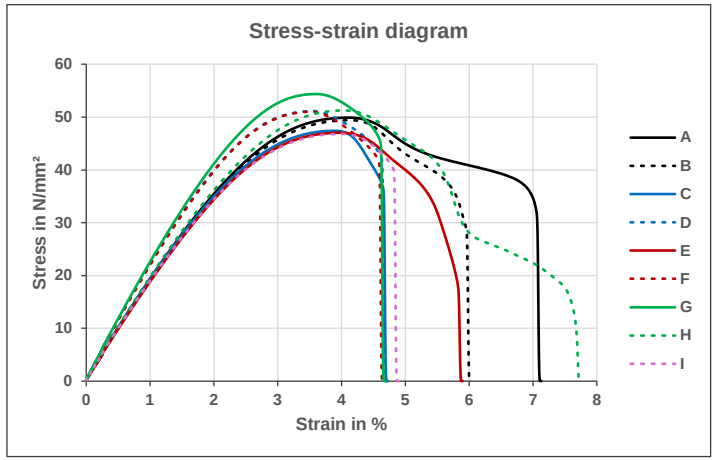


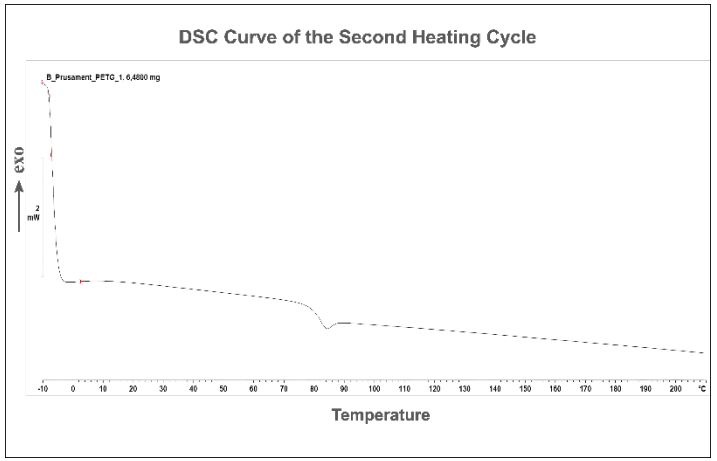
5. Results

Key figures:

- More than 700 printed specimens
- 630 measurements conducted
- Determination of 9 different material properties

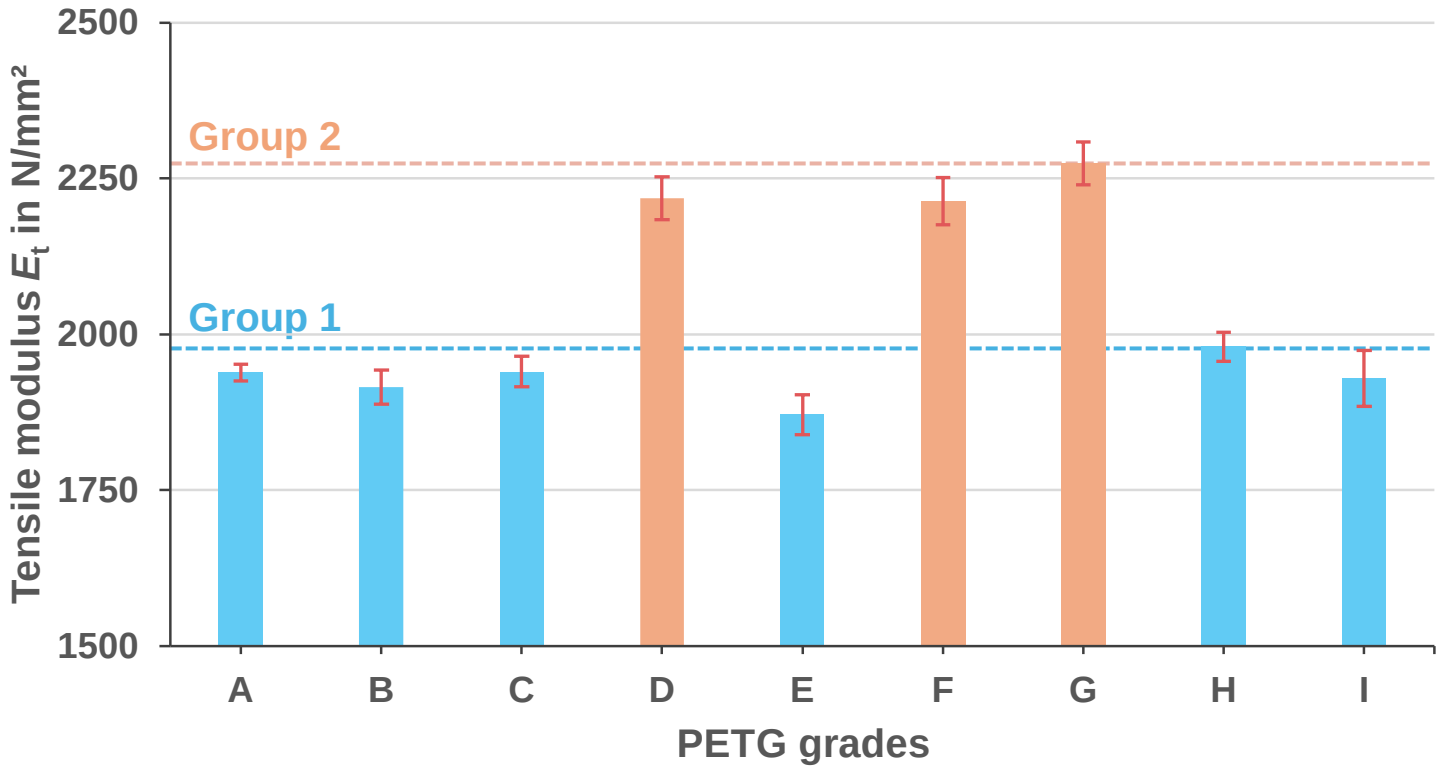






5. Results

Example: Tensile modulus E_t





- Two distinct groups of PETG grades with similar values were observed

5. Results

Pearson correlation coefficient *r*:

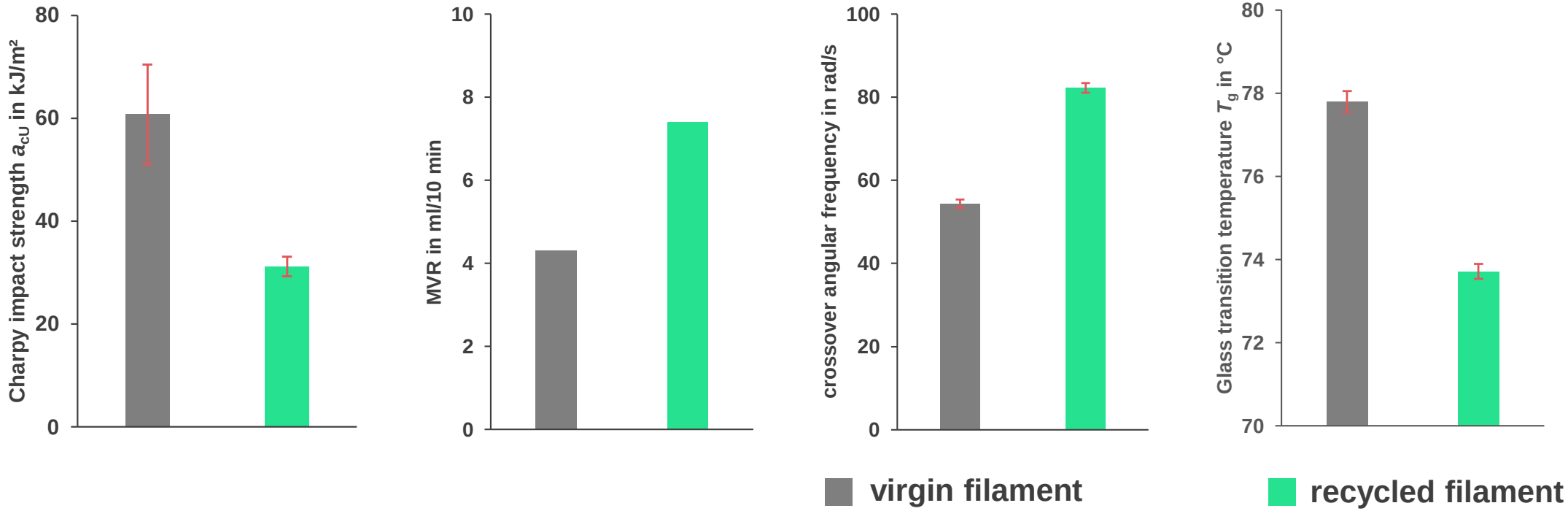
- Highest correlations are between **tensile modulus**, **elongation at tensile strength**, **crossover modulus**, and **shifts** of local **IR peaks 1** and **2**.
- Comparatively weak correlations mainly for **tensile strength** and **glass transition temperature**, except for the correlations of glass transition temperature with elongation at tensile strength, crossover angular frequency and MVR.

		Tensile test			Impact test	Rheology		IR spectroscopy			MVR
		E_t	σ_m	ε_m	a_{cU}	ω_c	G_c	peak 1	peak 2	peak 3	MVR
Impact test	a_{cU}	-0.84	-0.46	0.95							
Rheology	ω_c	0.81	0.58	-0.86	-0.71						
	G_c	**-0.98**	-0.75	**0.98**	0.92						
IR spectroscopy	peak 1	0.97	0.73	**-0.98**	-0.93	0.82	**-0.99**				
	peak 2	**0.98**	0.74	**-0.98**	-0.92	0.82	**-0.99**				
	peak 3	0.89	0.69	-0.89	-0.80	0.78	-0.90				
MVR	MVR	0.95	0.77	-0.94	-0.82	0.91	-0.95	0.94	0.95	0.84	
DSC	T_g	-0.79	-0.57	0.82	0.67	-0.82	0.75	-0.78	-0.79	-0.62	-0.82

5. Results

Comparison of virgin and recycled filament:

Compared with the virgin filament, the recycled filament exhibits increased brittleness, reduced melt viscosity, a lower average molecular weight (shorter polymer chains), a lower glass transition temperature, and shifts in local peaks in the IR spectra.



6. Conclusion

- Selected material properties of different PETG filaments indicated **pronounced linear relationships**, with **Pearson correlation coefficients *r*** of up to **0.99**
- **MVR**, **DSC**, and **IR spectroscopy** show potential for simplified feedstock characterization due to their **simple implementation** and lack of a defined specimen geometry
- Repeated processing led to **reduced molecular weight**, **toughness**, **glass transition temperature**, and **melt viscosity**, as well as **shifts in local IR absorption maxima**
- Further validation is required using **additional PETG grades** and a **broader** material extrusion **processing window**

Carl Zeiss Stiftung

Umwelt-Campus Birkenfeld | HOCHSCHULE TRIER



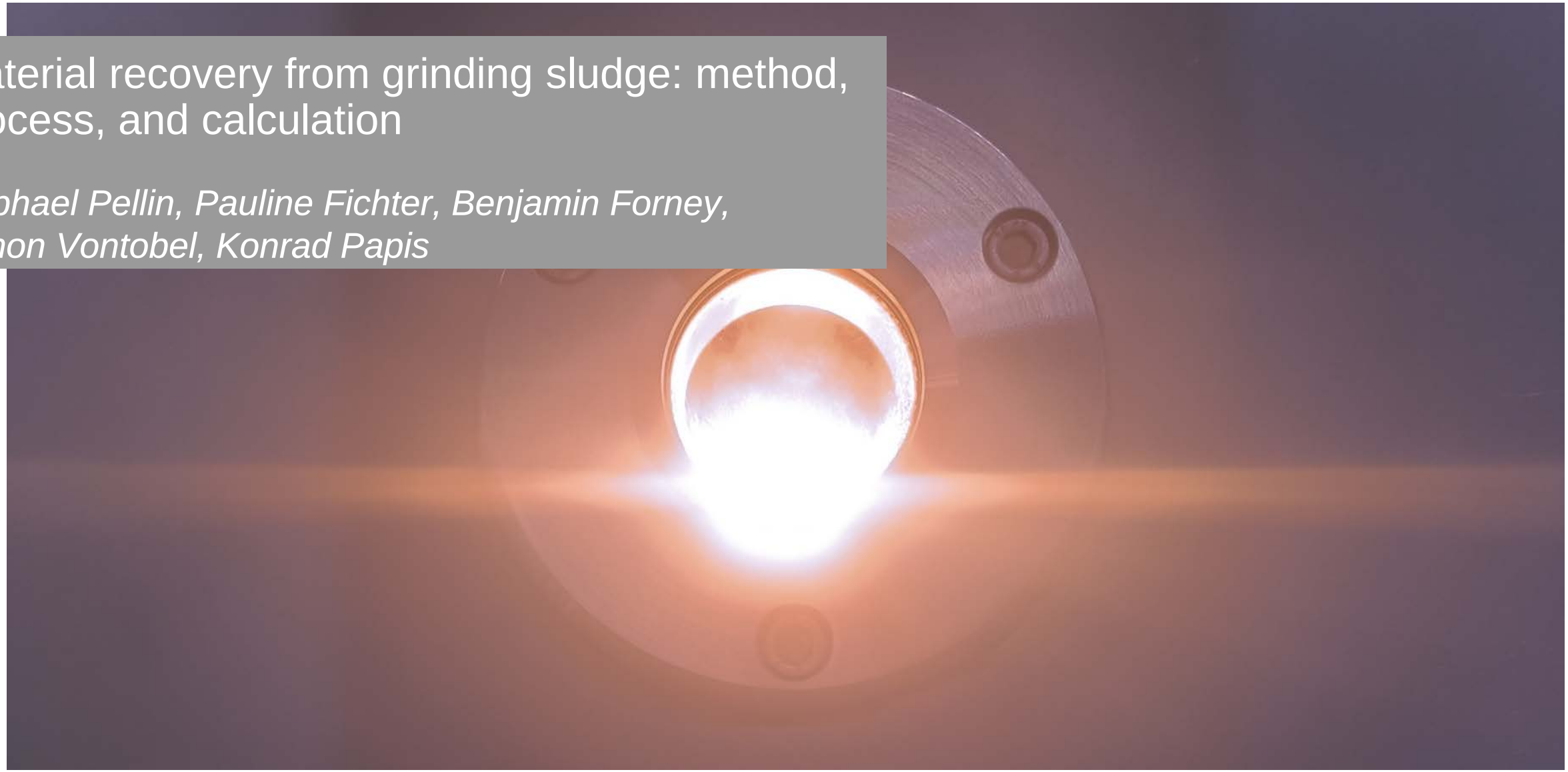
Questions?

For further questions:

✉ n.schneider@umwelt-campus.de

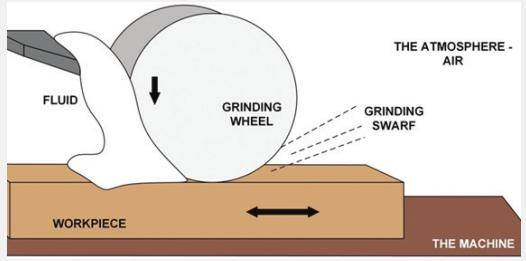
Material recovery from grinding sludge: method, process, and calculation

Raphael Pellin, Pauline Fichter, Benjamin Forney, Simon Vontobel, Konrad Papis



Grinding sludge journeys and recovery of liquids

Grinding



[1]

Grinding sludge



[2]

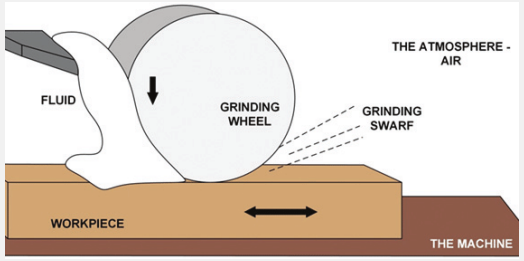
Composition of grinding sludge [3]

Elements	Weight percemtag
Iron	50 – 80 wt.-%
Abrasives (e.g. SiC, Al_2O_3)	4 – 20 wt.-%
Oil	0.5 – 40 wt.-%
Water	0 – 30 wt.%
Alloys	0 – 15 wt.-%

[1] Jamrozik, Artur, Łukasz Klapiszewski, Beata Strzemiecka, Adam Voelkel, and Teofil Jesionowski. 2018. 'Additives for Abrasive Materials'
[2] recyclinginternational.com/technology/millions-of-litres-of-oil-recycled-from-grinding-sludge/35834/
[3] Sebastian Jäger, Sebastian Weber, Arne Röttger, Potential of the Recycling of Grinding Sludge by various Powder Metallurgical Processes

Grinding sludge journeys and recovery of liquids

Grinding



[1]

Grinding sludge



[2]

Landfilling



[4]

worldwide
>12 mio t/yr

Downcycling as alloying elements



[6]

Briquettes



[2]

Cutting liquid recovery

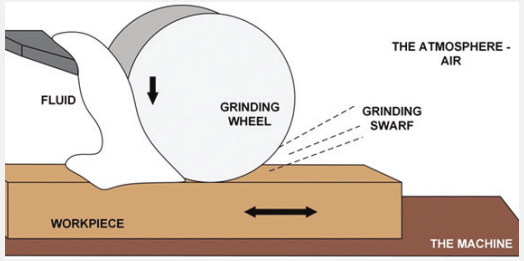


[2]

[1] Jamrozik, Artur, Łukasz Klapiszewski, Beata Strzemiecka, Adam Voelkel, and Teofil Jesionowski. 2018. 'Additives for Abrasive Materials'
[2] recyclinginternational.com/technology/millions-of-litres-of-oil-recycled-from-grinding-sludge/35834/
[4] Martin Boltižiar, Eva Michaeli and Vladimír Solár. "The landfill from nickel production in Danubian Lowland and its environmental implications".
[5] Dehghanpour Abyaneh, M., Sesana, R., et al.: Advances in grinding sludge val-orisation and recovery in the manufacturing industries
[6] https://briquettemachine.com/3-ways-to-recycle-converter-sludge-in-the-steel-plant/

Grinding sludge journeys and recovery of liquids

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[2]

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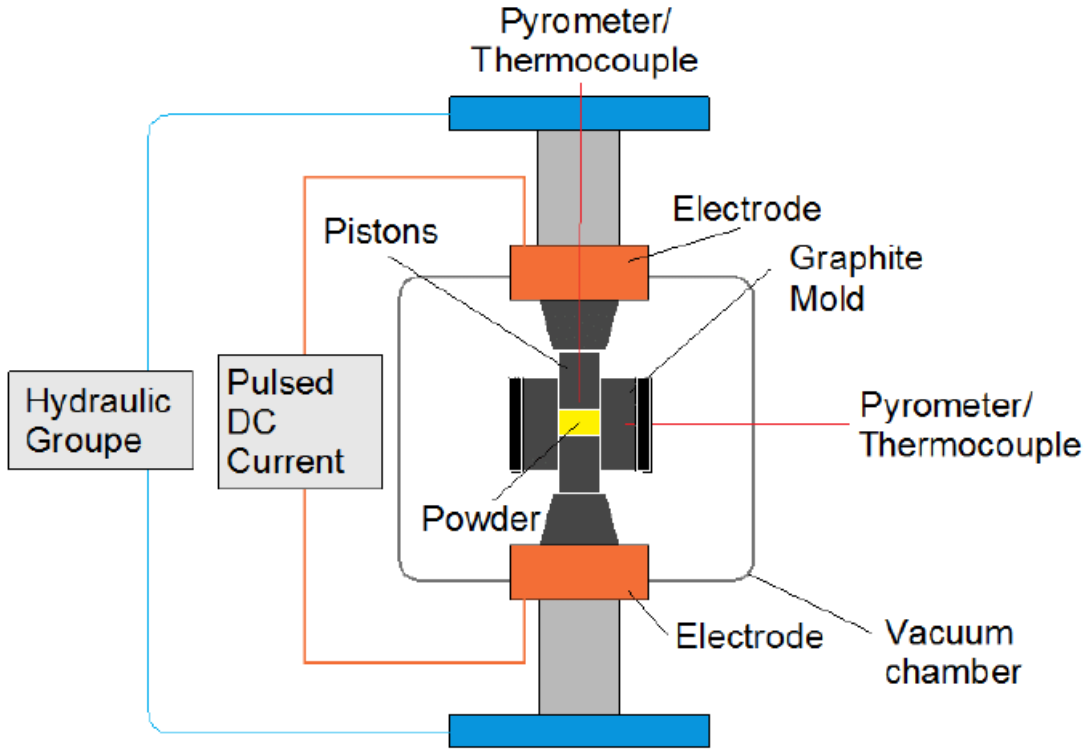
[6]

solid material recovery

Approach

- Recovering → comparable mechanical properties
- Limited cleaning
  - Ball milling
  - Washing (Ethanol, Acetone or Isopropanol)
  - Burnout (120°C or 150°C)
- Consolidation with low requirements to powder quality

  → Field assisted sintering (FAST)



Schematic of a FAST setup

Goal

LCA as an engineering tool

- Find the optimum between mechanical properties and emissions

- Characterization of process chains
  - Microstructure
  - Mechanical properties
  - Sustainability

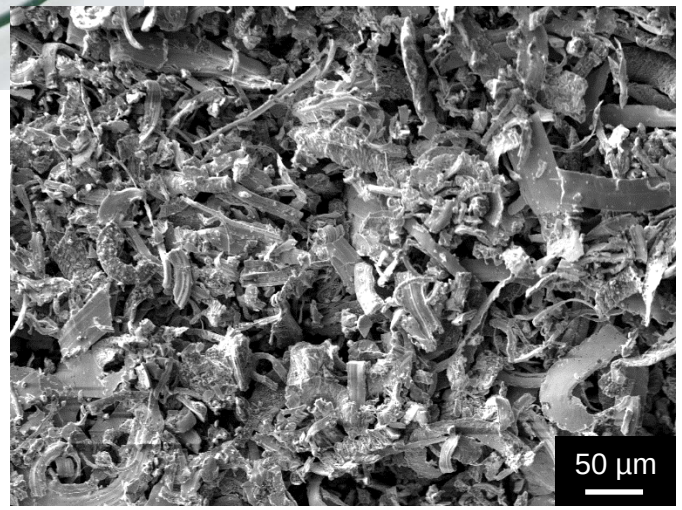
- Evaluate for optimal tradeoff
  - "Green" and "strong"

Grinding sludge

100Cr6 grinding sludge

- Standard bearing steel
- For linear guides





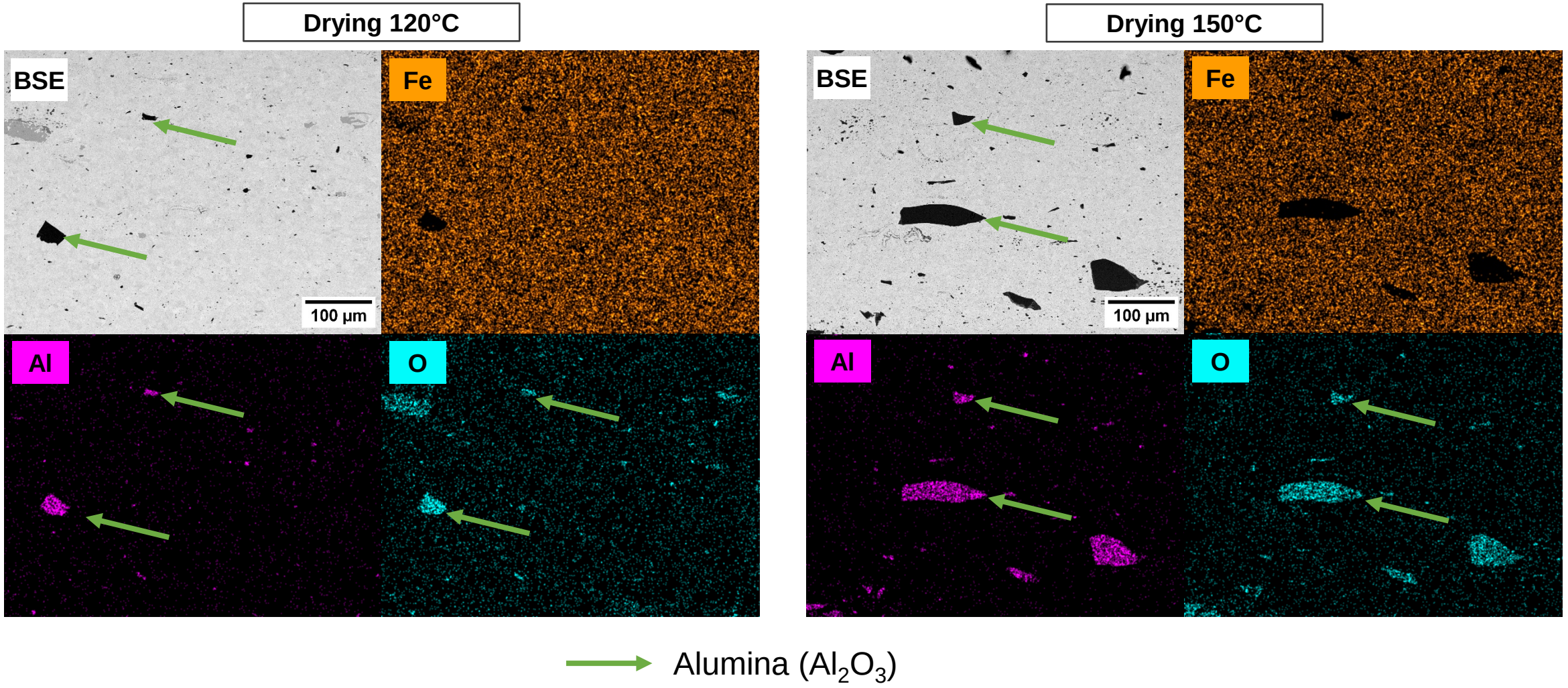
Mechanical properties achieved

- Solvent cleaning: No change in properties
- Inclusions:
  - 4.2 ± 1.4% for 120°C drying
  - 3.1 ± 0.6% for 150°C drying

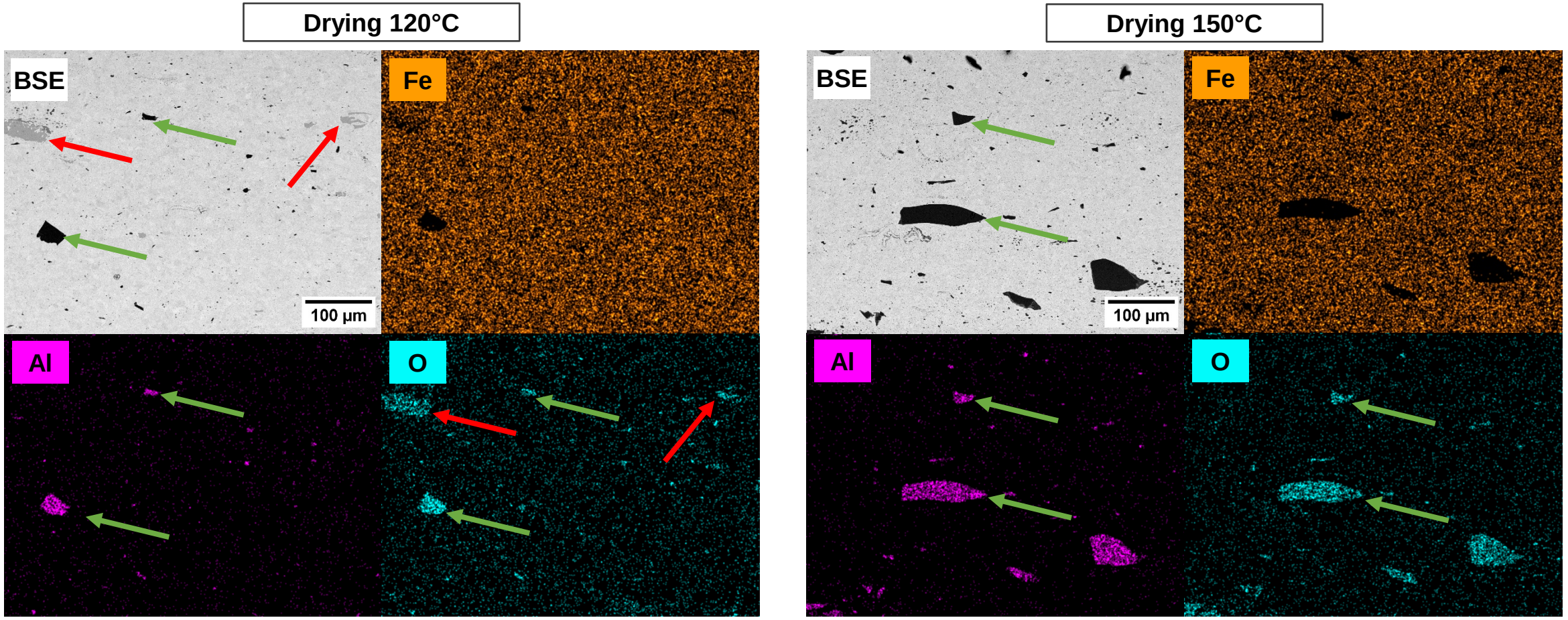


- Hardness after heat treatment
  - 313 ± 8.5 HV1 for 120°C drying
  - 761 ± 4.2 HV1 For 150°C drying
  - Reference 100Cr6: 751- 854 HV30

Chemical analysis (EDX)



Chemical analysis (EDX)

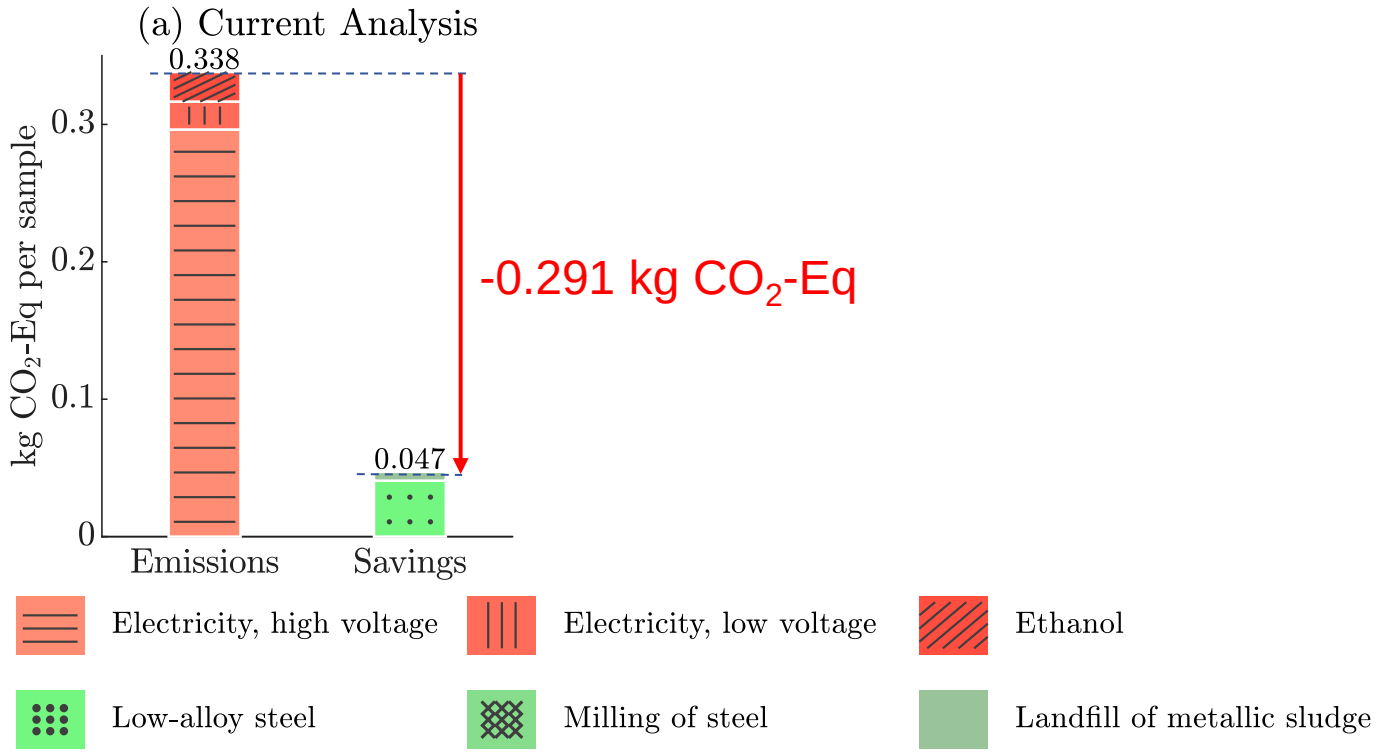


Alumina (Al_2O_3)

Organic inclusion

Current process

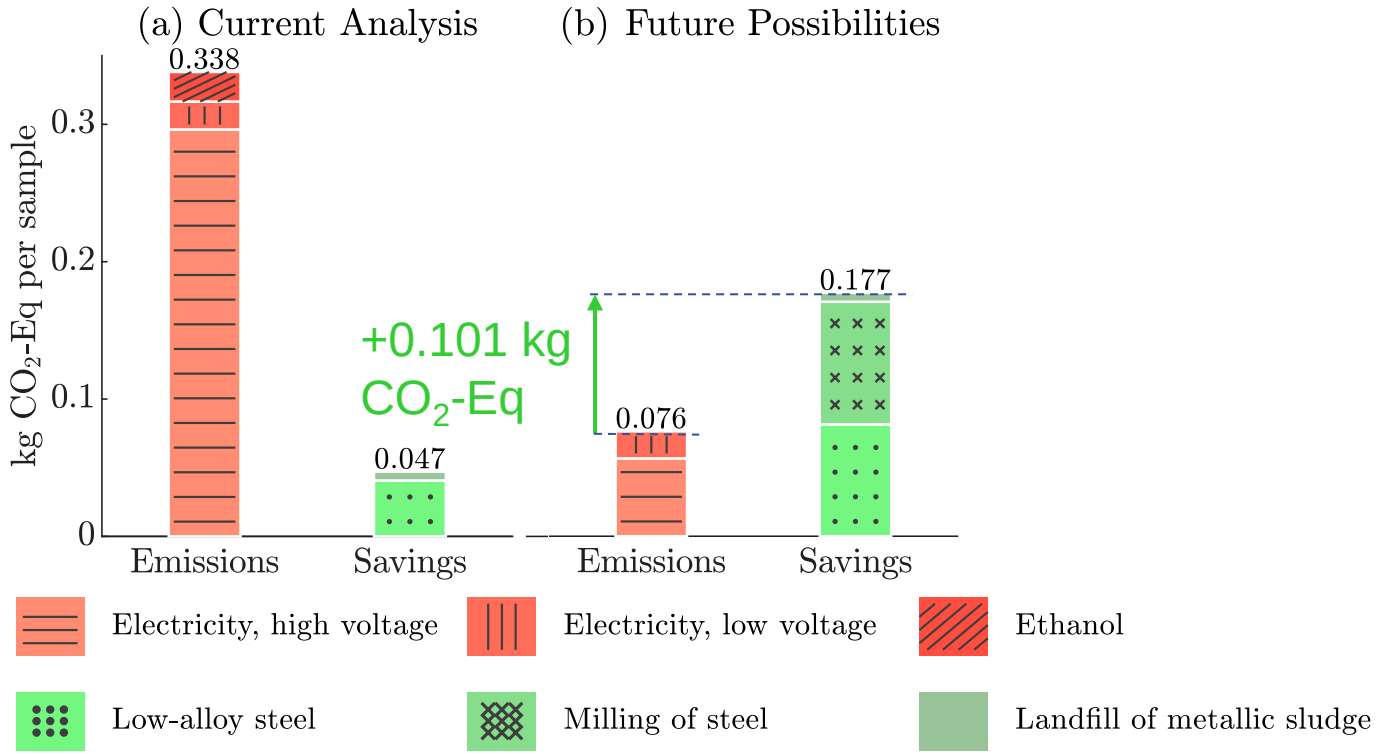
- Based on the ecoinvent database
  - Calculated according to EF3.1
- FAST has the highest contribution
- The landfilling impact needs to be studied further
- All solvents perform similarly



Strategic Partner
of ETH Zurich

Future work

- Less extreme sintering conditions
- (Near)-Net shaping
  - Removes a milling process
  - Reduces waste of final product (50%)
- How will the Near-net shaping affect the CO_2 balance?

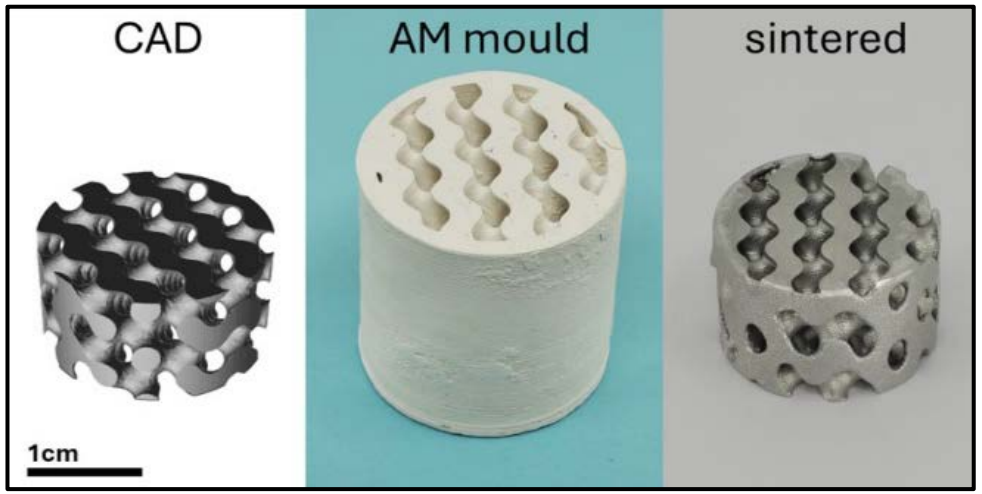


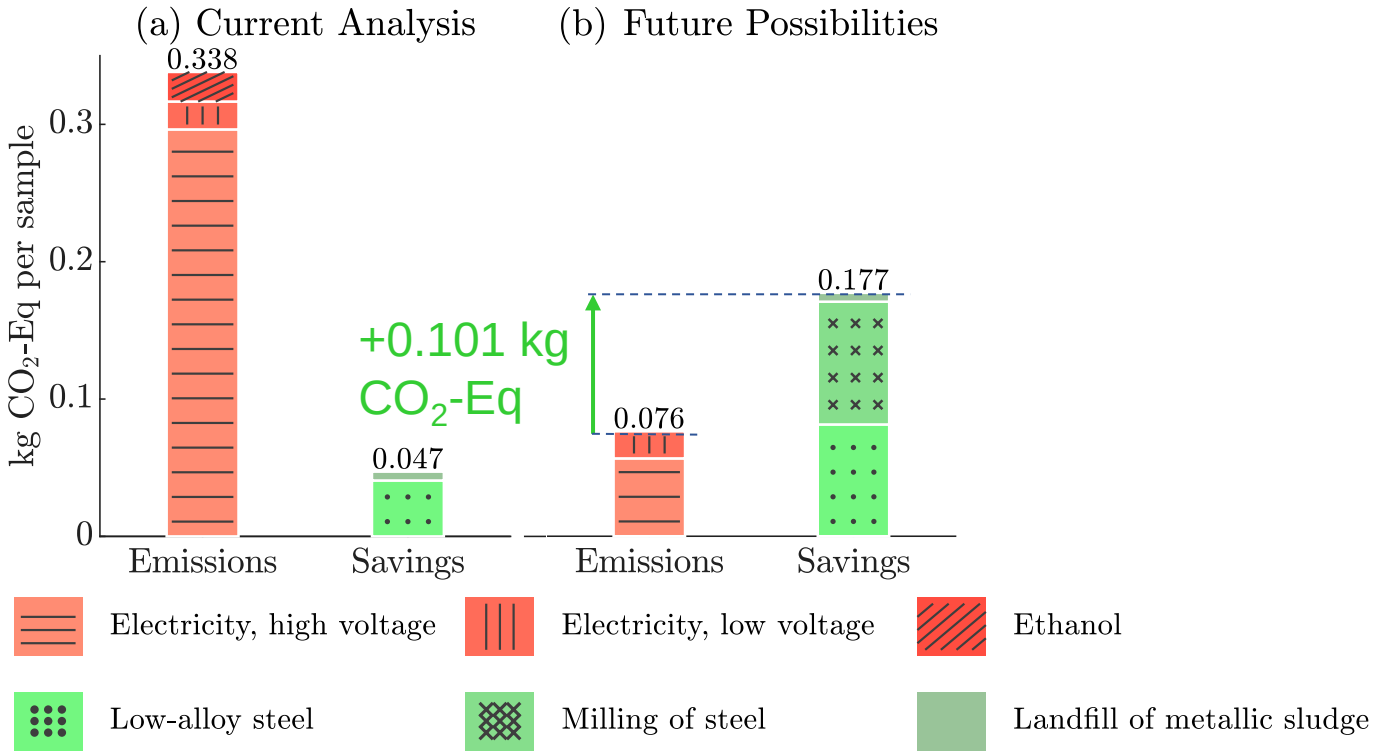
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Near-net shaping @inspire





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Conclusions

- Successful recovery of functional material from grinding sludge
  - More in-depth mechanical characterization needed
- The burnout stage plays the biggest role
- LCA of current process shows limited viabilities
  - Optimization of FAST sintering parameters for lower energy consumption
  - Near-net shaping as a possible solution

Inspire group - Materials, Processes and Sustainability

Raphael Pellin

Project Engineer

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From manufacturing to materials and back



High-Precision Manufacturing

Autonomous & Flexible Systems

Zero-Defect & Predictive Quality

Advanced Materials, Processes & Design

Data-Driven Process Innovation

Circularity & Sustainability in Production

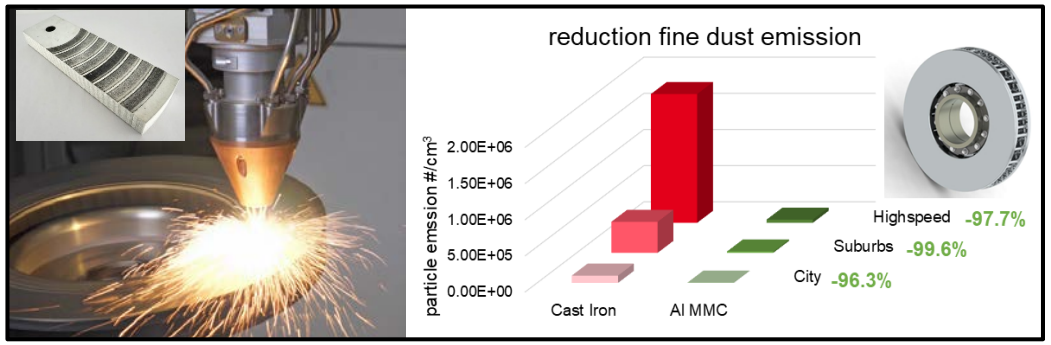
inspire MAPS-Raphael Pellin, raphael.pellin@inspire.ch

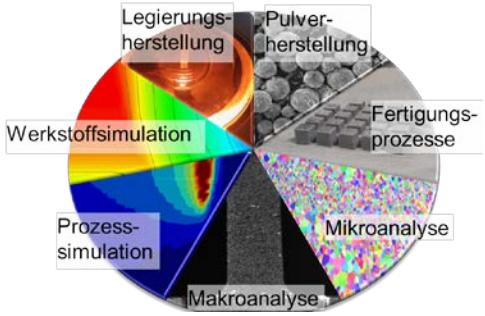
Group - Materials, Processes and Sustainability

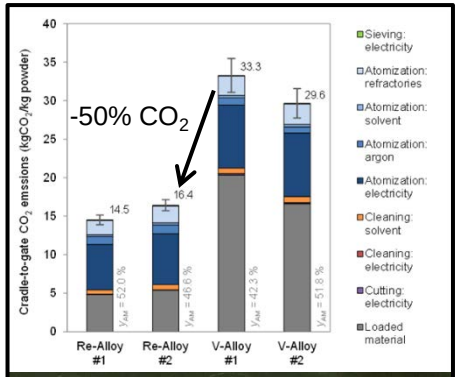
Sustainable material solutions for advanced manufacturing technologies

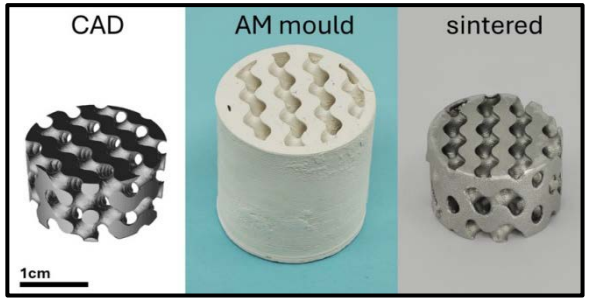
Key Competencies

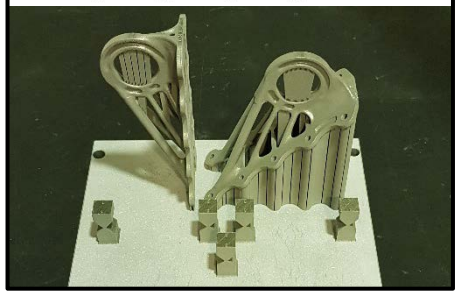
- Materials sustainabilty
  - LCA and sustainable materials in advanced manufacturing
  - Material efficient and bioinspired manufacturing
  - Industrial waste upcycling and remanufacturing
- Alloy development
  - High-throughput alloy development
  - Alloys for AM, cladding and joining technologies
  - Lab process and transfer to industry
- Hard materials processing
  - Ceramics, cermets, metallic glasses, tool materials
  - Net-shape and near-net-shape sintering









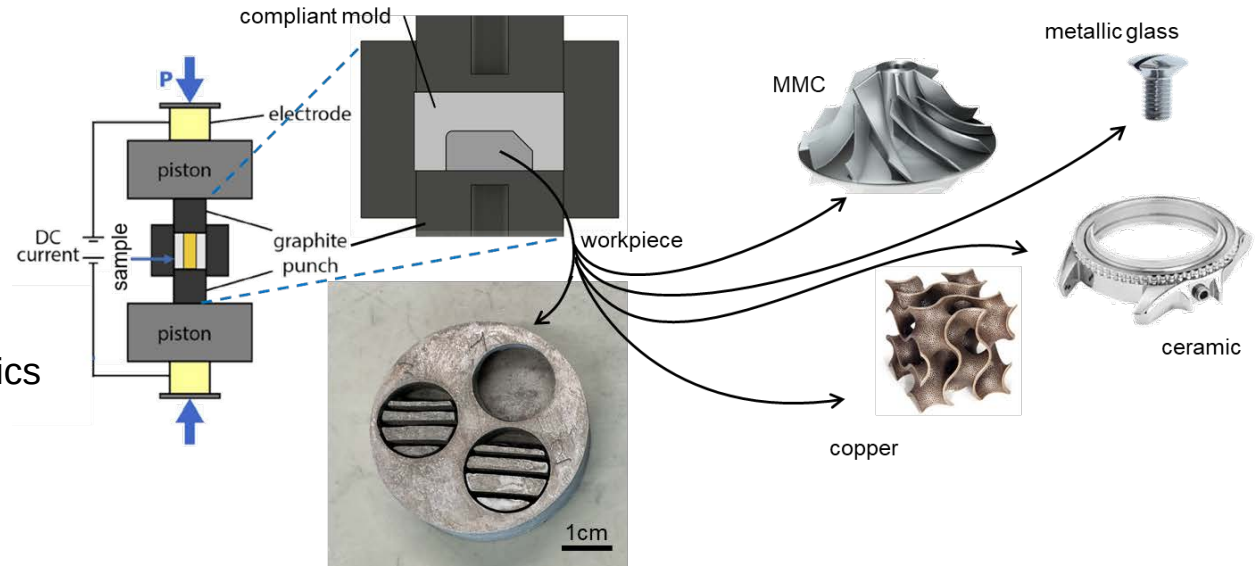


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3D-SPS concept: NNS and NS with sacrificial molds

Processing steps

1. Fabricate sacrificial mold
   - Binder jetting, stereolithography, …
   - Material is dependent on sintering temperature
     <700°C: NaCl
     >700°C: alumina or water-soluble ceramic
2. Fill with functional powder
   - Metals (precious/amorphous), MMCs, steel, cermets, ceramics
3. SPS run
   - Ca. 10x faster than conventional sintering or HIP
   - Full densification at lower temperature than conventionally
4. Remove space holder material

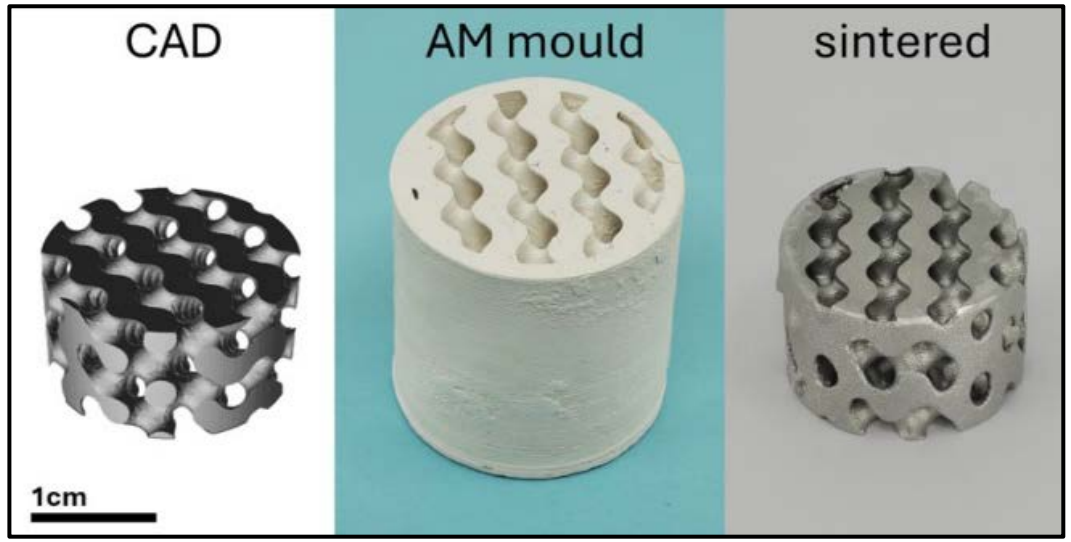




Low-temperature 3D-SPS with NaCl mold

Highly loaded aluminium/SiC-MMC

- MMCs cannot be made by SLM
  - AlSi10Mg matrix, 50 wt.% SiC particles

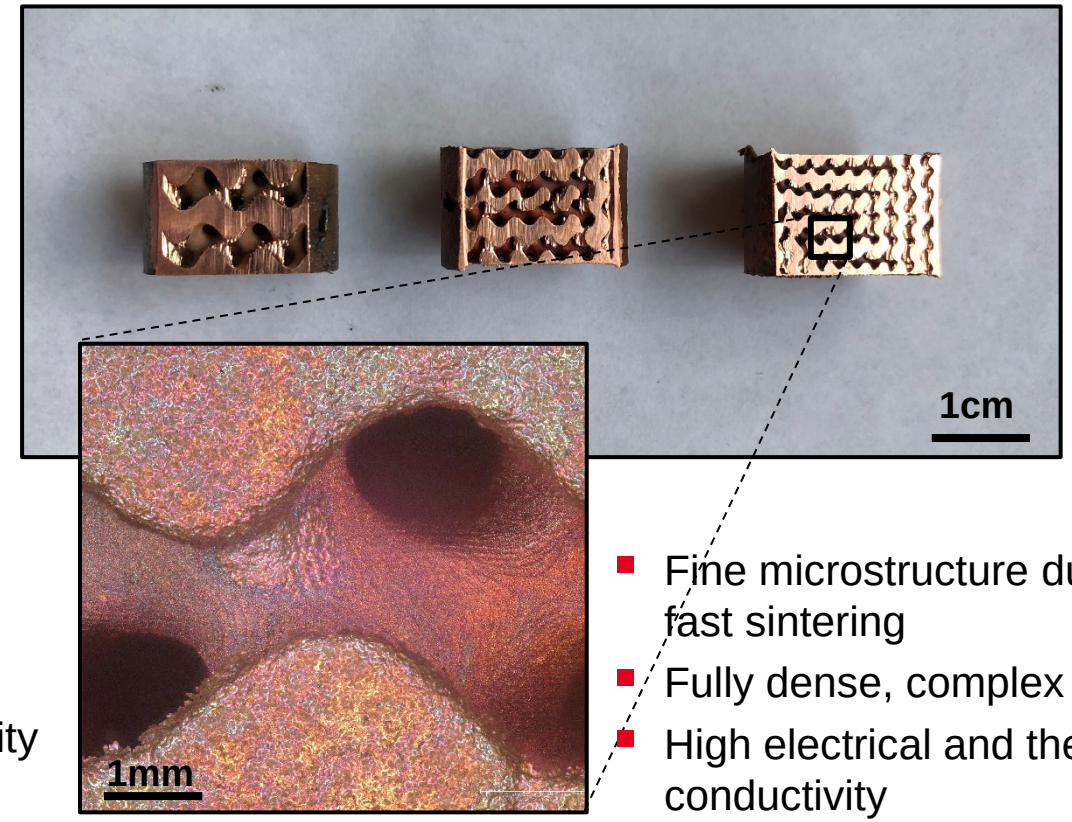




- High hardness
  - Wear resistance
- High thermal conductivity
  - Heat management

Pure copper

- Cannot be produced by standard SLM
  - Needs green/blue laser, or binder jetting



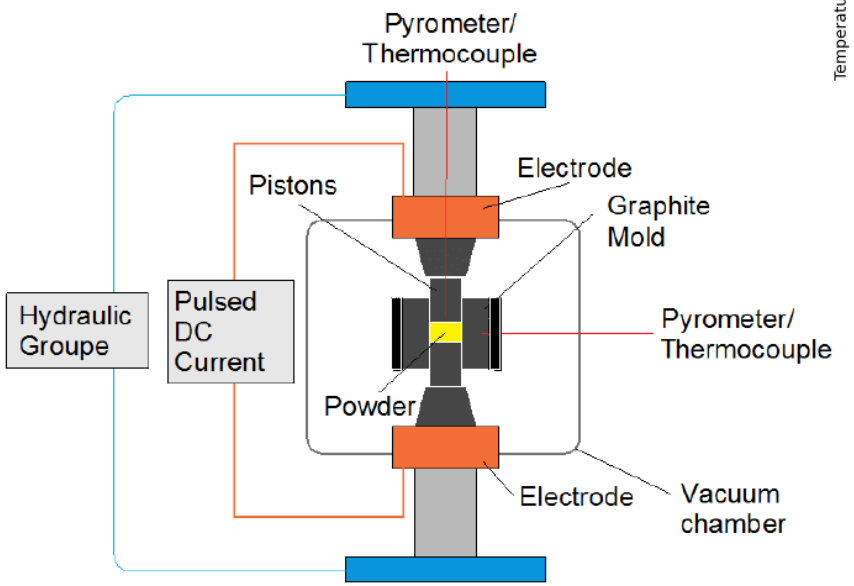
- Fine microstructure due to fast sintering
- Fully dense, complex shapes
- High electrical and thermal conductivity

Field assisted sintering (FAST/SPS)

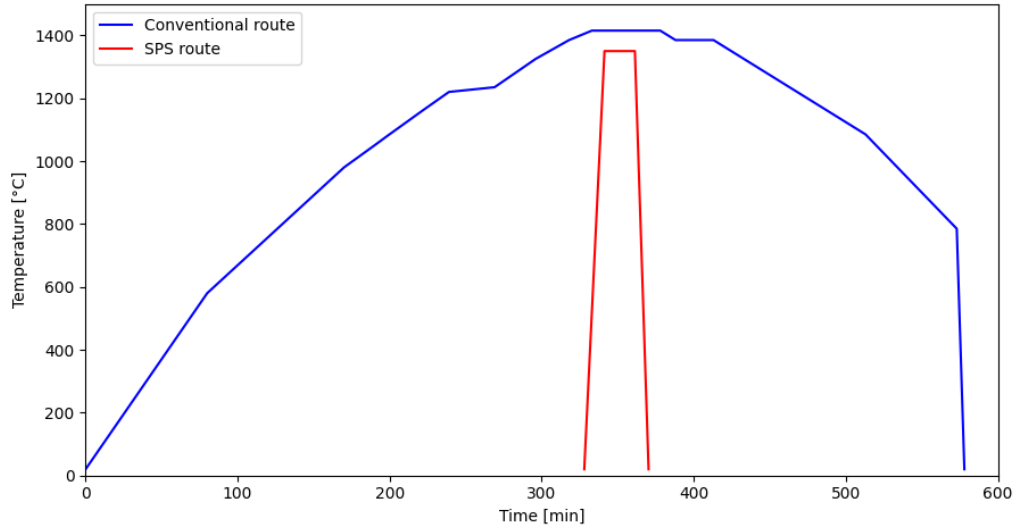
SPS sintering principles

- Sintering process driven by Joule heating: Electric DC pulses
- Performed in controlled atmosphere (vacuum, nitrogen, argon)
- Flexible conditions: Up to 2200 °C, 250 KN, 400 °C/min rates
- Parameters: **1000°C, 1h, 35 MPa, 100°C/min**



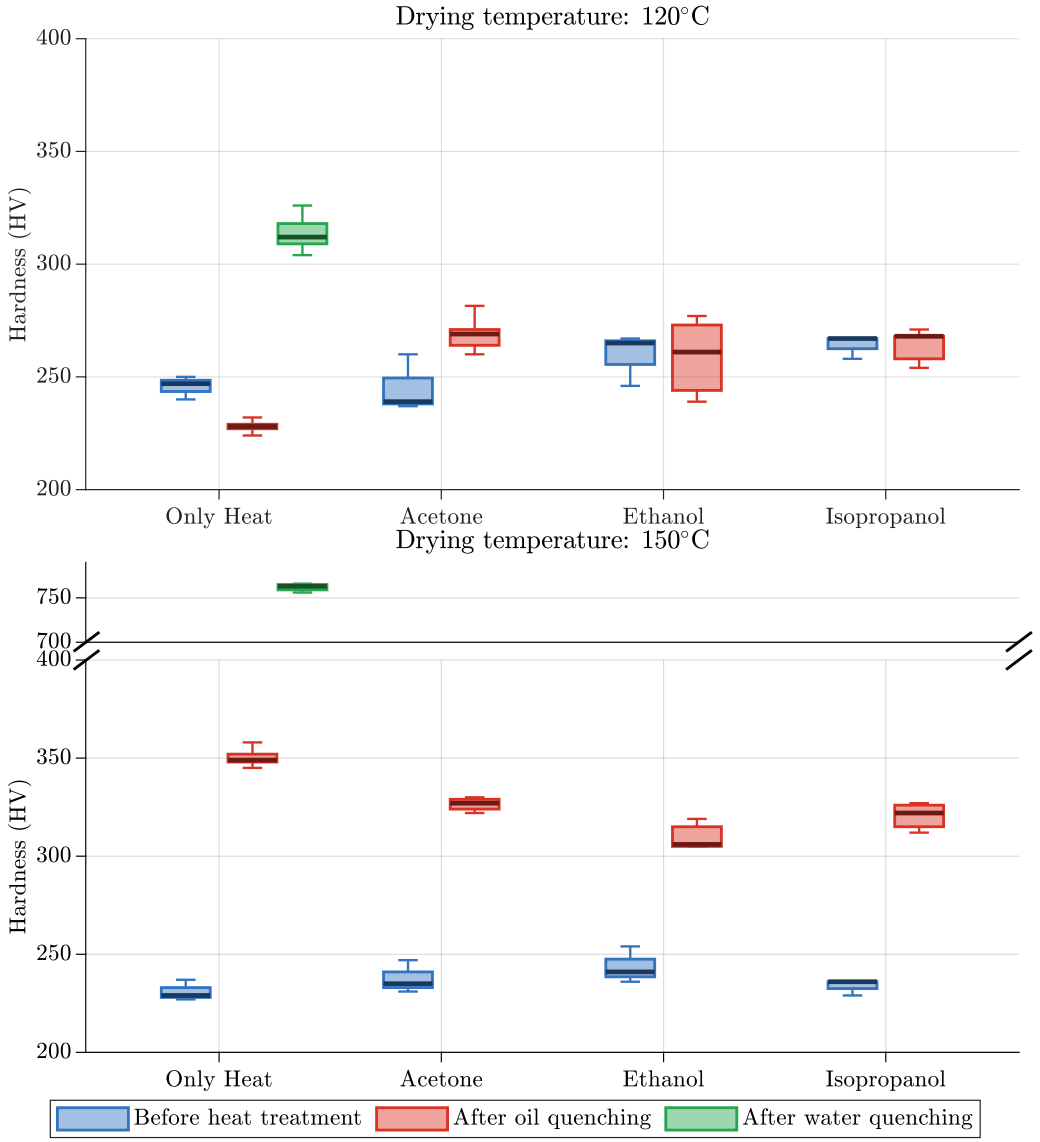


Conventional vs SPS sintering



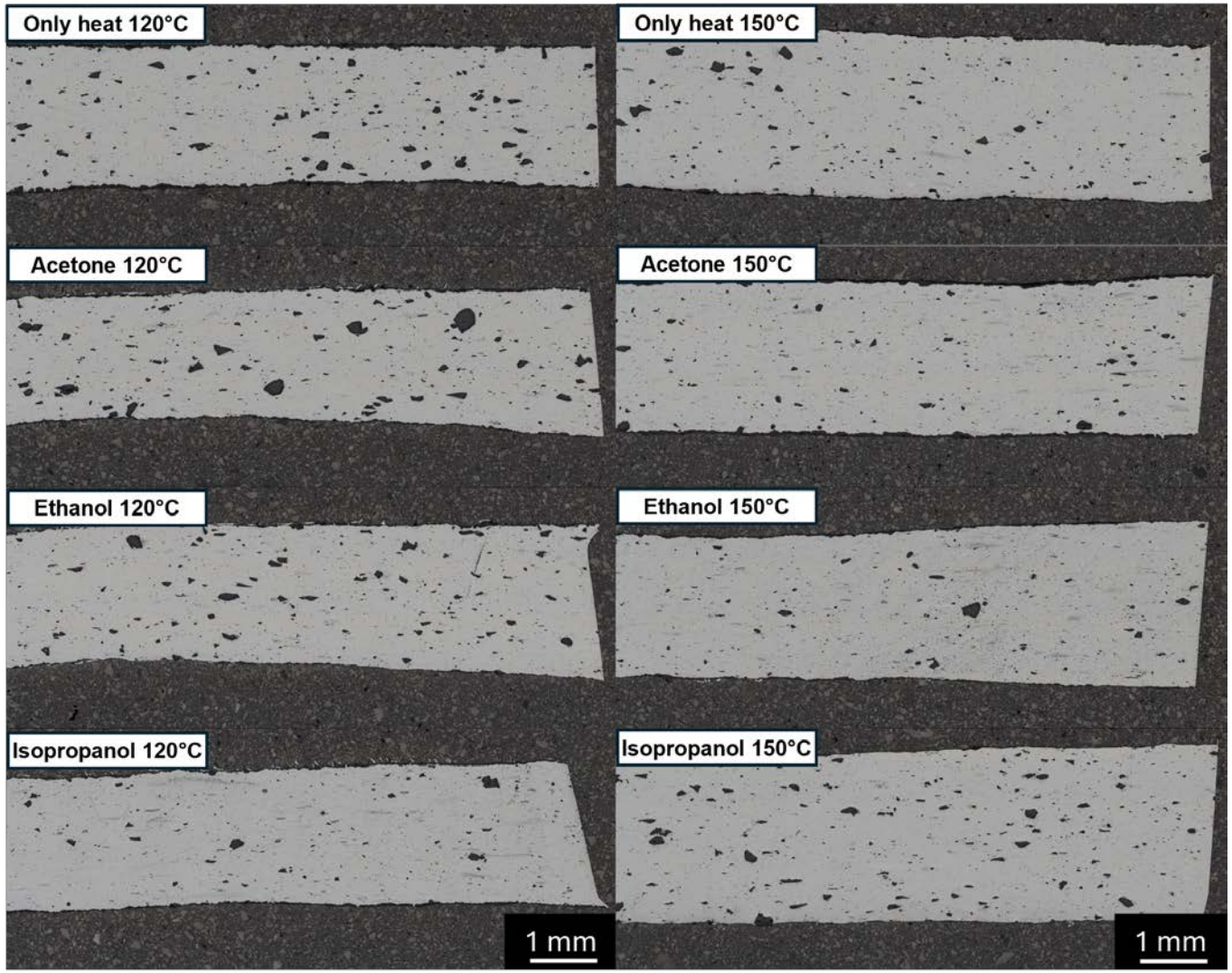
- It's fast!
  - Minutes instead of hours to full density
- It's cool!
  - Lower max temperatures compared to conventional sintering or HIP

What is grinding sludge?

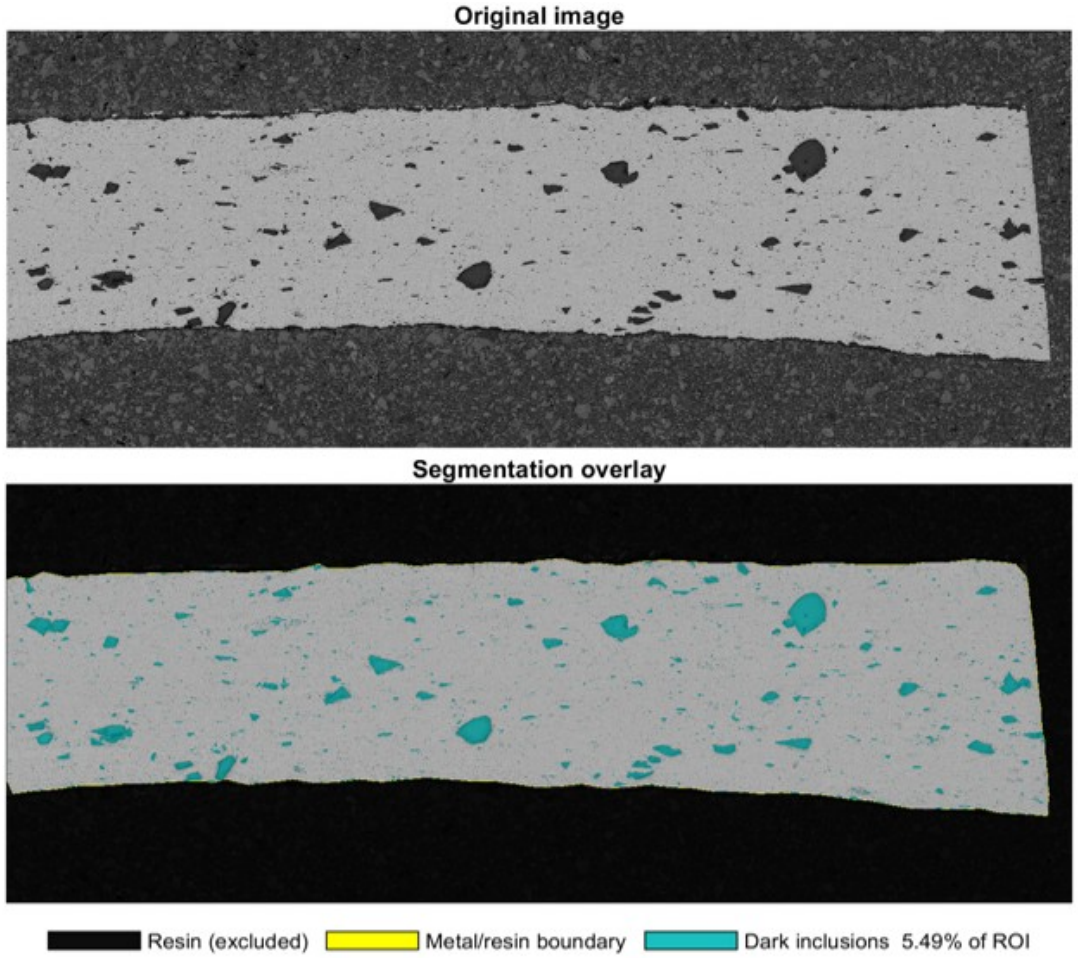


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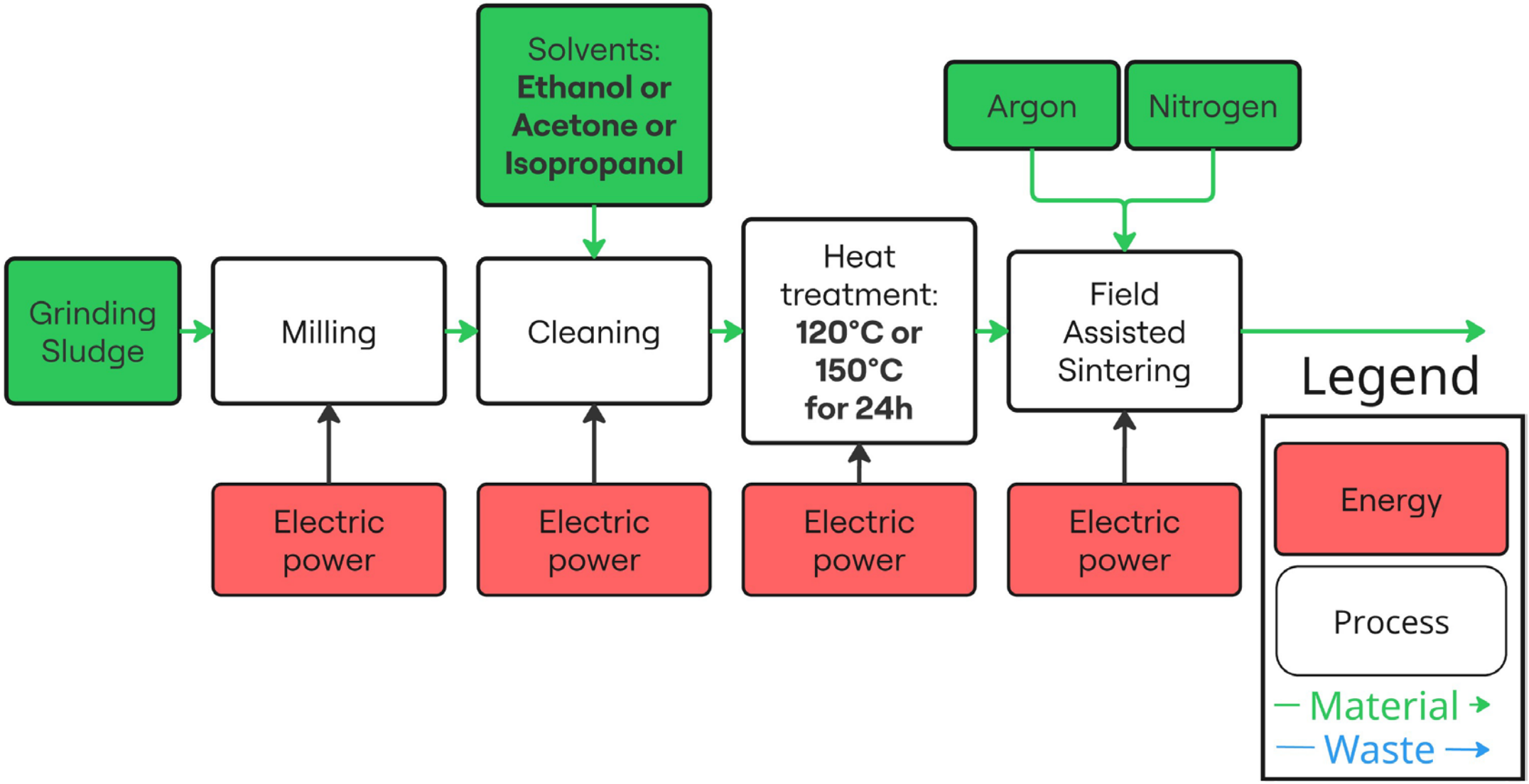
Microstructure



- **Volume fraction**
  - Abrasives + pores



Cleaning process

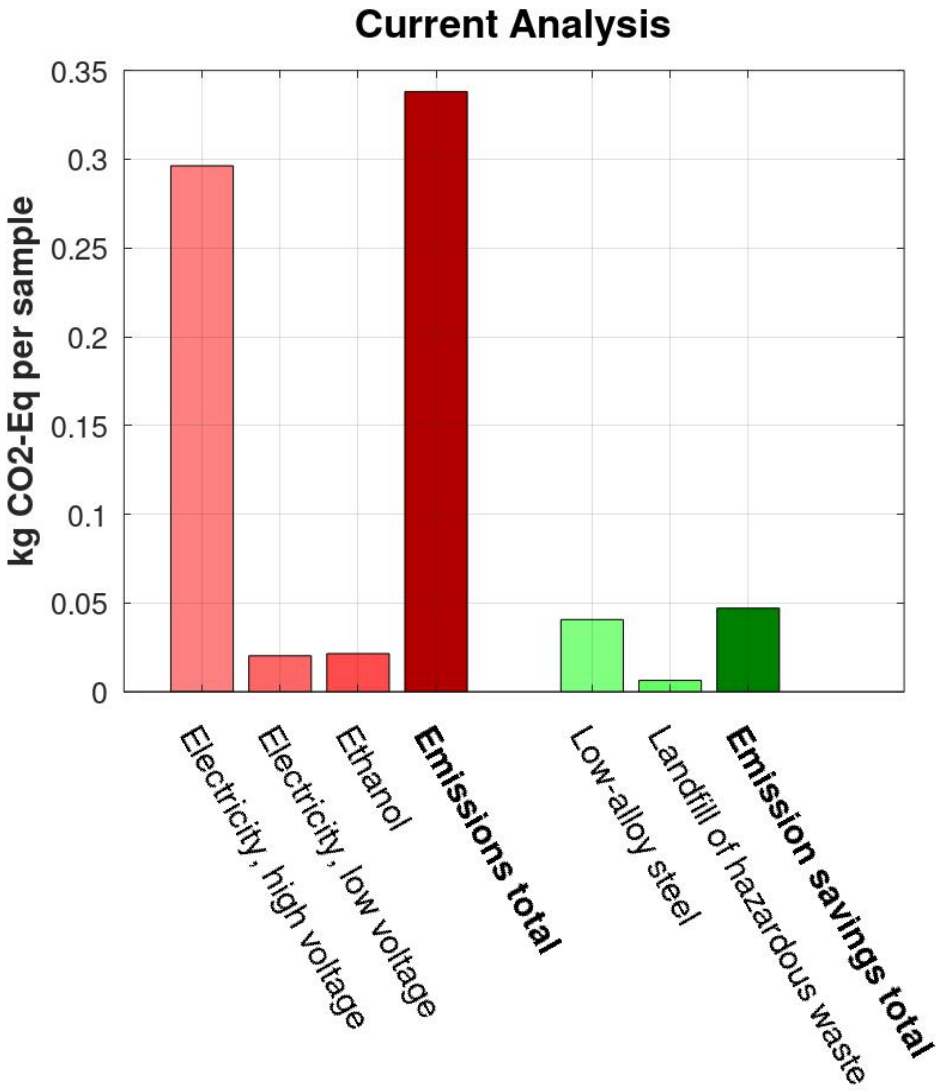


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LCA

Current process

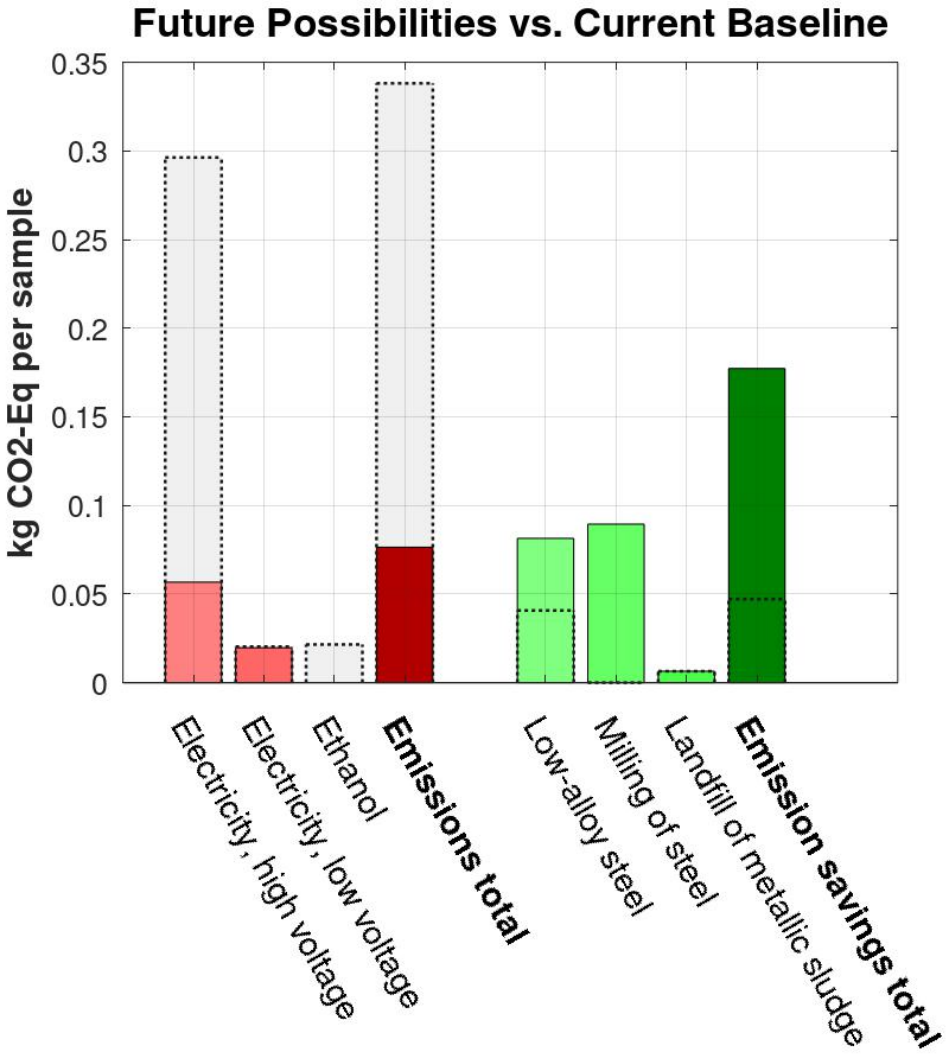
- Based on the ecoinvent database
  - Calculated according to EF3.1
- FAST has the highest contribution
- The landfilling impact needs to be studied further
- All solvents perform similarly
  - Ethanol is the lowest for CO2 - Eq



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Future possibilities

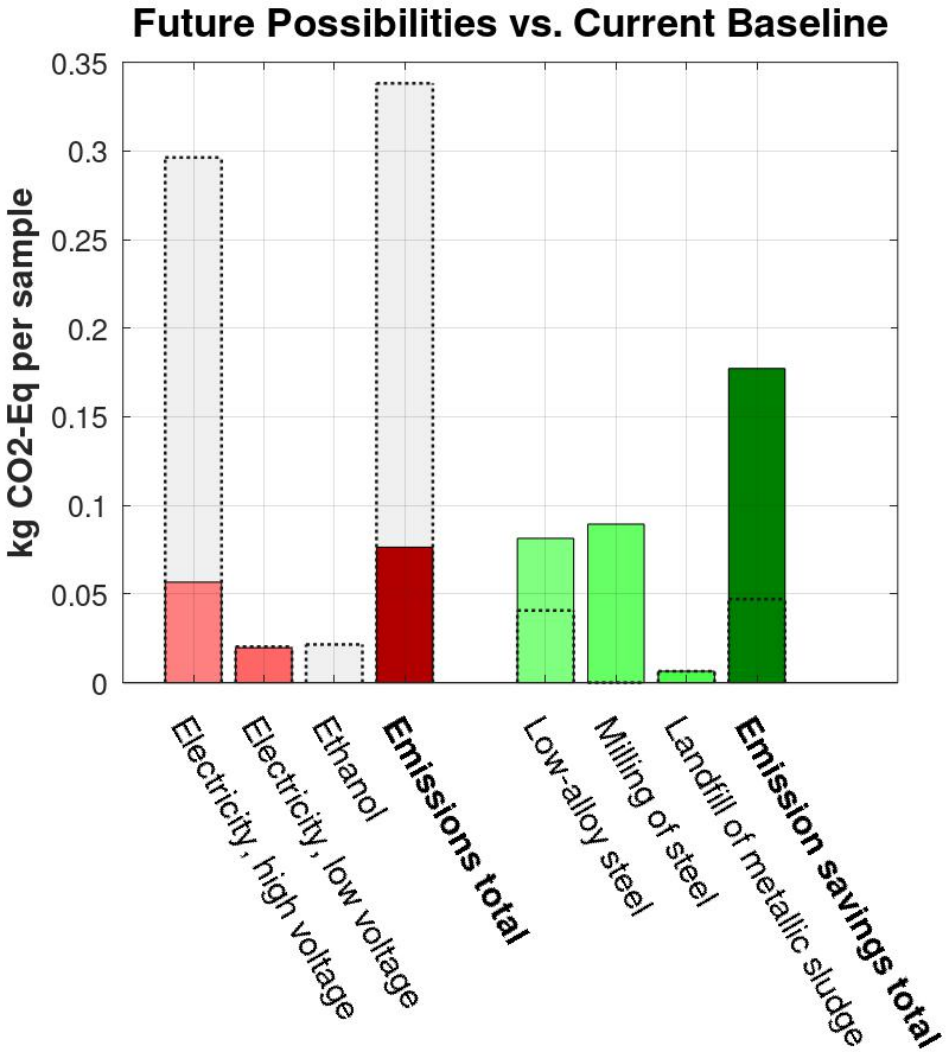
- Less extreme sintering conditions
- (Near)-Net shaping
  - Removes a milling process
  - Reduces waste of final product (50%)
- How will the Near-net shaping affect the CO2 balance?



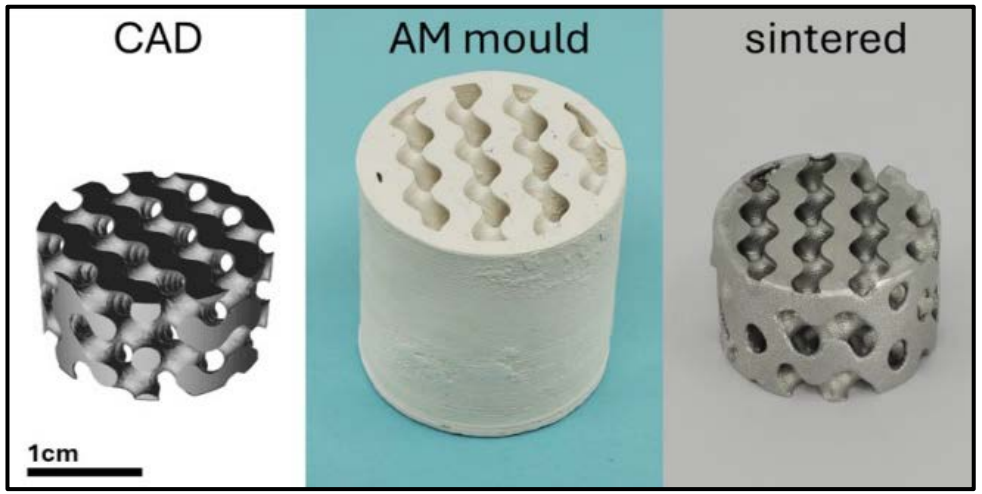
LCA

Future possibilities

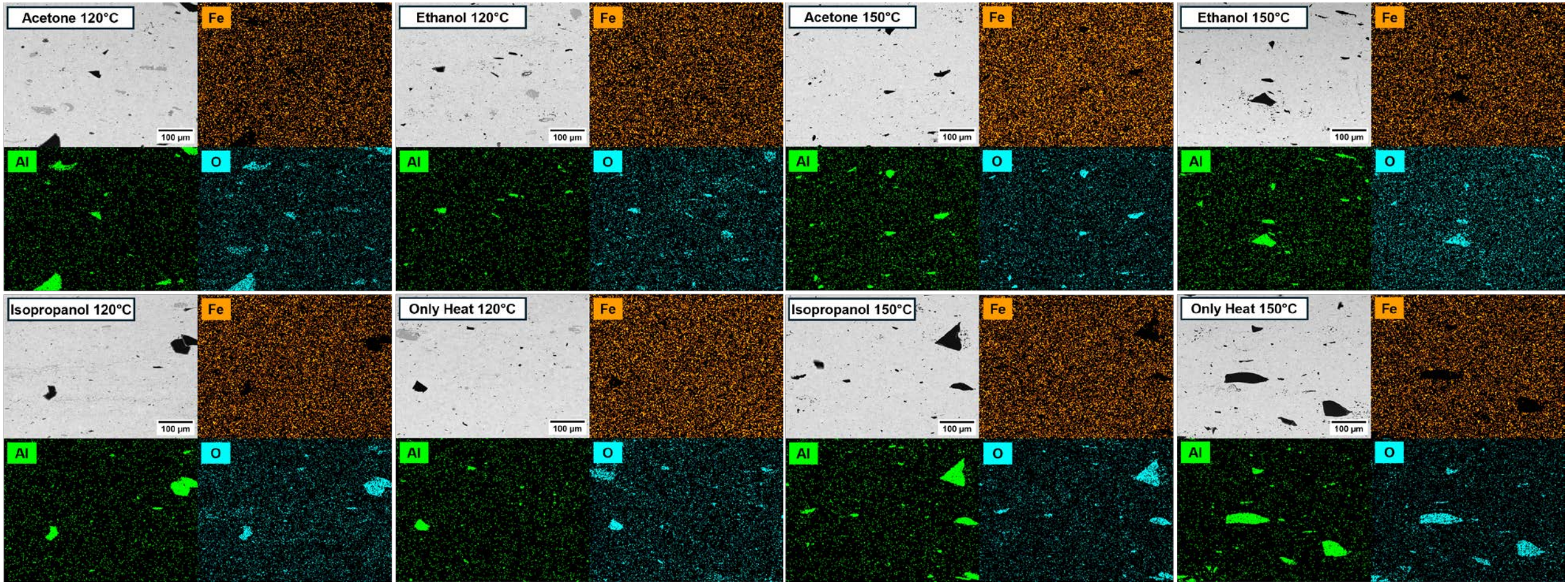
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- How will the Near-net shaping affect the CO2 balance?



Near-net shaping @inspire

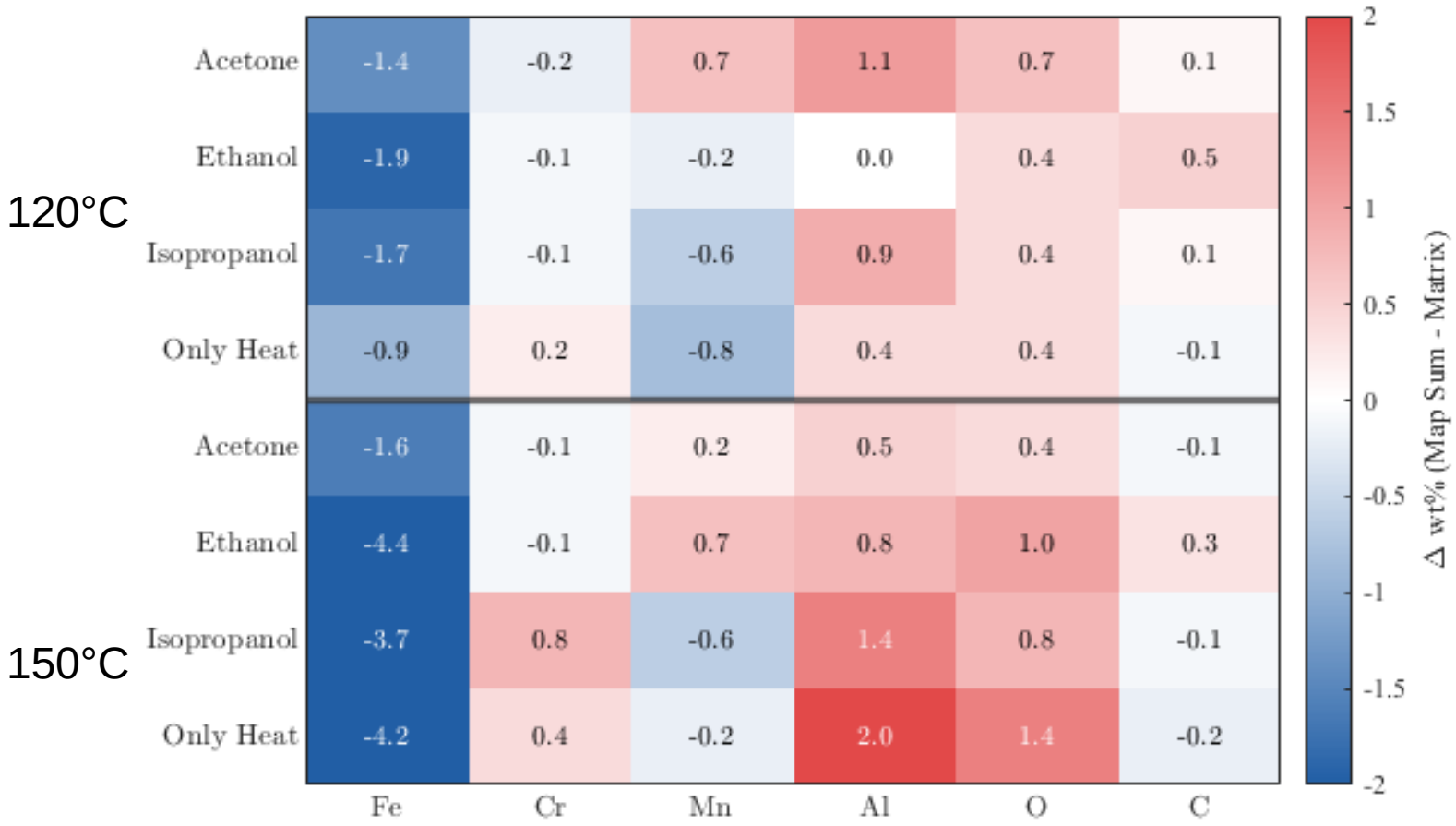


Chemical analysis



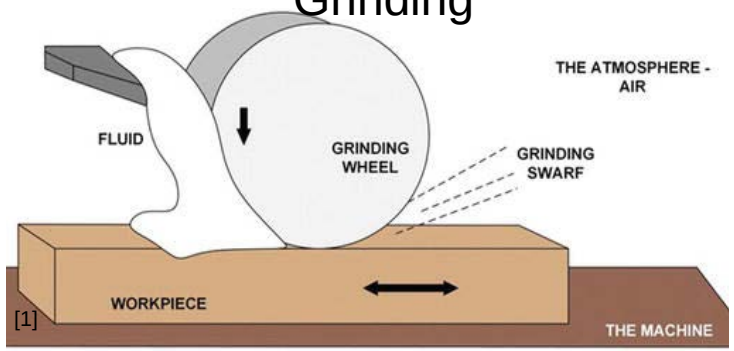
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Chemical analysis



Grinding sludge journeys and recovery of liquids

Grinding



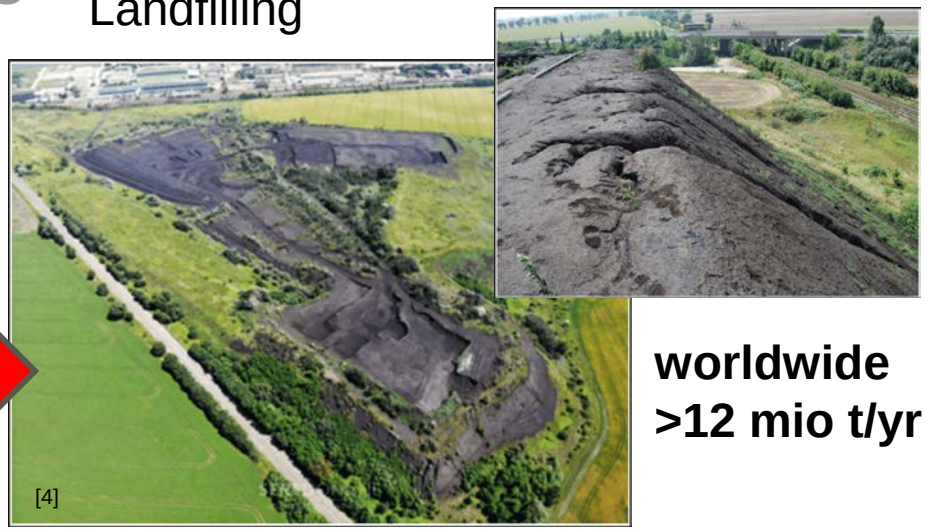
[1] Jamrozik, Artur, Łukasz Klapiszewski, Beata Strzemiecka, Adam Voelkel, and Teofil Jesionowski. 2018. 'Additives for Abrasive Materials'

Grinding sludge



[2] recyclinginternational.com/technology/millions-of-litres-of-oil-recycled-from-grinding-sludge/35834/

Landfilling



worldwide >12 mio t/yr

[5]

[4] Martin Boltižiar, Eva Michaeli and Vladimír Solár. "The landfill from nickel production in Danubian Lowland and its environmental implications".

[5] Dehghanpour Abyaneh, M., Sesana, R., et al.: Advances in grinding sludge valorisation and recovery in the manufacturing industri

Recovery of cutting liquids



Briquettes



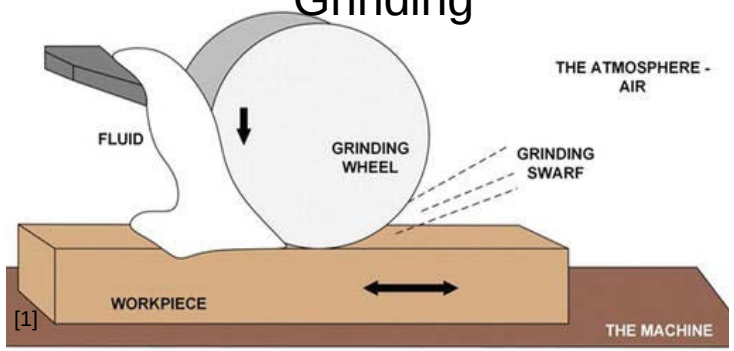
Downcycling as alloying elements



[6] https://briquettemachine.com/3-ways-to-recycle-converter-sludge-in-the-steel-plant/

Grinding sludge journeys and recovery of liquids

Grinding



[1]

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Briquettes



[2]

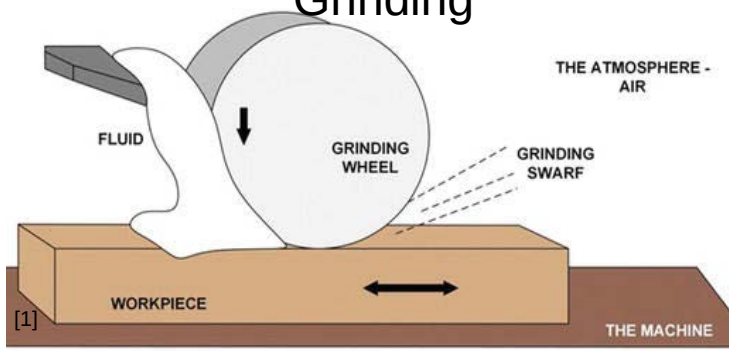
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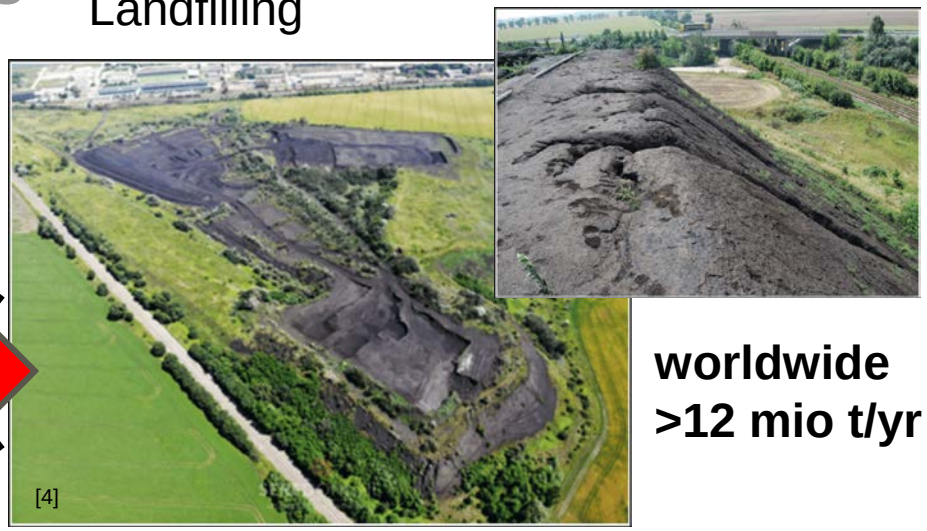


[2] recyclinginternational.com/technology/millions-of-litres-of-oil-recycled-from-grinding-sludge/35834/

Briquettes



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[5] Dehghanpour Abyaneh, M., Sesana, R., et al.: Advances in grinding sludge valorisation and recovery in the manufacturing industri

Conference Dinner

At the ZKM, 18:00

Exhibition: The Story that never Ends



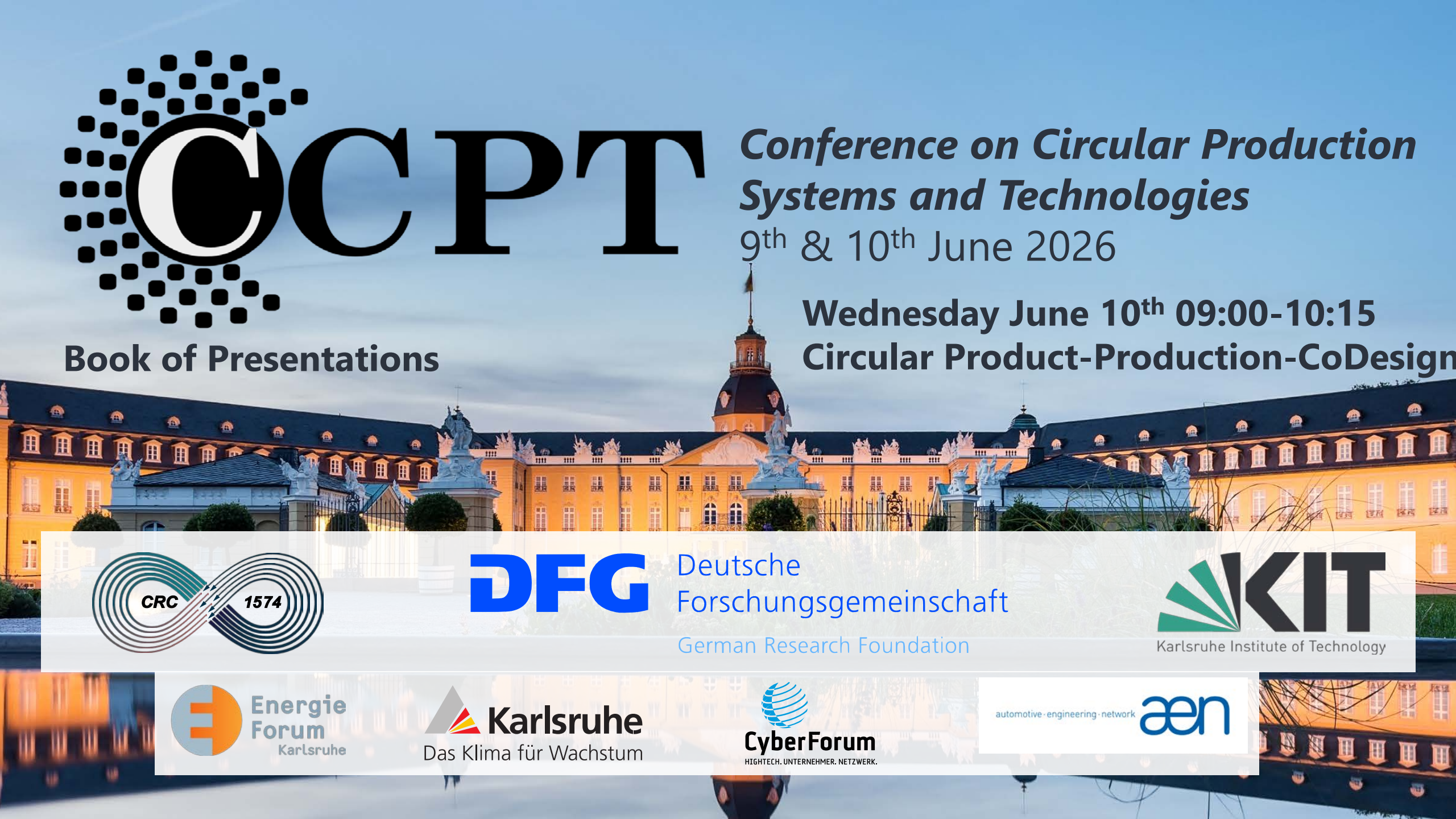
By Tram: Tram 2 to ***ZKM*** (Tram Ticket included)
By Car: ZKM car park via **Südendstraße 44**

CCPT

SFB 1574

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

KIT Karlsruhe Institute of Technology



CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 09:00-10:15
Circular Product-Production-CoDesign

CRC 1574

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

KIT Karlsruhe Institute of Technology

Energie Forum Karlsruhe

Karlsruhe Das Klima für Wachstum

CyberForum HIGHTECH. UNTERNEHMER. NETZWERK.

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Life cycle analysis of novel Posidonia-based filaments for circular additive manufacturing applications

Aikaterini Paraskevopoulou, Georgios Gkoumas, Vasiliki C. Panagiotopoulou, Alexios Papacharalampopoulos and **Panagiotis Stavropoulos**

Conference on Circular Production Systems and Technologies (CCPT)
9th and 10th of June 2026

LMS
Laboratory for Manufacturing Systems & Automation

Outline

- Introduction
- Aim
- Materials and Methods
- Results
- Discussion
- Conclusions

Introduction

On a daily basis, we see evidence of climate change:

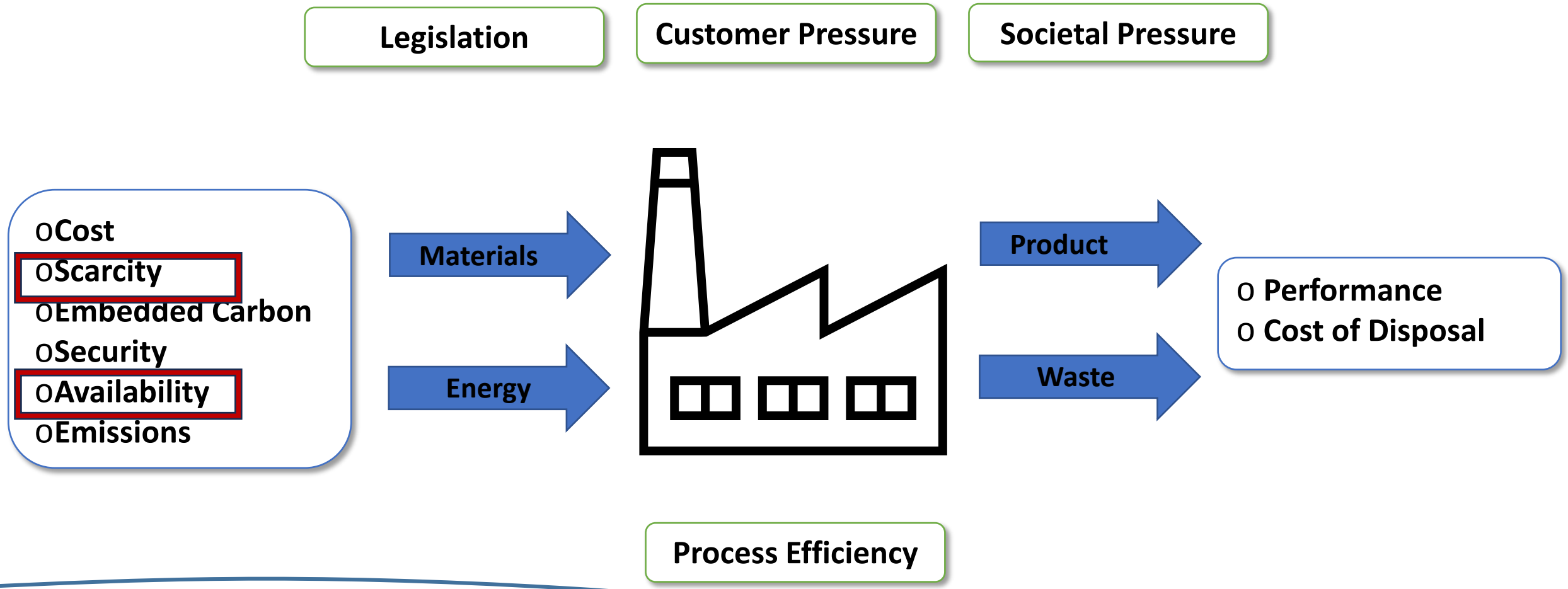
- Continuously **increasing global temperature**
- **Change of climatic conditions** and seasons
- **Melting of glaciers** and sea ice



Figure from World Meteorological Organization

Introduction

The Manufacturing Sector contributes approximately 29% of global CO_2 through material mining, energy and material consumption and transport of materials/ products.



Introduction

Definition: Circular Economy aims to minimize waste, extend product life cycles, and optimize resource use.

Why does it matter?

- ✔ Reduces environmental impact
- ✔ Creates business value from waste
- ✔ Enhances supply chain resilience





Circular economy act

Aim & Objectives

Aim: To determine whether the use of biobased materials as fillers in Additive Manufacturing resins lower carbon emissions of resins, Additive Manufacturing process and overall production

via performing a life cycle analysis of the following steps (a) production of resin focusing on the material and (b) manufacturing of a mobile phone case focusing on the energy.

Materials and Methods

Filaments

- PLA with 20% ***Posidonia Oceanica*** (Circular Filament 1)
- Pure PLA
- ABS with 20% ***Posidonia Oceanica*** (Circular Filament 2)
- Pure ABS

3D printer: Flashforge Inventor

AM process parameters	**Circular Filament 1**	**Circular Filament 2**
Printing speed	40-100 mm/s	40 mm/s
Nozzle temperature	195-220 ^{o}C	210-270 ^{o}C
Bed temperature	50-60 ^{o}C	80-120 ^{o}C

Materials and Methods

Life Cycle Assessment (LCA):

SimaPro Database 9.4 was used for the calculation of the carbon emissions with input from either literature in terms of material production or energy consumption during the AM processes (9.3.03, PRé Sustainability B.V., Amersfoort, The Netherlands), in combination with Ecoinvent Database 3.1, assuming “Allocation, default system model” as models for the carbon footprint. The LCA was performed to calculate the embodied carbon emissions for one spool of filament (four different combinations), for the energy consumption during printing one mobile phone case using the filaments (using 3.5% of the filament spool).

Results

Properties	Baseline	Target/ Achieved
Humidity level	7-10% w/w	3-5% w/w
Filler dimension	1mm	500-600microns
Filler fraction	10%	20%
PLA composition	90%	80%
Stable diameter	2 mm	1.75mm

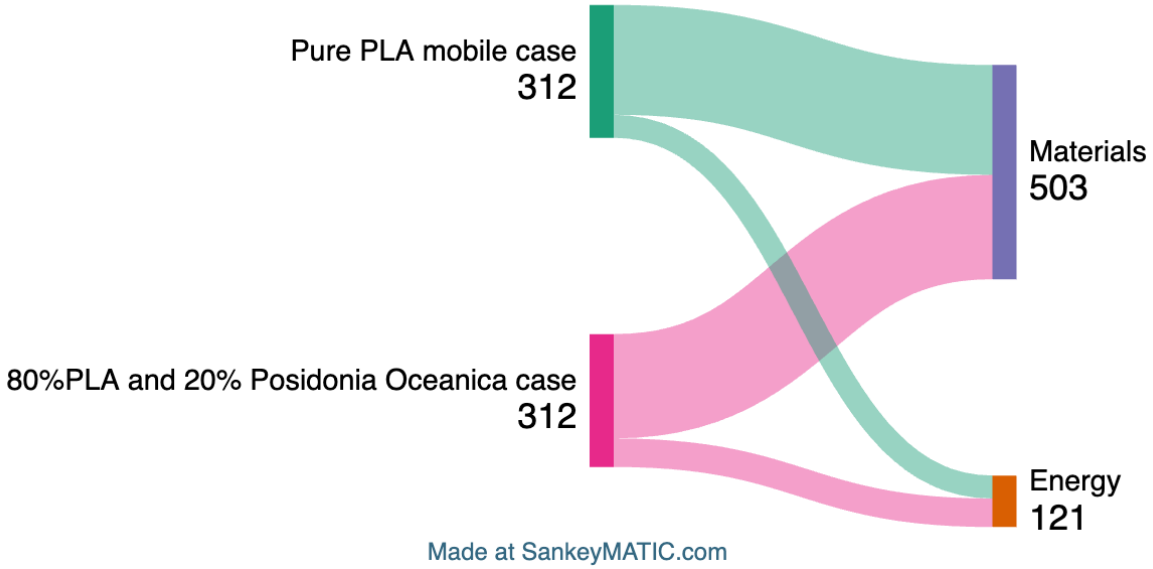
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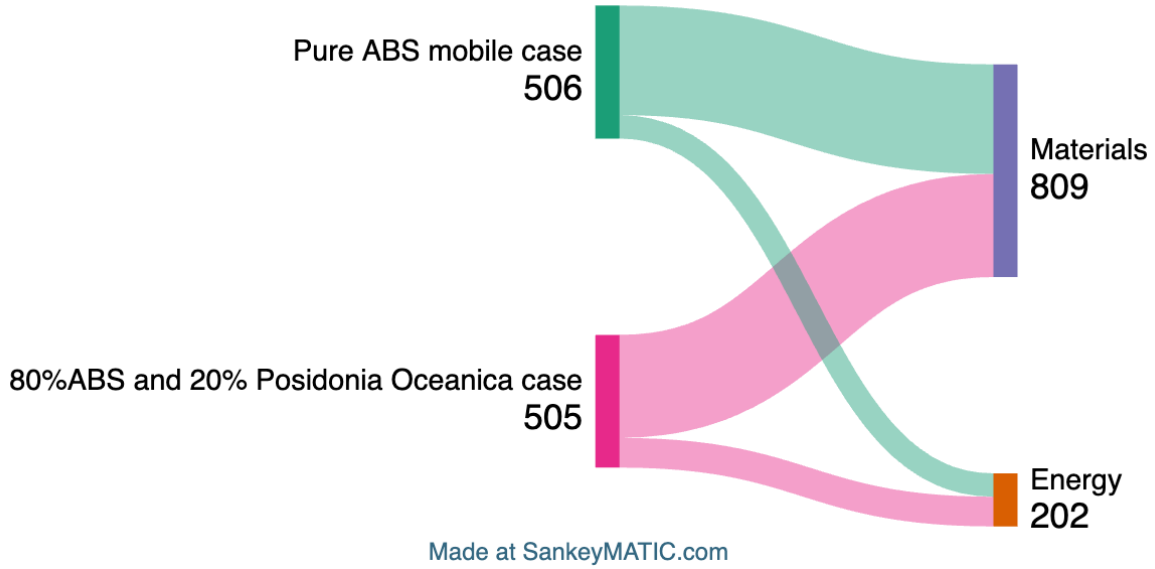
Results

AM process parameters	Pure PLA	Circular Filament 1
Printing speed	50-80 mm/s	30-60 mm/s
Nozzle temperature	190-210 ^{o}C	200-220 ^{o}C
Bed temperature	50-60 ^{o}C	50-60 ^{o}C

AM process parameters	Pure ABS	Circular Filament 2
Printing speed	40-50 mm/s	30-40 mm/s
Nozzle temperature	235-245 ^{o}C	240-250 ^{o}C
Bed temperature	90-100 ^{o}C	90-100 ^{o}C

Results


Pure PLA mobile case
312
80%PLA and 20% Posidonia Oceanica case
312
Materials
503
Energy
121
Made at SankeyMATIC.com


Pure ABS mobile case
506
80%ABS and 20% Posidonia Oceanica case
505
Materials
809
Energy
202
Made at SankeyMATIC.com

Discussion

- Use of Posidonia Oceanica as a filler → Lower carbon footprint for filaments
- Lower printing speed → Higher energy consumption → Higher carbon footprint for processing the filaments into mobile phone case
- Circular does not imply environmental sustainability

Conclusions

Residues from Posidonia Oceanica can be incorporated into PLA and/ or ABS filaments, after proper treatment, into creating circular filaments that can be used in 3d-printing products. This way, the circularity of additive manufacturing can be in-creased. Although, circular filaments have lower carbon emissions than pure filaments, they might require slower printing speed, increasing thus printing time and energy consumption. Overall, the carbon footprint of a product printed with circular filament can be the same as the carbon footprint of a pure filament, highlighting that circularity does not always imply sustainability too.

Further investigation regarding the optimal percentage of Posidonia Oceanica that decreases both material and energy carbon emissions is important. Additionally, further investigation and parametric analysis is important to identify the optimal process parameter values.



LMS

Laboratory for Manufacturing Systems & Automation

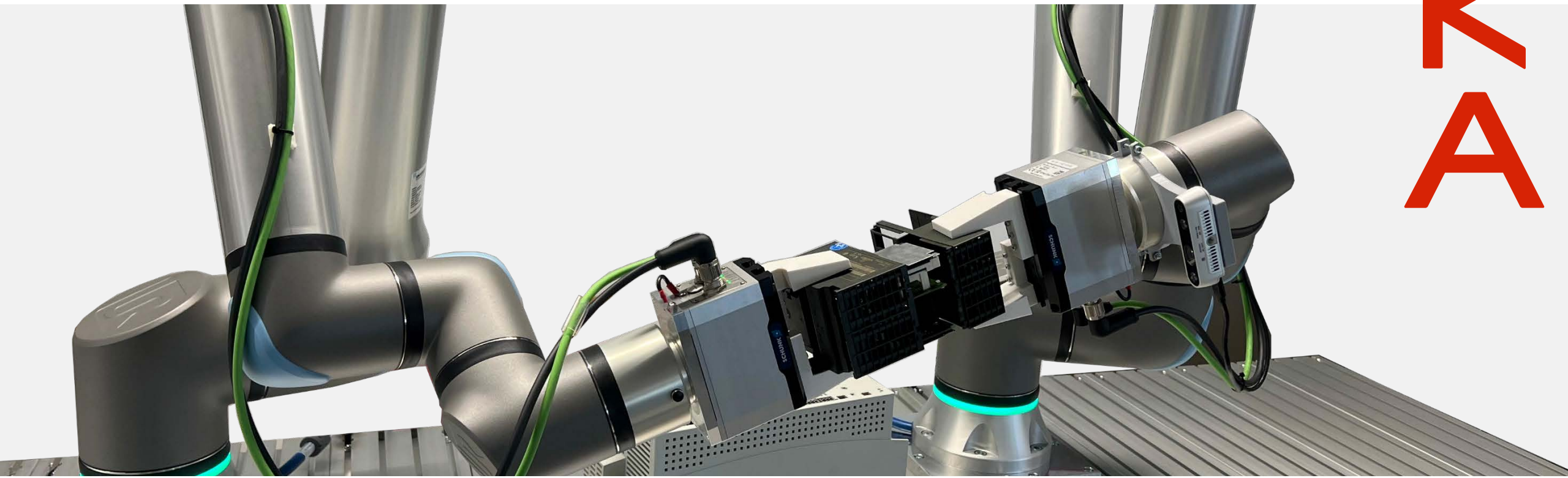
Laboratory for Manufacturing Systems & Automation (LMS)
Dept. of Mechanical Engineering & Aeronautics
University of Patras, Greece
www.lms.mech.upatras.gr

thank you

Hochschule Karlsruhe
University of
Applied Sciences

A Modular Dual-Arm Robotic Cell for Disassembly and Repair of Industrial Control Electronics

Maximilian Ruhe, Fabian Harlacher, Christian Friedrich, Martin Kipfmüller



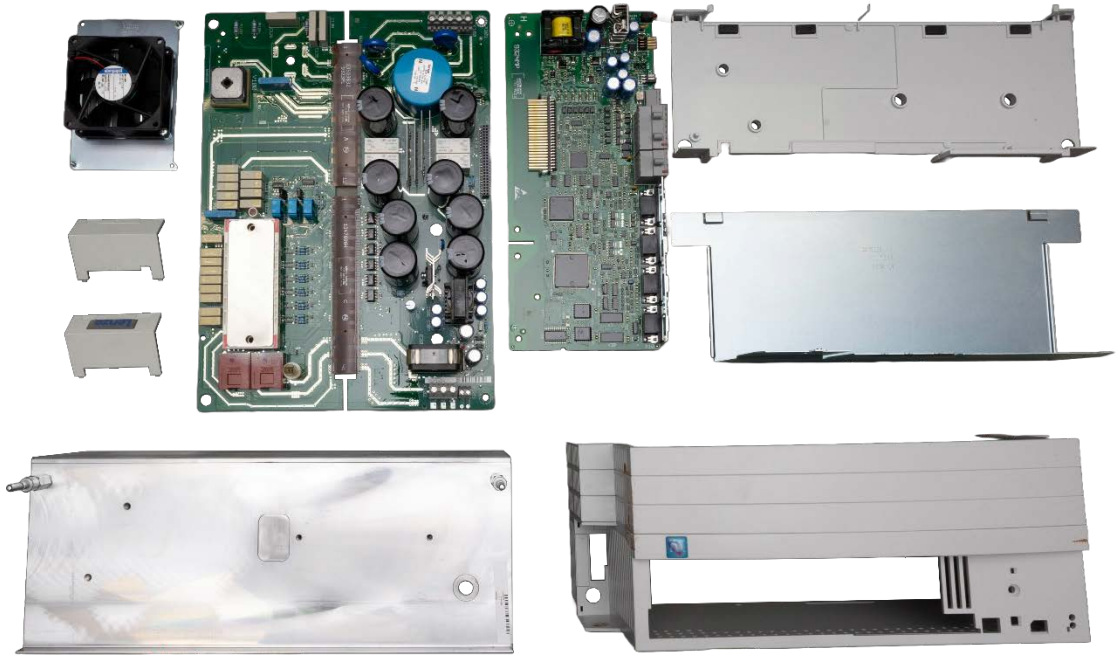
Motivation
Why repair industrial control electronics?

THE Opportunity

- PLCs, drives and operator panels are discarded over a single defect, while most of the device is reusable
- Repair preserves embedded energy and material instead of downcycling to scrap

WHY IT IS HARD

- Never designed for robotic service: varied geometry, uncertain wear, incomplete documentation.
- Contact-rich: release a snap-fit without cracking it, extract a PCB without bending, unplug within a narrow force window.
- **Pure scripts are brittle, pure vision is blind when the decisive cue is force.**



Contribution

A repair-oriented dual-arm cell for industrial control electronics, targeting non-destructive access to housings, connectors, PCBs and display modules

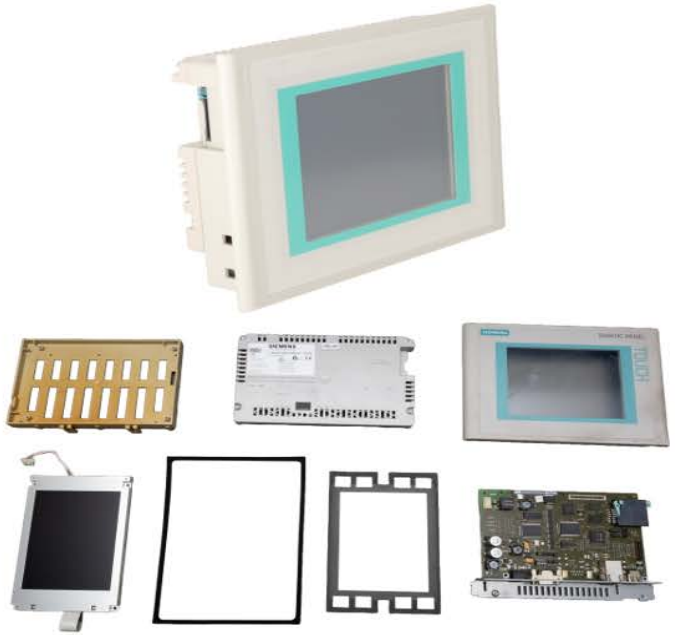
A device-grounded repair toolbox covering screws, damaged fasteners, snap-fits, plug connections, cooperative PCB extraction and inspection.

A CAD-supported sequence-planning layer that converts device-graph knowledge into executable operation objects

A force-aware Behavior Tree execution framework with explicit verification and deterministic fallbacks for contact-rich repair tasks.

A unified ROS 2-based integration of real hardware, teleoperation, digital twin and bounded learned contact skills.

Three target devices define the requirements



a)



b)



c)

a) TP177B panel
Layered display stack – preserve fragile bezel, LCD, gaskets

b) S7-300 PLC
Brittle aged snap-fit clips, narrow lever access

c) Lenze servo drive
Rigid screwing → cooperative PCB extraction

Hardware Cell
Required manipulation skills



Screw removal
Torque-limited driving with damaged-fastener fallback



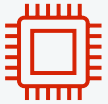
Levering
Force-limited snap-fit and bezel release



Dual-arm manipulation
Cooperative holding and synchronized extraction



Connector handling
Unplugging cables in a narrow force envelope



PCB extraction
Load-balanced removal without bending the board



Inspection & verification
Visual and force-based postcondition checks

Hardware cell and repair toolbox

CELL SETUP
2 × UR15-class cobots · 15 kg payload · 1300 mm reach · integrated F/T sensing · parallel Gripper with different Fingers

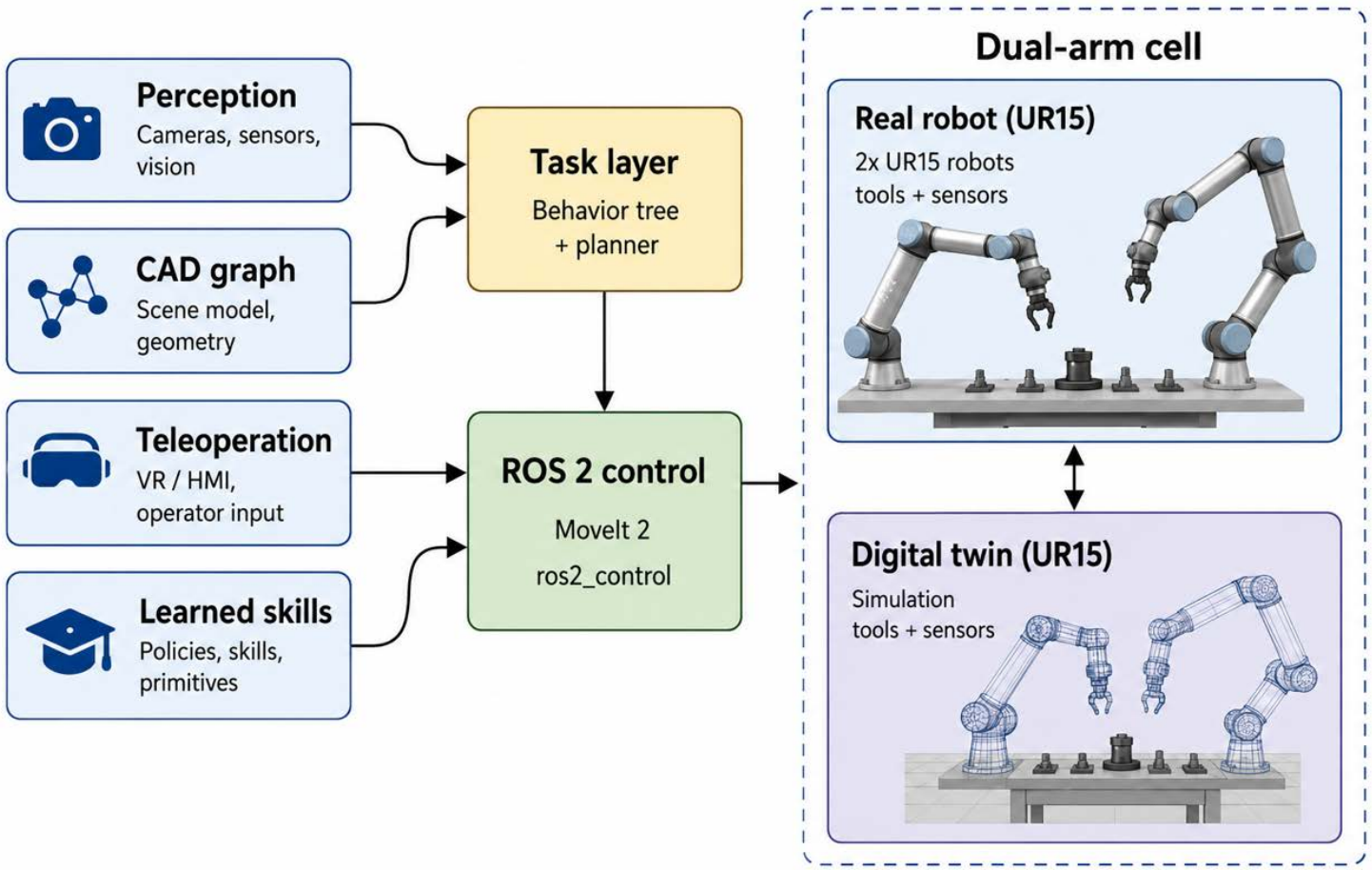
BIMANUAL REPAIR
One arm stabilizes the device while the other acts, or both arms cooperate

TOOLBOX & PERCEPTION
robot-mounted RGB-D camera · static 3D camera · F/T sensors





System Architecture

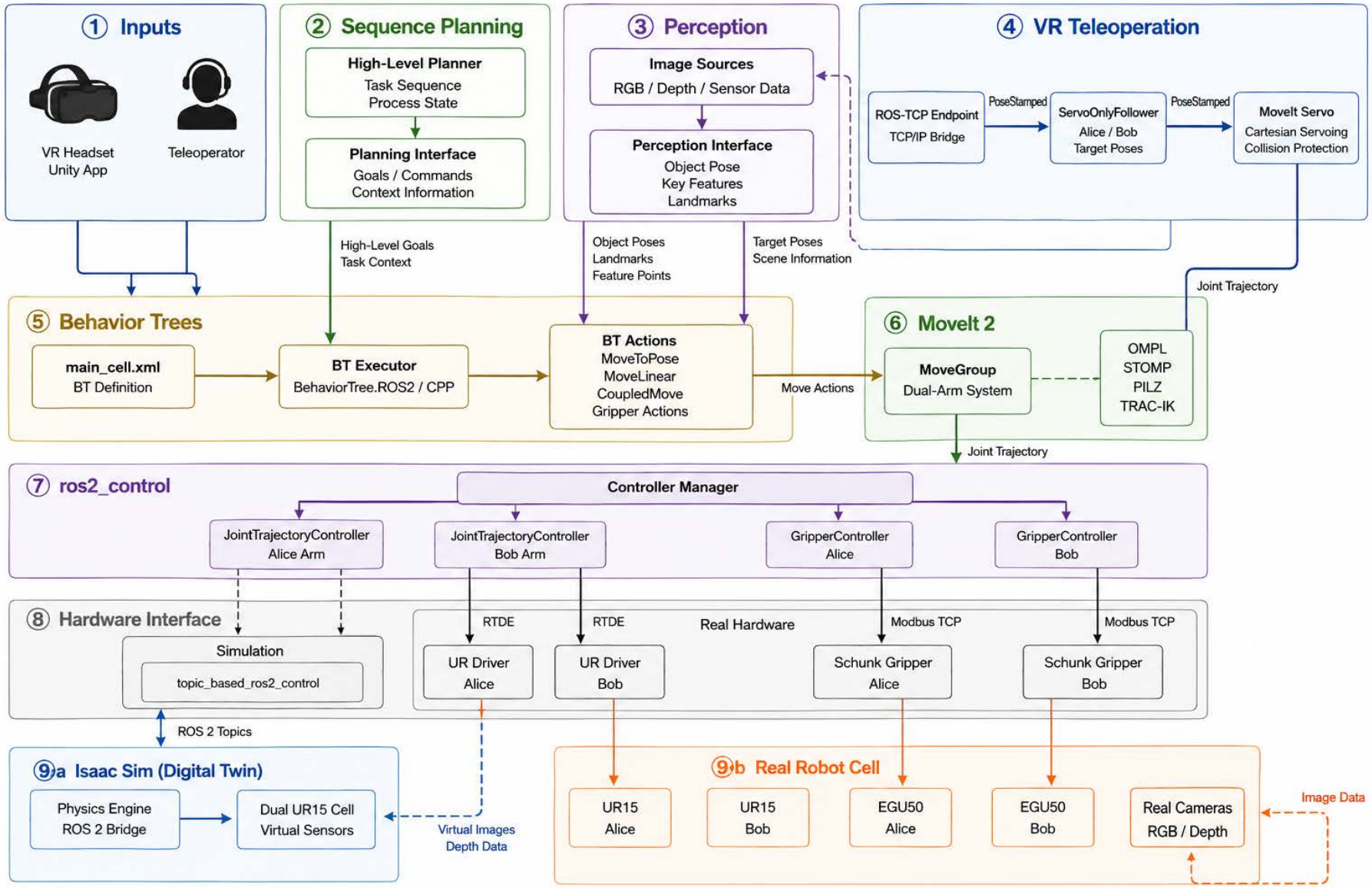


One interface
Perception, CAD graph, teleoperation & learned skills feed one shared task layer

Task layer
Sequence planning + behavior trees route every action through ROS 2 control

Sim = real
MoveIt 2 & ros2_control; Isaac Sim and the real cell share one command/observation path

ROS 2 implementation architecture



CAD-supported sequence planning



DEVICE GRAPH FROM CAD

- Relational model: parts, geometric constraints, symbolic relations
- Computes feasible removal directions & collision-free spaces
- Updated online — damage or blockage triggers replanning

SCHEDULING TICK

reachable frontier → perception labels → operation object → dispatch by resource class. The returned outcome updates the graph — planning is the memory of the process.

OPERATION OBJECT *planning ⇄ execution contract*

Target element part / fastener / connector

Tool class screwdriver · lever · gripper · spindle

Primitive UNSCREW · LEVER · PULL

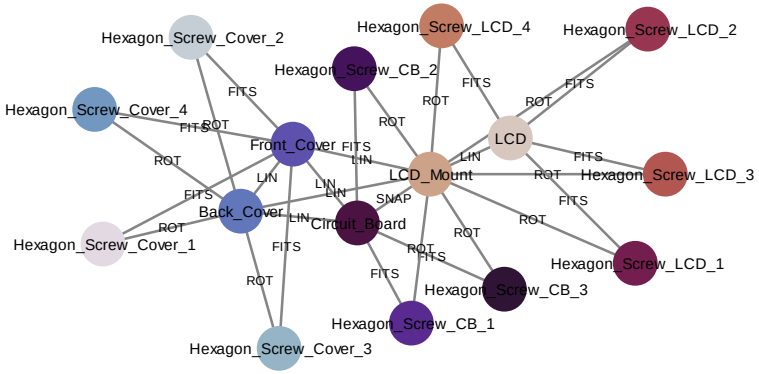
Pose & approach target frame + approach constraint

Force & safety admissible wrench, speed, workspace

Verification observable postcondition

Resource class single-arm · fixture · cooperative

Removal direction safe extraction axis





Execution, perception, teleoperation & digital twin

BEHAVIOR TREE

- Compact subtree per operation; structural fallbacks reroute on failure (damaged screw → milling, over-force → re-approach)
- Learned compliance (ACP) runs inside the tree under a force-limited wrapper

DIGITAL TWIN

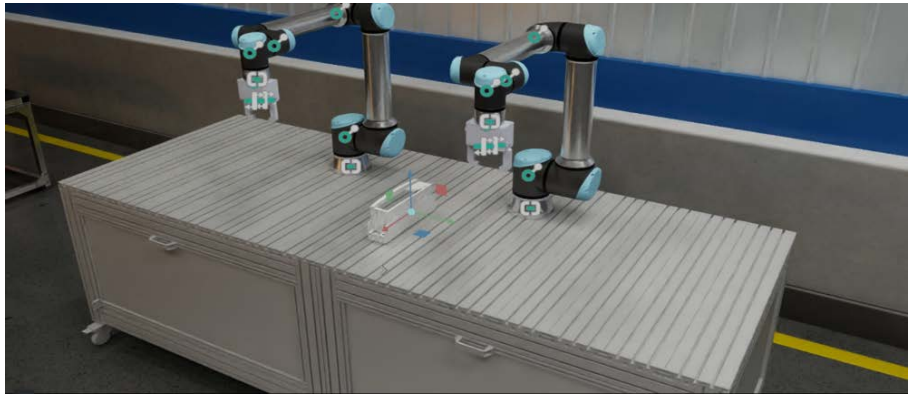
- Isaac Sim / Isaac Lab on the same ROS 2 interface; seamless real ↔ sim transition
- Validation, synthetic data and skill pre-training

PERCEPTION

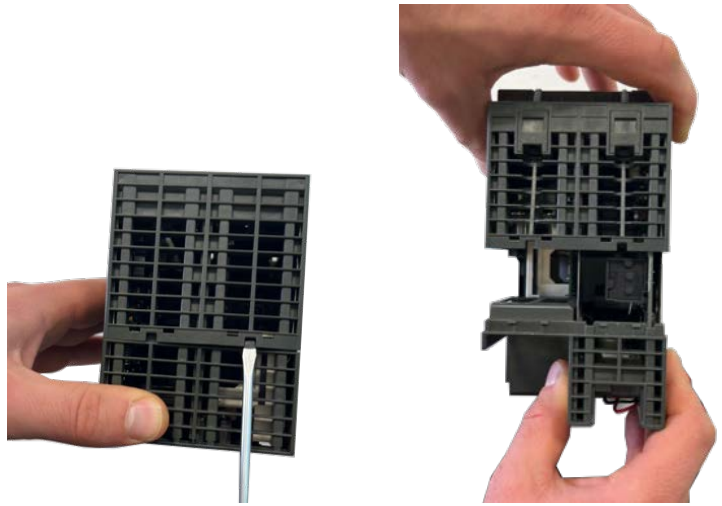
- Two-stage: scene-level (RGB-D) localizes, wrist-level refines and classifies screws, connectors, damage
- PCB defect inspection switches recovery → targeted repair

TELEOPERATION

- VR and GELLO-style leader arm; operator intervention on low-confidence skills
- Demonstration capture for imitation learning



Digital Twin in Omniverse Isaac Sim



Siemens S7-300 PLC; opening snap-fit joint and housing

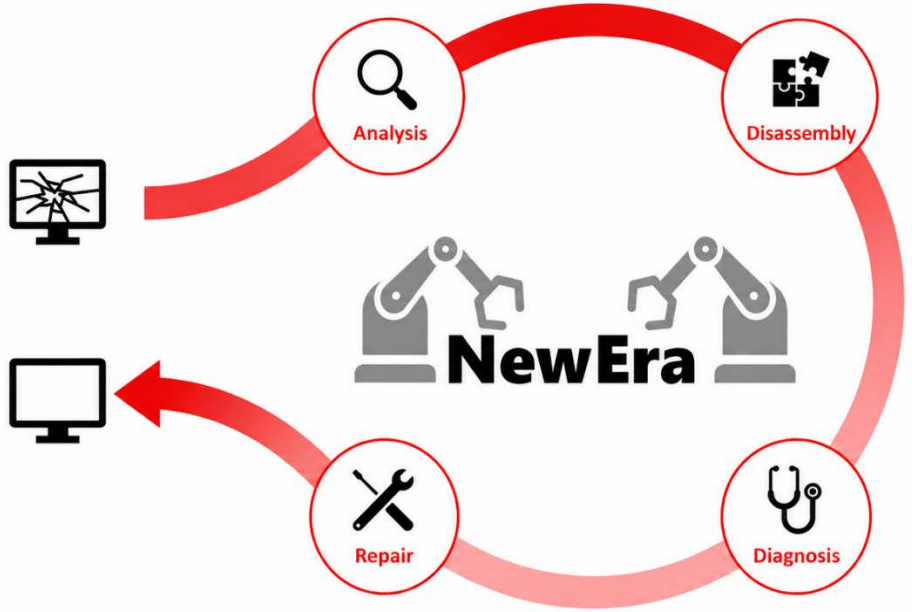
Status, outlook and conclusion

IMPLEMENTED TODAY

- Dual-arm hardware · Isaac Sim twin · ROS 2 stack
- CAD device graphs · first tool operations
- Demos: screw removal, cover opening, force aware snap-fit opening
- VR teleoperation & demontstration capture

FUTURE WORK & EVALUATION

- Quantitative subtask and full-cycle evaluation Baselines: scripted / teleoperated / hybrid execution
- Robustness tests: aged plastic · damaged screws · blocked connectors
- Transfer to additional industrial device variants



TAKE-AWAY Devices, tools, perception, task knowledge and verification share one ROS 2 loop, a high-value entry point for circular production.

Hochschule Karlsruhe
University of
Applied Sciences

Thank you for your attention!

With funding from the:

Federal Ministry
of Research, Technology
and Space

FONA
Research for Sustainability

CCPT

CCPT– 9-10th June 2026

Plastic Circularity: Influence of the indicators on the feasibility of circularity

PhD student : Madeline LAIRE-LEVRIER

Lab : I2M

Supervisors : Nicolas PERRY, Carole CHARBUILLET, Carola GUYOT-PHUNG

School : SMI - ENSAM Arts et Métiers

Funders :

ADEME : Aline GRUDET

ECOLOGIC : Victor FRANCOIS

I2M INSTITUT DE MÉCANIQUE ET D'INGÉNIERIE BORDEAUX

RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité

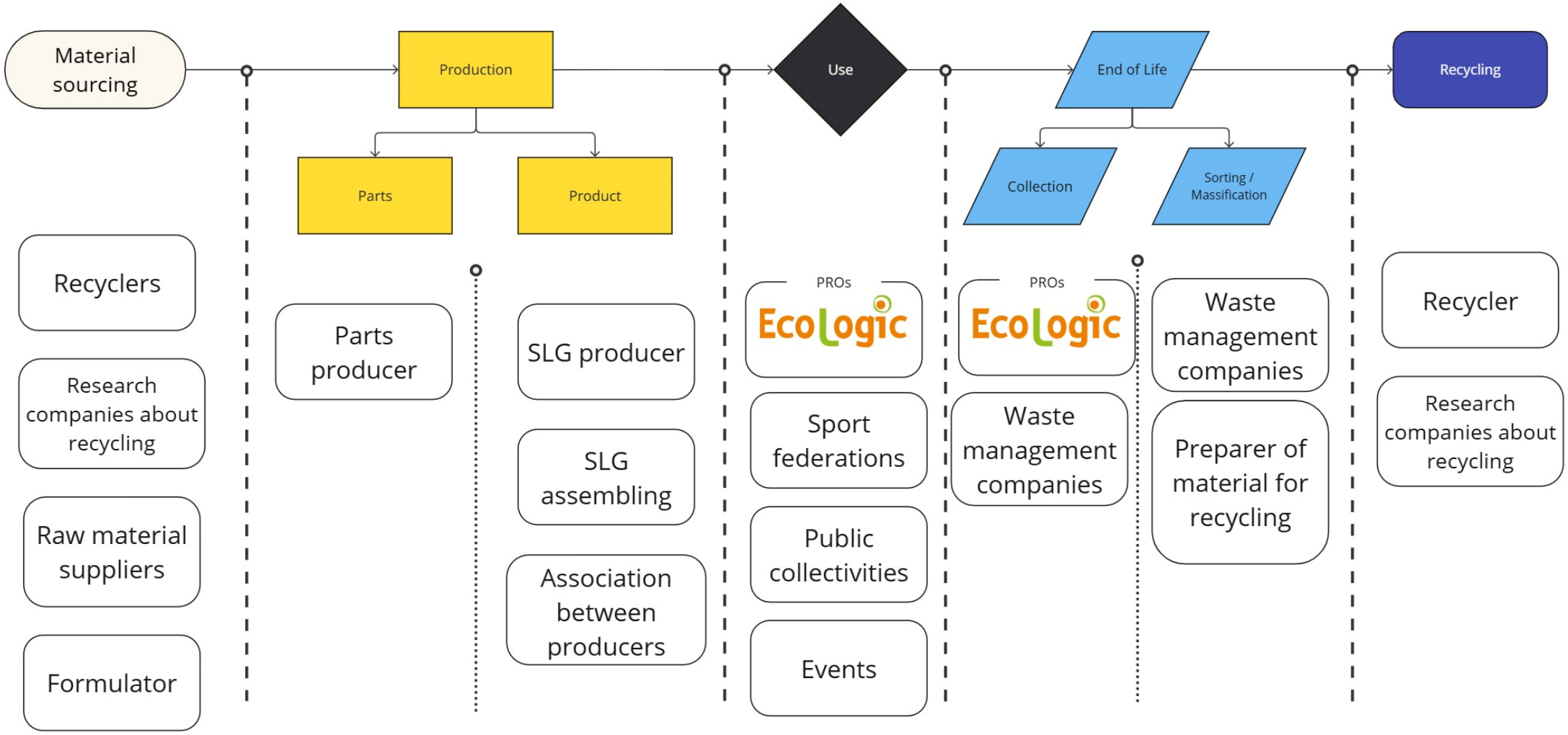
ADEME AGENCE DE LA TRANSITION ÉCOLOGIQUE

EcoLogic

Arts et Métiers Sciences et Technologies

Stakeholders

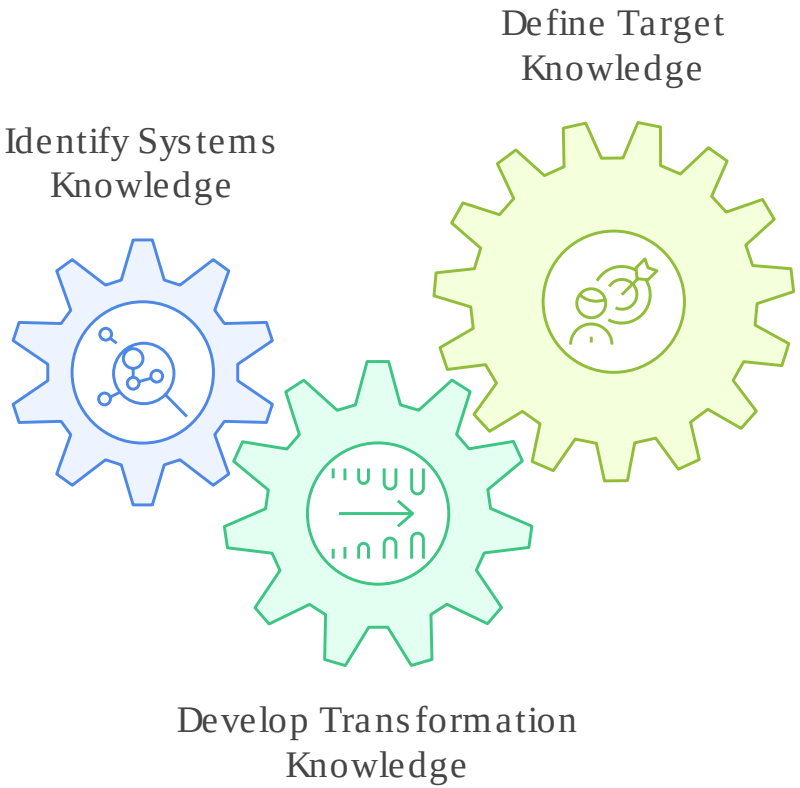
Understand the expectation of all the stakeholders of the plastic sector



How this benefits the industry: a better understanding of the drivers and barriers to circularity to find the most suitable **compromise** for a **long term and sustainable solution**

Method 3 Types of Knowledge

- **Method developped by the Swiss Academies of Arts and Sciences**
- **Trandisciplinary**
- **Involvment of heterogeneous panel**



Cirteria & Categories

Criteria

- Political – Legal
- Technical - Technology
- Operational - Logistic
- Social
- Economical
- Territory
- Environmental
- Sanitary - Health

Type of company

- Research
- Public institution
- Association
- Industry:
  - Manufacturing
  - Engineering
  - Waste management
  - Recycling
  - Raw material

Roles

- Polymer expert
- Design & Production
- Waste Management
- Economics
- Legal

Sector

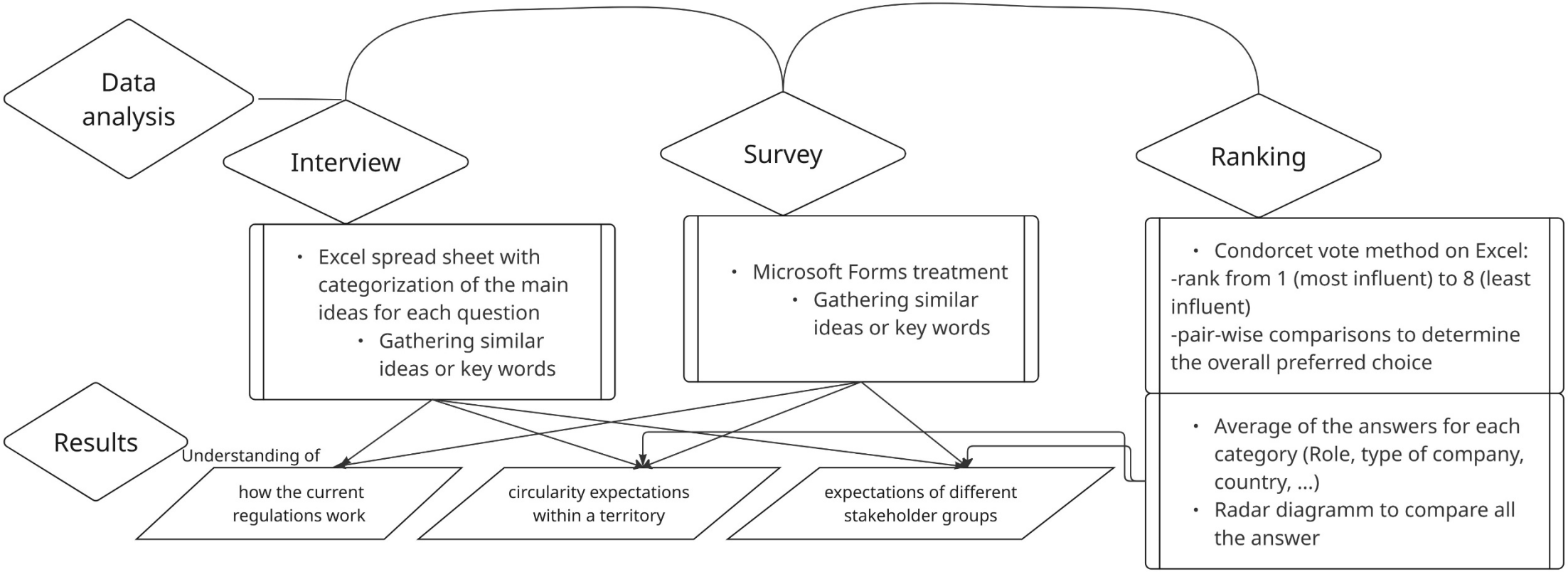
- WEEE
- Automotive
- Sport & Leisure Goods
- Packaging
- Energy
- …

Country

Roles		Countries		Type of Company	
Polymer expert	11	France	24	Research	18
Production & Design	9	Germany	4	Association - NGO	2
Waste management	12	Australia	4	Waste management	1
Legal	2	Other EU+CH	4	Industry	15
Economics	5	Other	3	Public institution	3

Method for the data collection

Method for the data analysis



Survey and interviews

1. Current waste regulations:

- Most of the countries apply national regulations
- Some others apply federal policies

→ **EPR System that can be national or EU level**

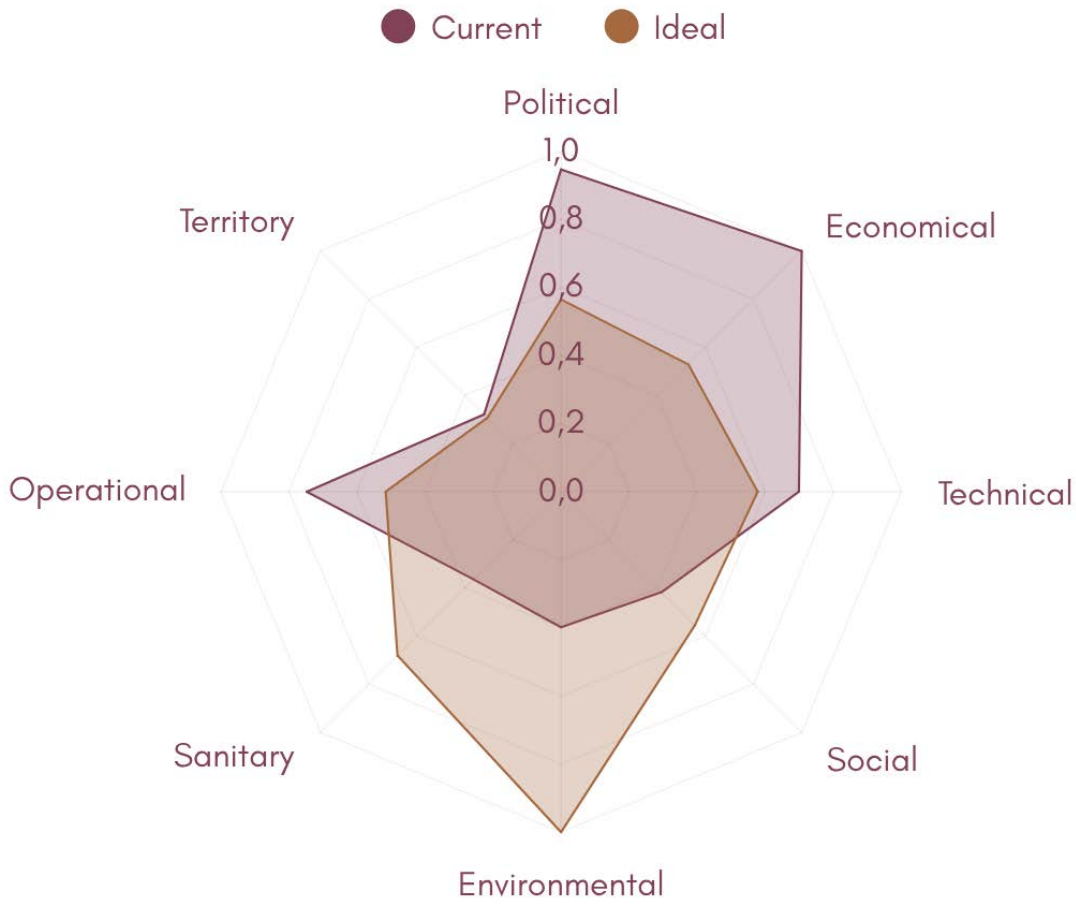
2. Ideal scale for plastic circularity:

- 76.9% prefer local scale
- Others national/1 500km

➢ Some suggest that it would be worthy to introduce laws with international scope

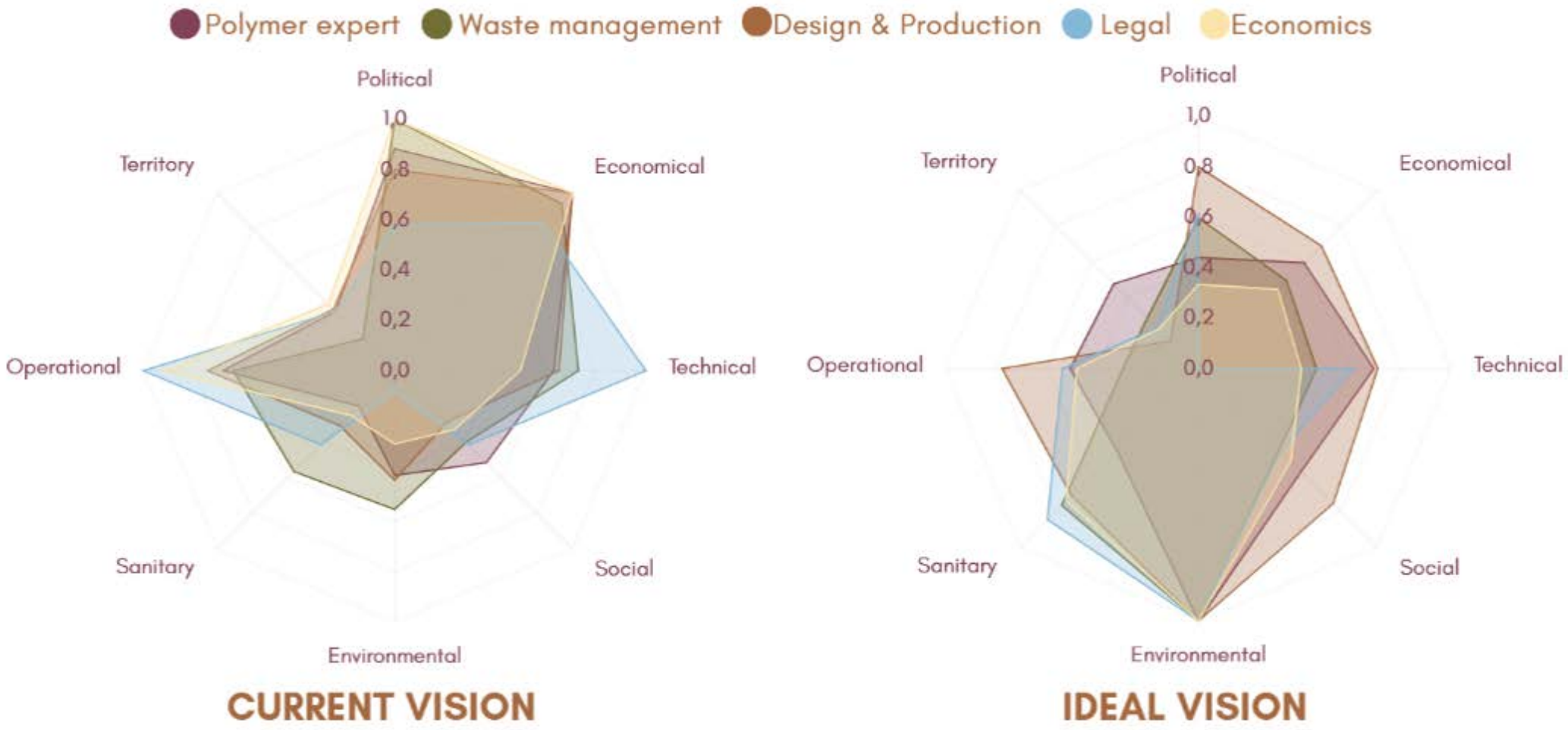
Global ranking

- **Territory is behind: at odds with the local vision of circularity highlighted in the survey**
- **Environmental and sanitary criteria are not given sufficient consideration in the current situation.**
- **Political and economical are given too much weight in the current approach**



Ranking visions

Comparison by roles



Homogeneous in the current vision, but expectation different (in the ideal vision)

Suggestion for a better circularity

- Adapt the operational to the territory: materials depend on the product use in the local territory
- Involve all the roles for the law redaction.
- Law redaction must take more into account environment and sanitary criteria
- Regulation and responsibility of the waste management should be adjusted to the size of the territory



Link of the survey
~10min to complete



Institut de Chambéry

madeline.laire-levrier@ensam.eu

Prospect per criteria

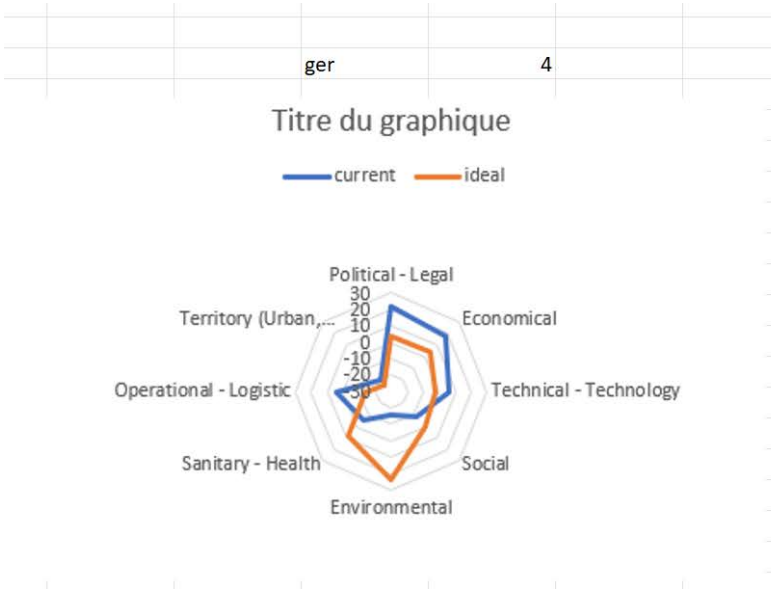
Criteria	Highlighted ideas	Prospects
Political	International waste laws	International homogenization
Technical	A greater importance in the current vision of the Economics	-Not the biggest barrier -Competitiveness of the facilities
Economical	Highly important for everyone in the current vision	Evaluate the value of the material and the use (no over-quality)
Operational	-Policies easily bypassed -Extremely important in the current vision of the Economics and Legal and has great importance for others -A greater importance in the ideal vision of Production & Design	-Make the use of available technologies more easily (cartography, information, network, …) -Developing Eco-Design competencies
Social	Quote: local plastic resource management to connect consumer to the product	-Consumer awareness -Make alternatives available
Environmental	The greatest important in the global ideal vision	Must lead the decision making (regulation and industrial policies/strategies)
Sanitary	Greater importance in the global ideal vision	Must lead the decision making (regulation and industrial policies)
Territory	-As local as possible (but territory ranking stays with bad score) -Greater importance for the ideal vision of Polymer experts	-Being local requires adaptation to the territory -Fill in the gaps in the infrastructures in the territory

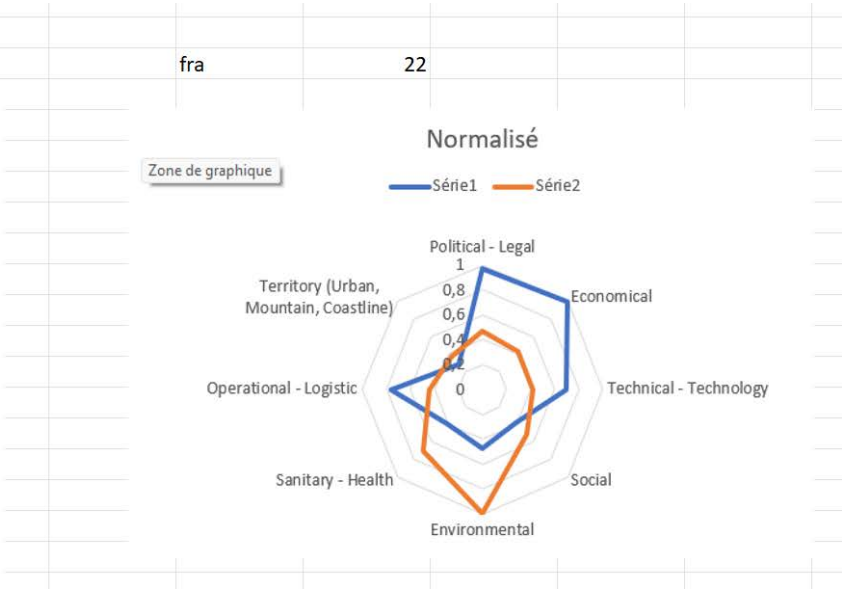
Etude circularité de la filière plastique

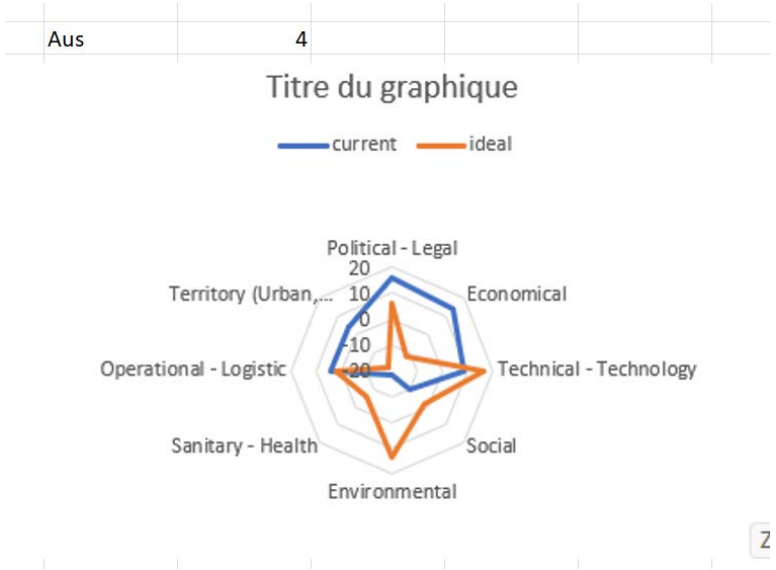
Per countries

Homogeneous vision inside europe

No significant number of answer for countries outside europe



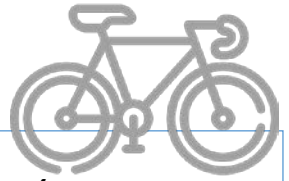




Arts et Métiers Sciences et Technologies

Sélection des études de cas

- Des cas d'études qui ne se superposent pas
- Evaluer les MP critiques
- Séparation des matières avant broyage

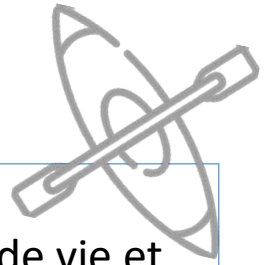




Centré sur un matériau spécifique (fibre carbone, fibre de verre … ?)

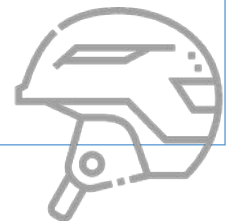


Centré sur la durée de vie et la difficulté de collecte/tri





Centré sur la complexité du produit : étude du désassemblage



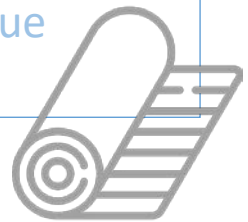


Modèle circulaire déjà mis en place -> pour évaluer la performance sociétale et sanitaire





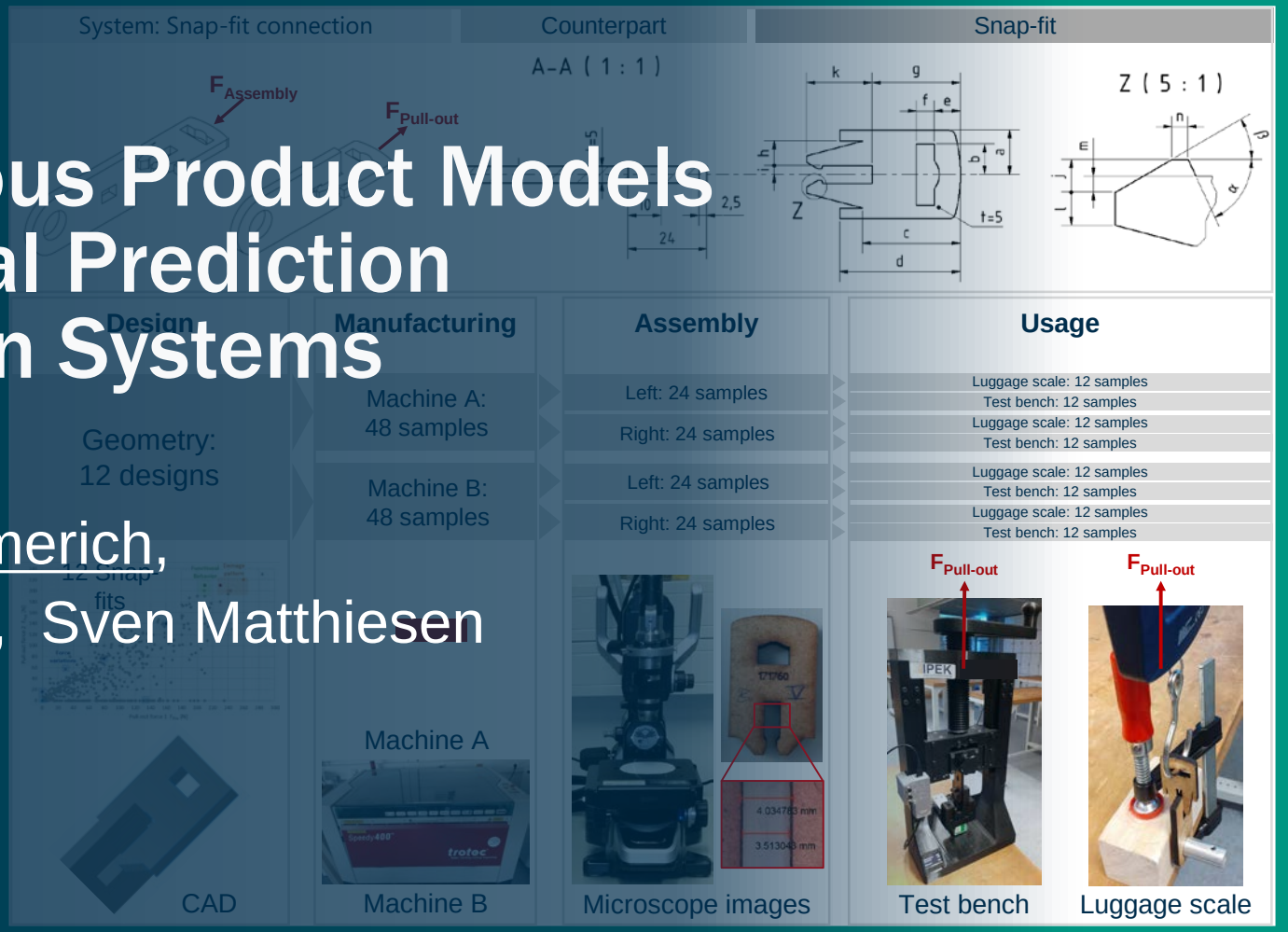
Mutualisation de filière pour une matière spécifique



Linking Heterogeneous Product Models to Improve Functional Prediction in Circular Production Systems

Johanna Lüning, Jonas Hemmerich,
Jiahang Li, Patric Grauberger, Sven Matthiesen

CCPT 2026 - Karlsruhe



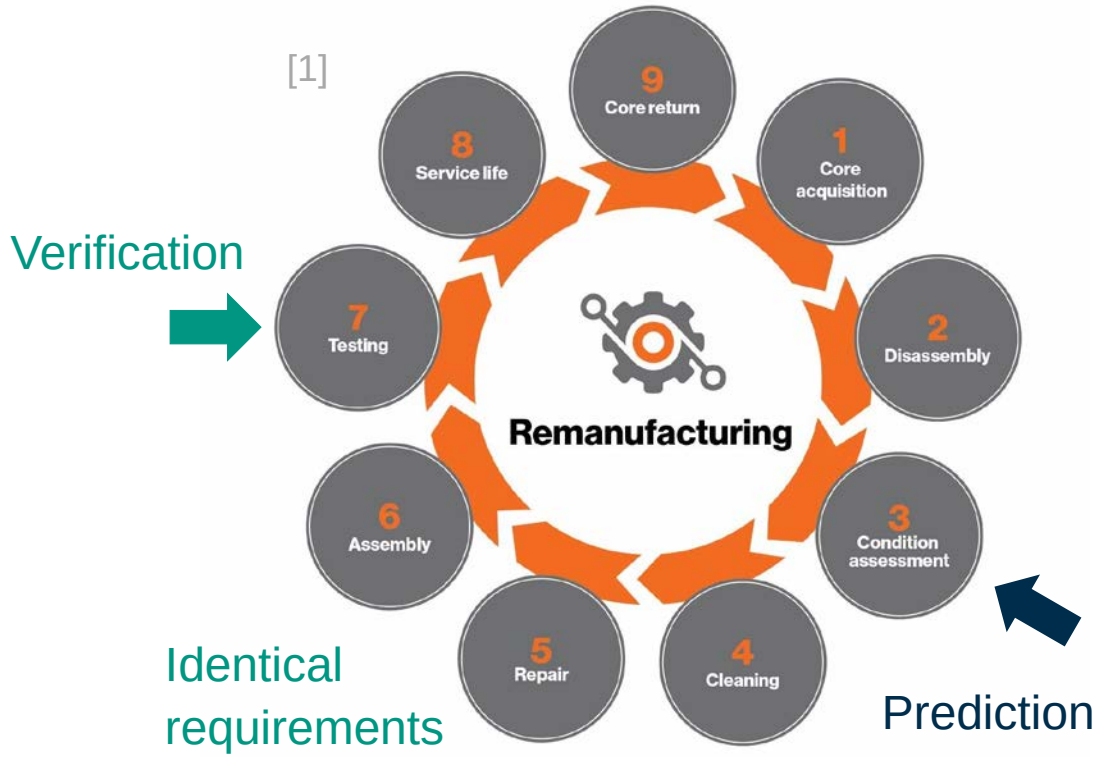
Functional Prediction in Circular Production Systems

Motivation

Setting

- Circular value creation relies on remanufacturing of returned cores
- Decision making requires an objective prediction of the component's condition and its functional behavior

[1]



Functional Prediction in Circular Production Systems

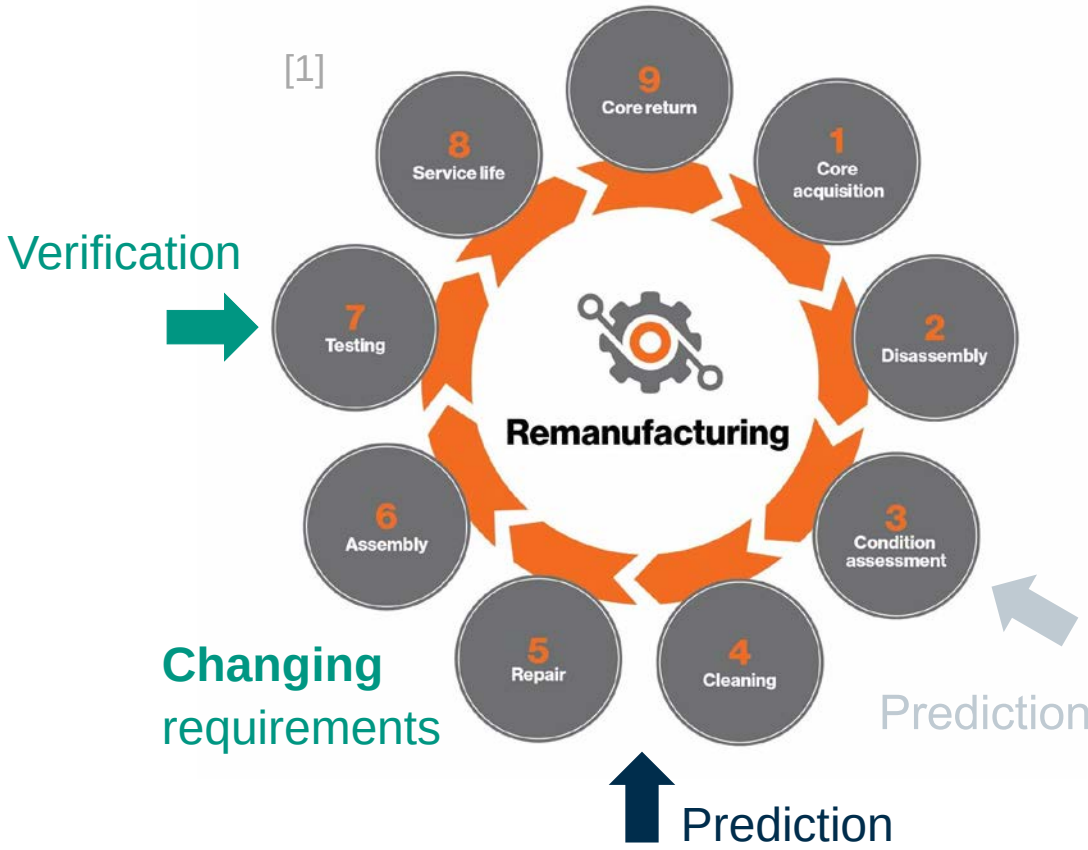
Motivation

Setting

- Circular value creation relies on remanufacturing of returned cores
- Decision making requires an objective prediction of the component's condition and its functional behavior

Challenge

- Functional requirements change across variants, which introduces an additional functional prediction
- Returned components carry individual deviations and uncertainties evolving throughout the lifecycle



Functional prediction for returned components requires **models that capture individual deviations**.

Consideration of Deviations in Product Models

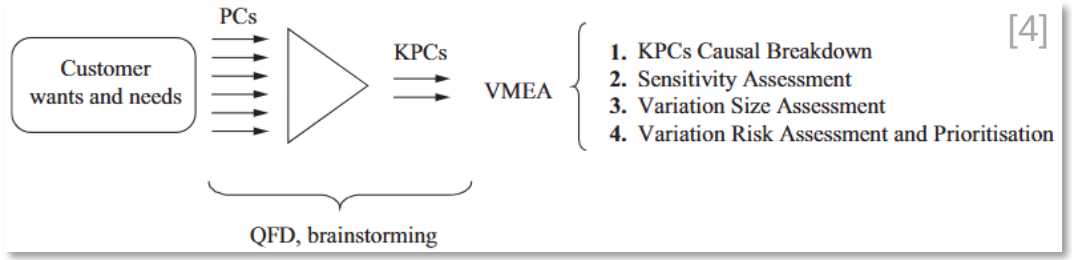
Research Focus

Consideration of Deviations in Product Models
Research Focus

Qualitative

- Identify critical sources of deviation and uncertainty within technical systems
- Represent deviations either within existing models or through dedicated uncertainty models

VMEA



[4]

Consideration of Deviations in Product Models

Research Focus

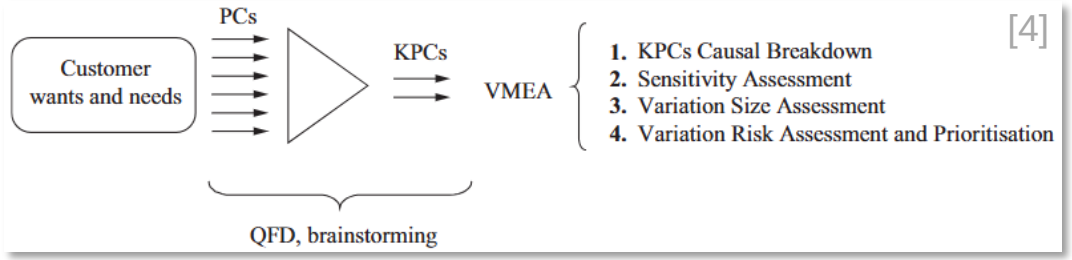
Qualitative

- Identify critical sources of deviation and uncertainty within technical systems
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Quantitative

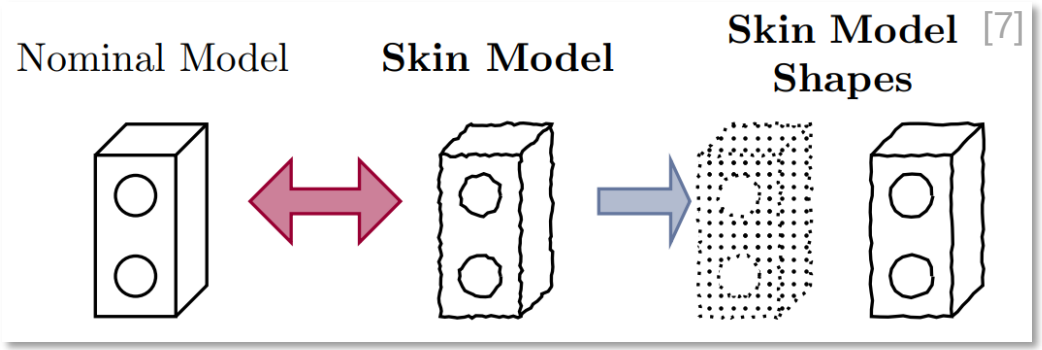
- Capture and quantify the present deviations within technical systems
- Use deviations as inputs for physics based models or transition towards data-driven predictions

VMEA



[4]

Skin Model Shapes



[7]

Consideration of Deviations in Product Models

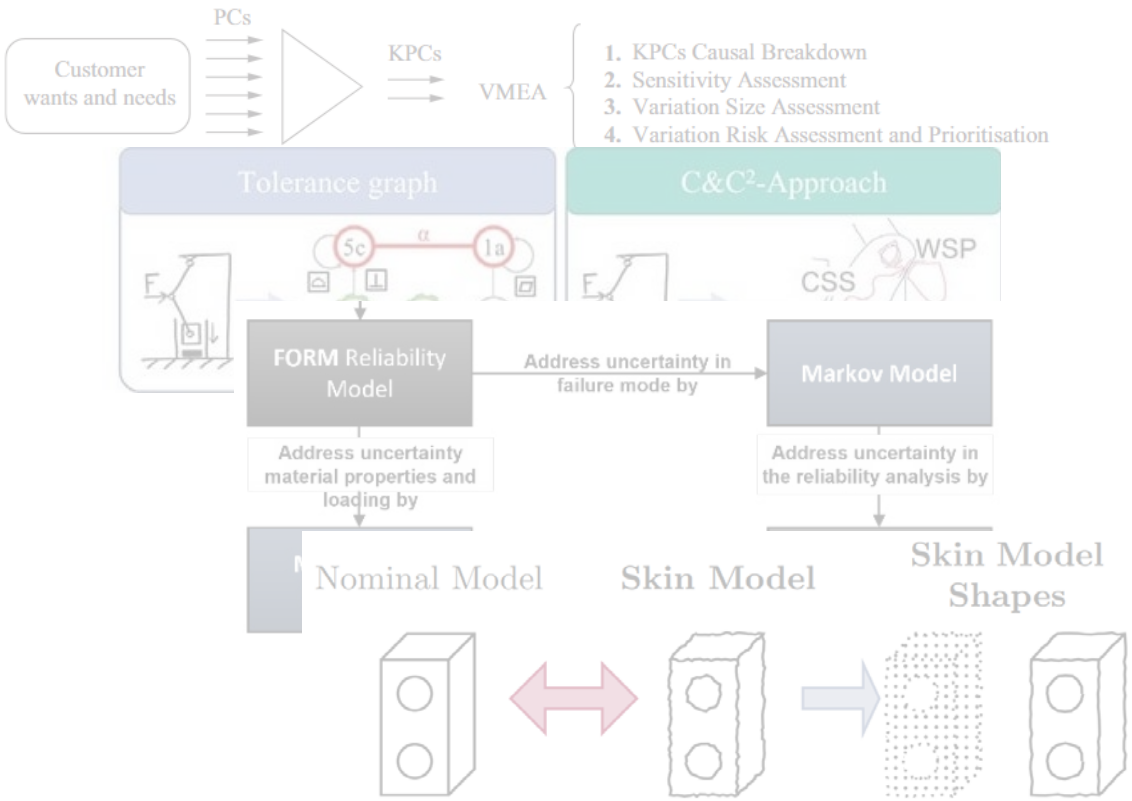
Research Focus

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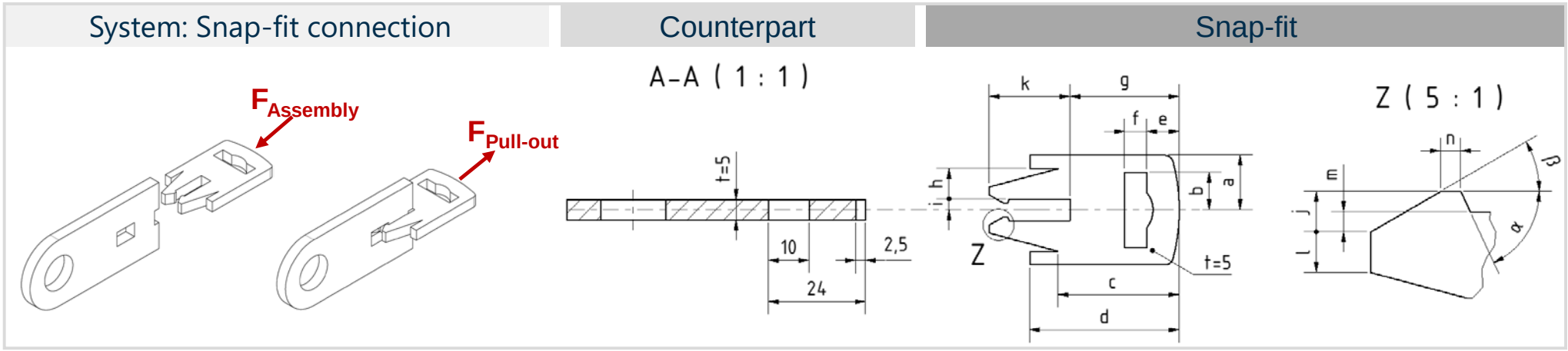
Research Question

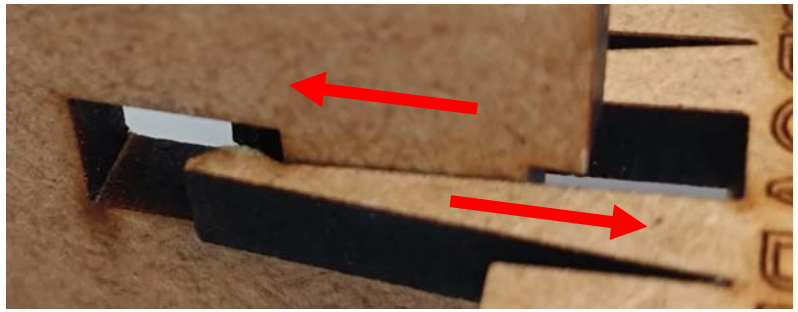
How should **empirically observed deviations** be **fed back** into the respective **product models**?

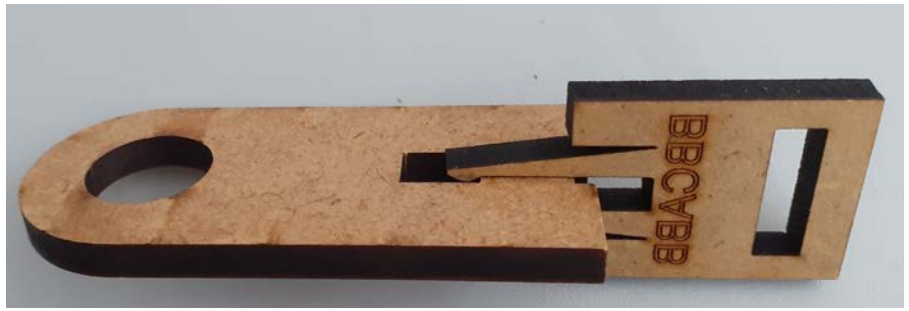
Inductive Case Study with Stagewise Model Confrontation

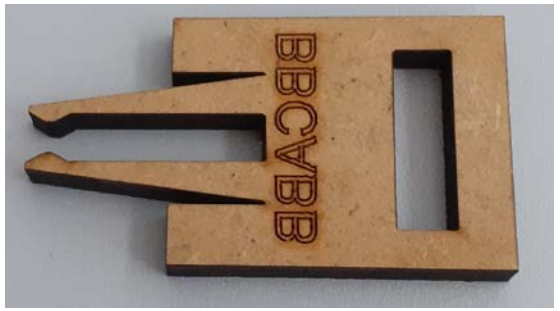
Methodological Approach

Snap-Fit Connection





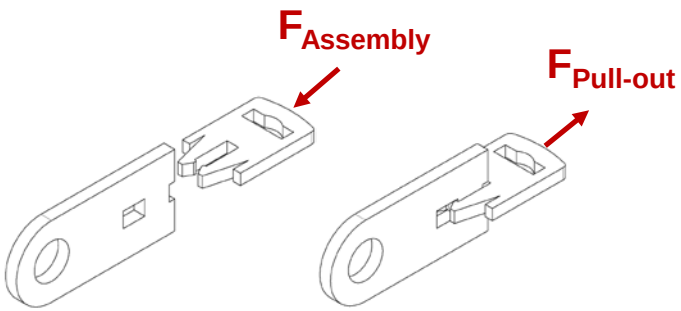




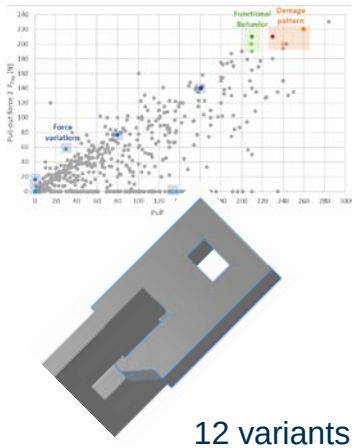
Inductive Case Study with Stagewise Model Confrontation

Methodological Approach

Snap-Fit Connection



Design



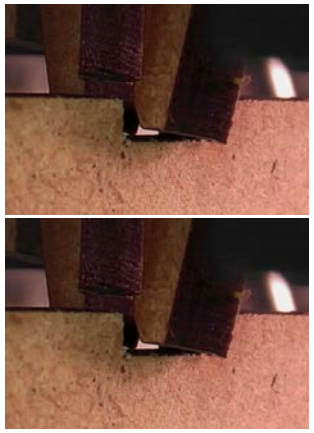
12 variants

Manufacturing



Machine A / B

Assembly

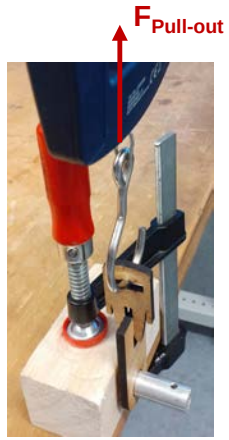


Side left / right

Usage



Test bench

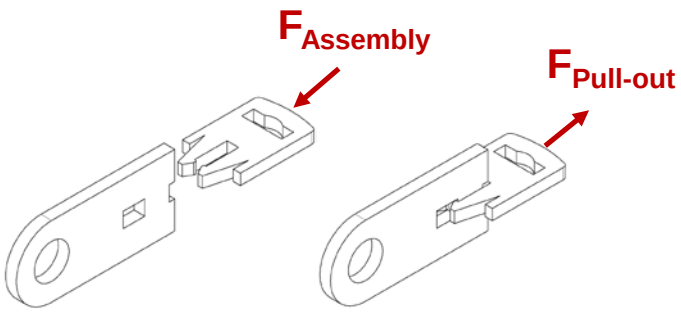


Luggage scale

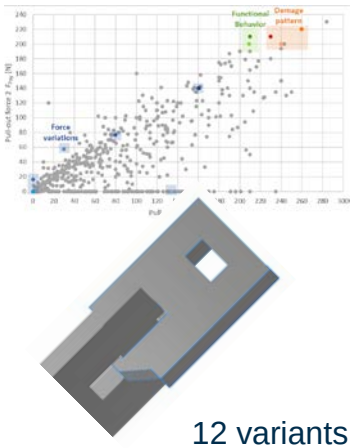
Inductive Case Study with Stagewise Model Confrontation

Methodological Approach

Snap-Fit Connection



Design



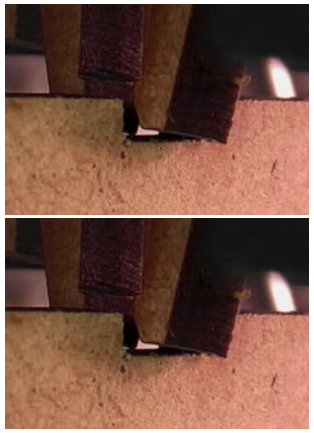
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Manufacturing



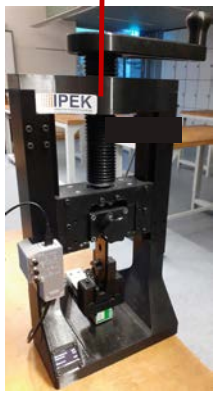
Machine A / B

Assembly

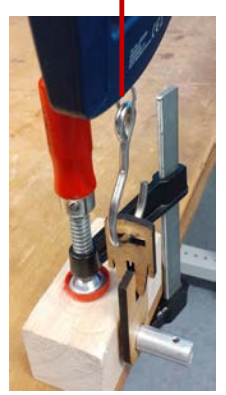


Side left / right

Usage



Test bench

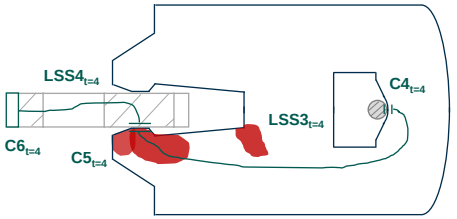


Luggage scale

Stagewise Model Confrontation

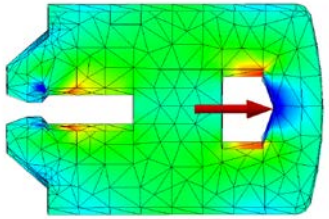
- Minimum effort models as baseline representation
- Predictions confronted with empirical data for each lifecycle stage combination
- Integration of deviations based on model refinement

Qualitative: C&C² Model



Damage location and mode

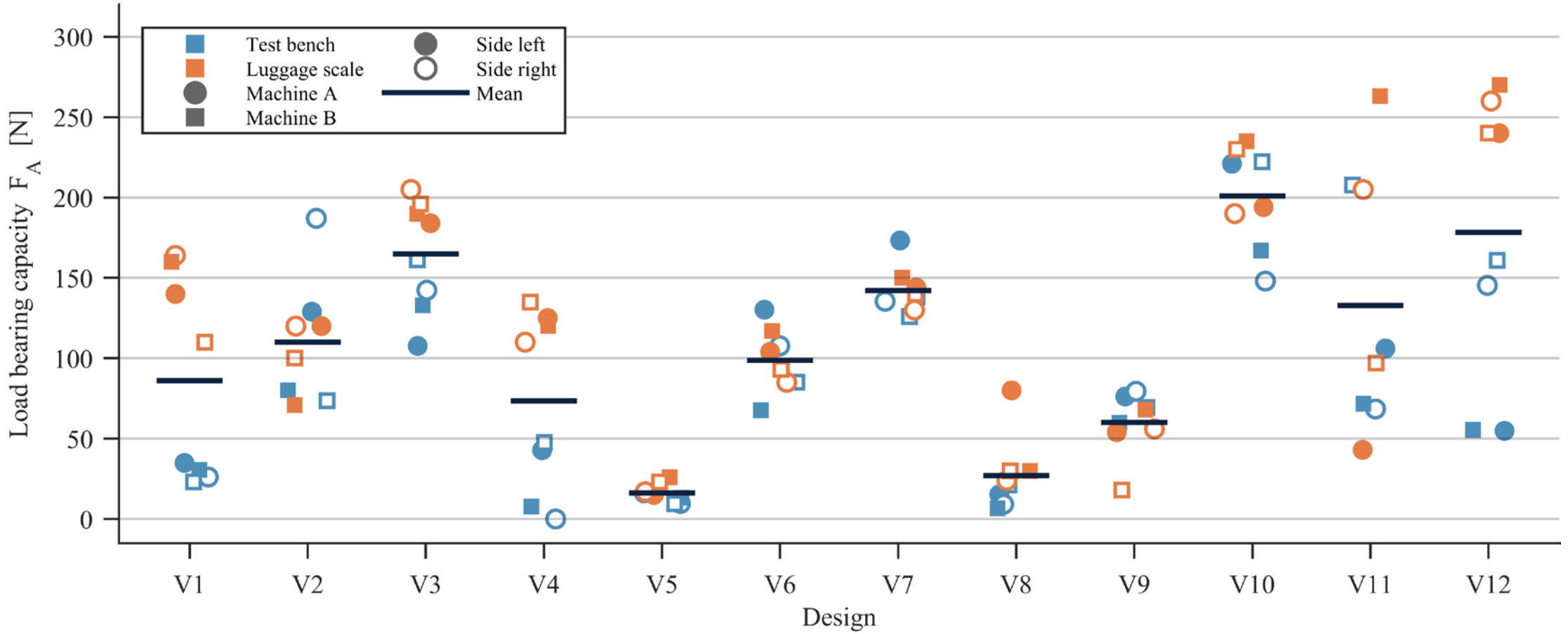
Quantitative: FEM Model



Load bearing capacity

Empirical Data on Pull-Out Force

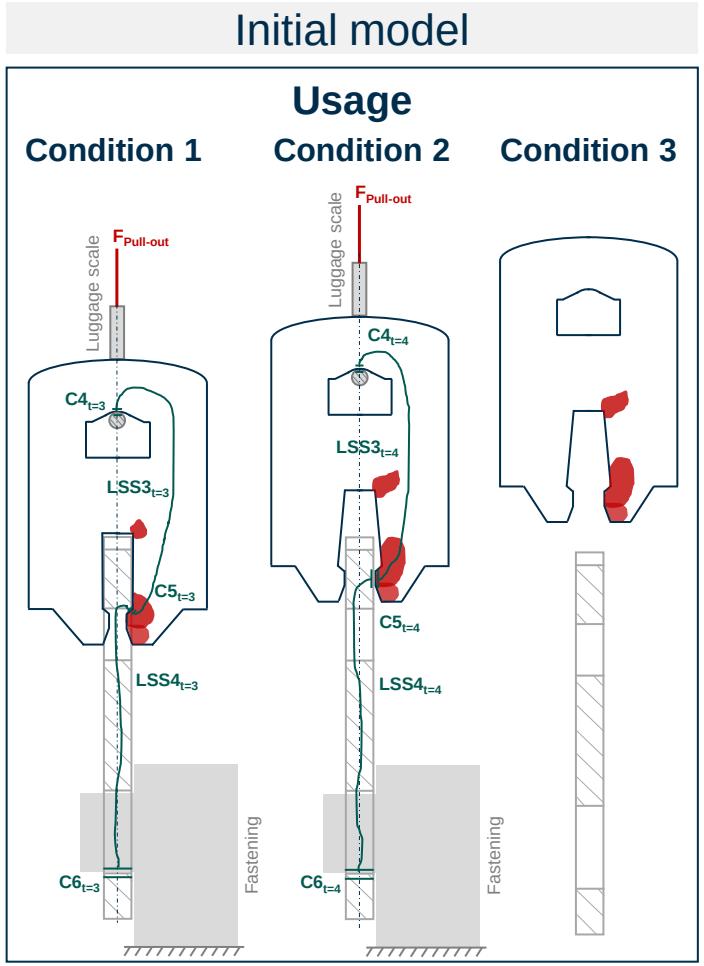
Case Study



Spread within and between can reach **identical magnitudes** across designs and lifecycle stages.

Iterative Model Refinement

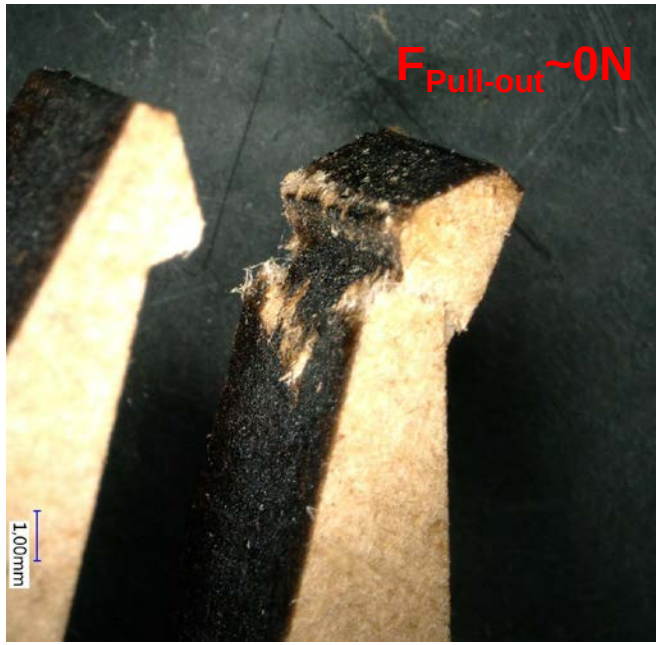
Case Study



Iterative Model Refinement

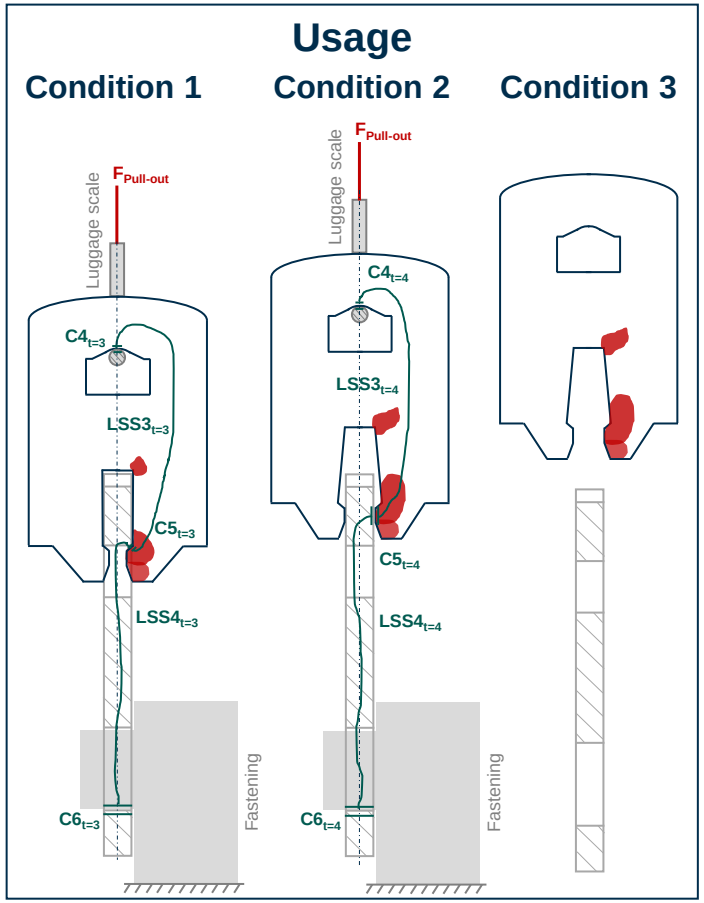
Case Study

V4 - Machine B - Left side - Luggage scale



Snap-fit is damaged during assembly

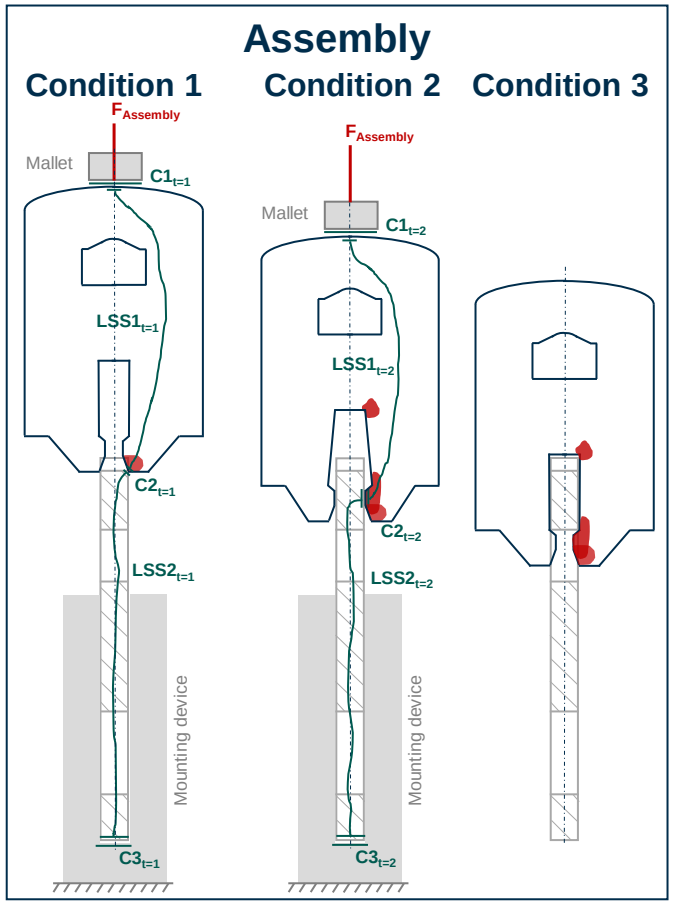
Initial model



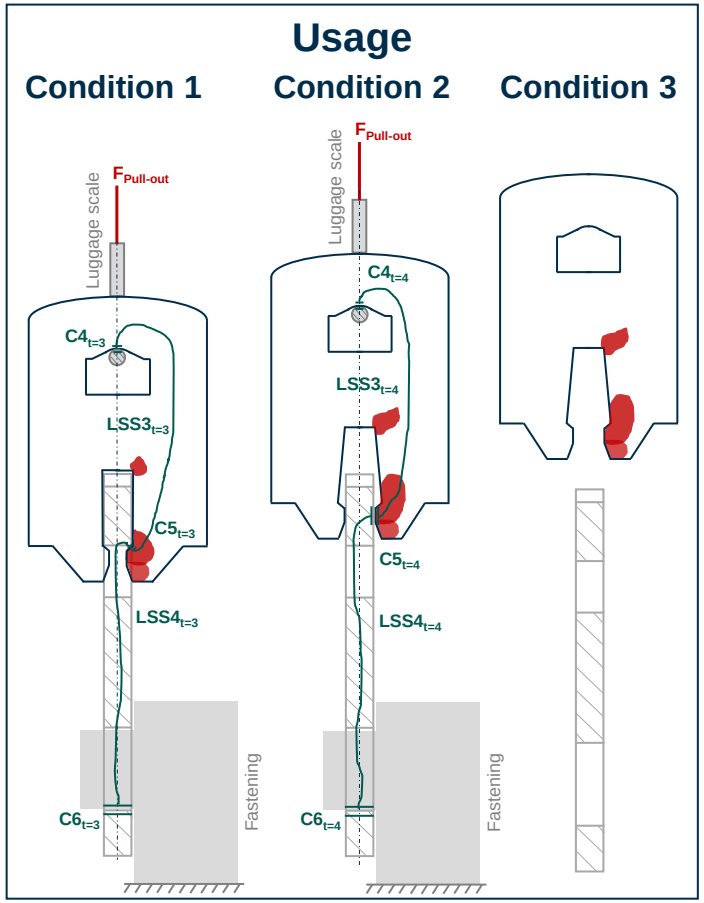
Iterative Model Refinement

Case Study

Observation 1



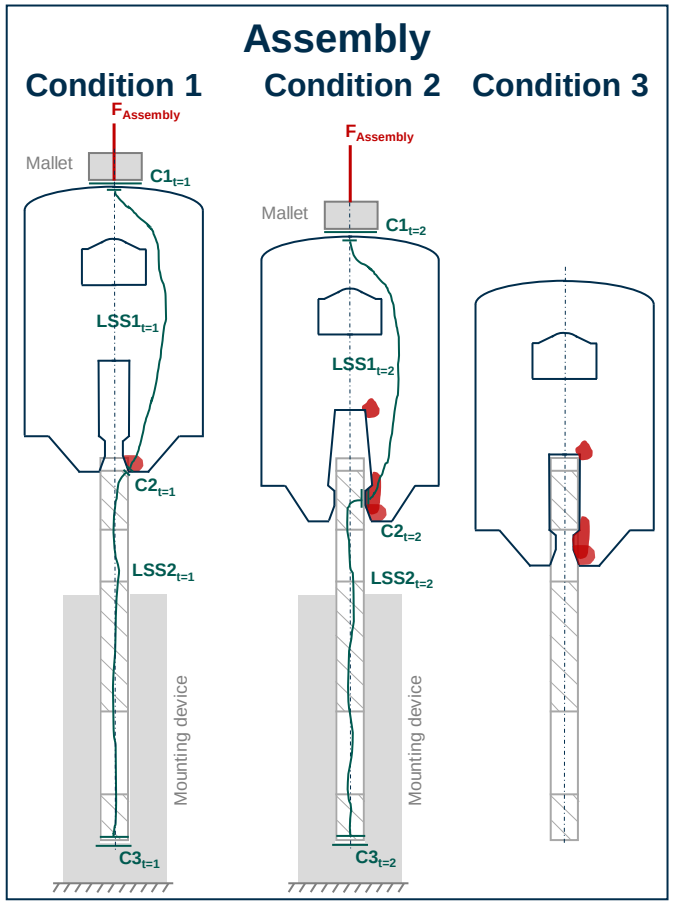
Initial model



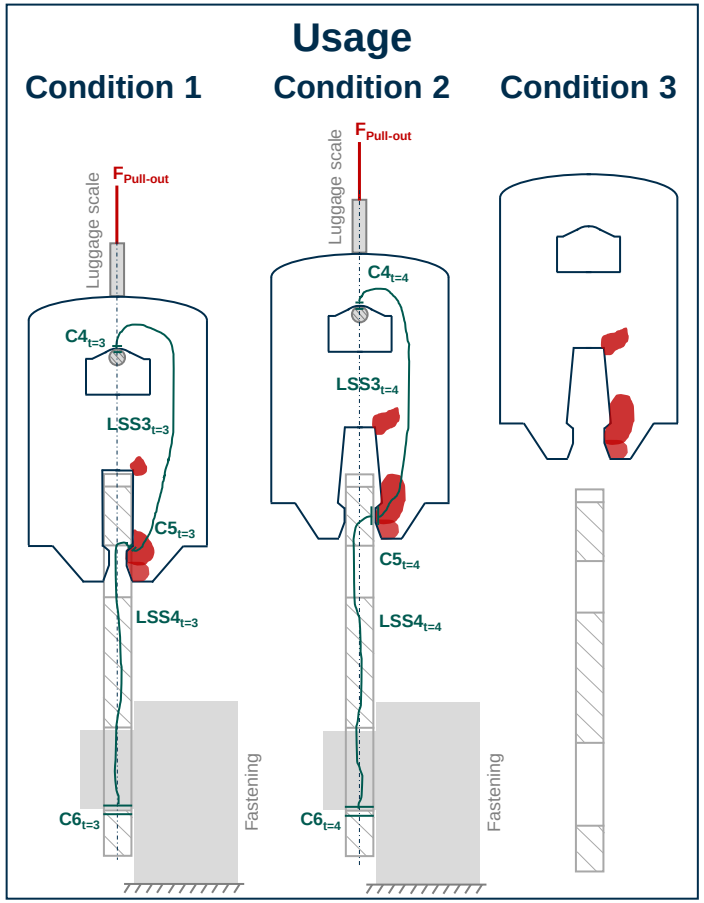
Iterative Model Refinement

Case Study

Observation 1



Initial model



V1



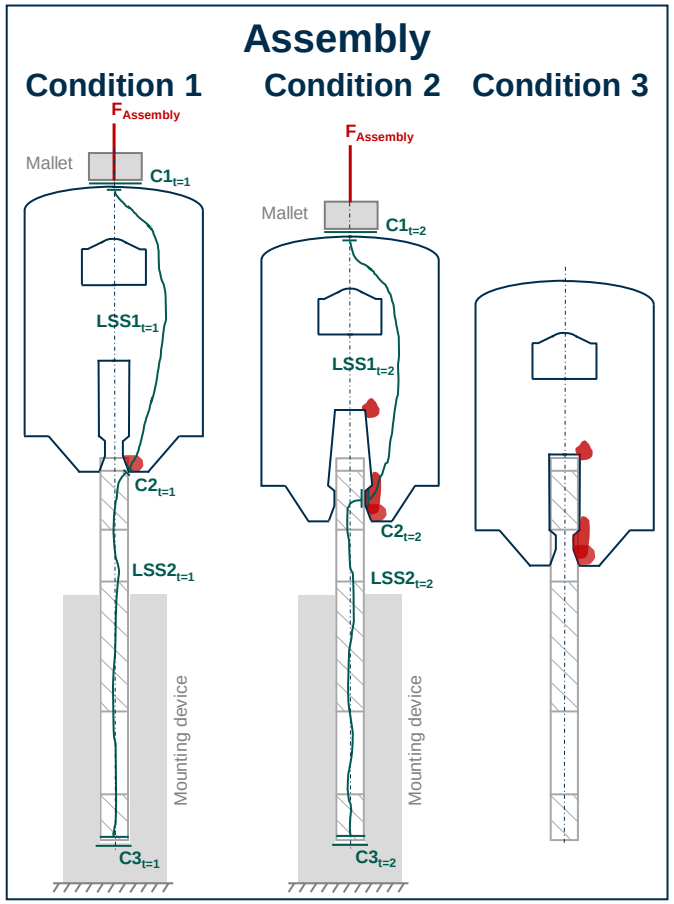
V3



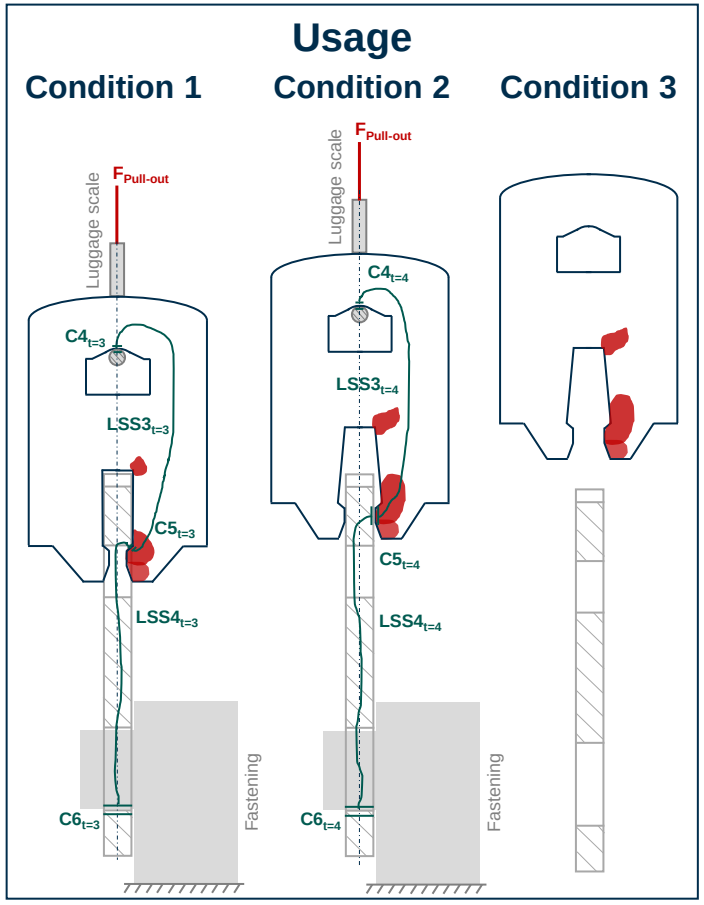
Iterative Model Refinement

Case Study

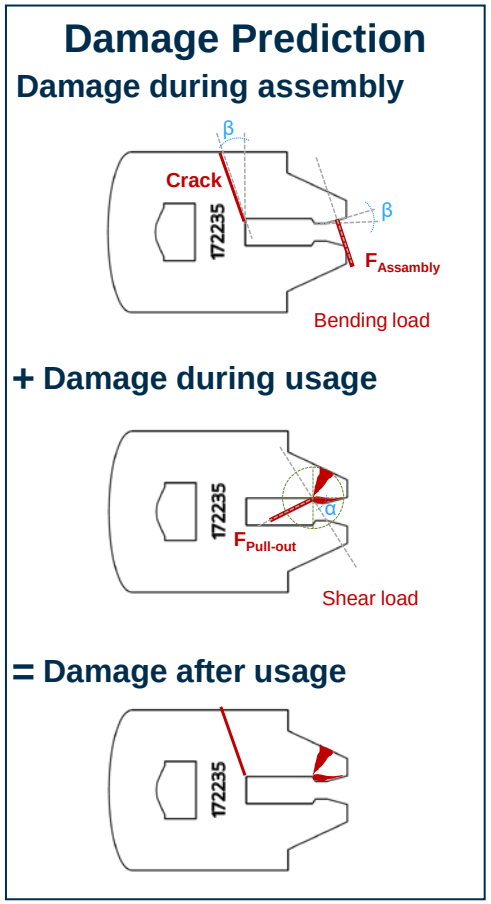
Observation 1



Initial model



Observation 2



Insights Beyond the Case Study
Results

Findings

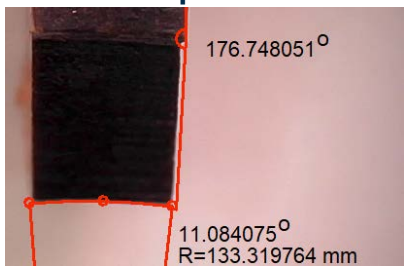
- Nature of deviation determines feedback path
  - Stochastic: statistical correction
  - Systematic: structural integration

Design + Manufacturing

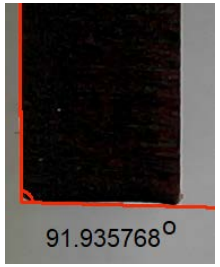
Oblique cut



Sickle-shaped cut



Oblique cut



Oblique cut



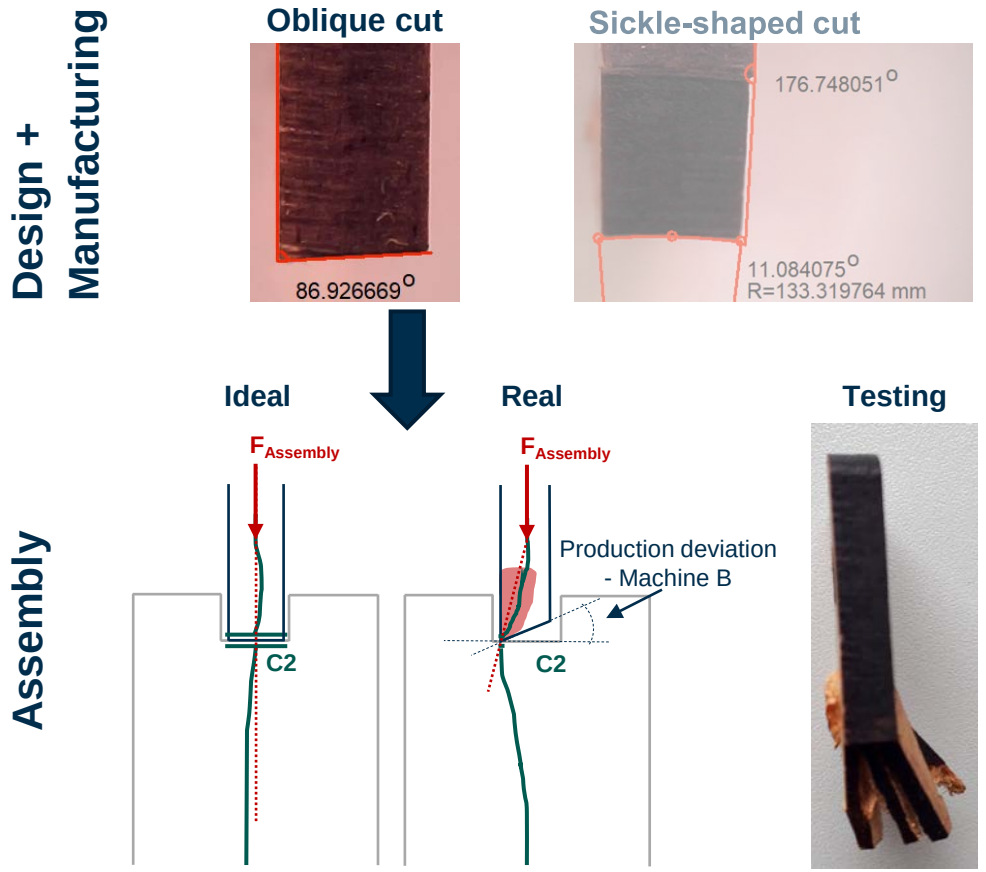
Insights Beyond the Case Study
Results

Findings

- Nature of deviation determines feedback path
  - Stochastic: statistical correction
  - Systematic: structural integration

- Coupling across lifecycle stages is the criteria that makes linking necessary
  - Otherwise linking is optional

- Hypothetical assumptions guide investigation, but empirical observations drive learning



Stochastic is **manageable**. **Systematic** requires **structure**. **Linking** required **across lifecycle stages.**

Deviation Routing Replaces Isolated Modeling

Discussion

Implications

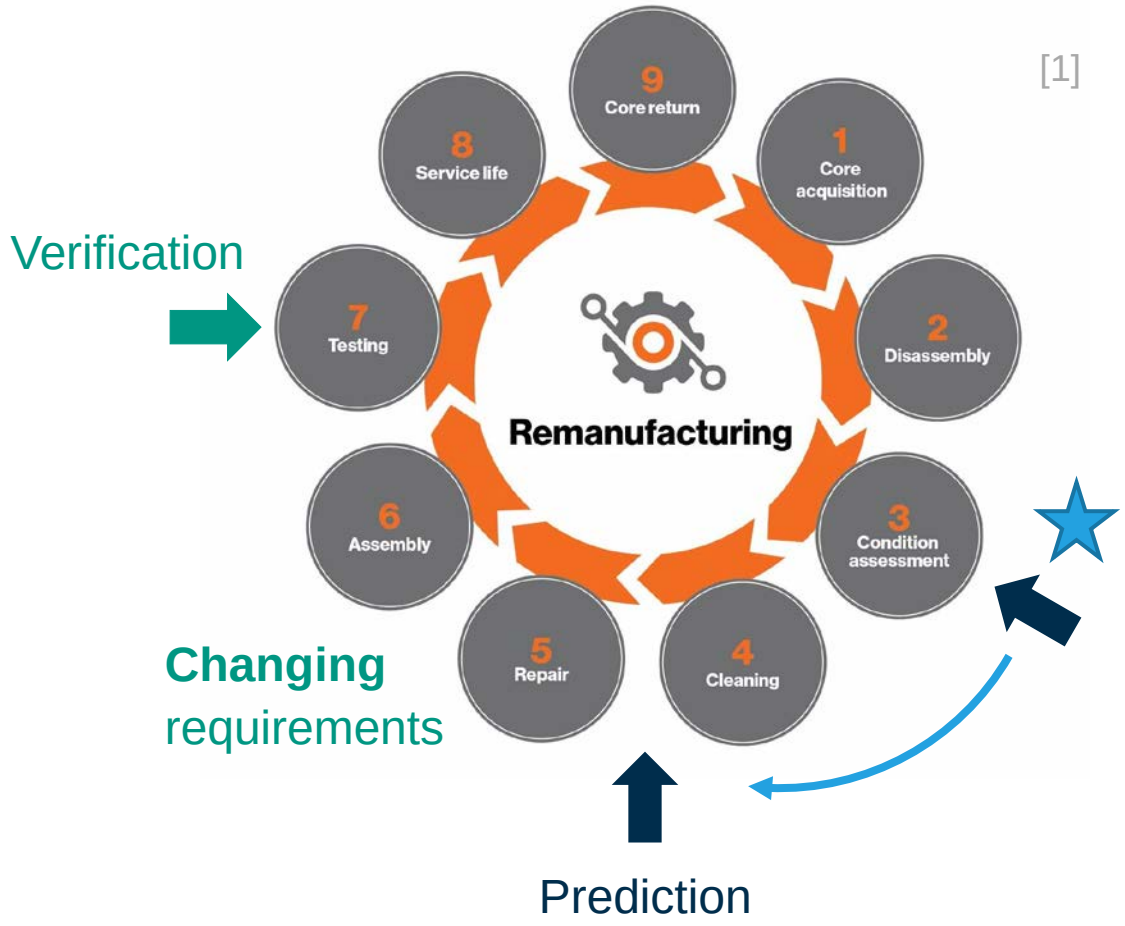
- Empirical observations must be triggered for learning
- Reuse decisions move upstream on instance level

Limitations

- No actual closed loop of lifecycle stages
- Individual case study on academic example

Outlook

- Application to other technical systems
- Bridge to data-driven prediction approaches



Stochastic deviations allow statistical correction.
Systematic deviations require structural model updates.
Coupled lifecycle effects demand linking across models.



Jonas Hemmerich

jonas.hemmerich@kit.edu

This research was funded by the German Research Foundation DFG in the collaborative research center 1574 “Circular Factory for the Perpetual Product” with the project ID 471687386.

[1] https://www.rit.edu/sustainabilityinstitute/blog/what-remanufacturing

[2] DOI: 10.5445/IR/1000185998

[3] https://www.linkedin.com/pulse/being-data-informed-data-driven-anton%C3%ADn-ku%C4%8Dera/

[4] DOI: 10.1109/RAMS.2004.1285476

[5] DOI: 10.1017/dsj.2024.48

[6] DOI: 10.1109/RAMS50514.2026.11424541

[7] DOI: 10.1016/j.procir.2014.03.129

IPEK – Institute of Product Engineering

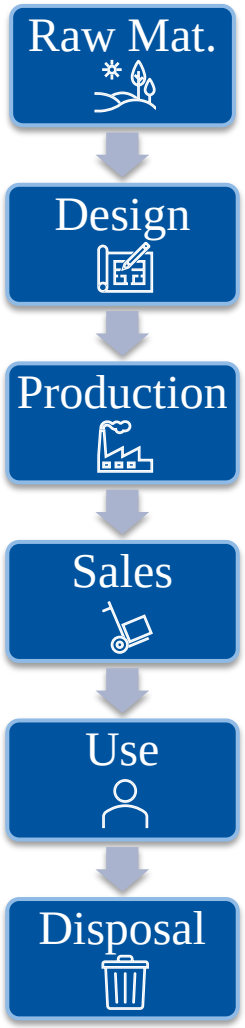


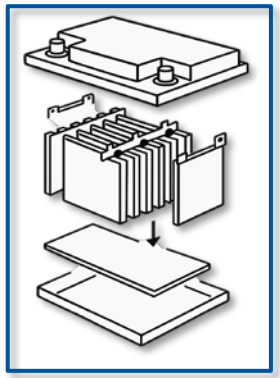
Data-driven decision support framework for the design of hybrid circular production systems

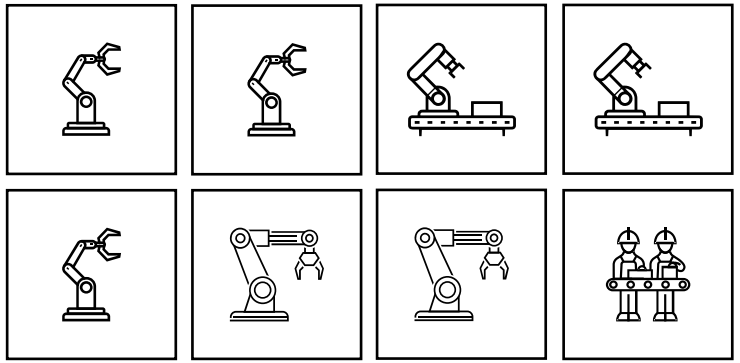
C. Weckendrup, S. Saeed, L. Bergs, A. Moriz and Prof. Dr.-Ing. Robert H. Schmitt

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Motivation



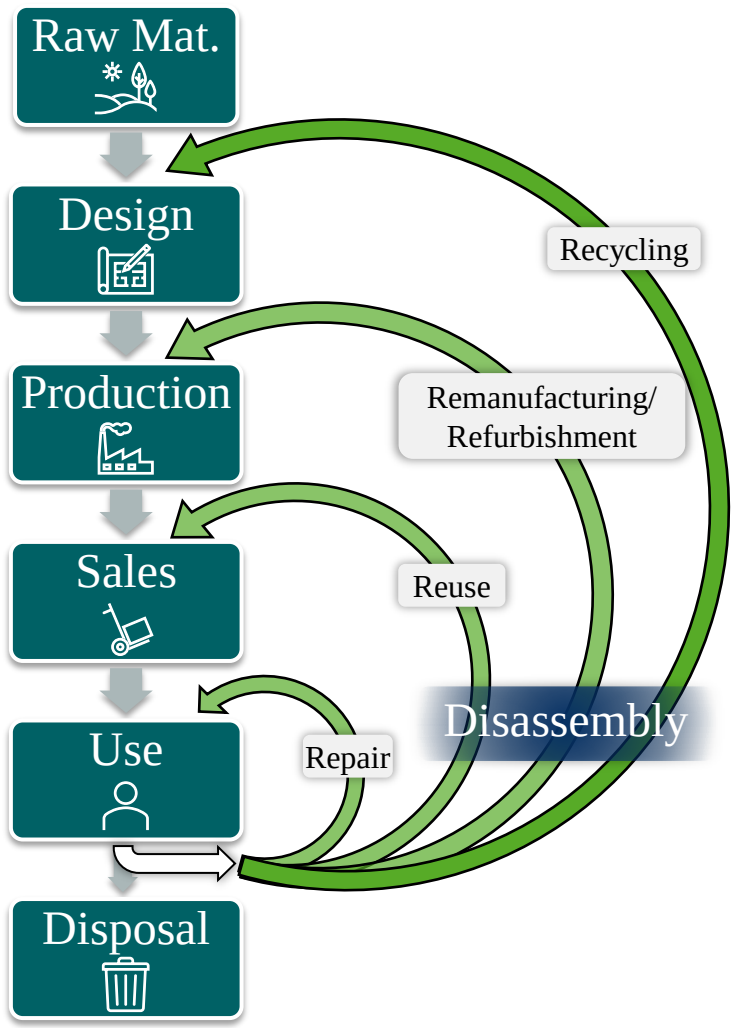




Decision Making Processes

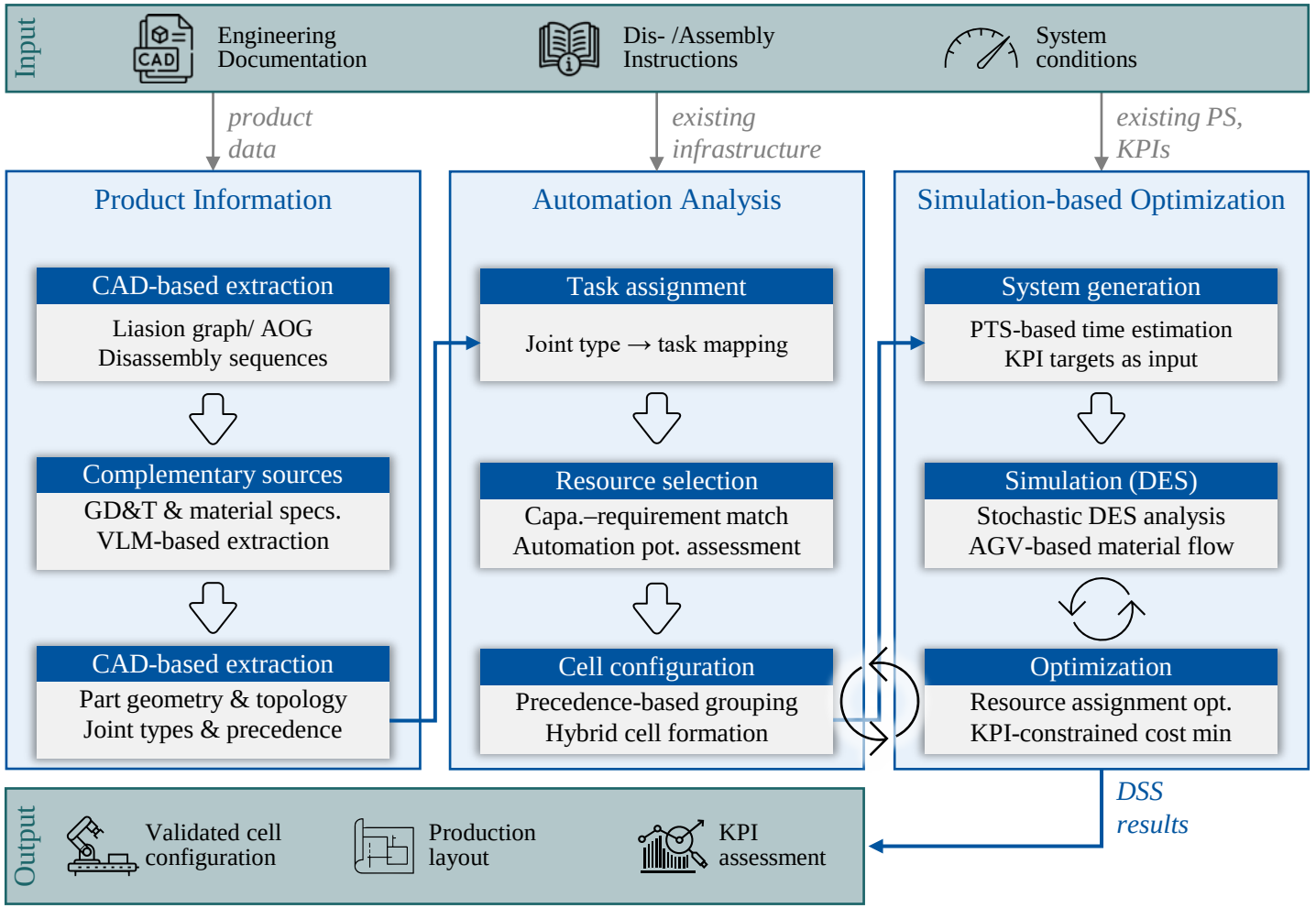
- Product (Re)Design
- Process Planning
- Resource Planning
- Structure Planning

Existing decision support systems for the design of hybrid circular production systems only consider isolated subproblems



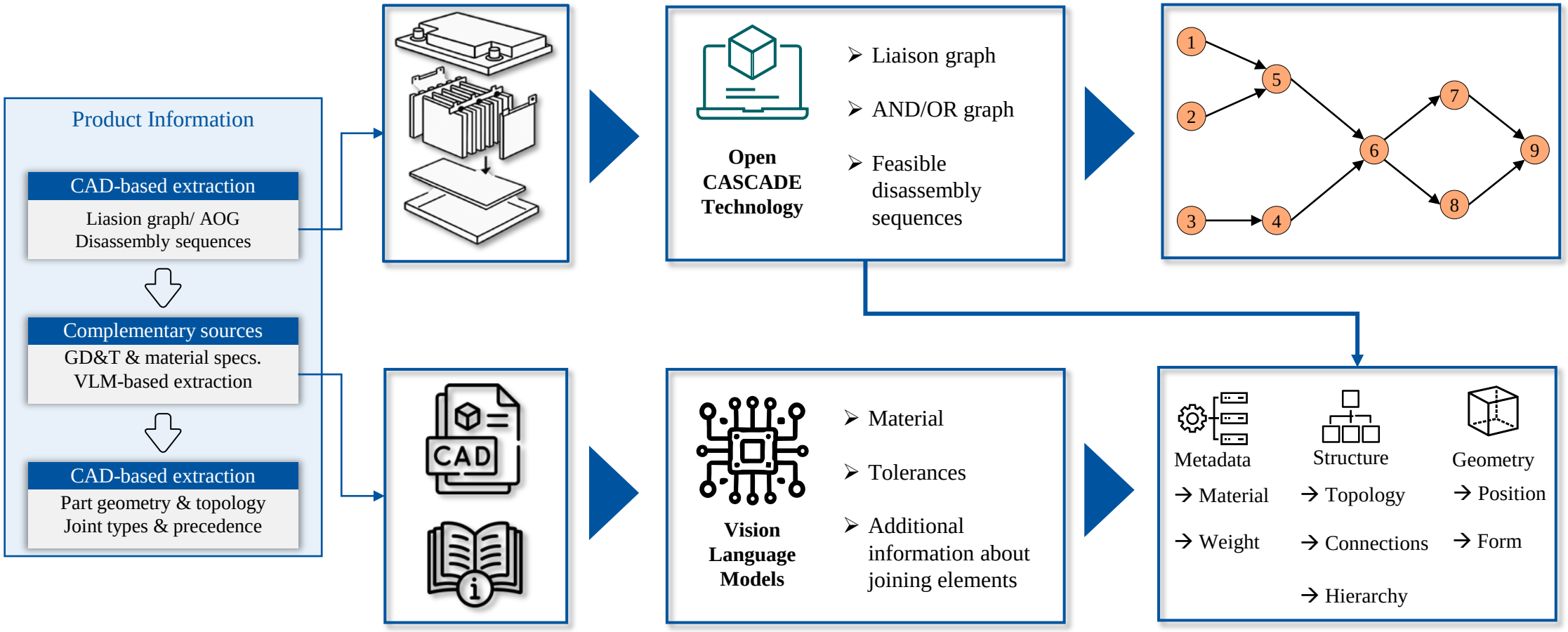
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Decision Support Framework
Overview



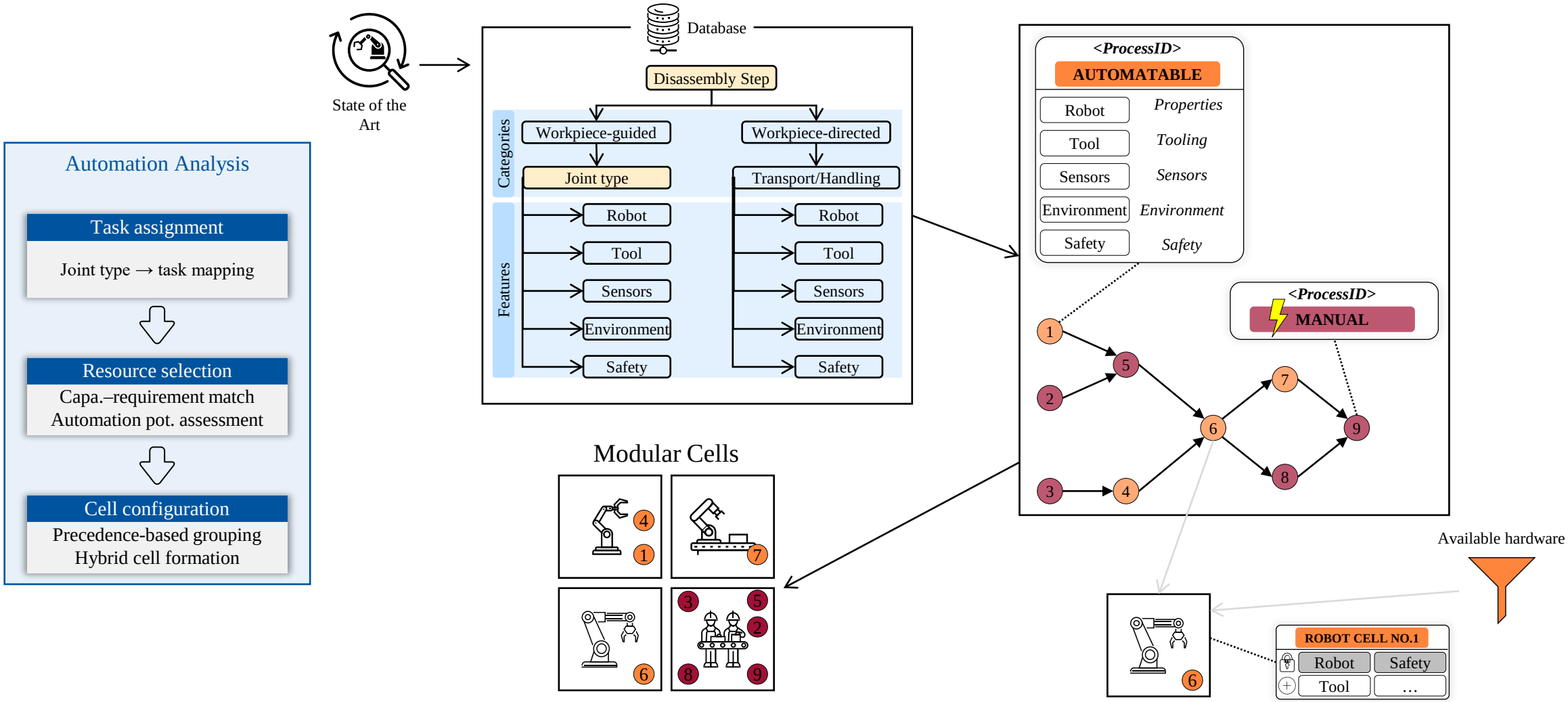
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Decision Support Framework
Stage 1: Product Information



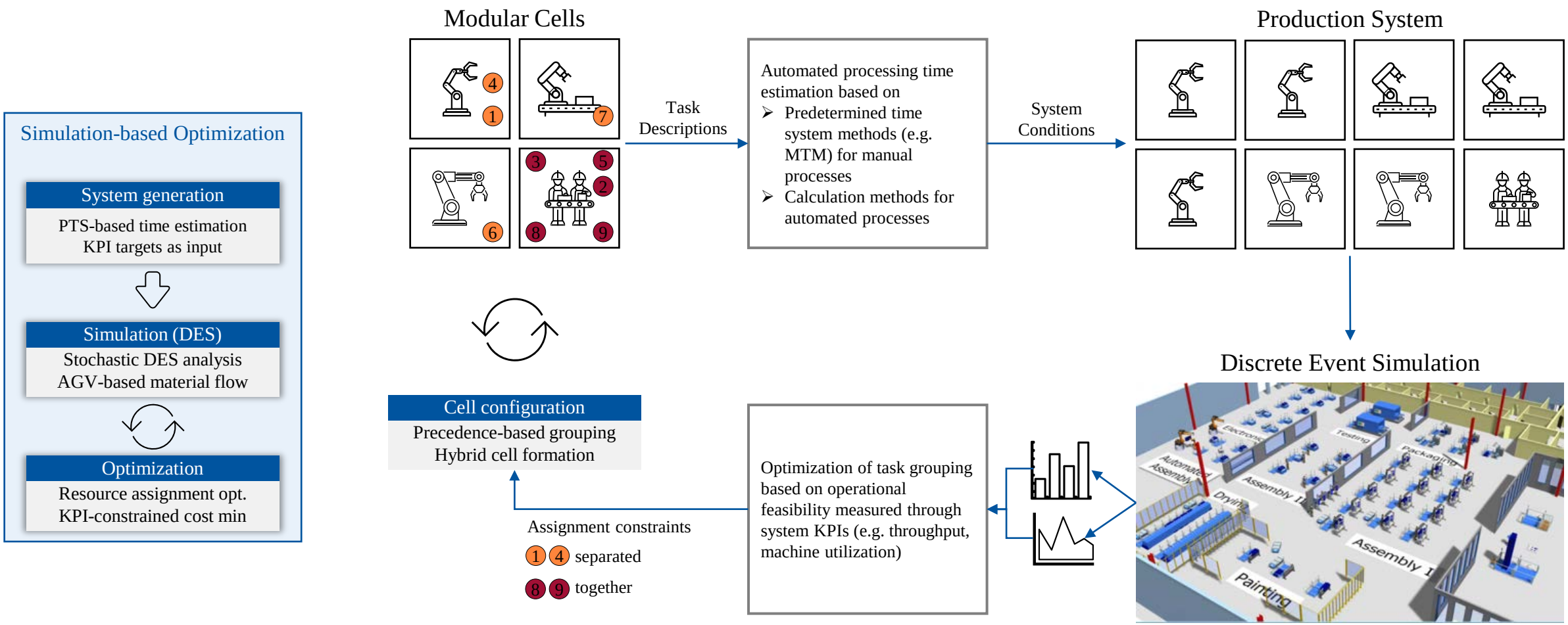
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Decision Support Framework
Stage 2: Automation Analysis



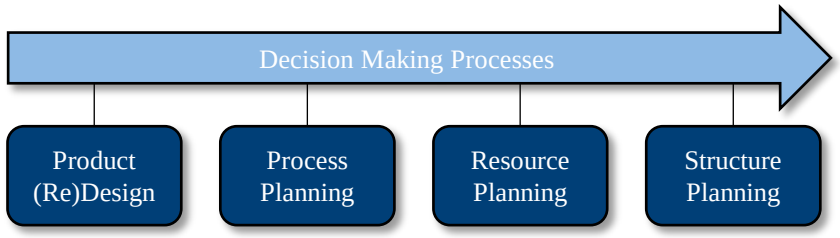
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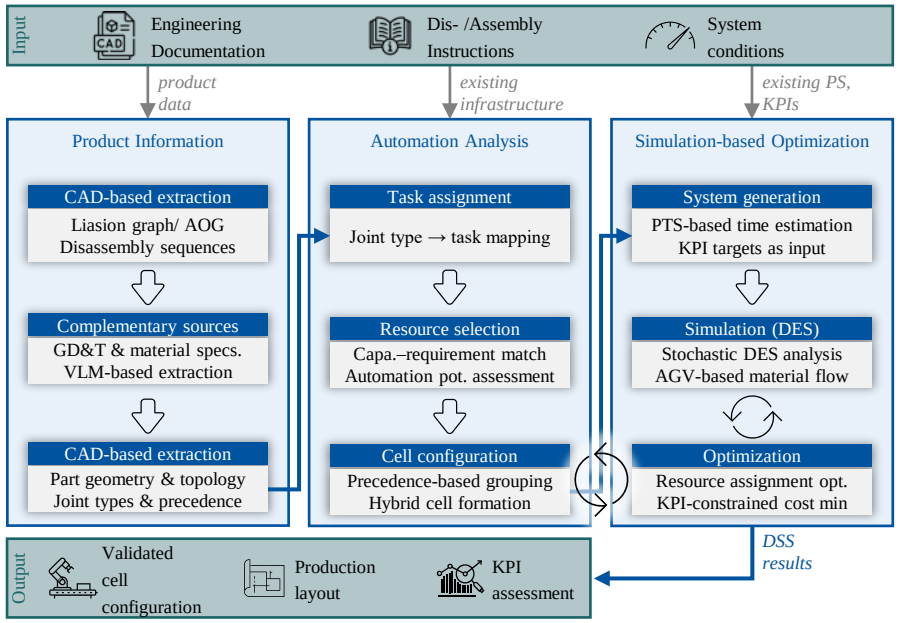
Decision Support Framework
Stage 3: Simulation-based Optimization



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Conclusion and Outlook





Usage

- Decision support for the design of hybrid circular production systems
- Potential analysis of circular production using currently available resources

Limitations

- Complete product data required
- Ontological database must be updated continously
- Processing time estimations do not fully capture condition dependence
- Optimization loop is subject to convergence limitations

Outlook

- Implementation of the framework
- Empirical validation through application to an industrial use case

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Thank You!

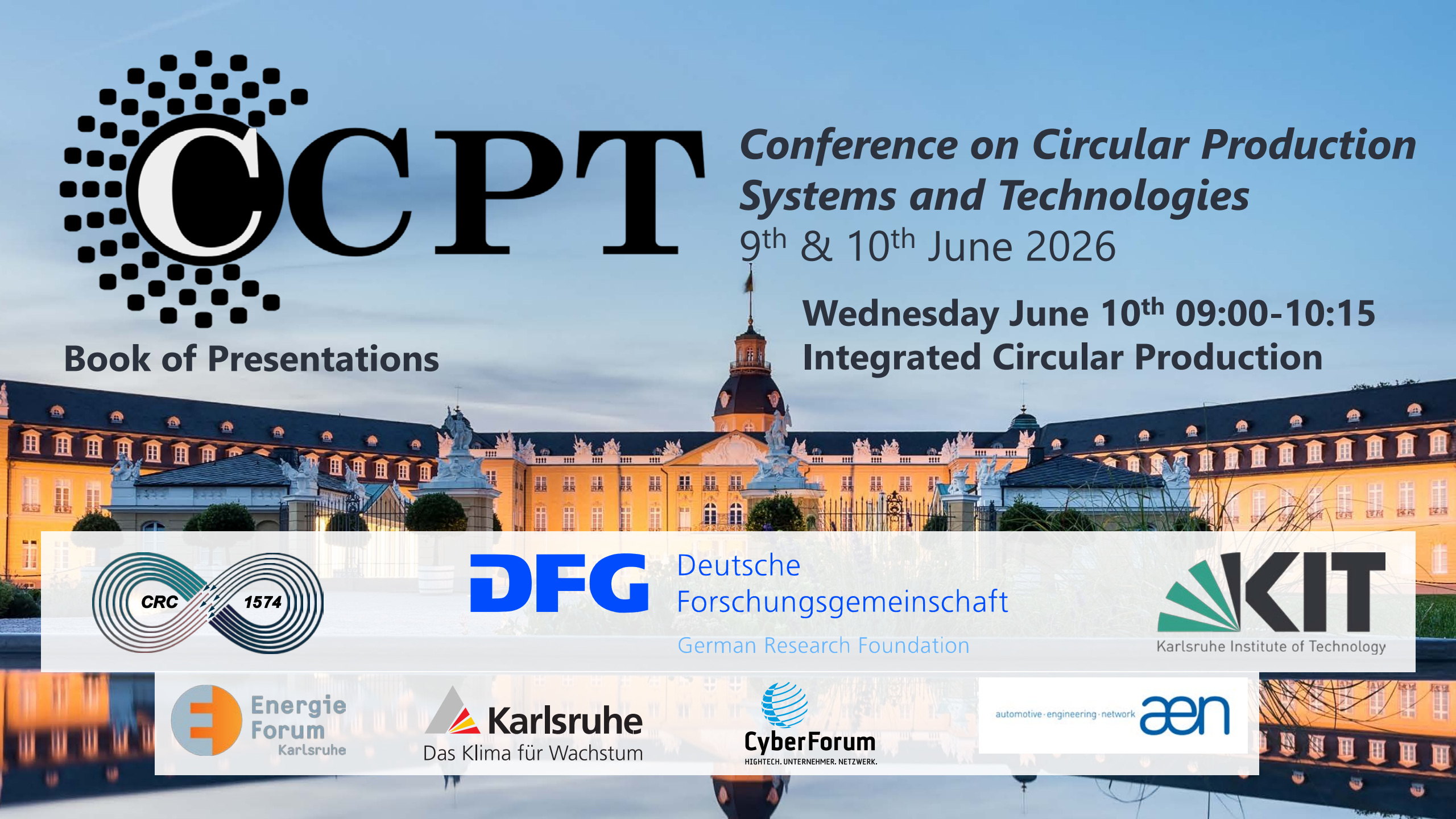
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CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 09:00-10:15
Integrated Circular Production

CRC 1574

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

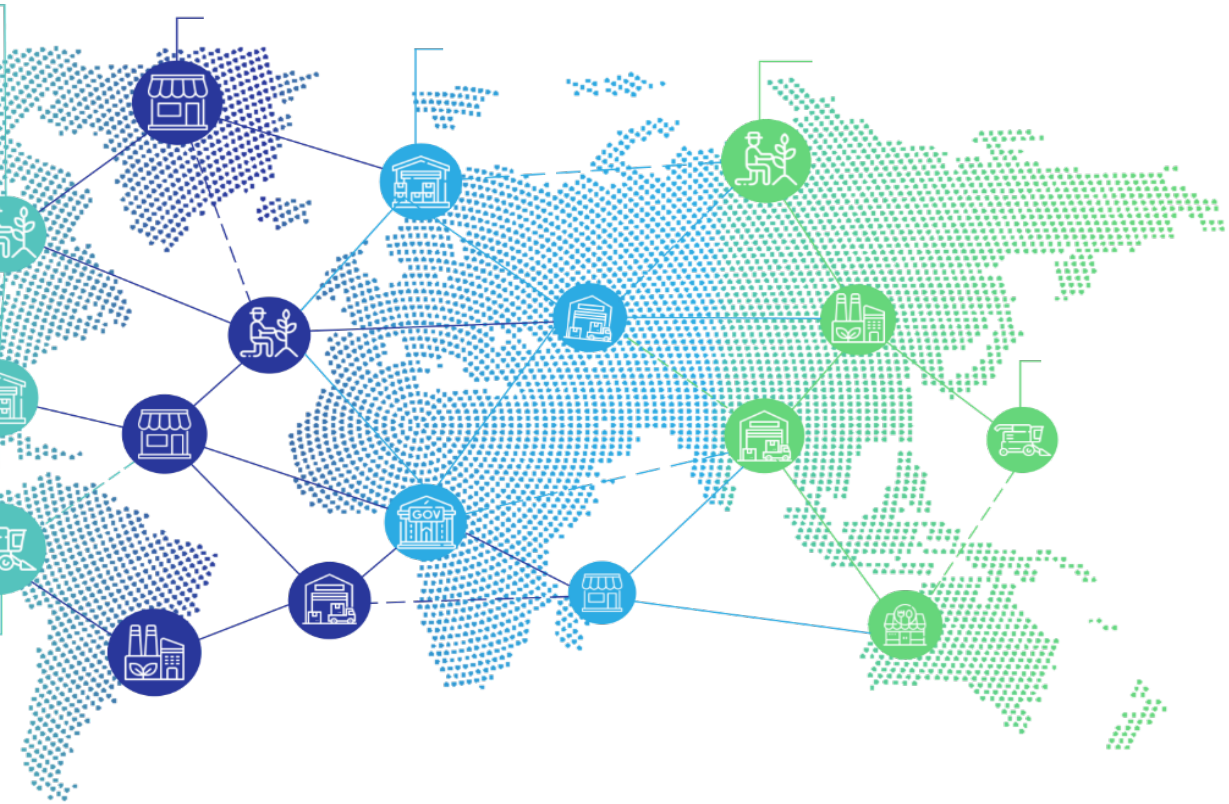
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Energie Forum Karlsruhe

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automotive · engineering · network aen



Role of Supply Chain Network Design on Circular Factory Concept

Themiya Kuruppuge**, Asela Kulatunga**, Martino Luis, Ion Voicu Sucala

ExeterDigital Enterprise Lab

University of Exeter, Exeter, UK

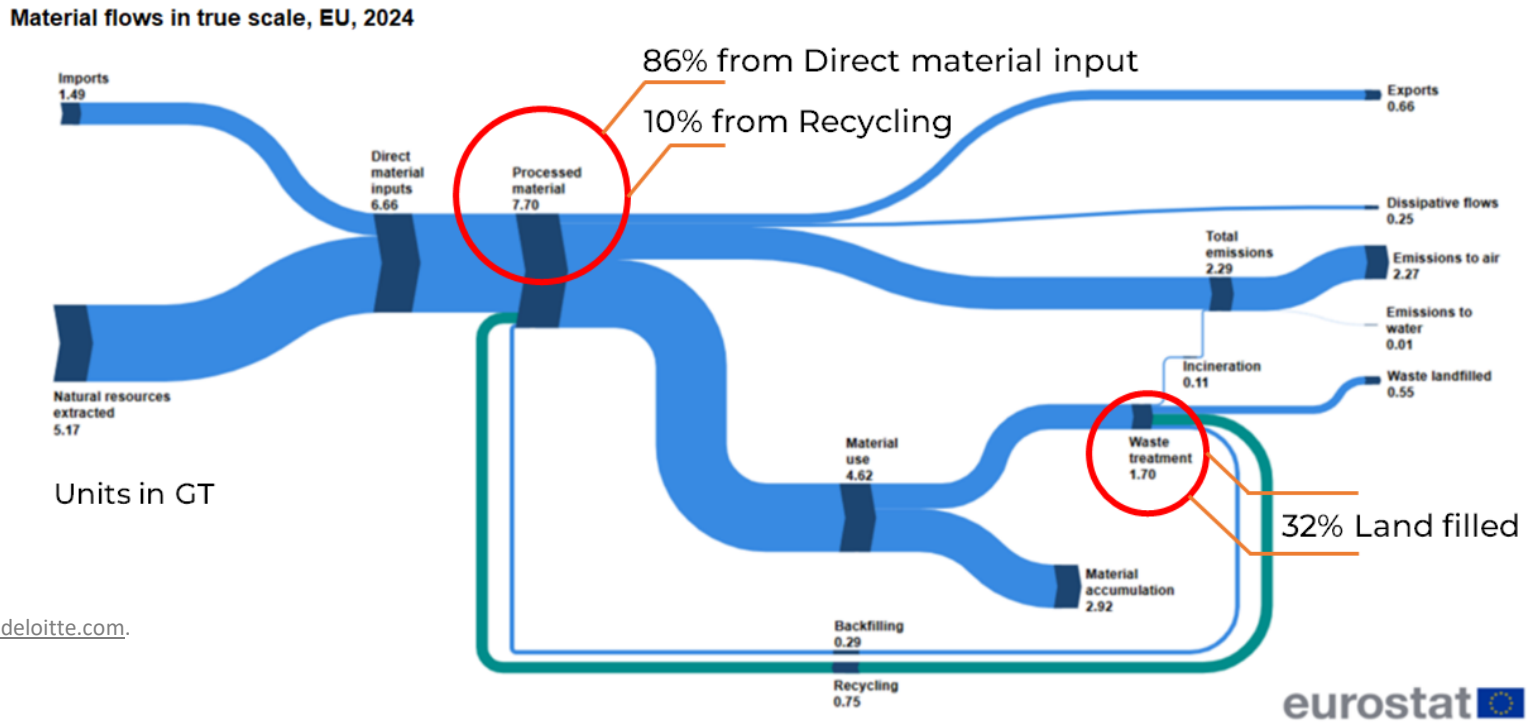
Introduction



In 2023, more than 90% of global materials were either lost during non-compliant recycling processes or disposed of through ineffective systems

Circle Economy Foundation, 2024, The Circularity Gap Report 2024. [Online]. Available: www.deloitte.com.

The linear **take-make-dispose** model is bleeding out our most valuable resources.



Material flows in true scale, EU, 2024

https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Circular_economy_-_material_flows

Introduction

Regulatory & industrial context

EU Ecodesign for Sustainable Products Regulation (2024) embeds circularity into product design, covering durability, reparability and recyclability

European Commission, 2024, "Directive on Repair of Goods." [Online]. Available: https://commission.europa.eu/law/law-topic/consumer-protection-law/directive-repair-goods_en.

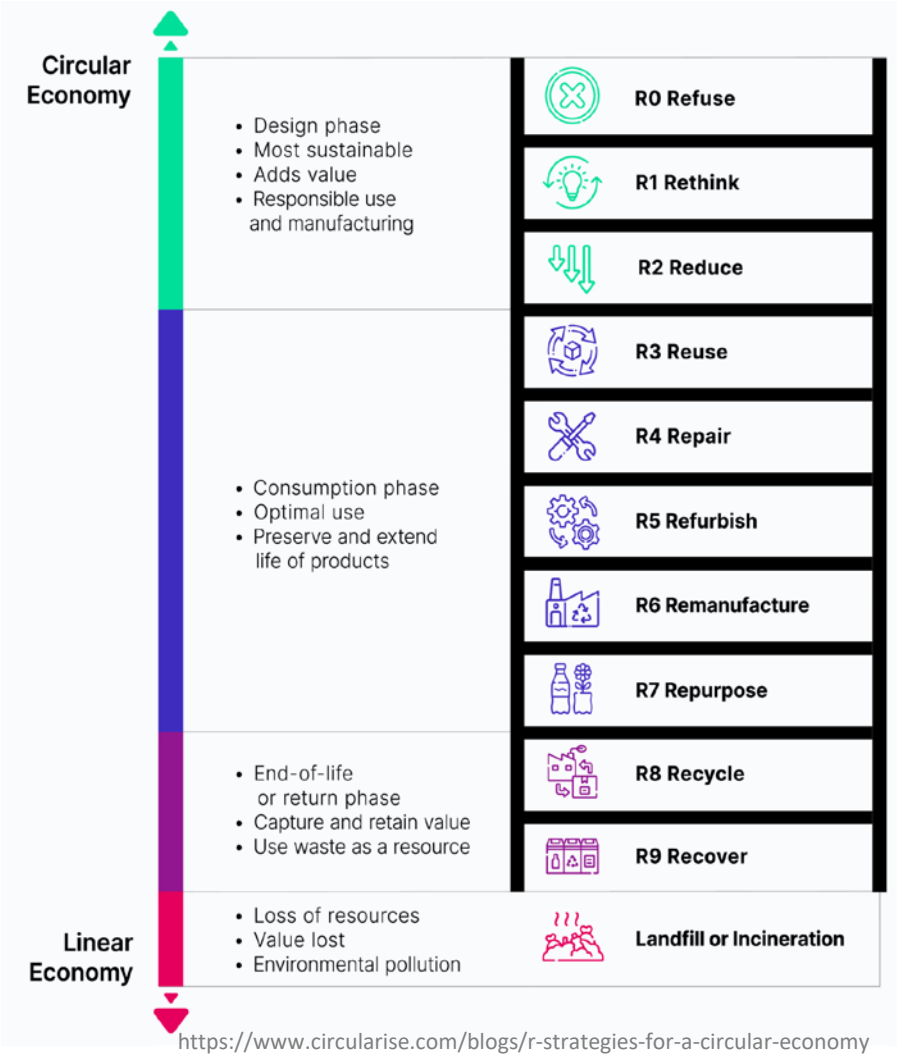
Geopolitical disruptions and critical material shortages have placed supply chain resilience at the top of industrial agendas

Circular factory

Closed-loop production system in which manufacturing, repair, remanufacturing, re-furbishment, and material recovery are all undertaken within a single, coordinated factory

Cerdas, F., Kurle, D., Andrew, S., Thiede, S., Herrmann, C., Zhiquan, Y., Jonathan, L. S. C., Bin, S., and Kara, S., 2015, "Defining Circulation Factories - A Pathway to-wards Factories of the Future," Procedia CIRP, Elsevier B.V., pp. 627–632. https://doi.org/10.1016/j.procir.2015.02.032

R-Strategies for a Circular Economy



https://www.circularise.com/blogs/r-strategies-for-a-circular-economy

The Research Gap

- Supply chain implications of integrated versus decentralised circular factory configurations remain underexplored.
- Decisions about facility placement made after capital is committed are costly to reverse, yet no structured framework connects these decisions to early-stage product and process design.

Research Objectives

01

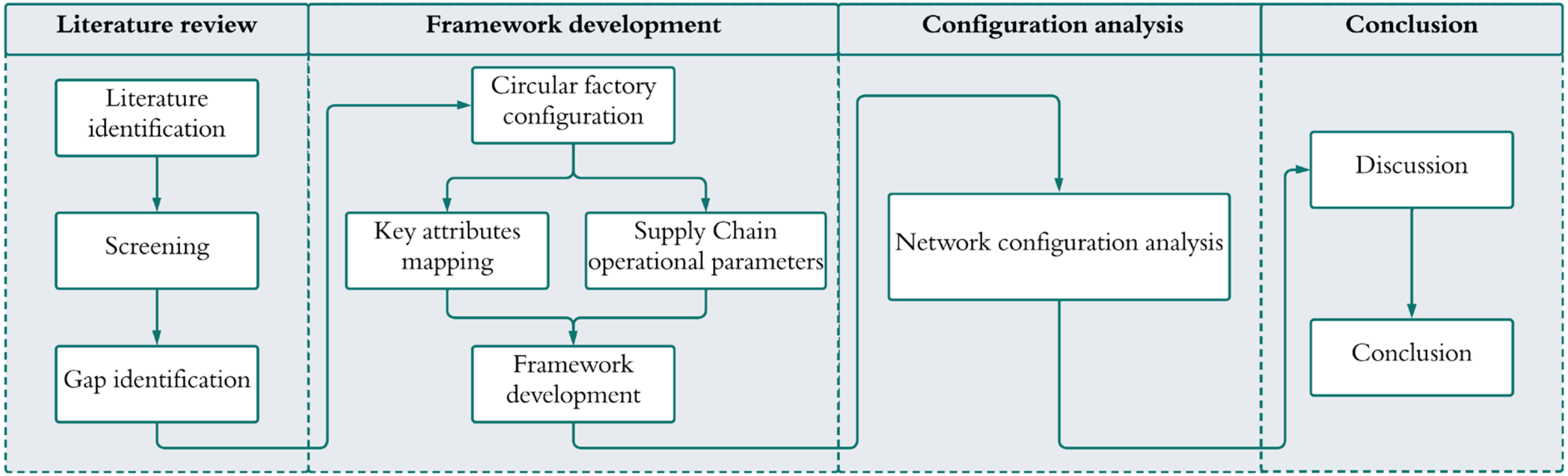
Examine how integrated and decentralised circular factory configurations differ from the SCND perspective, characterising each configuration across network input parameters and four recovery strategies: **repair, refurbishment, remanufacturing, and recycling**.

02

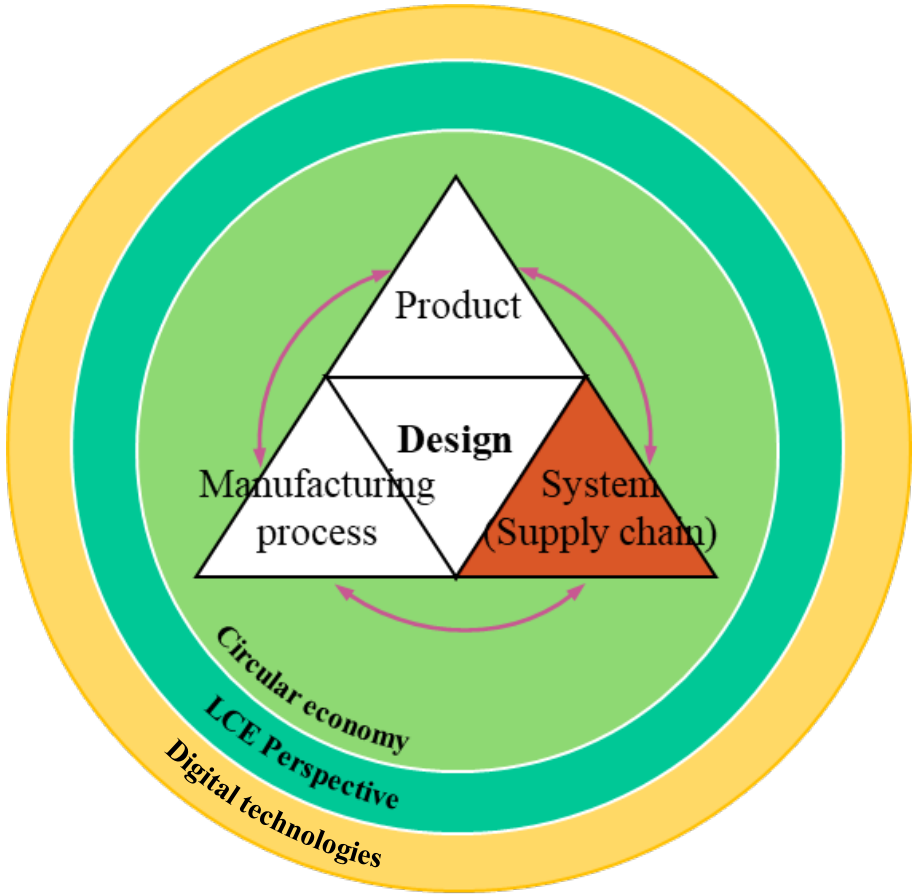
Propose a decision support framework linking circular factory configuration selection to early-stage product, process, and supply chain network design decisions, evaluated against economic, environmental, and social performance dimensions.

SCND: Supply chain network design

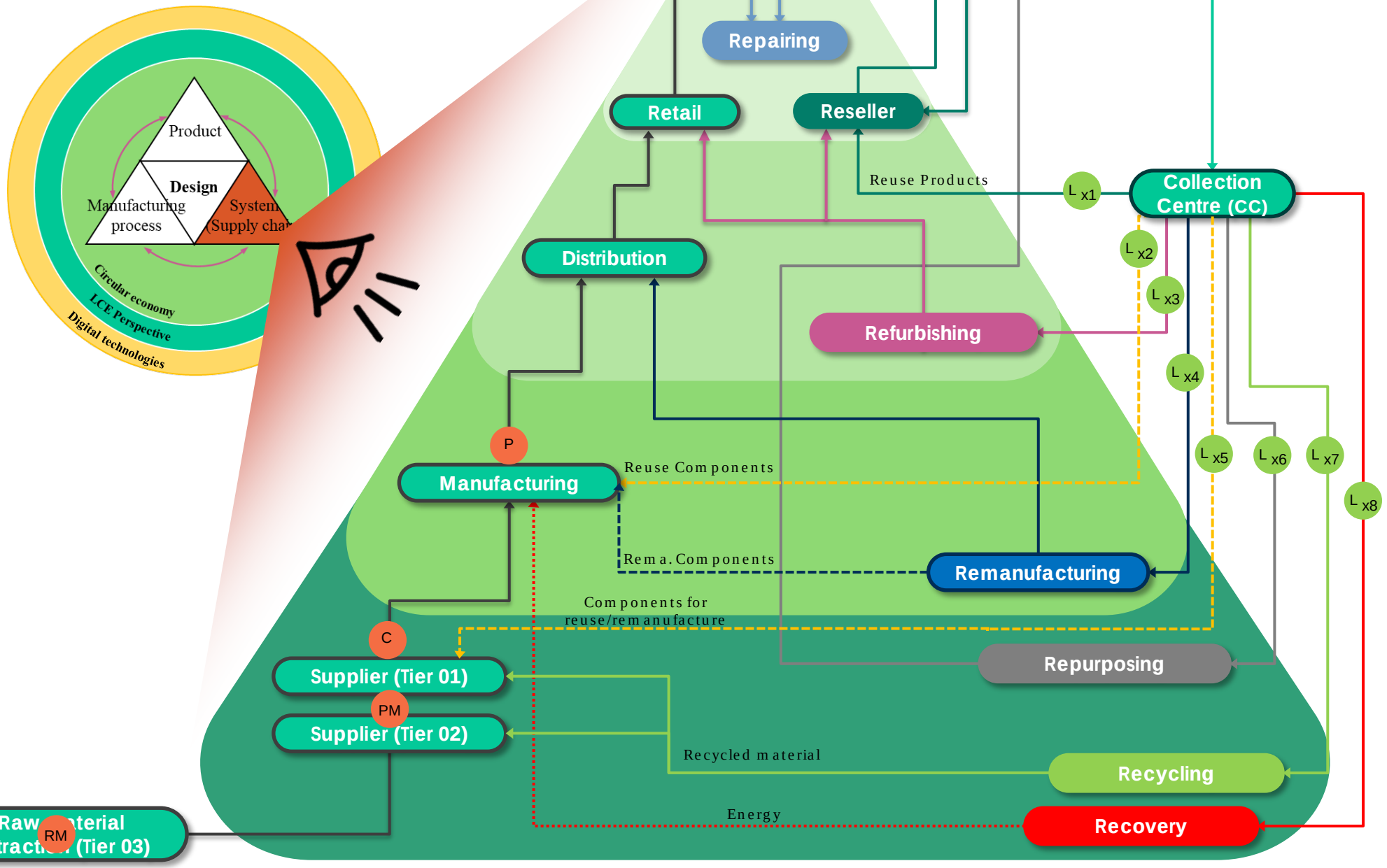
Research Methodology



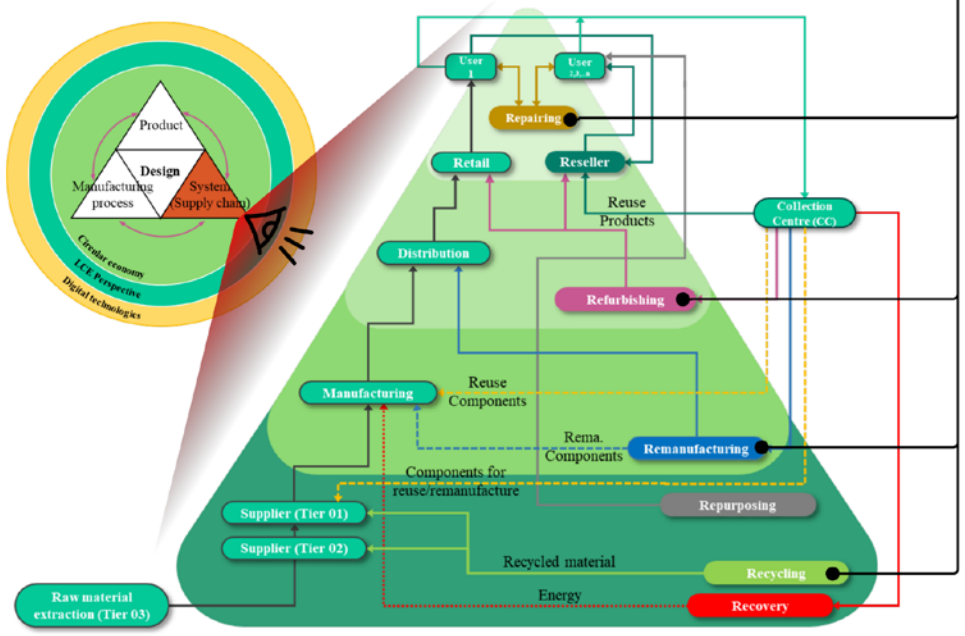
Proposed Framework

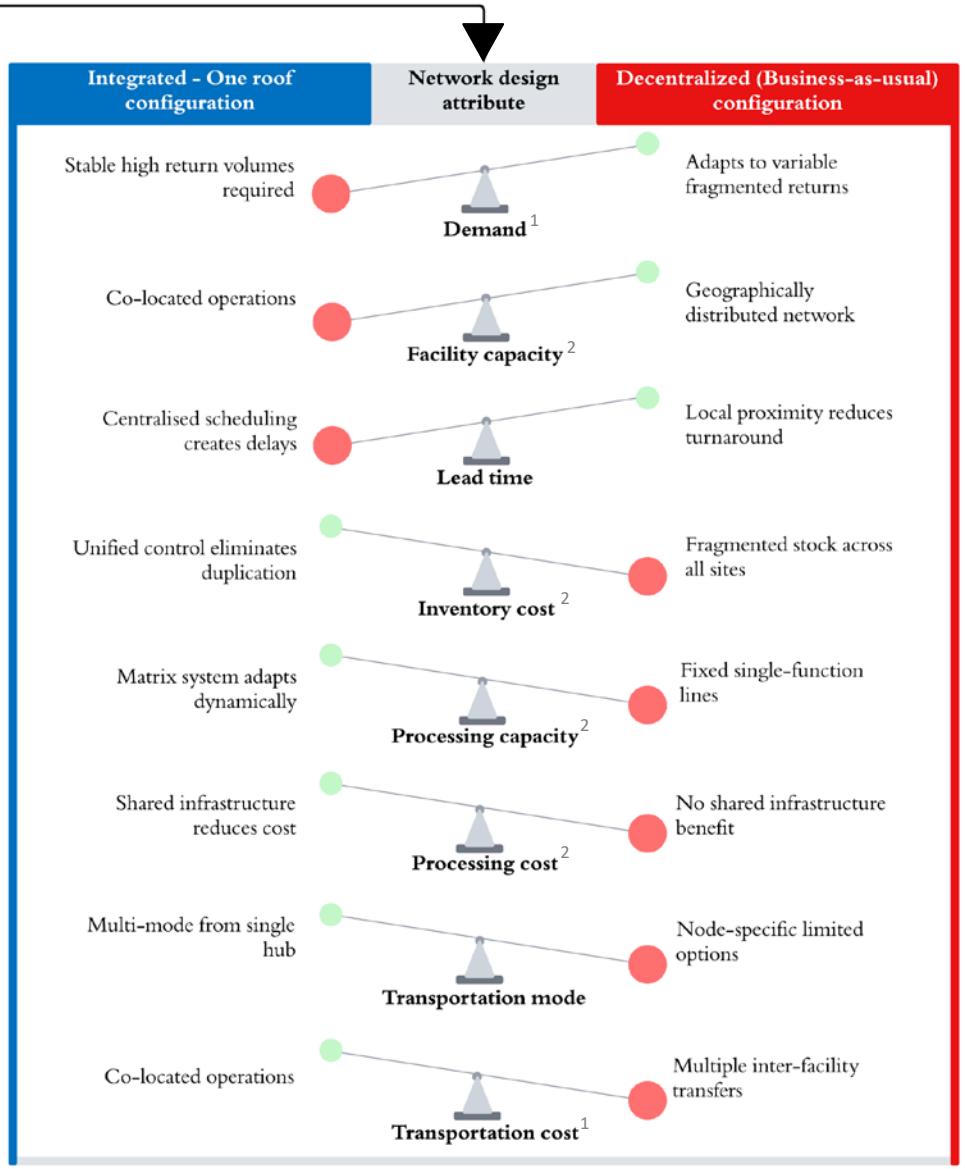


Proposed Framework



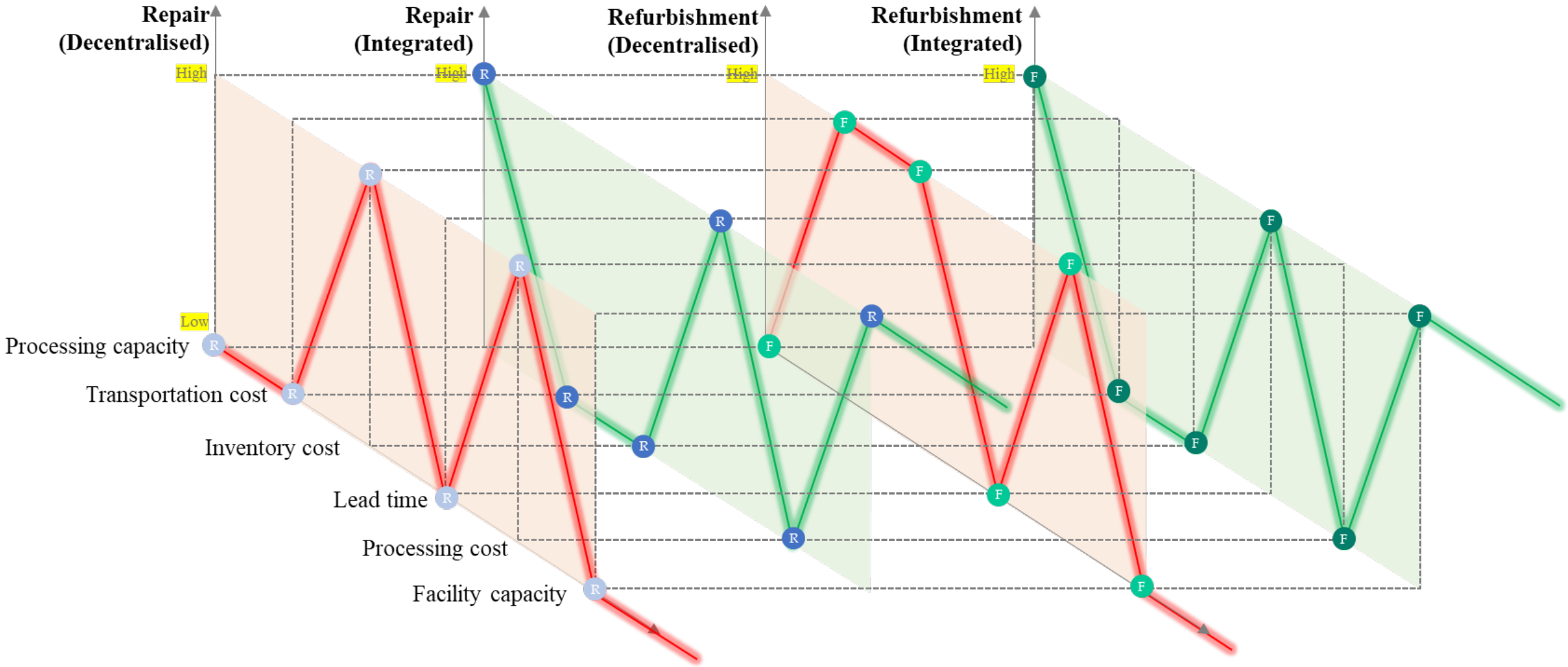
Proposed Framework





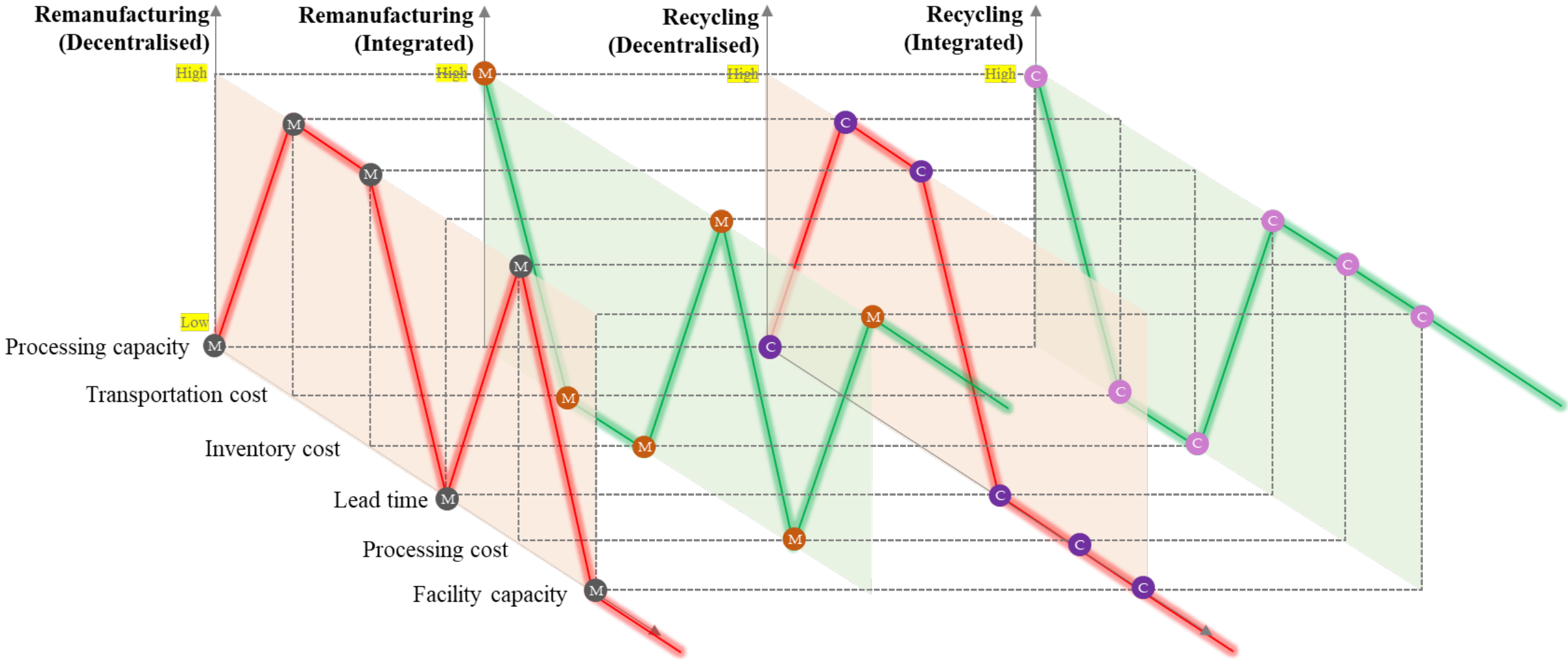
1. Salehi, N., Amir, S., Roci, M., Shoaib-ul-Hasan, S., Asif, F. M. A., Mihelič, A., Sweet, S., and Rashid, A., 2024, "Towards Circular Manufacturing Systems Implementation: An Integrated Analysis Framework for Circular Supply Chains," Sustain. Prod. Con-sum., 51, pp. 169–198. https://doi.org/10.1016/j.spc.2024.09.008.
2. Cerdas, F., Kurle, D., Andrew, S., Thiede, S., Herrmann, C., Zhiquan, Y., Jonathan, L. S. C., Bin, S., and Kara, S., 2015, "Defining Circulation Factories - A Pathway to-wards Factories of the Future," Procedia CIRP, Elsevier B.V., pp. 627–632. https://doi.org/10.1016/j.procir.2015.02.032.

SCND Implications for Circular Factory Configurations



SCND: Supply chain network design

SCND Implications for Circular Factory Configurations



SCND: Supply chain network design

Key Findings

01

Integrated model delivers consistent advantages in processing, inventory, and transportation costs through shared infrastructure and unified inventory control.

02

Decentralised model retains advantages in lead time and transport cost for customer-facing, short-loop recovery strategies such as repair.

03

Some parameters (logistics cost and processing cost) are determined by the recovery operation itself rather than by network structure, and the decision to adopt an integrated or decentralised configuration must be conditioned on which recovery strategies dominate a given product's return profile.

Conclusion

Limitations
Conceptual framework Organisational factors excluded

Future work
Run integrated vs decentralised GFA in AnyLogistix to evaluate economic, environmental and social KPIs Apply framework to selected industrial product category using real flow data

The integrated model delivers advantages across all three sustainability dimensions.

- **Economic:** Reduced processing cost, inventory cost and transportation cost through shared infrastructure
- **Environmental:** Fewer inter-facility transport and direct component reutilisation, reducing GWP and material waste across recovery cycles
- **Social:** Improved service levels and faster recovery cycle times enabled by co-located operations

GFA: Green field analysis

Thank you for your attention



a.k.Kulatunga@exeter.ac.uk



An AAS-based Semantic Digital Infrastructure for Decision Support in Circular Manufacturing

Dimosthenopoulos Dimosthenis

on behalf of the authors team: ***A. C. Bavelos,[1] D. Dimosthenopoulos[2], R. Santos,[3] C. Gkournelos[2], E. Xanthakis,[1] R. Bröchler[1] and S. Makris[2]***

[1] Netcompany, rue Nicolas Bove, Luxembourg, 1253, Luxembourg

[2] Laboratory for Manufacturing Systems & Automation, University of Patras, Greece

[3] Institute for Systems and Computer Engineering, Technology and Science, Rua Dr. Roberto Frias, Porto, 4200-465, Portugal

LMS Laboratory for Manufacturing Systems & Automation

Agenda

Introduction & Challenge

Proposed Framework & Architecture

PPR-aligned AAS Taxonomy

Dynamic Lifecycle Management

Infrastructure & Interaction Scheme

Case Study

Conclusions & Future work

The Challenge: From Linear to Circular Manufacturing

Why a new digital infrastructure?

High Variability

Uncertain return timing and product condition

Fragmented Data

Lifecycle data fragmented across enterprise systems

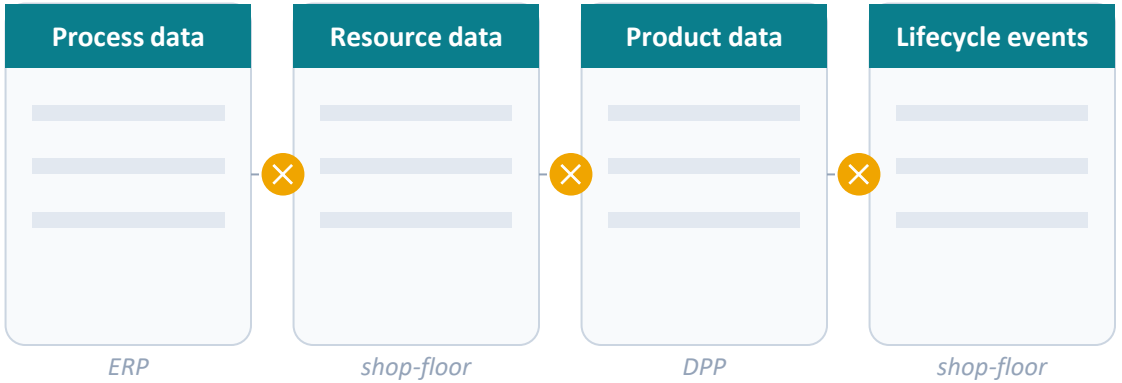
Static Digital Twins

Existing AAS implementations remain static at runtime

Missing Integration

No runtime link between enterprise and operational control systems

Today: Enterprise/Operational/Lifecycle data lives in disconnected silos



No live runtime exchange — each system holds its own truth

The gap: Static AAS cannot synchronize at runtime
products · resources · operational states

Need for continuously synchronized semantic assets

Proposed Framework: AAS-based Digital Vault

Four layered contributions

Layered Semantic Architecture

AAS-based modelling + configurable semantic mapping pipeline

Dynamic Lifecycle Updates

Proactive AAS Environment: continuous sync between physical assets and digital counterparts

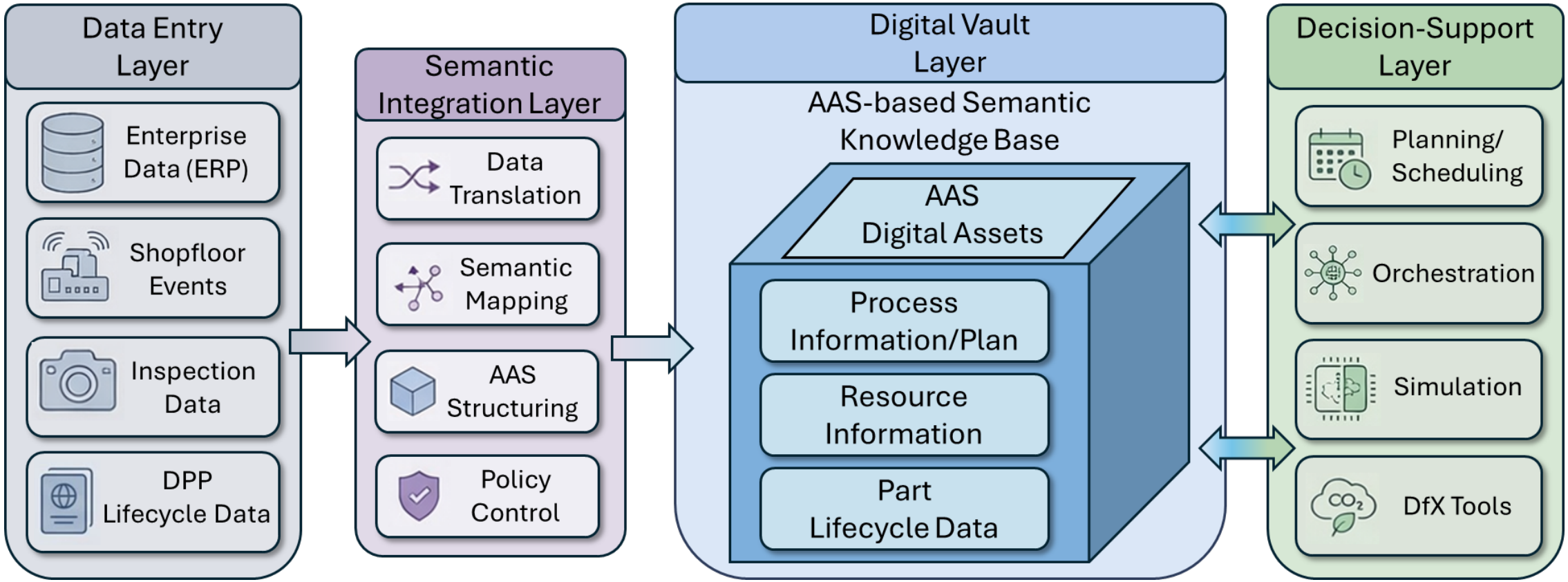
PPR-aligned AAS Taxonomy

ProductType/Instance twins, hierarchical resources & process entities with Catena-X DPP submodels

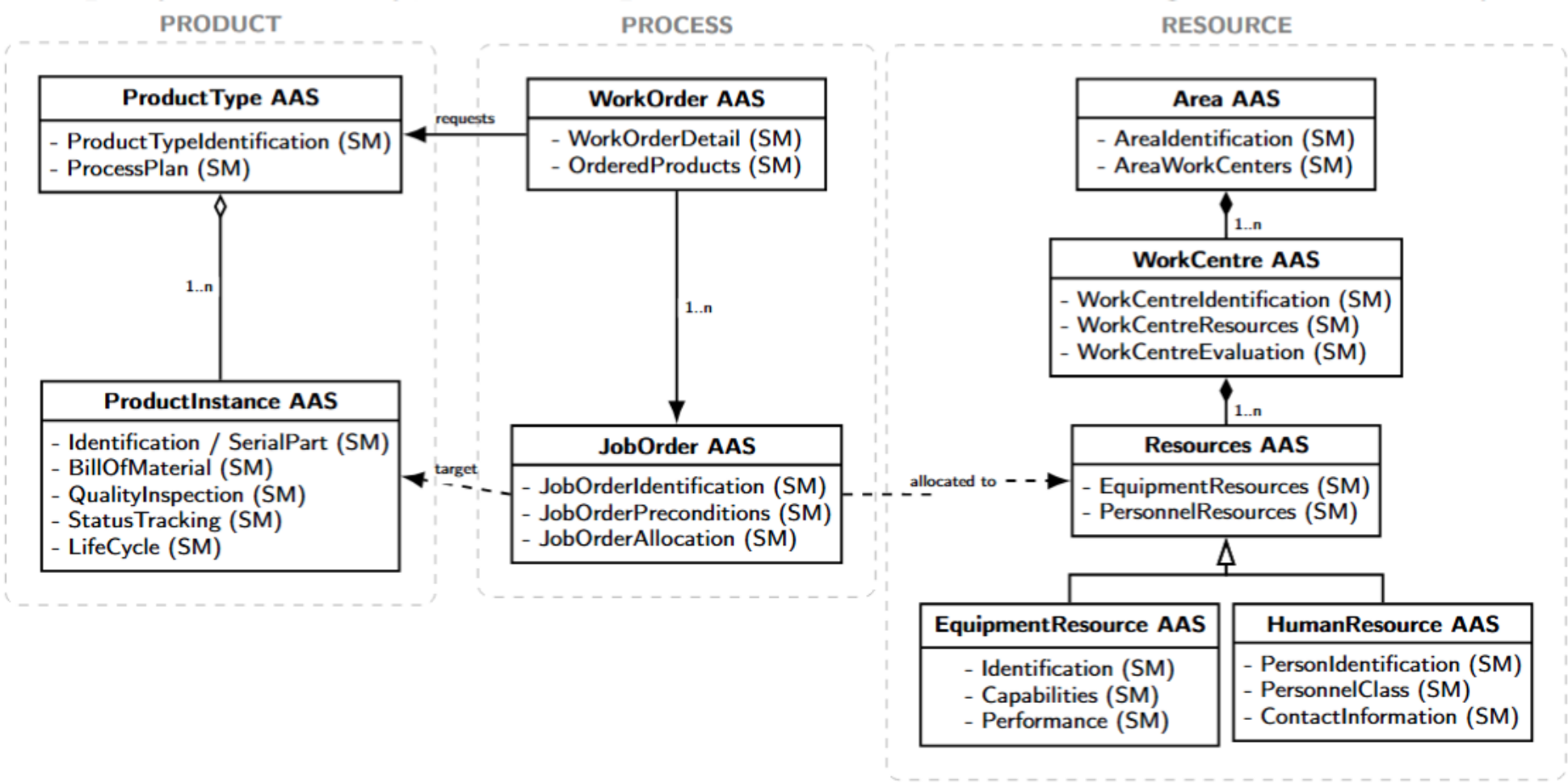
Validated Case Study

Household-appliance remanufacturing (EoL refrigerator disassembly)

System Architecture: Four-Layer Design



PPR-Aligned AAS Taxonomy



Dynamic Lifecycle Management

Static AAS offline engineering description → **Type 2** event-driven updates → **Type 3** proactive monitoring & autonomous reactions

TYPE 2 — Event-Driven Update

- **Sources (active):** ERP order updates → AAS submodel write; shopfloor monitoring signals → resource status patches
- **Mechanism:** per-source AI agent does relevance assessment, normalisation, and routing; targeted PATCH to individual submodel elements; no full asset re-ingestion
- **Result:** digital representations stay consistent with physical counterparts

TYPE 3 — Proactive AAS Environment

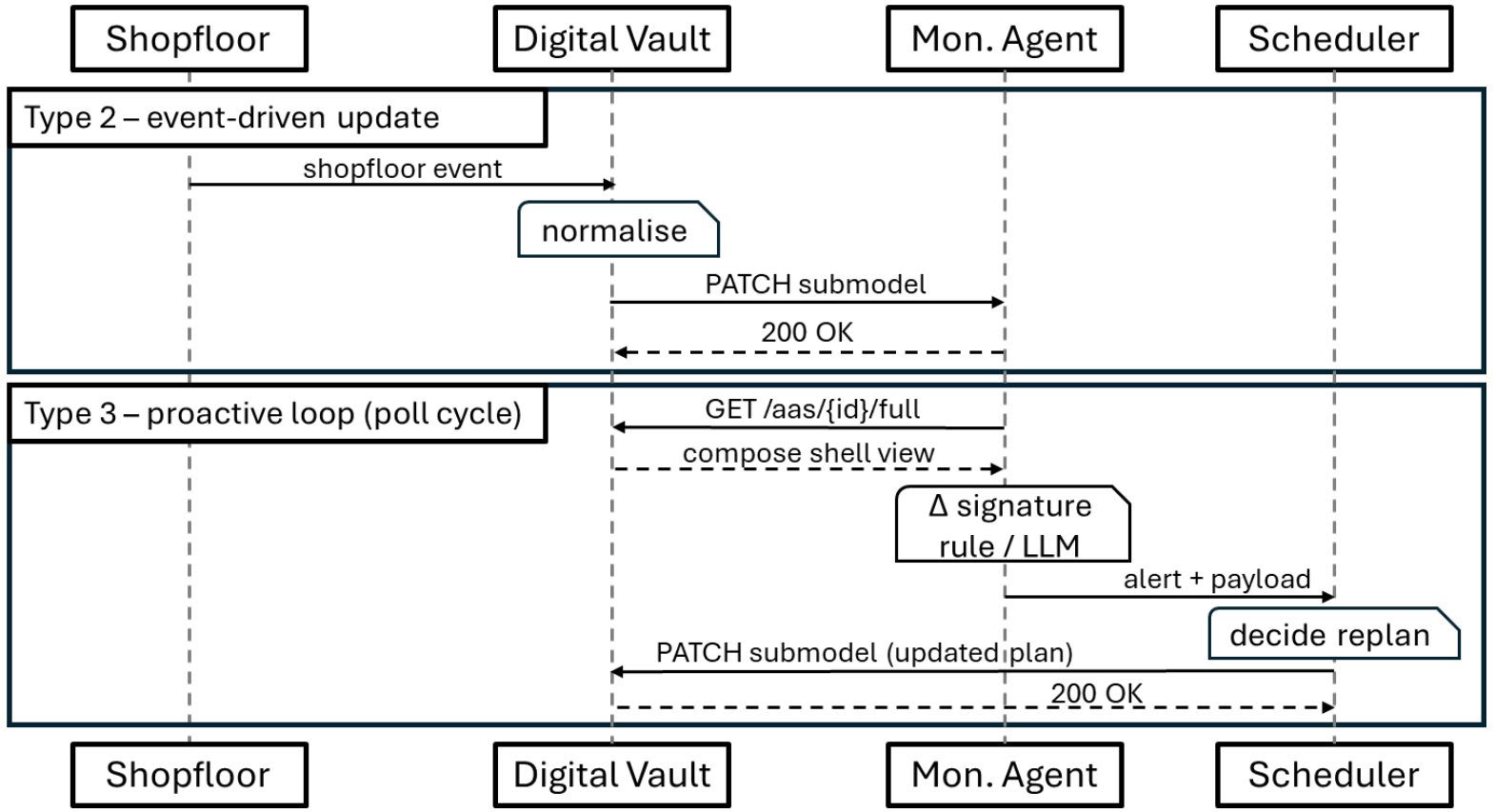
- **Polling agents:** agent polls composed shell every N s; computes structural signature → detects any submodel change; threshold alerts on transition
- **LLM-assisted enrichment:** shell payload + domain prompt → typed alert/resolution events

The closed loop: Signal → Scheduler → updated plan PATCH → DV

Digital Vault Infrastructure & Interaction Scheme

Persistence & Service Layer

- **MongoDB** — 3 collections: assetAdministrationShells · submodels · conceptDescriptions
- **Storage** — shell and submodel records stored separately, linked via explicit references
- **Authenticated API** — guided input + direct JSON ingestion
- **On retrieval** — referenced submodels resolved into composed view
- **Bidirectional** — external modules (planning, scheduling) read AND write



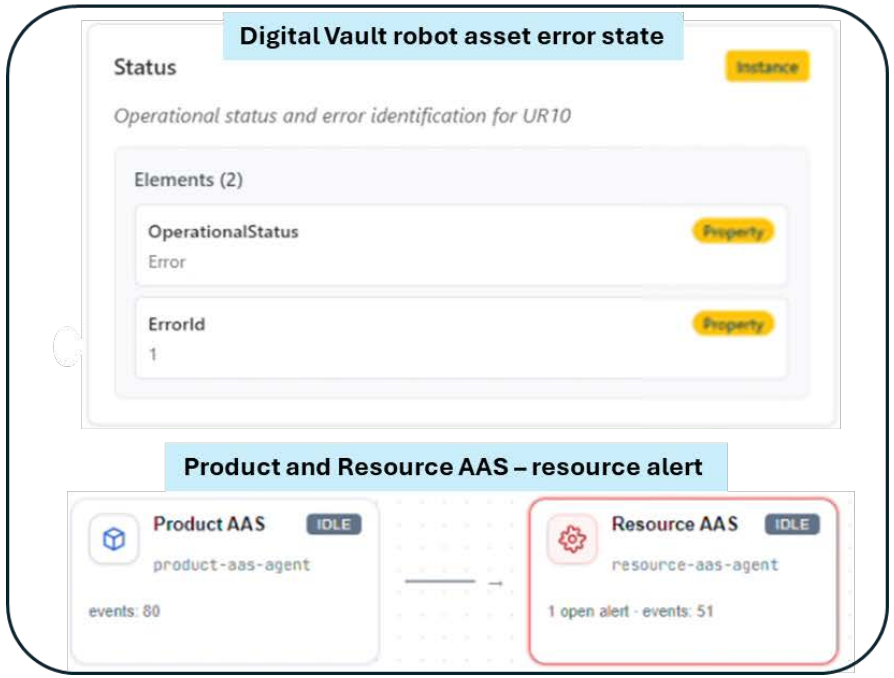
Case Study: EoL Refrigerator Disassembly

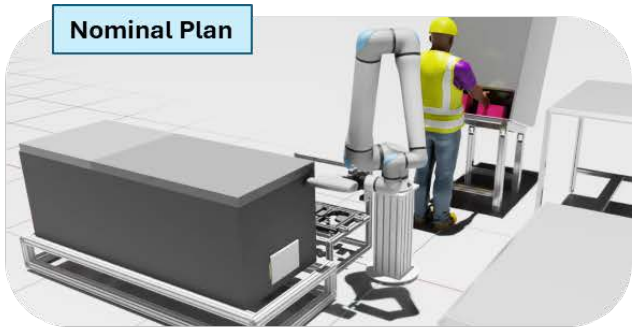
Setup & Deployment

- High variability: damage, missing parts, undocumented modifications
- Full AAS taxonomy instantiated per incoming refrigerator unit
- ProductInstance ← Catena-X identification + lifecycle submodels
- WorkOrder/JobOrder AASs generated from ERP via LLM mapping pipeline
- EquipmentResource + HumanResource shells maintained in real time

Proactive Monitoring Test

- Scenario: robot–human disassembly operated in simulation
- Fault injection: OperationalStatus → Error at N random snapshots
- Metric: interval from vault update to first proactive alert (operational_status_error)
- All deliberate fault injections detected under stable polling conditions







Key Result

Scheduler successfully reassigned tasks to available resources in response to monitoring alerts

Conclusions & Future work

The benefits of the proposed framework:

- AAS-based DV closes the static-twin gap — structural interoperability with runtime-responsive intelligence
- PPR-aligned taxonomy (ISA-95 + Catena-X) — coherent semantics across product, process, and resource
- Type 2 + Type 3 loop enables proactive replanning from shopfloor signals, without full re-ingestion
- Validated on EoL refrigerator disassembly: data ingested, representations synchronised, fault-driven re-scheduling demonstrated

Future work

- Predictive maintenance: exploit equipment performance data in the monitoring layer
- Extend monitoring to human resource performance and end-to-end product traceability
- Scale up and validate in large-scale industrial environments

Acknowledgements



Flexible Remanufacturing Using AI and Advanced Robotics for Circular Value Chains in EU Industry

https://renee-project.eu/

Project Coordinator
Laboratory for Manufacturing Systems and Automation (LMS)
E-Mail:
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This research has been supported by the European project "RENÉE – Flexible Remanufacturing using AI and advanced Robotics for Circular Value Chains in EU Industry" (Grand Agreement: 101138415) (https://www.renee-project.eu/) funded by the EC.

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….

Thank you!

An AAS-based Semantic Digital Infrastructure for Decision Support in Circular Manufacturing

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Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

Karlsruhe Institute of Technology

Classification of Disruptions in Remanufacturing Systems

Matthieu Poyer, Jan Baumgärtner, Helena Wexel, Aleksandar Taranovic, Finn Bail, Dominik Koch, Maurice Engels, Jens Becker, Julius Pfrommer, Nicole Stricker, Jürgen Fleischer, Frederik Zanger, Gerhard Neumann3 and Gisela Lanza

The Case for Unavoidable Disruptions in Remanufacturing

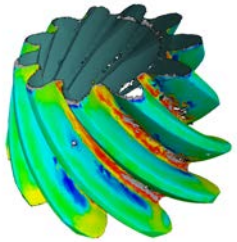
The Karlsruhe Circular Factory

- Physical Circular Factory Setup
  - Central research subject and demonstrator of the DFG CRC 1574
- *Automated Remanufacturing* Steps and *Automated Material Handling*
  - Visual Inspection
  - Ponticon for Additive Manufacturing
  - AGV + Robotic Manipulation
- Angle Grinder Example Product Family

Considered Product for Remanufacturing: Angle Grinder



Incomplete optical measurement of a helical gear



Tooth flank damage: pitting and surface degradation



Unavoidable Disruptions

Traditional Manufacturing	Circular Manufacturing
Controlled inputs	Unknown product history
Standardized parts	Variable product conditions
Stable processes	High process uncertainty
Disruptions are exceptions	Disruptions are commonplace

- Automation of remanufacturing is important for scaling and making it economically viable
- But: **Process stability cannot be achieved in most remanufacturing settings**
- Instead of eliminating disruptions, remanufacturing systems must be designed to recover from them efficiently
  - This is a fundamental departure from traditional process management and QM practices
  - Requires much more flexibility and intelligence on the level of the automation system

Disruption Classification Based on the PPR Model

Product Disruptions

- *Physical disruptions:* wear, deformation, corrosion, non-original parts, missing parts, ...
- *Information disruptions:* missing traceability data, incomplete sensor readings, incorrect identification, …
- *Recoverable product disruptions* can be managed through inspection, updated product data, adaptive process plans, …
- *Non-recoverable product disruptions* lead to scrapping or harvesting, reducing yield and potentially require rescheduling.

Process Disruptions

- *Deviations during operation* execution where the intended state transition is not achieved
- Examples: Execution failures, abnormal processing times, incomplete operations, …
  - Not just processing but also handling tasks!
- *Process Disruptions can lead to Product Disruptions*, e.g. by an unknown product state
- *Recoverable process disruptions* by additional inspection and repetition or rerouting of a processing step

Resource Disruptions

- *Deviations in the availability or capability of resources*, such as machines, robots, tools, sensors, fixtures, human operators, …
- *Typical resource disruptions* include binary failures, degraded performance, and configuration related capability losses.
- *Can propagate into system-wide bottlenecks,* when affected resources / capabilities are unique.

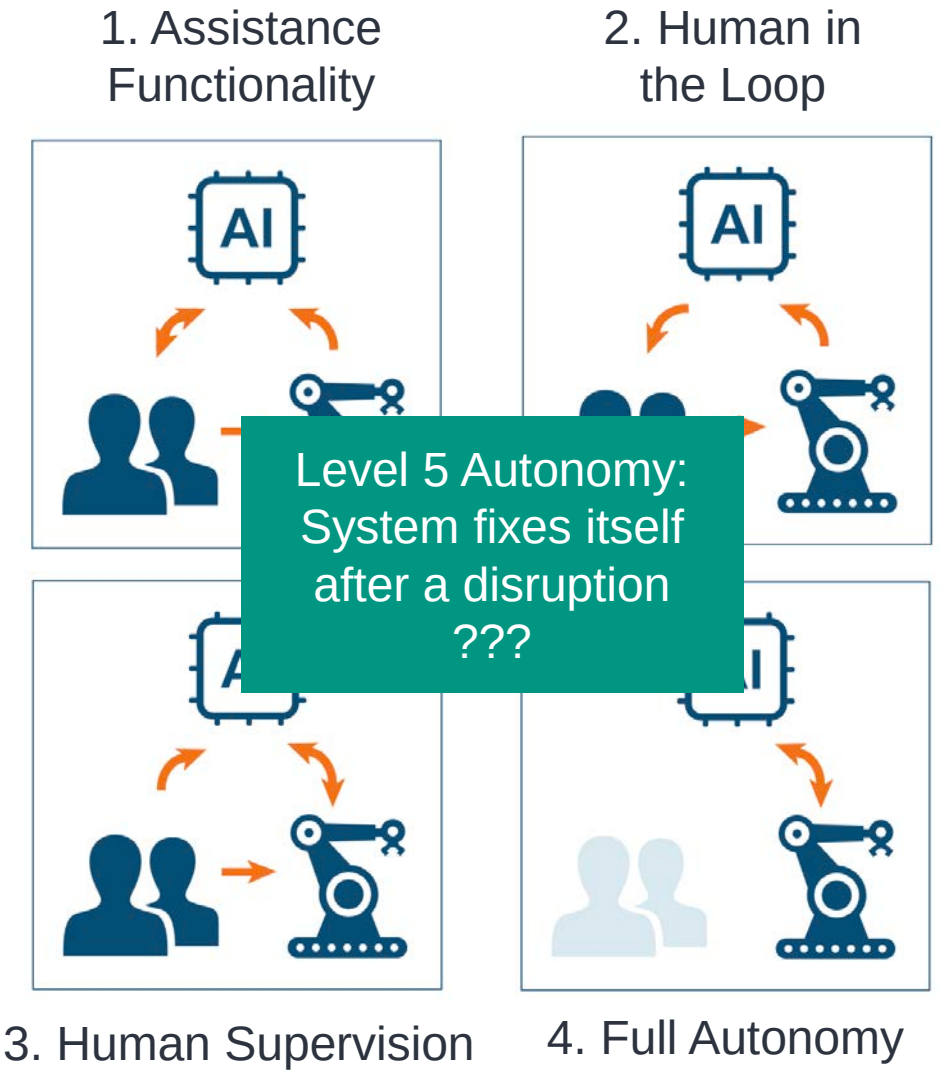
(Automatically) Recovering From Disruptions

Levels of (automatic) recovery

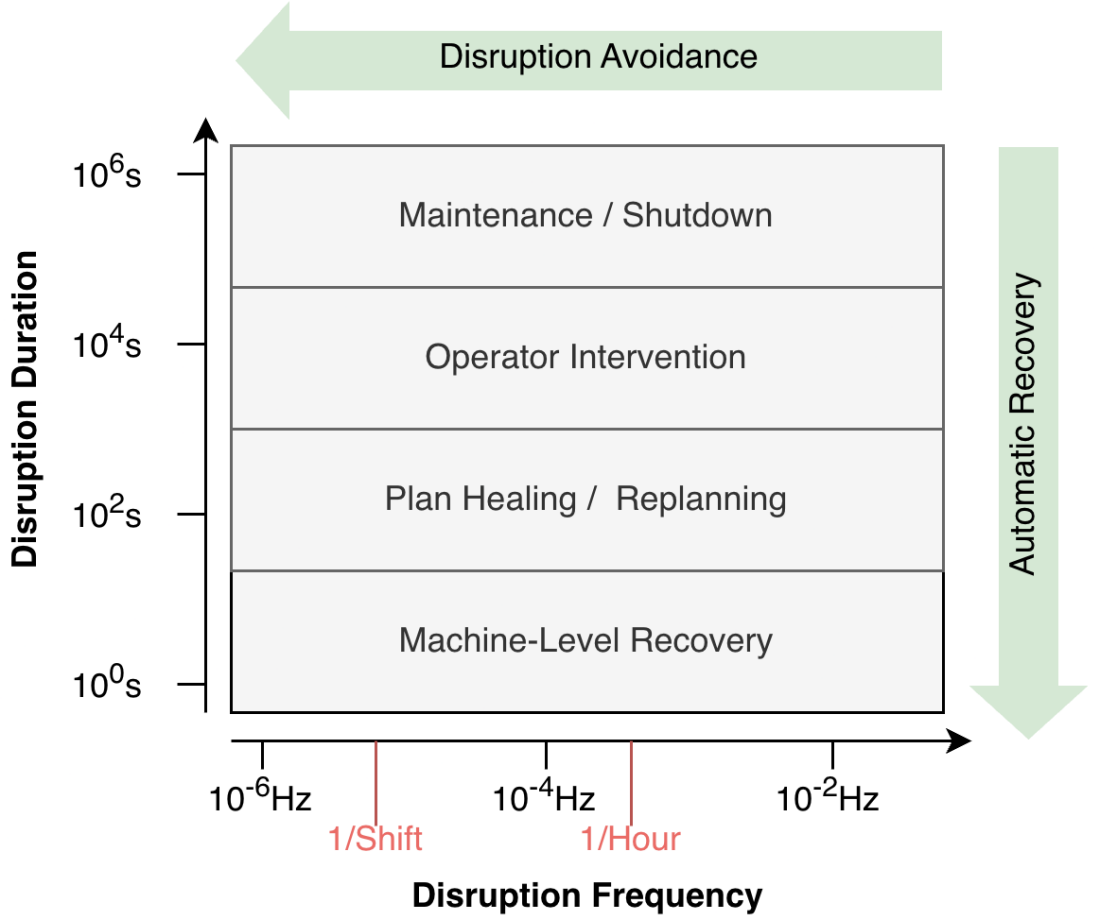
1. Shutdown / Maintenance
2. Operator Intervention
3. Plan Healing / Replanning
4. Machine-Level Recovery

Problems to Solve for Remanufacturing

- Automatic recovery is always desirable. But the implementation can be very costly. When to implement which mitigation?
- Get a complete view of the disruptions impact already during the remanufacturing system design.
  So that mitigations can be considered from the start.
- Ready-made technical solutions against typical disruptions.



Remanufacturing Disruption and Recovery Framework





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Adaptive Staffing for Manual Disassembly: Dynamic Capacity Control with Worker Learning Curves

Maurice Engels, Linus Kunzmann, Aaron Elias Hoffmann, Finn Bail, Jens Becker, Jan Baumgärtner, Martin Benfer, Nicole Stricker, Barbara Deml, Gisela Lanza

Conference on Circular Production Systems and Technologies – 10.06.20206



Remanufacturing

Complexity of Process Chain

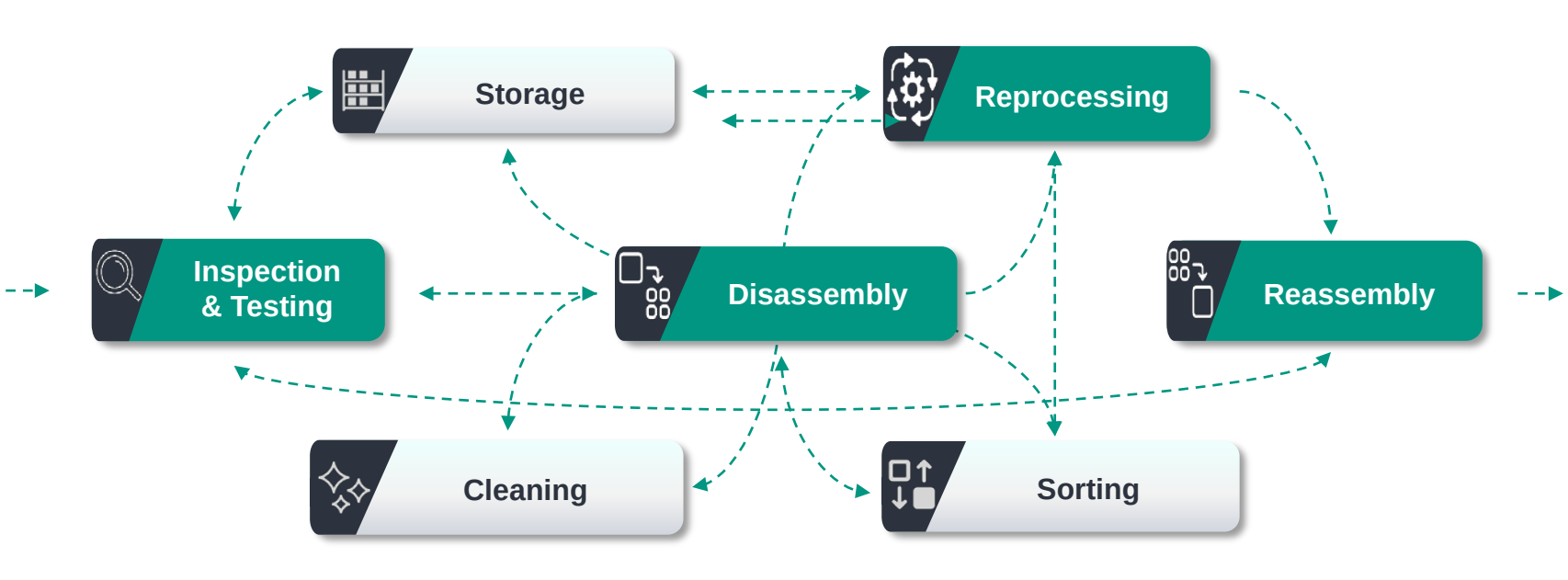
Linear

Resources → Manufacturing → Assembly → Service & Operation → Customer

Circular

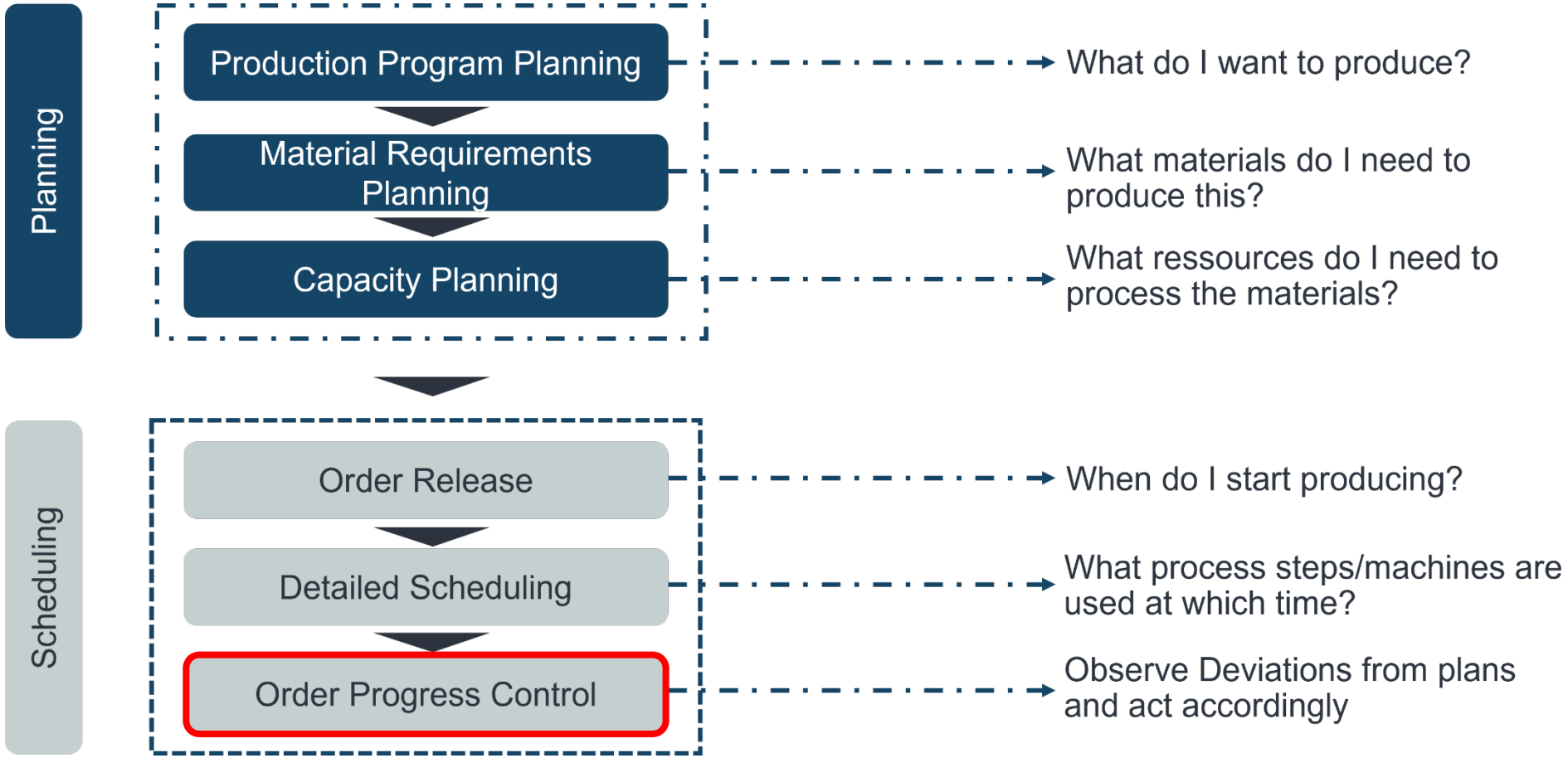
Diversity of variants and generations

High uncertainty regarding prod. condition



Production Planning and Control Tasks

Influence of process-chains uncertainties on PPC



Due to the stochastic, dynamic nature of the remanufacturing process, deviations from plans occur regulary. Dynamic Planning/Scheduling approaches are needed.

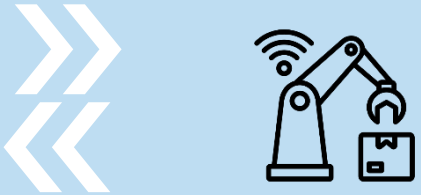
[1]

Manual Disassembly

Relevance despite increasing automation

Why does manual disassembly remain relevant with increasing automation?





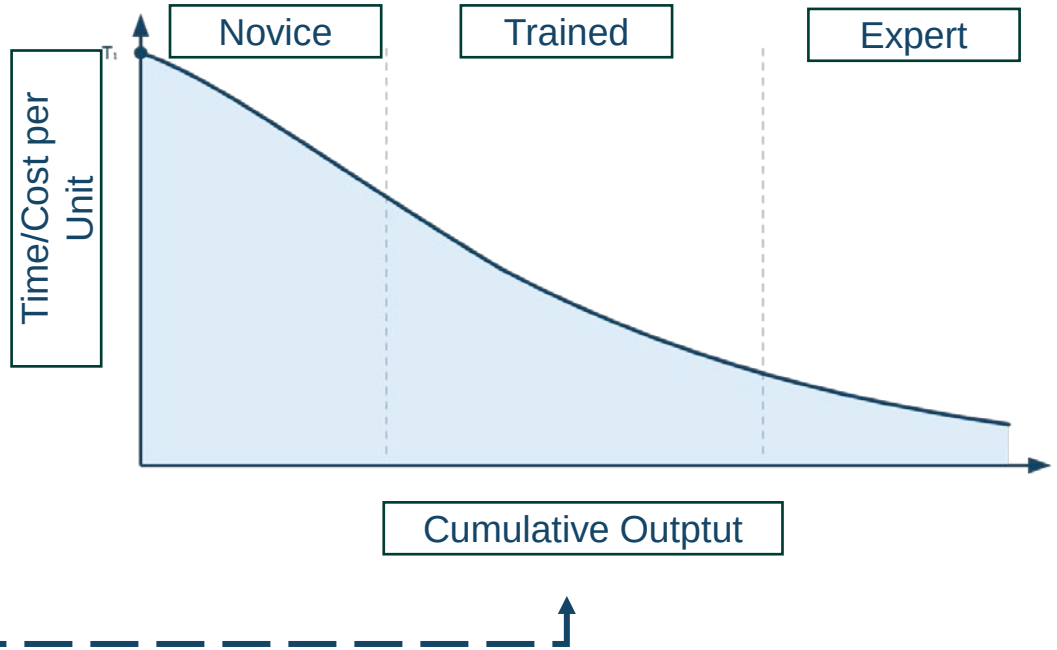
- **High Variant Flexibility:** Humans adapt to a wide range of product variants and varying core quality, where robots cannot always match this flexibility.
- **Uncertain process steps:** The disassembly sequence is not fixed; end states are unclear and step ordering varies, requiring human judgment in the moment.
- **Learning & Improvement:** Humans improve through training and experience, reducing cognitive load and building transferable skills that can also be used to train robotic systems.

[2] [3] [4]

Manual Disassembly – Learning & Improvement

Two Pathways to Learning: Dedicated learning and learning by doing

Cognitive Load Theory: Experts reduce mental effort by storing complex task knowledge in long-term memory, freeing working memory for adaptive decision-making



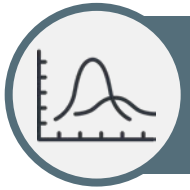
[5] [6]

Capacity control of manual processes

Key Challenges



Manual disassembly workstations face highly variable processing times due to differences in worker skill, core condition, and product variants



Remanufacturing adds further uncertainty through unpredictable core quality, making arrival rates and processing demands harder to forecast

Manual disassembly in remanufacturing is characterized by high process uncertainty, variable core quality, and heterogeneous worker skill levels that evolve over time.

Current Planning Approaches

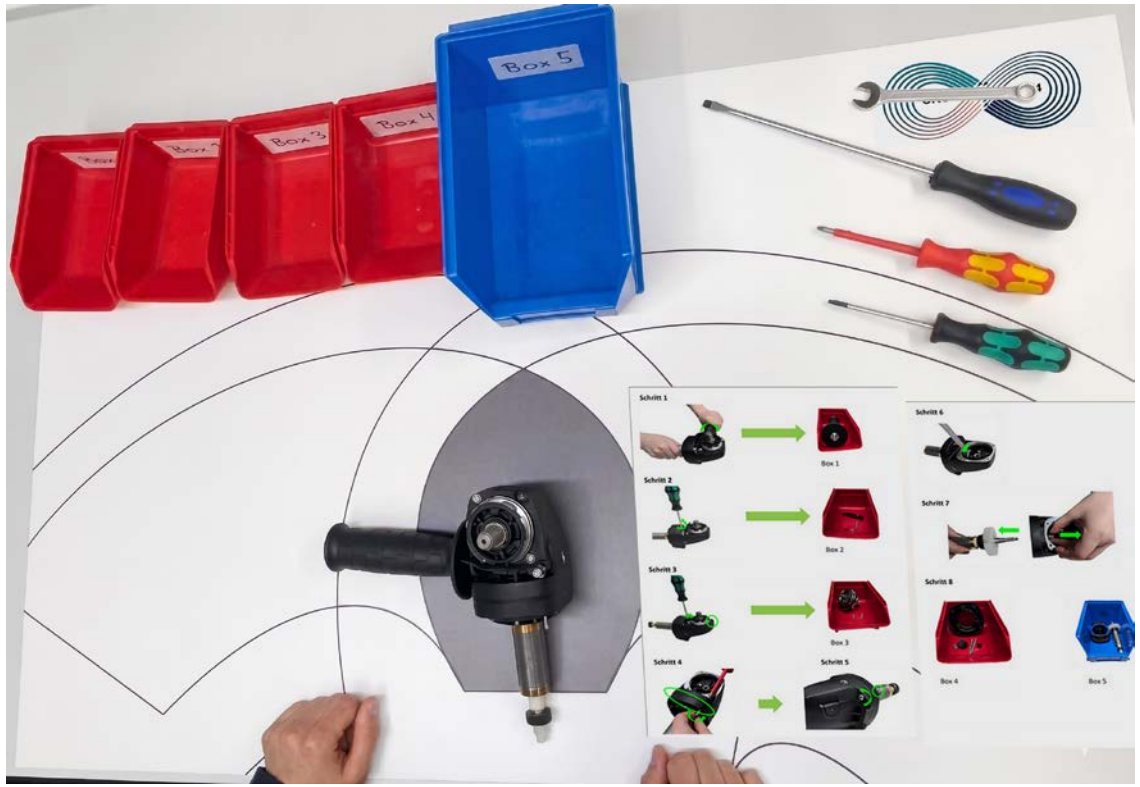
Classical capacity control assumes deterministic or stationary processing times — poorly suited to disassembly variability

Simulation-based methods allow more realistic modelling but don't incorporate worker skill as a dynamic input

Skill-aware control adapts capacity decisions in real time based on observed worker performance, better reflecting remanufacturing conditions.

[7] [8] [9]

Gathering Disassembly Data



- Task: disassemble and reassemble an angle grinder (shell removed, 8 steps each)
- Between-subjects design: trained group and untrained group
- 5 iterations per participant: runs 1–4 on the same grinder, run 5 on a different variant to test knowledge transfer
- Trial time measured from first touch to final placement. 38 participants, mean age 25.9

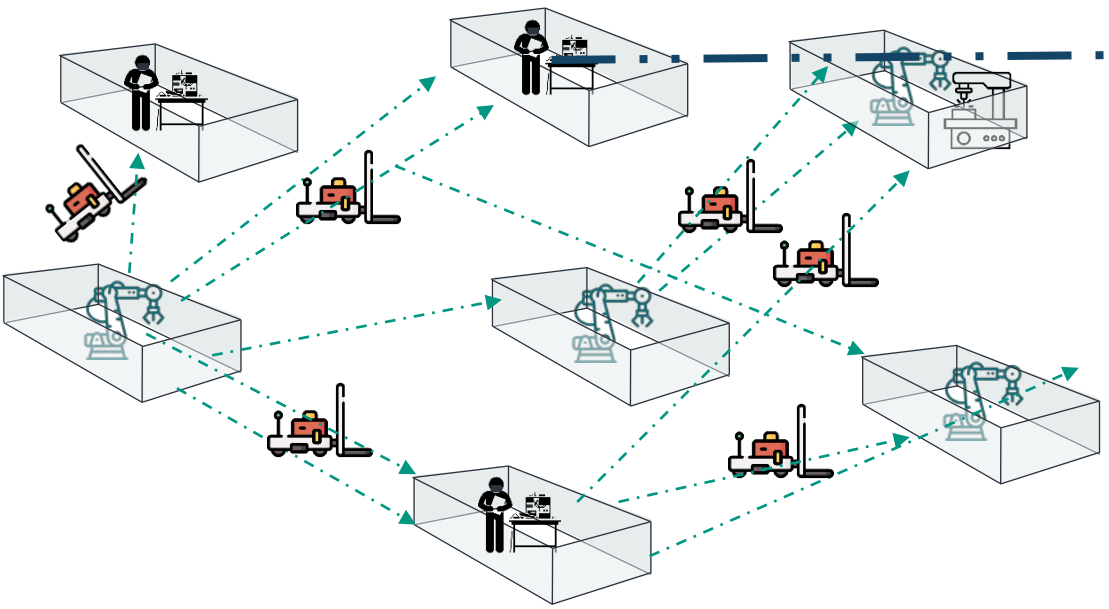
Gathering Disassembly Data

Run	Untrained (s)	Trained (s)	Δ (s)
1	370.4	176.5	193.9
2	223.7	154.3	69.4
3	184.1	145.8	38.3
4	165.6	140.5	25.1
5	277.0	239.5	37.5

- Significant main effects on trial duration: training, high expertise and a learning effect across runs
- Significant training × run interactions confirm learning curves differ between trained and untrained groups
- Run 5 (new variant) shows times rising sharply for both groups

Dynamic allocation of workers

Approach & Simulation Set Up



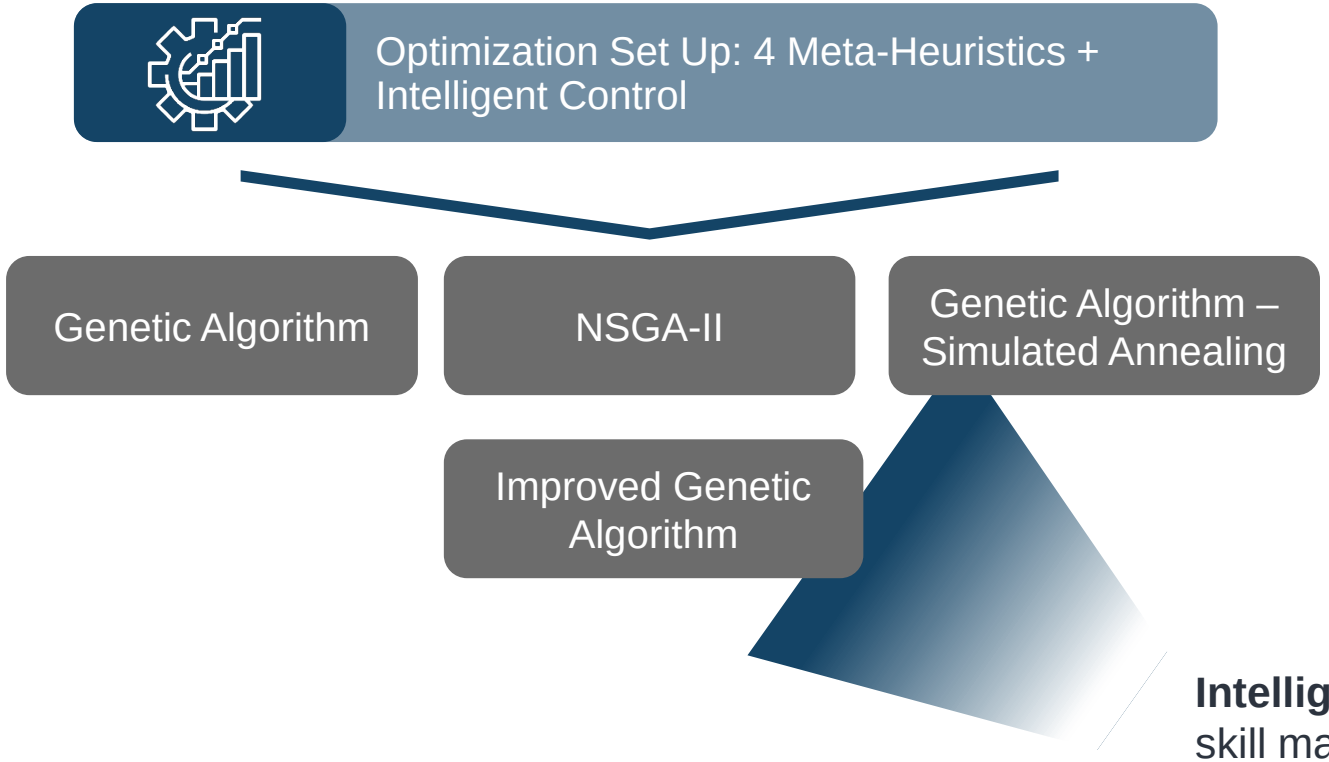
- Wright's Law: $T_w = T_w(1) \cdot n^{(b_w)}, with\ b_w \in (-1, 0)$ fitted by least squares
- One curve per (worker, variant) pair → dynamic skill matrix (operators × variants) refined as new observations arrive

- Shopfloor: 5 manual workstations + 7 reconfigurable robotic transformer cells, connected by a shared order pool
- Stochastic order arrivals, processing times, and operator availability

[10]

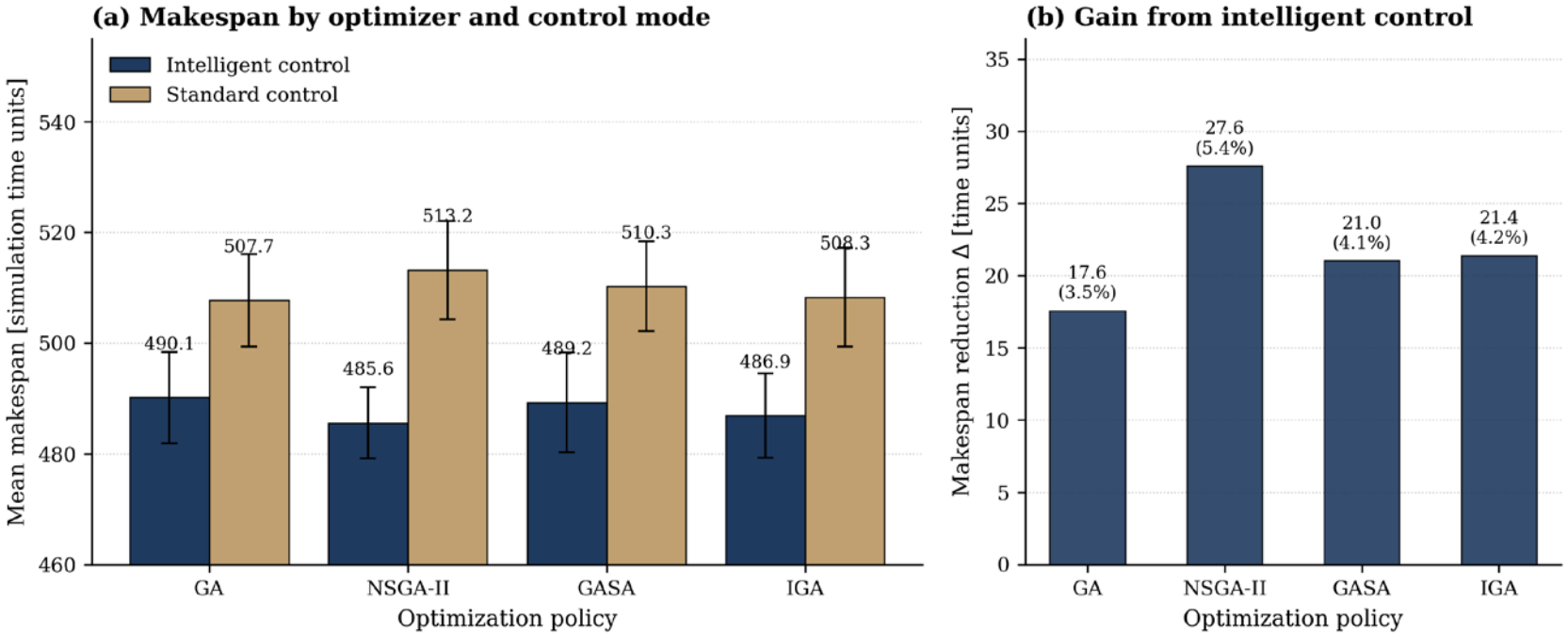
Dynamic allocation of workers

Optimization Approach



Intelligent mode: optimizer sees system KPIs and the dynamic skill matrix; operator identity becomes a decision variable
Standard mode: optimizer sees only system KPIs; operators treated as interchangeable

Results



Across 400 simulation runs, intelligent skill-aware control reduced makespan by 3.5–5.4% in every design cell, with NSGA-II benefiting most, showing that how manual capacity is allocated matters more than which optimizer is used.

Conclusions & Outlook

Key Findings

- Skill-station matching reduces makespan by up to 5% across all optimizers and dominates optimizer choice as a control lever. Observed learning data work as a live planning input, not a static parameter

Limitations

- Learning curves calibrated under lab conditions with one product type and a young participant sample, field validation on industrial lines still needed
- Results based on a fixed-size system; scalability to larger worker pools and longer horizons remains open

Technical Extensions

- Add off-the-job training as a planner action (cost, lead time, expected learning shift)
- Model cross-variant transfer dynamics, calibrated against the run 4-to-5 penalty
- Benchmark against reinforcement-learning staffing policies

Sources

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Thank you!



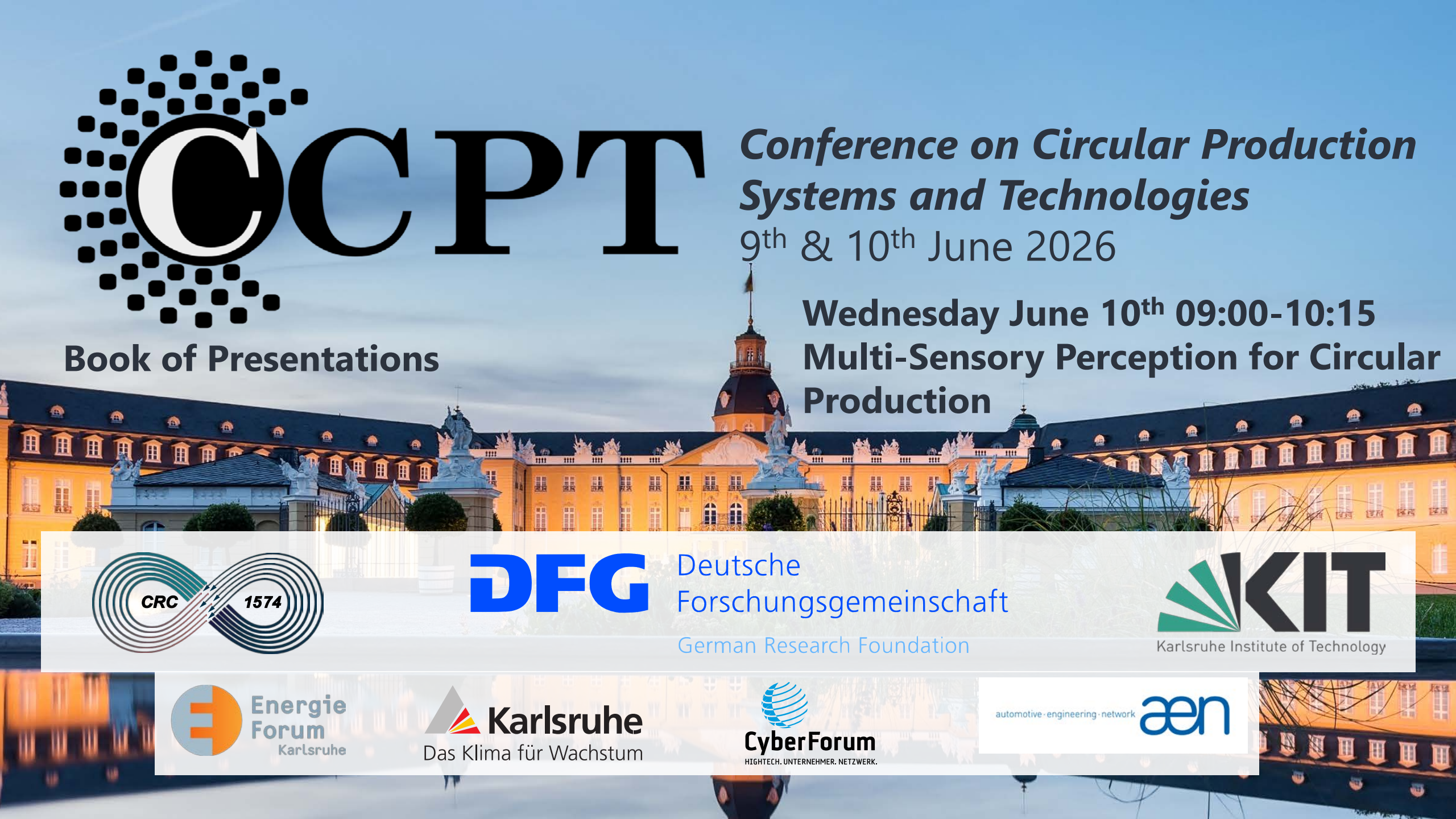
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CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 09:00-10:15
Multi-Sensory Perception for Circular Production

CRC 1574

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

KIT Karlsruhe Institute of Technology

Energie Forum Karlsruhe

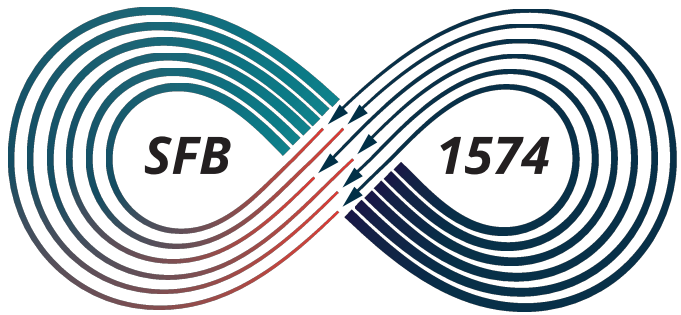
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Stakeholder-Based Deterministic and Probabilistic Quality Control Using Gaussian Mixtures for Circular Factories

Ali Darijani



10th of June, 2026
Germany

Motivation

Problem

If you are producing something how do you do quality assurance?

Solution (Open Loop)

Tight input tolerances $\Longrightarrow$ *tight output tolerances*

Solution (Closed Loop)

Tight input tolerances $\Longrightarrow$ *unimodal models*

Problem

How should multimodal inputs be handled? Provide a decision making framework for the stakeholders.

Framework Overview

Definition

Stakeholders requirements modeled as:

$$\mathcal{G}(x|g_A), \tag{1}$$

the product at hand is modeled by:

$$\mathcal{G}(x|g_{\text{prod}}), \tag{2}$$

and the threshold of acceptance is modeled by:

$$\tau \in \mathbb{R}_{\geq 0} \tag{3}$$

Solution (Distance/Divergence Based Acceptance)

If

$$D(\mathcal{G}(x|g_{\text{prod}}) : \mathcal{G}(x|g_A)) < \tau \tag{4}$$

then we have acceptance.

Why Gaussian Mixture Models?

Theorem

GMMs can model everything given enough regularity.

Proposition

The GMM framework can represent both deterministic (Dirac Delta) and probabilistic regimes.

Remark

Some distances and divergences for GMMs admit closed-form expressions.

Remark

Efficient and fast computation.

Instant Specific Representation

Problem

The probability PDF is for the ensemble but you are talking about a product instance?

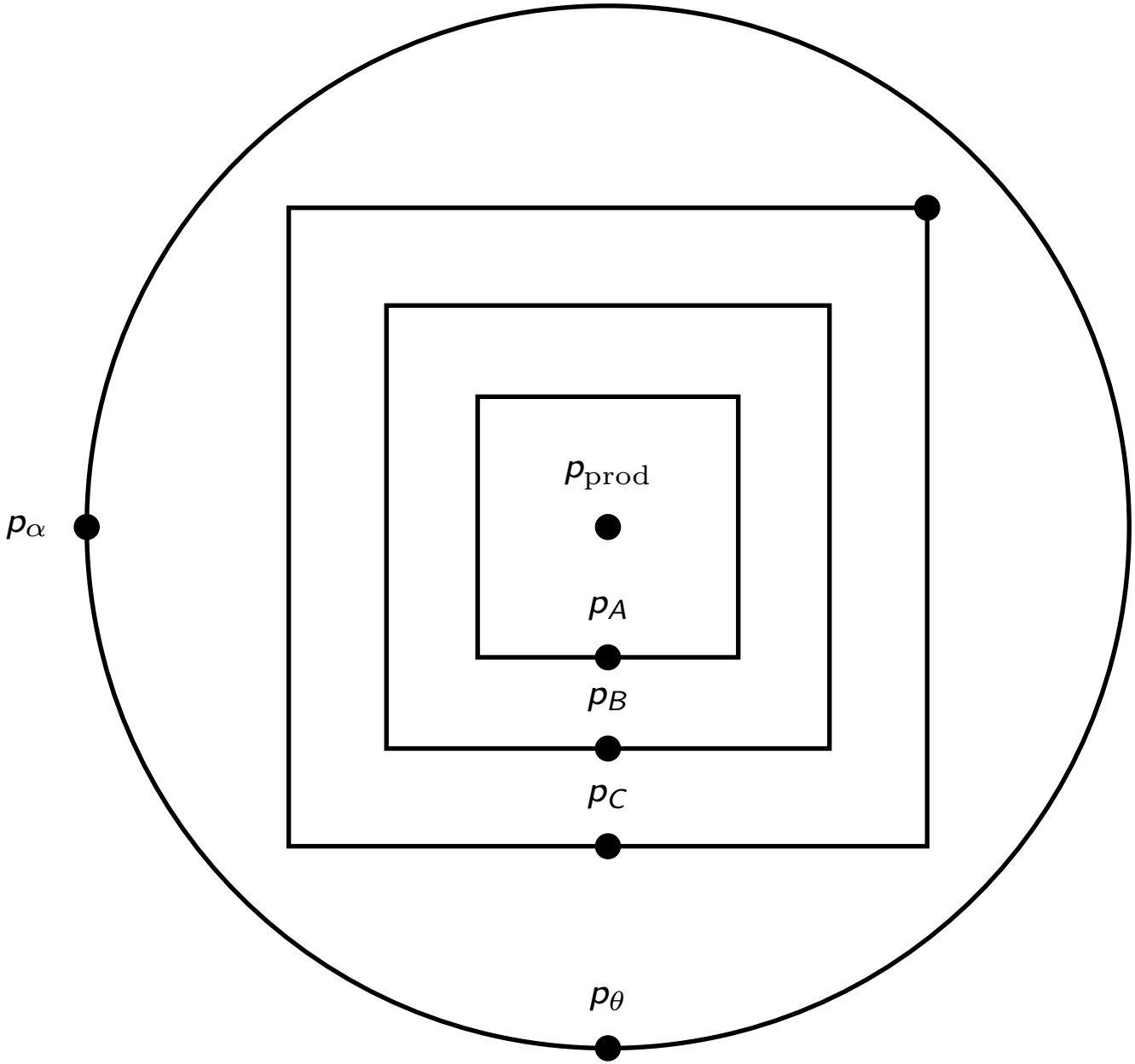
Solution

Historical data gives an ensemble GMM and the initial inspection of the product gives evidence. Using the Bayes' rule we can get the instance specific GMM.

Problem

With what probability the sun will rise tomorrow?

Metrics



Closed-Form Divergences for GMMs

- L^2 distance
- Total Squared Loss (tSL-Total Bregman Quadratic Divergence)
- Cauchy-Schwarz divergence
- Jensen-Quadratic Rényi (JQR) divergence

Cultural Shift

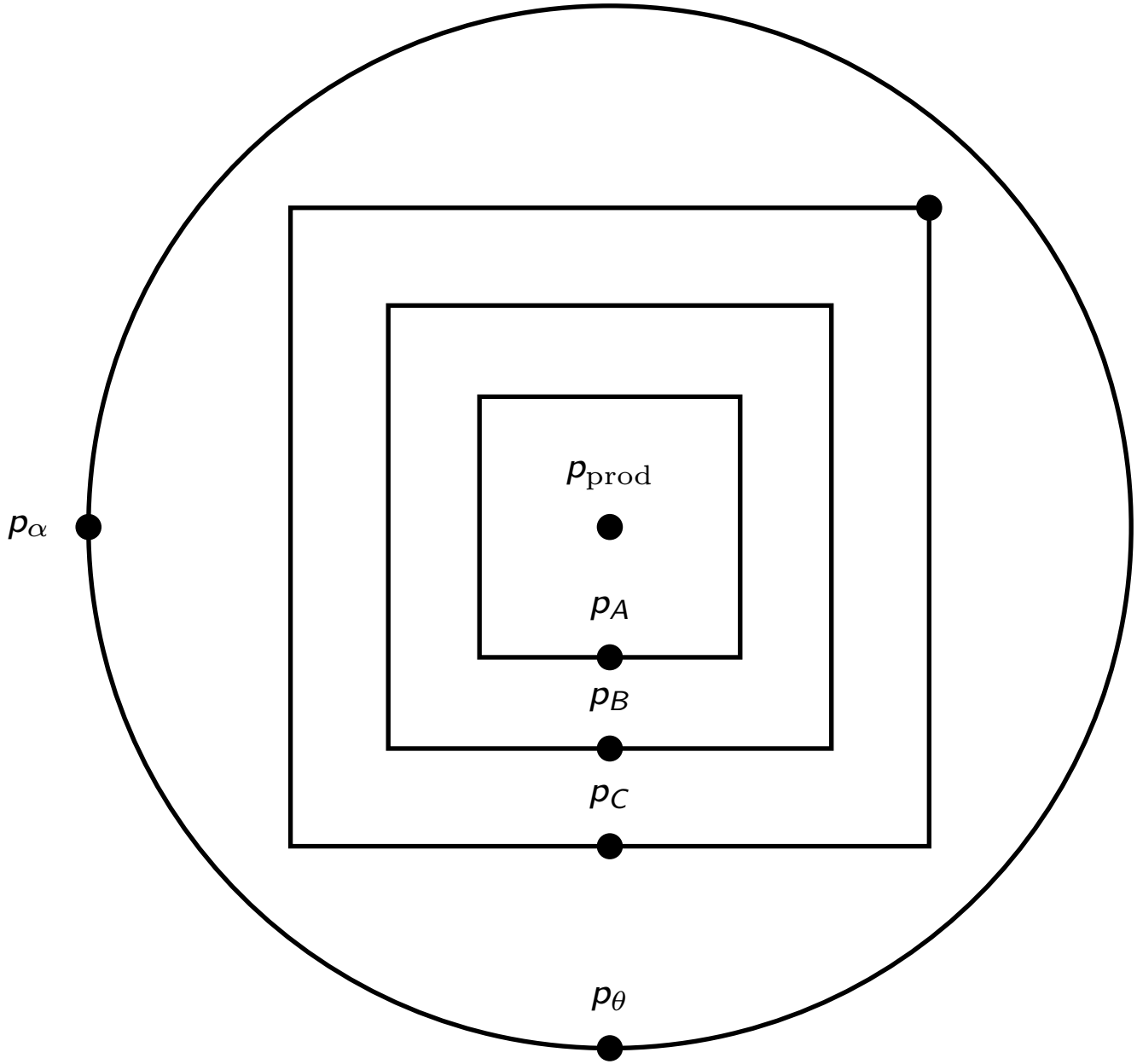
Proposition (KL divergence between 1D Gaussians)

Let $p = \mathcal{N}(x|\mu_0, \sigma_0^2)$ *and* $q = \mathcal{N}(x|\mu_1, \sigma_1^2)$. *Then*

$$D_{\mathrm{KL}}(p \,\|\, q) = \log \frac{\sigma_1}{\sigma_0} + \frac{\sigma_0^2 + (\mu_0 - \mu_1)^2}{2\sigma_1^2} - \frac{1}{2}.$$

In particular, $D_{\mathrm{KL}}(p \,\|\, q) \geq 0$, *with equality iff* $\mu_0 = \mu_1$ *and* $\sigma_0 = \sigma_1$.

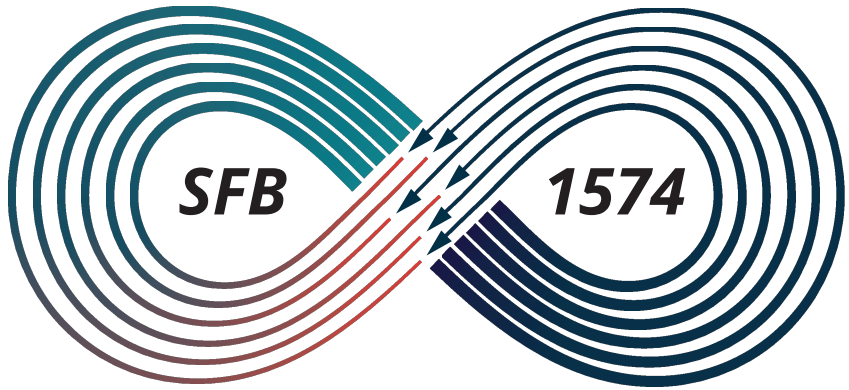
Threshold Design and Interpretation



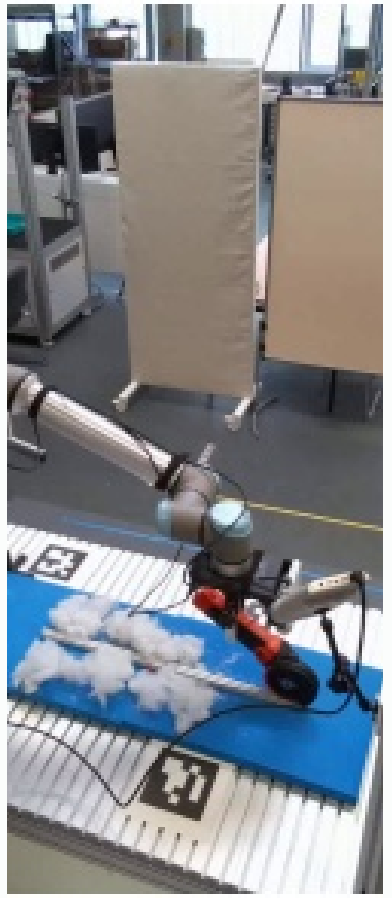
Conclusion and Outlook

- Understanding the divergences
- Selecting the best tool for the job
- Threshold design
- Extensive references in the full paper

Fortis fortuna adiuvat

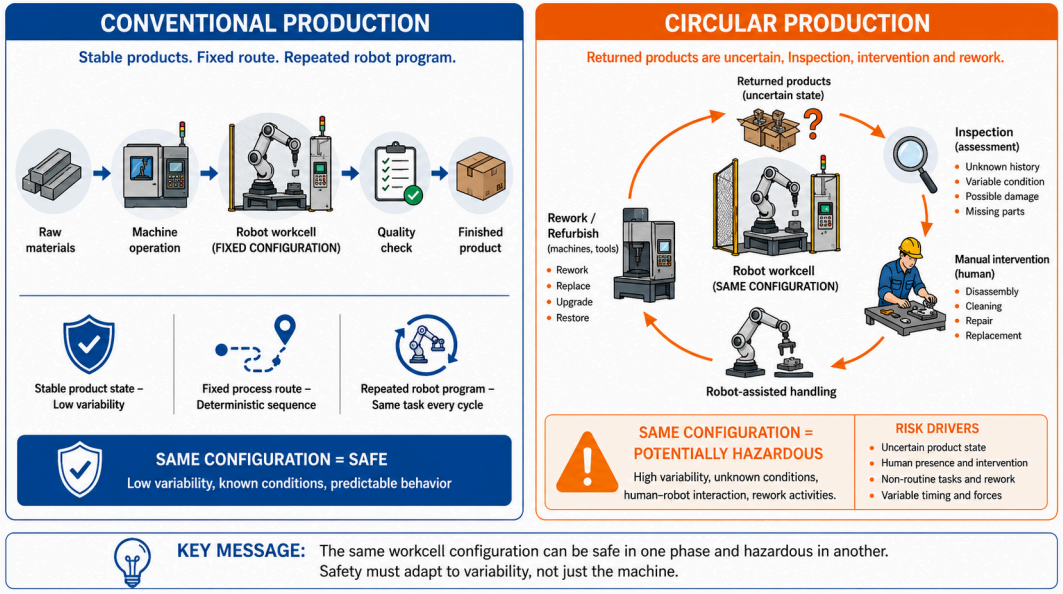


Specification-Driven Safety Event Localization for Human–Robot Collaboration



MOTIVATION

Circular production makes safety context-dependent



Returned products bring uncertain states, possible defects, and changing reprocessing paths.

- inspection and rework coexist with robot-assisted handling
- human intervention becomes routine rather than exceptional
- the same spatial scene changes meaning across phases

> A safe configuration in observation may become hazardous during active robot execution.

PROBLEM SOURCE

The gap between safety rules and perception outputs

SAFETY ENGINEERING EXPECTS	PERCEPTION USUALLY GIVES
hazards and risk reduction	detections
workspace zones and safeguards	tracks
robot and process states	distances
PPE and site policies	confidence scores
documentation and evidence	frame-level alarms

> The missing part is a **perception-to-specification event layer**.

FORMULATION

Localize violations, not objects

Deployment specification

$$\Omega = (Z, C, S, \Pi, R, \Lambda)$$

zones, entities, states, predicates, rules, and timing parameters

$$inside(hand, z_robot, t) \wedge active(robot, t) \rightarrow intrusion(t)$$

a hand detection becomes a safety event only under the active rule

Localized event record

$$\hat{e}_j = (y_j, t_s, t_e, z_j, O_j, c_j, \rho_j, \eta_j)$$

type · time span · zone · entities · criticality · rule · evidence

> The output is an auditable interval-level event, not a frame-level alarm.

METHOD

From visual observations to rule-grounded events

1. PERCEPTION STREAM

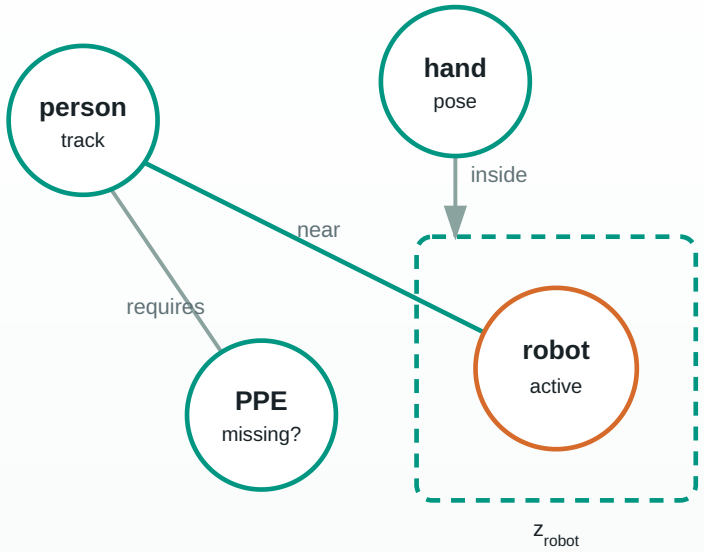
$$x_t = (I_t, D_t, r_t, p_t)$$

Visual input
person, hand, object, PPE cues

Robot state
active, stopped, operation mode

Process context
inspection, intervention, handling

2. OBJECT-CENTRIC SAFETY MEMORY



$inside(hand, z_{robot})$
$near(person, robot) \cdot active(robot) \cdot missing(PPE)$

3. RULE EVALUATION

$$A_i(t) = \varphi_i(G_t, r_t, p_t, \Omega)$$

Output
rule-grounded event interval with evidence

EXECUTION

Different safety queries deserve different rates

High-criticality hazards

human proximity · hand intrusion



frequent evaluation / low latency

Lower-criticality compliance

PPE checks · site policies



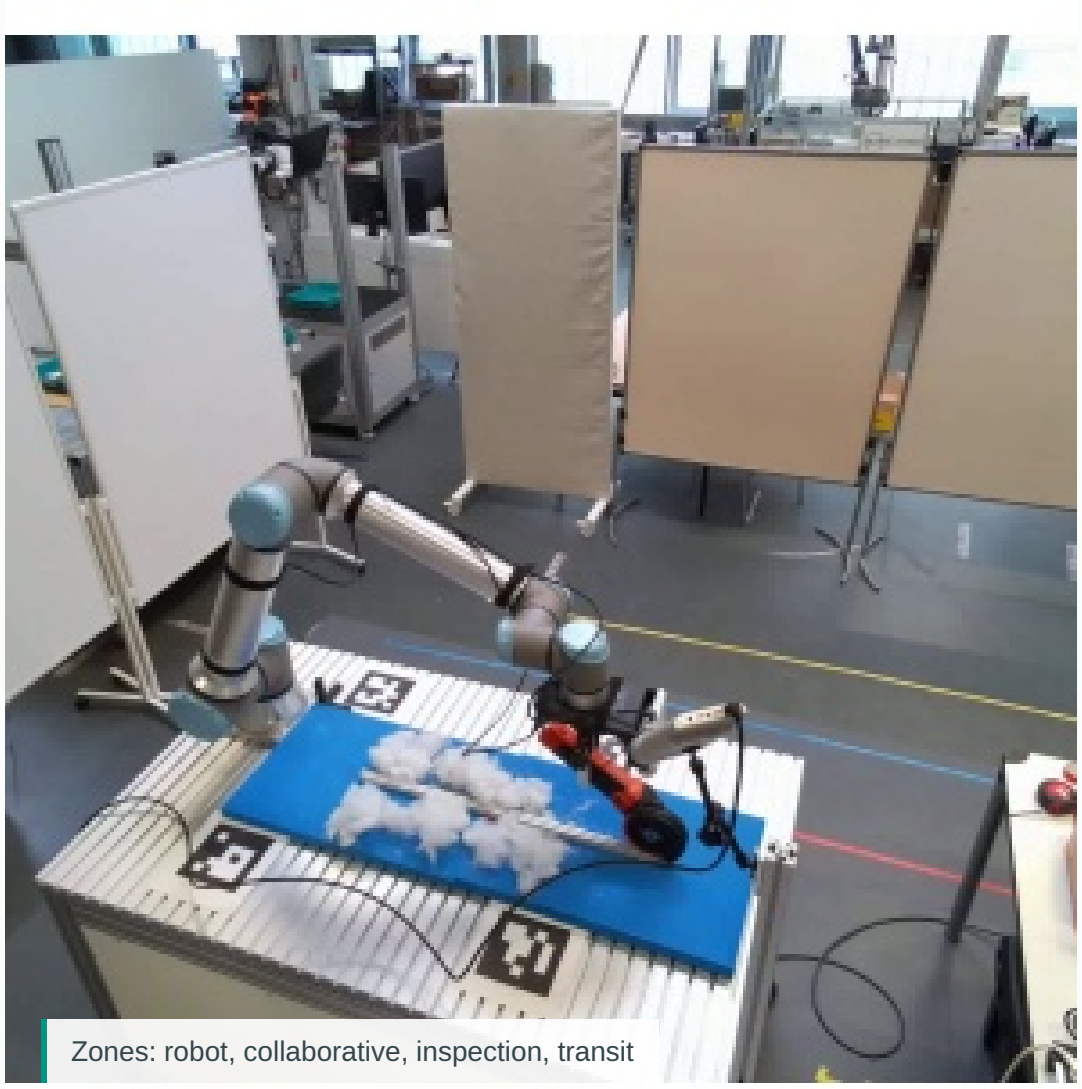
sparse or triggered evaluation

$$\Delta_i(t) + T_i^{\text{inf}} + T_i^{\text{mem}} + T_i^{\text{rule}} \leq L_i$$

Illustrative rule evaluations: uniform 90/s → multi-rate 61/s. This is design rationale, not a runtime benchmark.

CASE STUDY

Real workcell, compact rule catalog



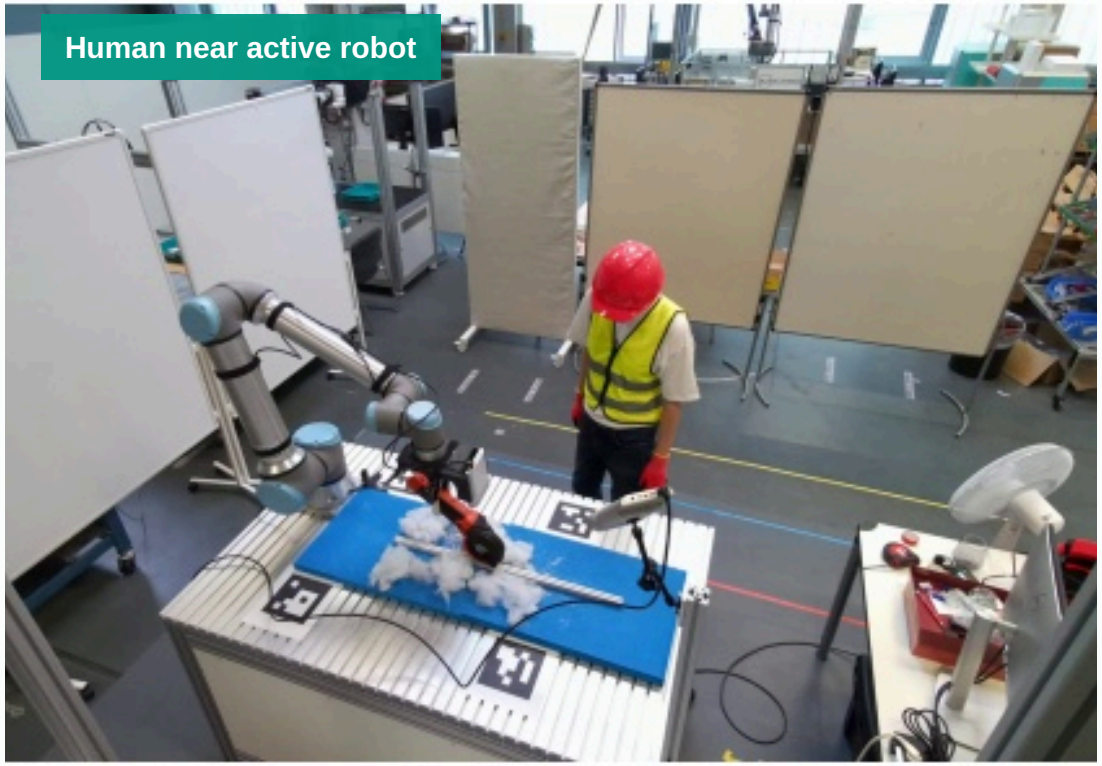
Zones: robot, collaborative, inspection, transit

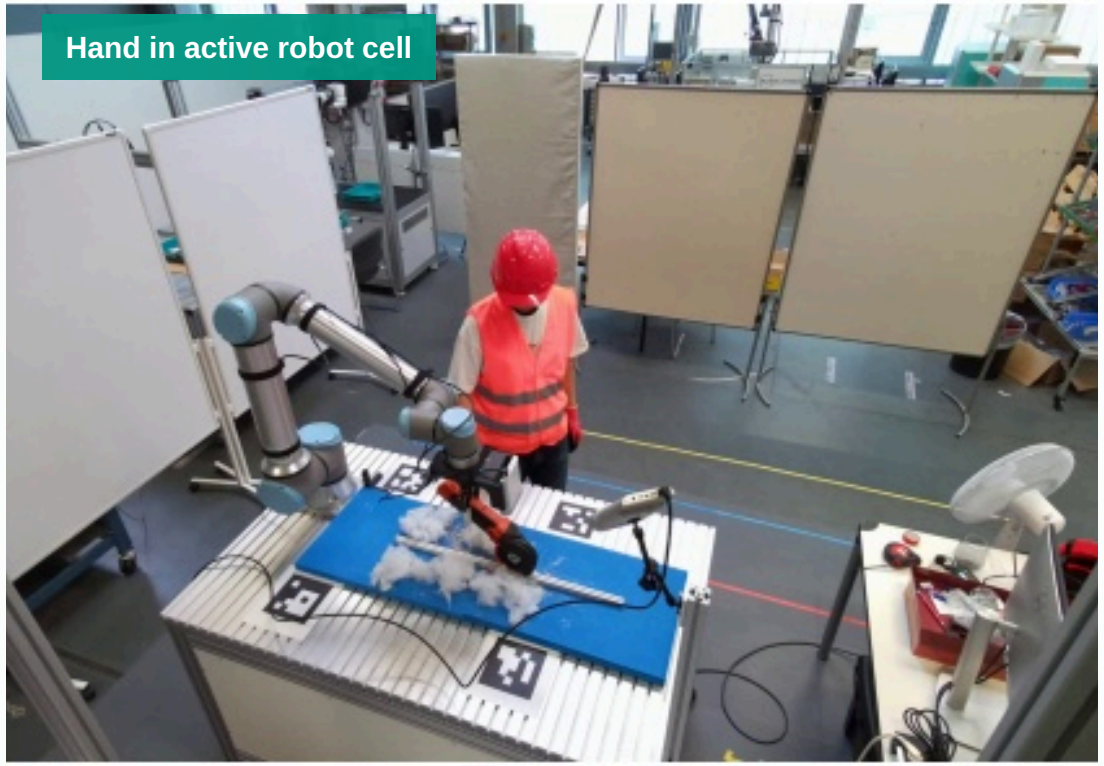
Rule	Event	Crit.	Condition
R-PROX	Human near active robot	High	near ∧ active
R-HAND	Hand in active robot cell	High	inside ∧ active
R-PPE	Missing required PPE	Low	requires ∧ missing

> Rules, not detector outputs, define events.

EVENT EXAMPLES

Events are temporal, contextual, and rule-grounded

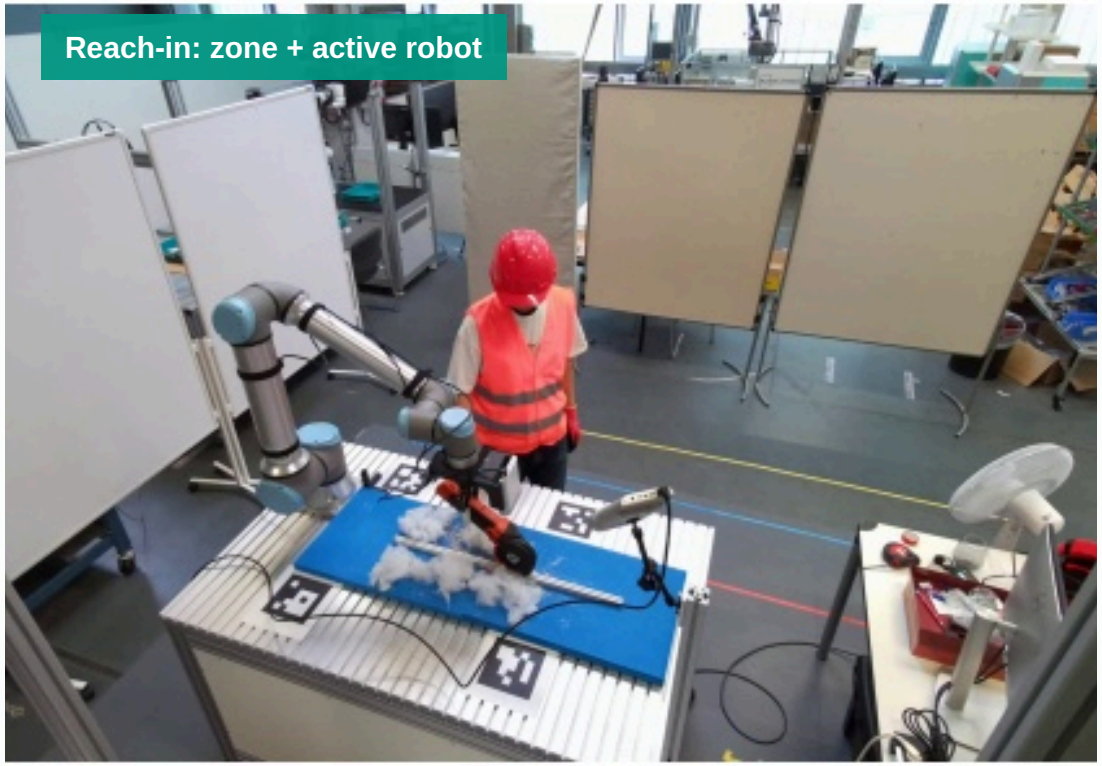


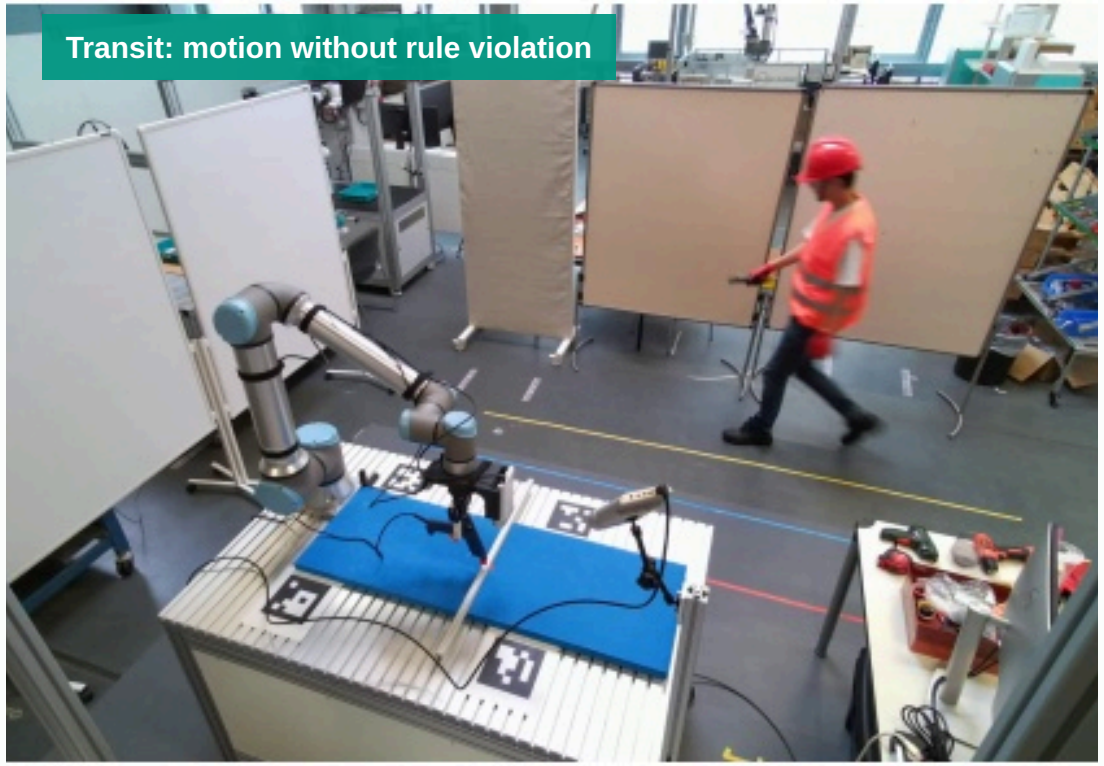


> A detection becomes a safety event only when the relevant predicates persist under the active rule.

CONTRAST

Context separates hazardous from non-hazardous motion





> The same visual primitives are reused; interpretation changes with zone, robot state, and rule context.

TAKEAWAY

A perception-to-event layer for auditable safety monitoring

Specification-driven

Rules are explicit, editable, and linked to site requirements.

Object-centric

Events are grounded in entities, zones, states, and temporal relations.

Auditable

Each event retains interval, rule, criticality, and evidence.

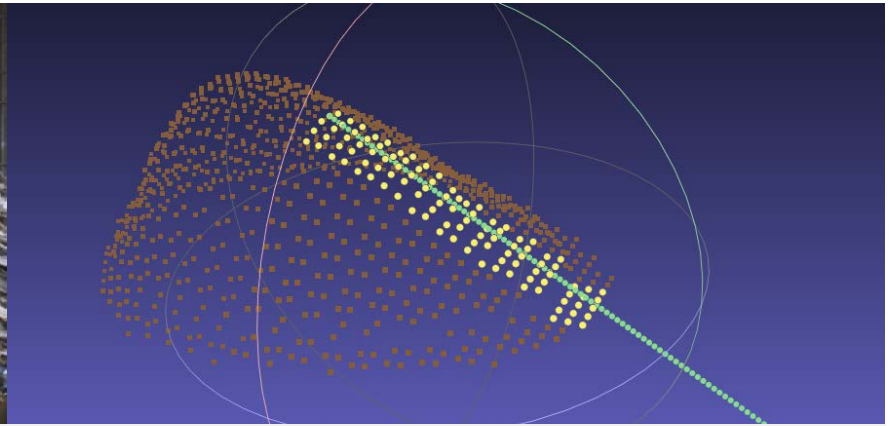
> Not a certified safety function. A structured layer for inspection, debugging, documentation, and future engineering validation.

Technische Universität Braunschweig

GITZ Gauß-IT-Zentrum

Institut für Werkzeugmaschinen und Fertigungstechnik





Cost-Efficient Detection of Hidden Metal Foreign Objects in Reclaimed Timber Beams for the Automated Individual Removal Process

Enabling the Reuse as Structural Elements

Introduction

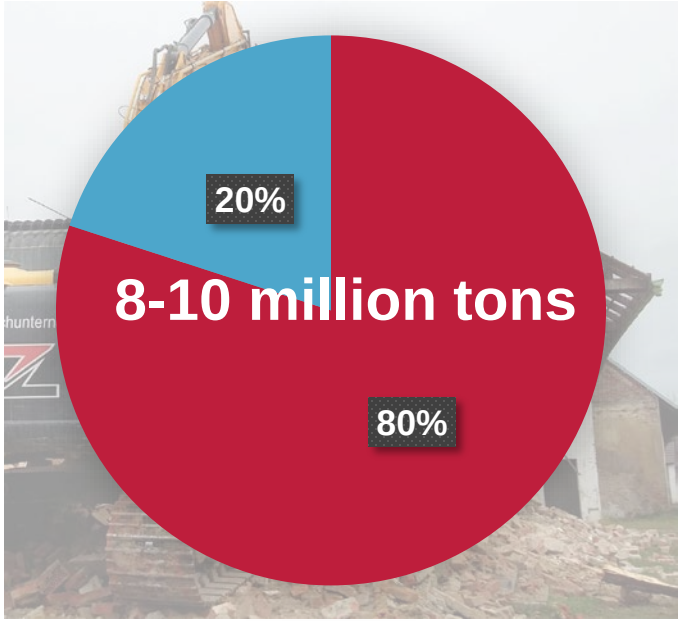


[1]

[1] Image source: Abbruch & Baggerunternehmen Dieter Utz Website: https://www.utz-bagger.de/uploads/cache/image_large_jpg/uploads/media/5a99245e26293/20171121-135450.jpg

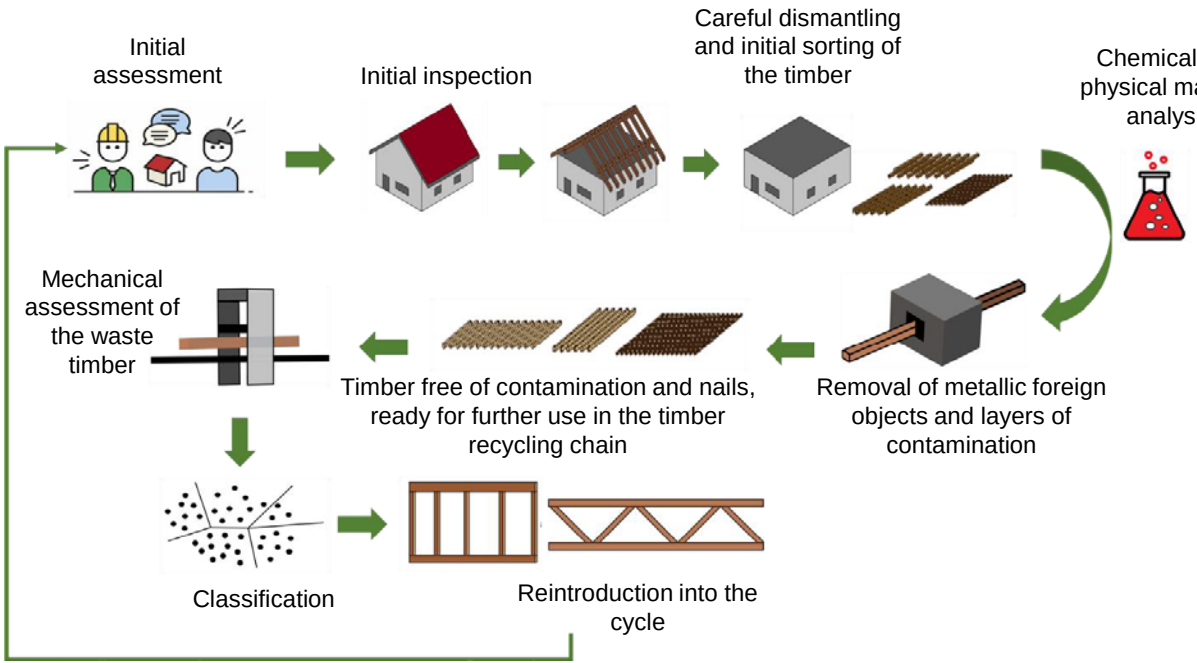
Introduction

Annual Volume of Waste Timber in Germany



Introduction

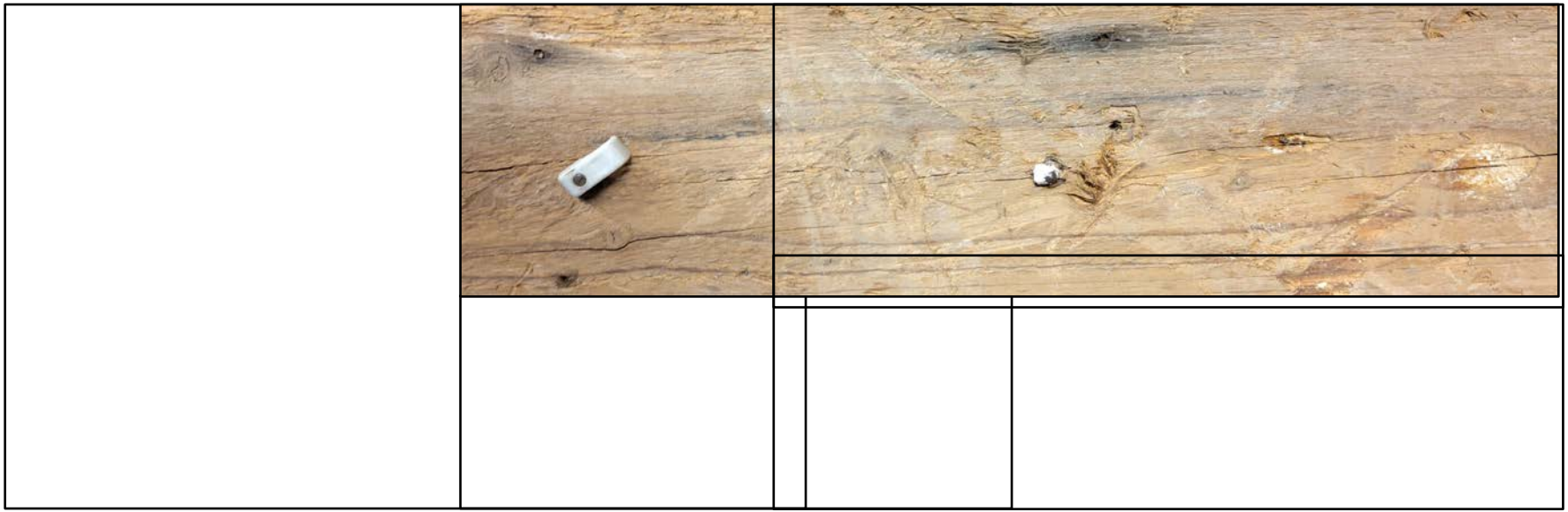
Collaborative Research Project: „Recycling for Reuse“ (Funding code: 2221HV031D)



iBHolz Institut für Baukonstruktion und Holzbau
IWF
I-ITWK Hochschule für Technik, Wirtschaft und Kultur Leipzig
Fraunhofer WKI
ING.-HOLZBAU SCHNOOR
RINN TECH METRI WERK

Typical Foreign Objects

Examples of Metallic Foreign Objects like:
Nails, Screws, Staples…



Approaches for Removal of Foreign Objects



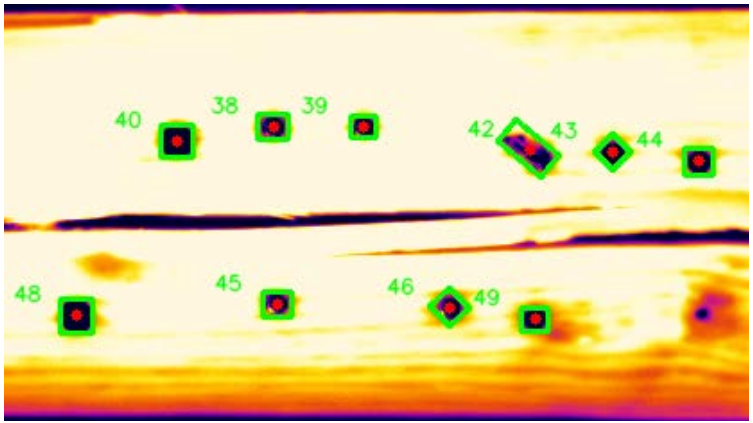


Optical Scan of Timber for Metal Objects

RGB image



Thermographic image of the same sample



Electromagnetic Scan of Timber for Metal Objects

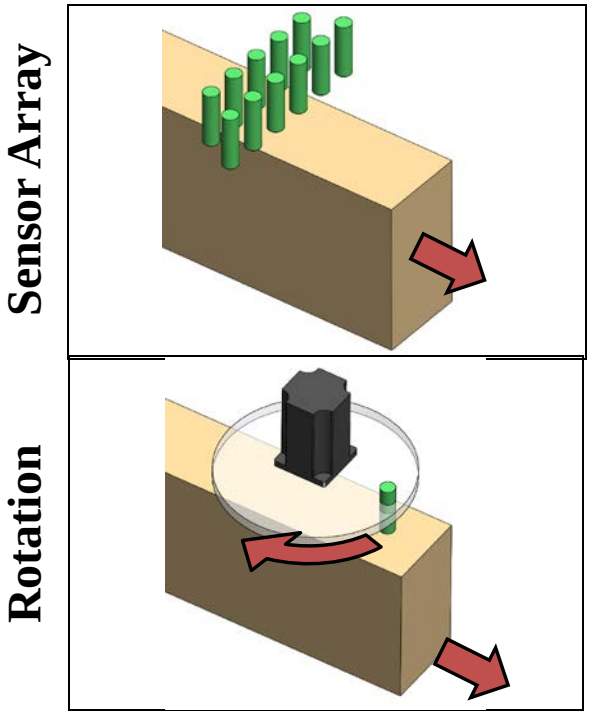
CT Scan of a Timber Beam
With Metal Object

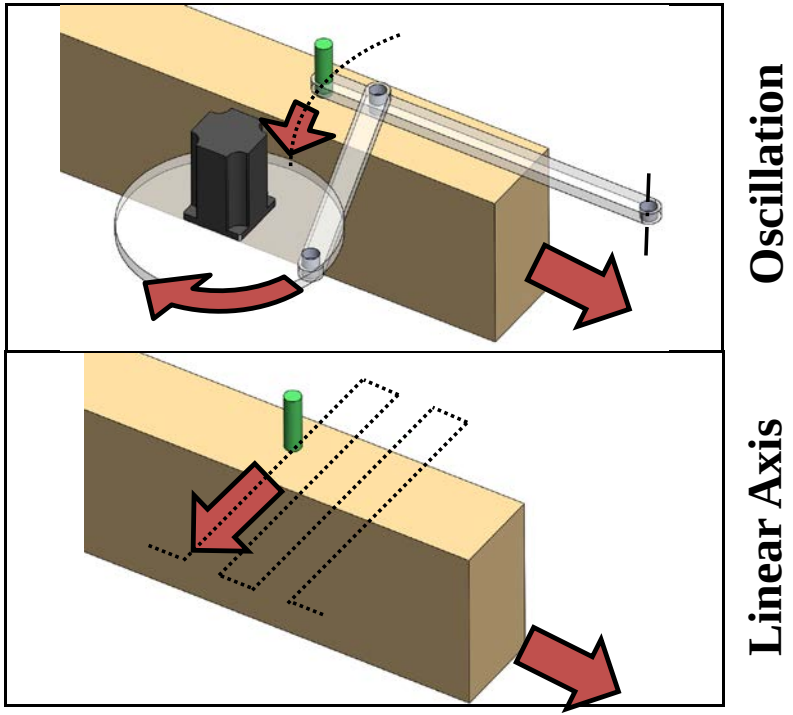
78 mm

Electromagnetic Sensor Tests

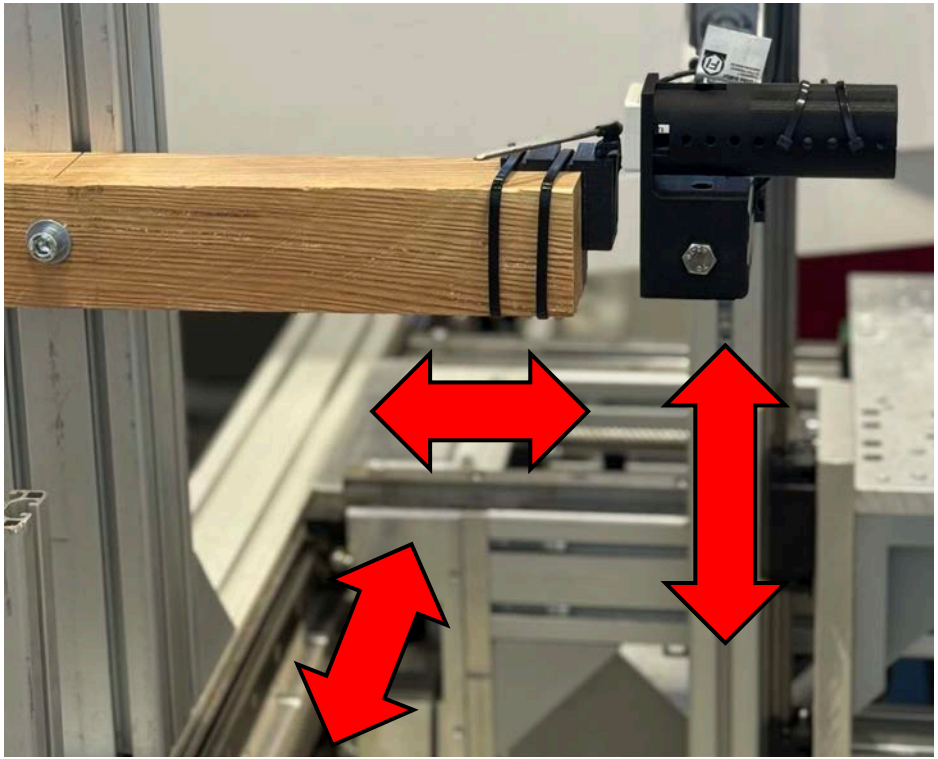


Approaches for Arrangement and Trajectory of the Sensors



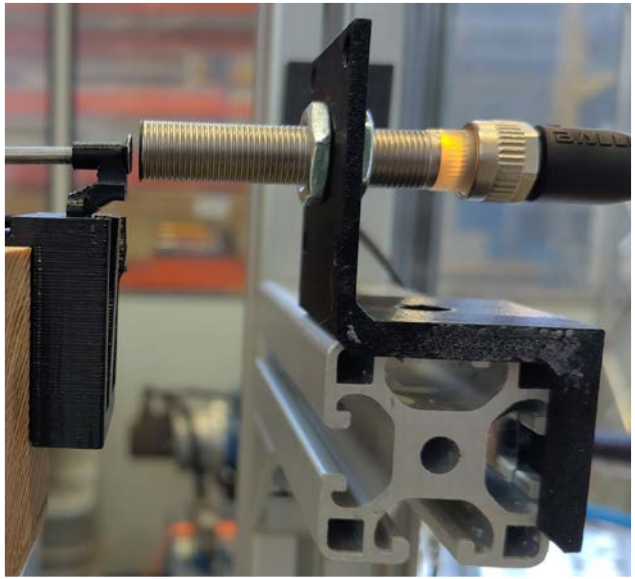


Test Setup for Sensors

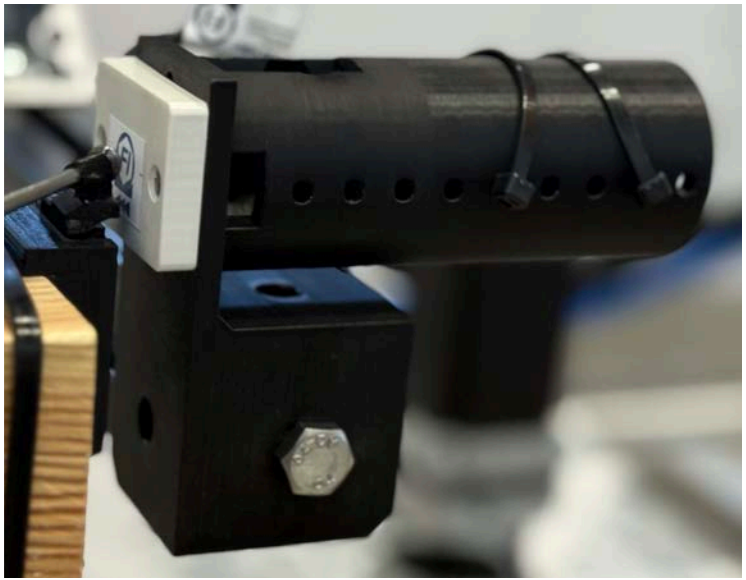


Sensors

Inductive Sensor



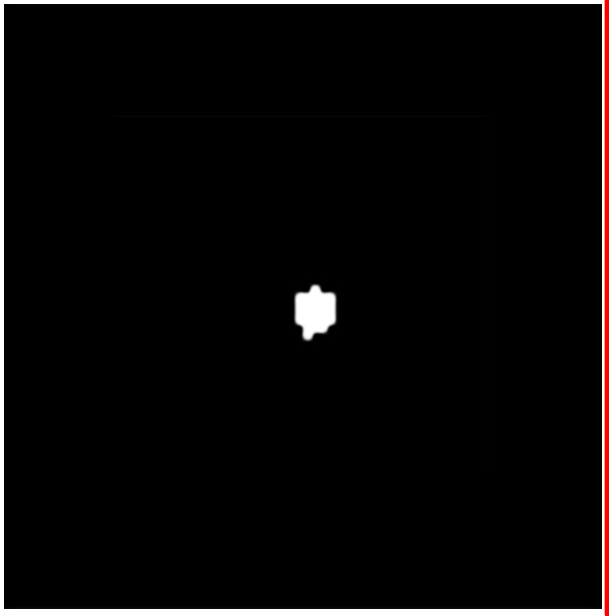
Magnetic Sensor



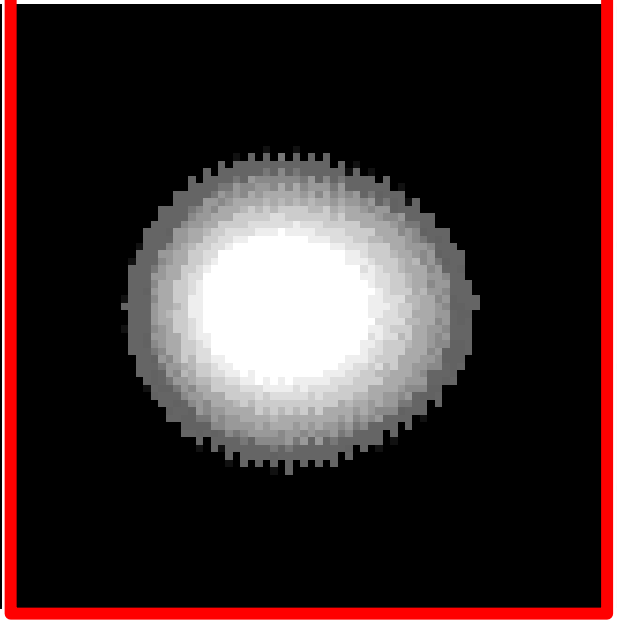
Metal Detector

Sensor Data of the Different Sensors

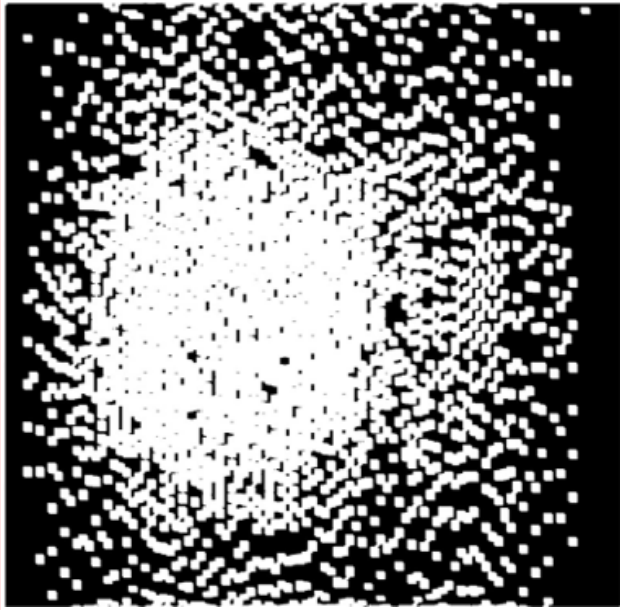
Inductive Sensor



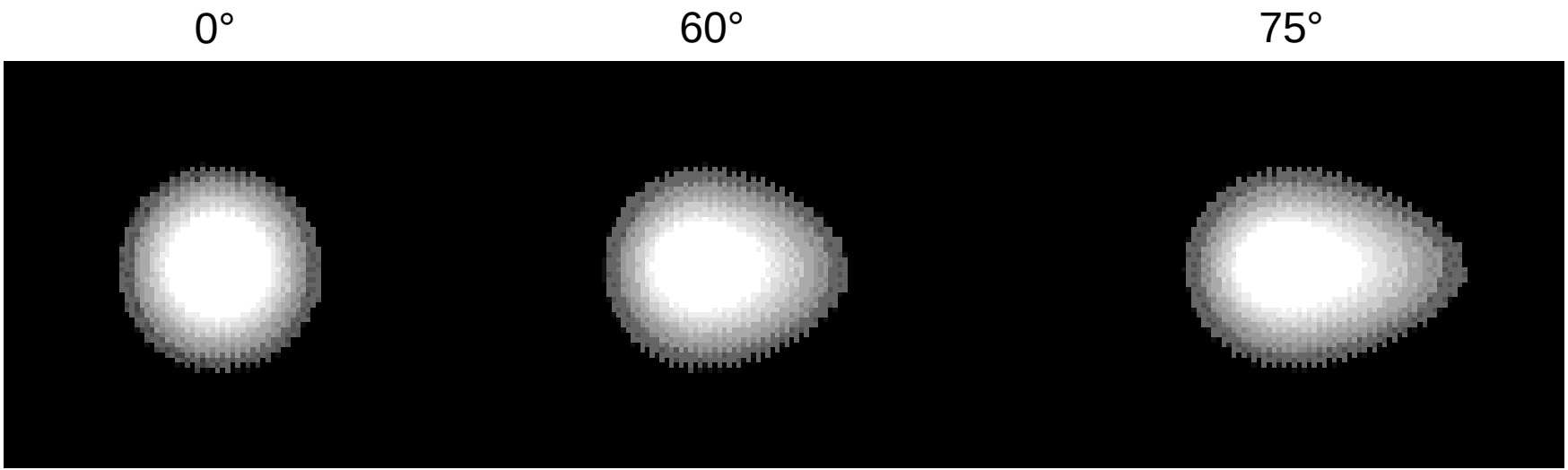
Magnet Sensor



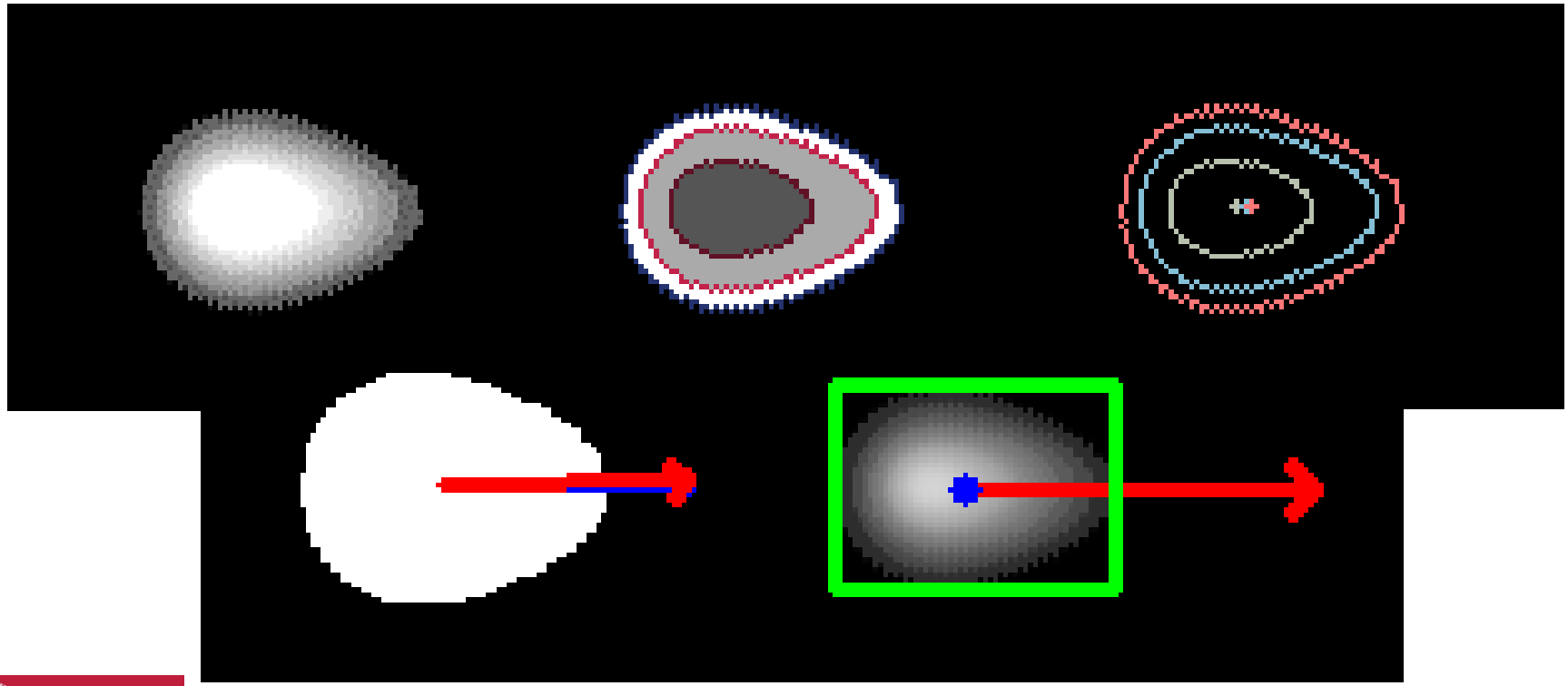
Metal Detector



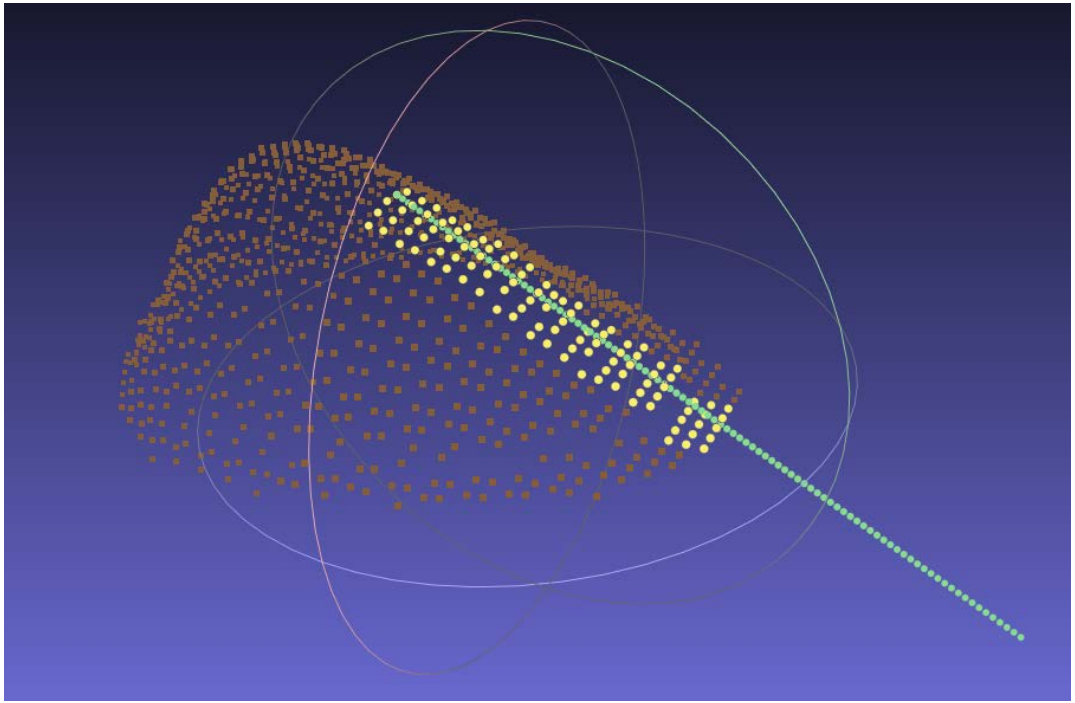
Influence of Angle on Data From Magnetic Sensor



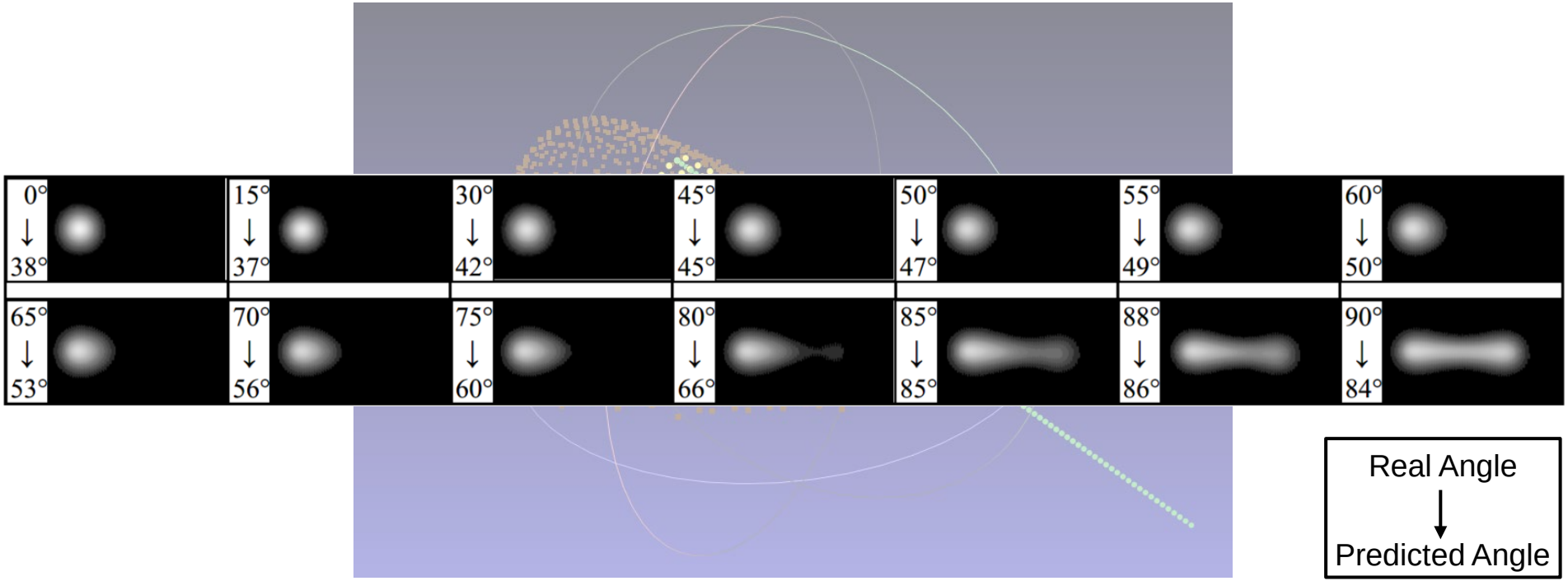
Data Processing



Angle Prediction From 3D PCA on Filtered Point Cloud



Results of Data Processing



Thank you for your Attention

ACKNOWLEDGEMENTS

Federal Ministry of Agriculture, Food and Regional Identity

Funded by the Federal Ministry of Food and Agriculture on the basis of a resolution of the German Bundestag

Coordinator: FNR

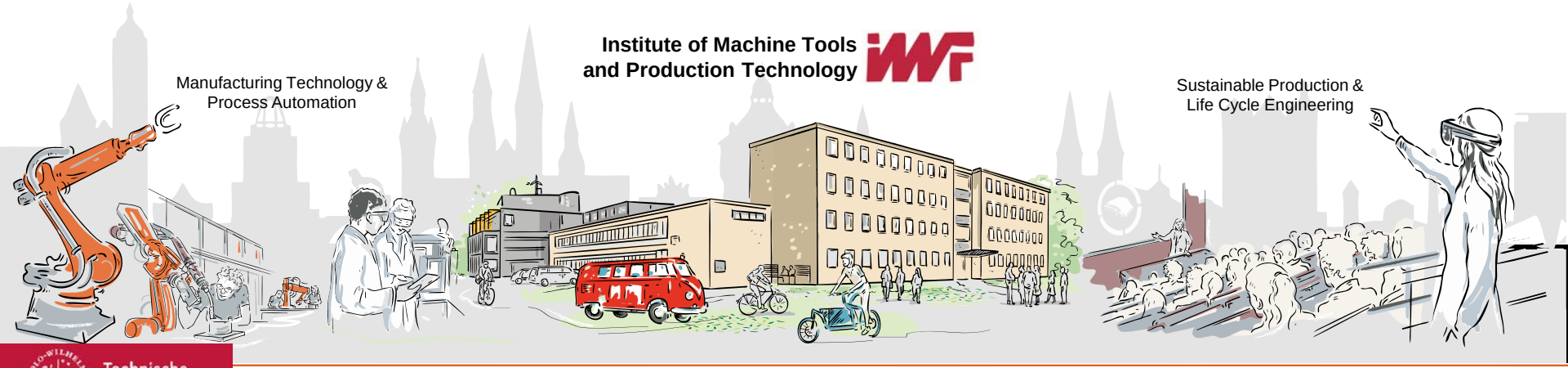
FNR Fachagentur Nachwachsende Rohstoffe e.V.

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m.ruhnke@tu-bs.de



Karlsruhe Institute of Technology

Institute of Production Science

How to Qualify Industrial CT Workflows for Component Inspection Inside Products

Edwin Blum, Martin Benfer, Gisela Lanza



Benefits of industrial CT in Circular Factories

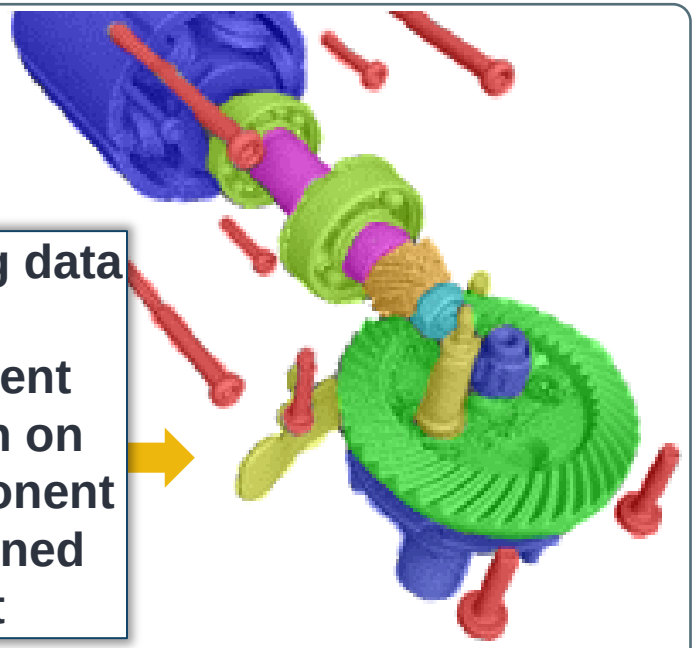
CT is a non-destructive testing method



Virtual Product



The resulting data yields measurement information on every component of the scanned product



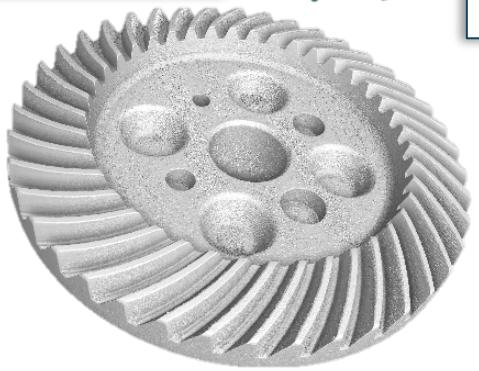
CT yields the potential to avoids costly disassembly, but industry needs measurand-based decisions

[1]

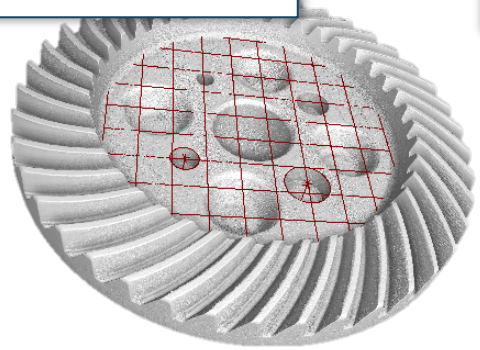
Reproducible measurements require a datum reference frame (ISO 5459)

Setup (on CAD)

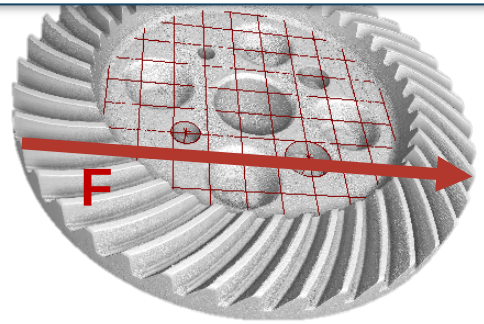
CAD file



Define the reference frame from datums

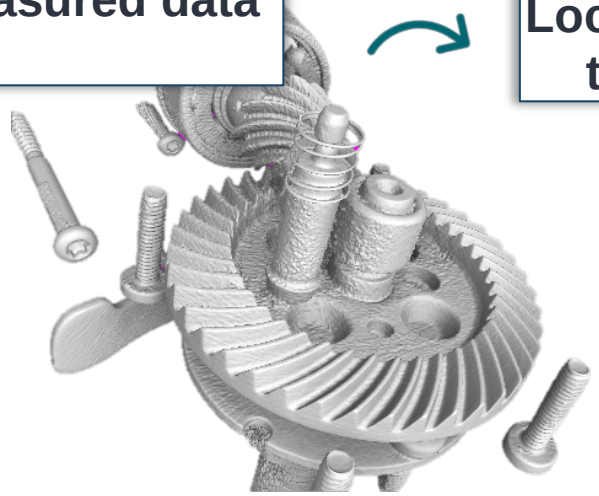


Define the measurement plan in this frame

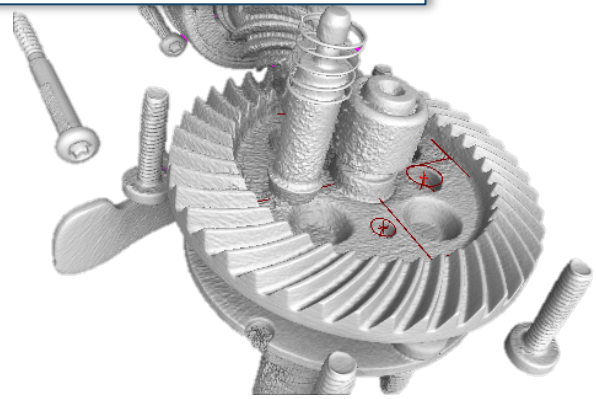


On the shopfloor

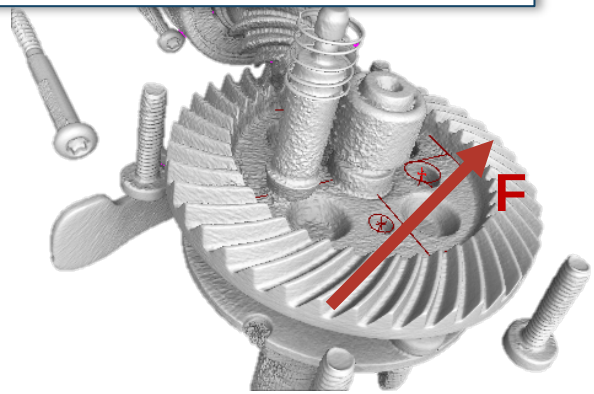
Measured data



Locate the datums, build the reference frame

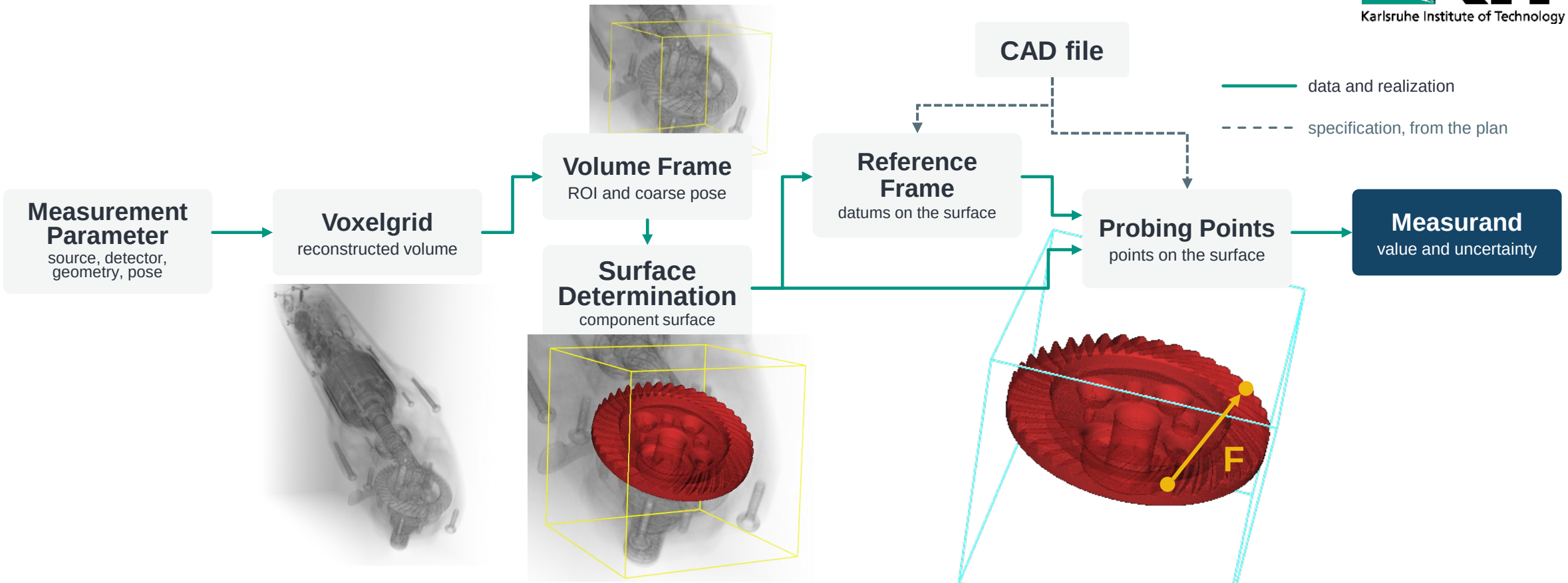


Apply the plan to extract the measurand



[2]

The artifacts along the measurement chain



Voxelgrid

CT parameters (source, detector, geometry, pose) set the voxel size and image quality [3, 4].

Surface Determination

Surface determination is a local problem: errors stay local and global drift is negligible [1].

Frame and probing

Datums and probing points are specified a priori from the plan and realized on the surface [2].

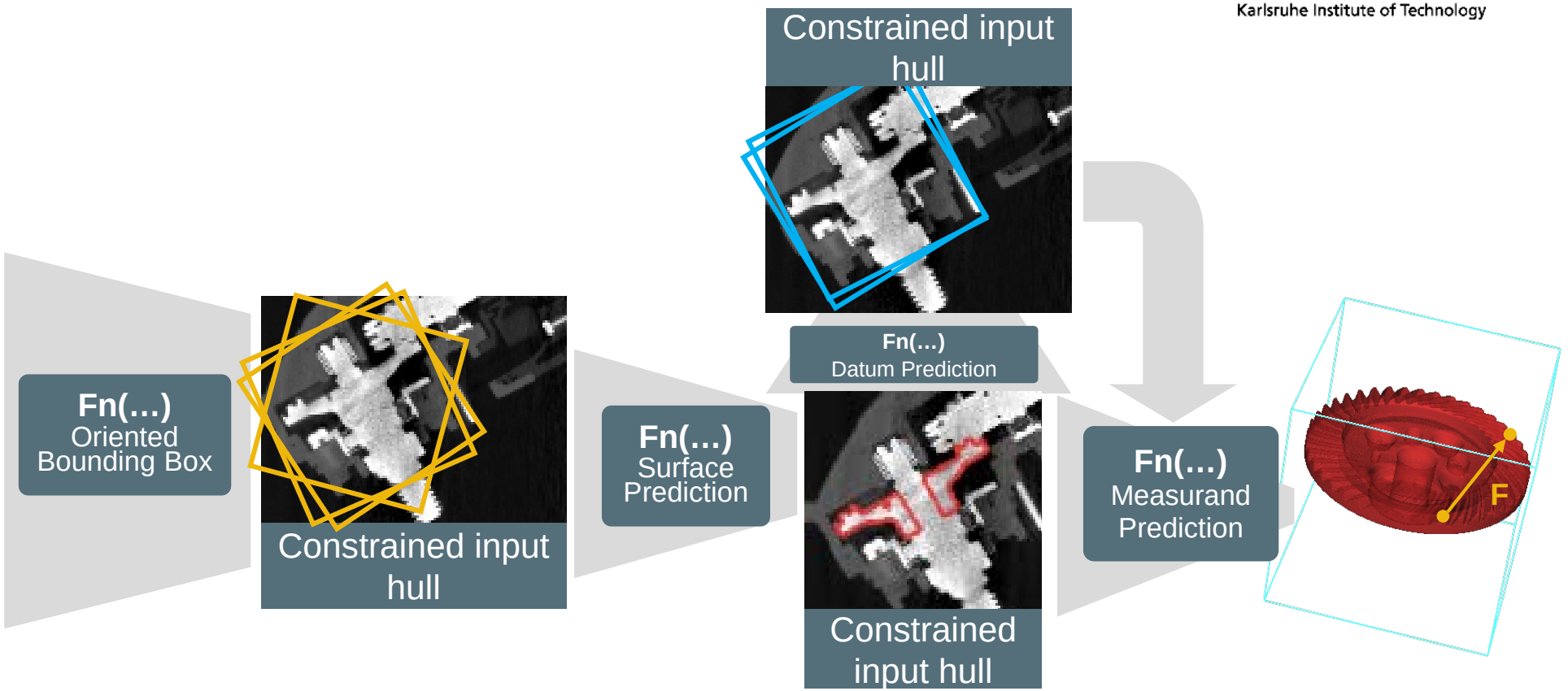
Stages for component inspection inside products

Constrained input hull

Input parameter are not arbitrary:

- Different wear states are covered by the training dataset
- Low product-pose variance from dedicated fixtures
- Scan settings fixed per measurand





Each stage must be robust enough to bound the error and uncertainty it adds. The chain is quantifiable once the input solution space is small enough.

Evaluating the chain for industrial robustness

1 Structured stress tests

Sample the input hull, especially at its edges

- Define the input variables of the hull
  - Vary product and component pose across its feasible range
  - Cover the whole range of realistic wear states
  - Repeat measurements to capture stochastic effects

▶ By covering the full range of realistic input conditions, the dataset keeps the network in the interpolation regime.

2 Stage-coupled metrics

Each stage must succeed on the defined stress tests

- A defined level of accuracy and robustness must be met
- Well-designed interfaces let each stage bound the error and uncertainty it adds

▶ Training the whole pipeline sequentially yields a constrained input hull at every stage

3 Reference strategies

Calibrated reference parts give traceable ground truth

- Evaluate and optimize against real quantity values, not just benchmark scores

▶ Reference measurements or held out data can be used to calibrate the stages and reduce the overconfidence of ML methods.

[5, 6]

Conclusion

CT workflows become qualifiable through a constrained input and stage-wise assessment, not just benchmark scores

Stage-coupled problem

Localization and surface determination, linked through the chain to a frame-based measurand.

Constrained input

Each learned stage works in a constrained, quantifiable solution space.

Assess, not benchmark

Stress tests, stage-coupled metrics, and reference strategies expose failure modes and quantify error at the measurand.

Qualification is demanding

- Calibrated reference parts required as traceable ground truth
- Stress-test coverage across the whole data input range
- (Re-)Validation of every stage
- Effort re-incurred per component

- Synthetic and digital-twin references
- Targeted stress testing
- Automated training and evaluation pipelines
- Use adapted smaller state-of-the-art neural networks [1]

Literature

[1] Blum, E., Hild, T., Koch, D., Benfer, M., & Lanza, G. (2026). *Fast Industrial Computed Tomography for Remanufacturing: Evaluating Measurement Time savings with 3D UNETR Sparse-view Segmentation*. https://doi.org/10.5445/IR/1000192598

[2] International Organization for Standardization. (2024). Geometrical product specifications (GPS) - Geometrical tolerancing - Datums and datum systems (ISO Standard No. 5459:2024). https://www.iso.org/standard/87855.html

[3] Kruth, J.-P., Bartscher, M., Carmignato, S., Schmitt, R., De Chiffre, L., & Weckenmann, A. (2011). Computed tomography for dimensional metrology. CIRP Annals, 60(2), 821-842. https://doi.org/10.1016/j.cirp.2011.05.006

[4] Carmignato, S., Dewulf, W., & Leach, R. (Eds.). (2018). Industrial X-ray computed tomography. Springer.

[5] Joint Committee for Guides in Metrology. (2008). Evaluation of measurement data - Guide to the expression of uncertainty in measurement (JCGM 100:2008). https://doi.org/10.59161/JCGM100-2008E

[6] Verein Deutscher Ingenieure. (2015). Computed tomography in dimensional measurement - Determination of the uncertainty of measurement and the test process suitability of coordinate measurement systems with CT sensors (VDI/VDE Standard No. 2630 Blatt 2.1:2015-06).

Thank you for your attention.



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German Research Foundation

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Thank you for your attention!

Karlsruhe Institute of Technology

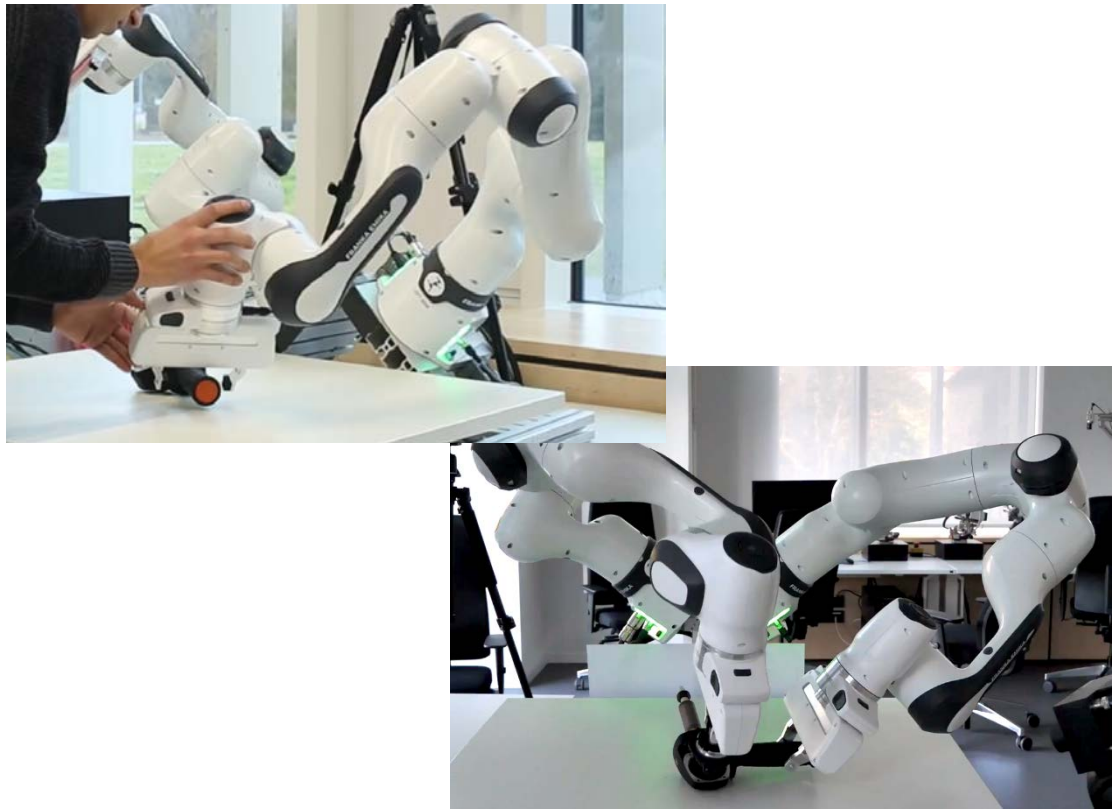
Learning Via-Point Movement Primitives With Object End Pose Estimators for Robot Disassembly Tasks

Christian Dreher, Tilman Daab, Andre Meixner, Sebastian Rietsch, Annemarie Schaub, David Vigneron, and Tamim Asfour

Institute for Anthropomatics and Robotics (IAR), Karlsruhe Institute of Technology (KIT)

Motivation

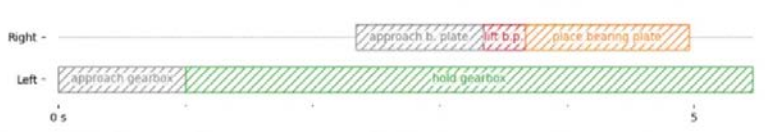
- Assembly and disassembly is ubiquitous in a circular factory
- **Disassembly remains challenging** due to varying conditions, small quantities
- **Learning from human demonstration** is a powerful paradigm to enable teaching robots new skills without tedious manual programming (also called Programming by Demonstration)
- We present **two contributions** towards this vision



Approach

System overview







Learn Unimanual VMPs
using kinesthetic teaching
⇒ Library of motion primitives

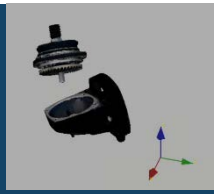
Synchronize VMPs
using temporal task constraints
⇒ Bimanual task execution plan

Bimanual Robot Execution
using VMPs and temporal plan

Learn VMP end pose estimators
w.r.t. object parts

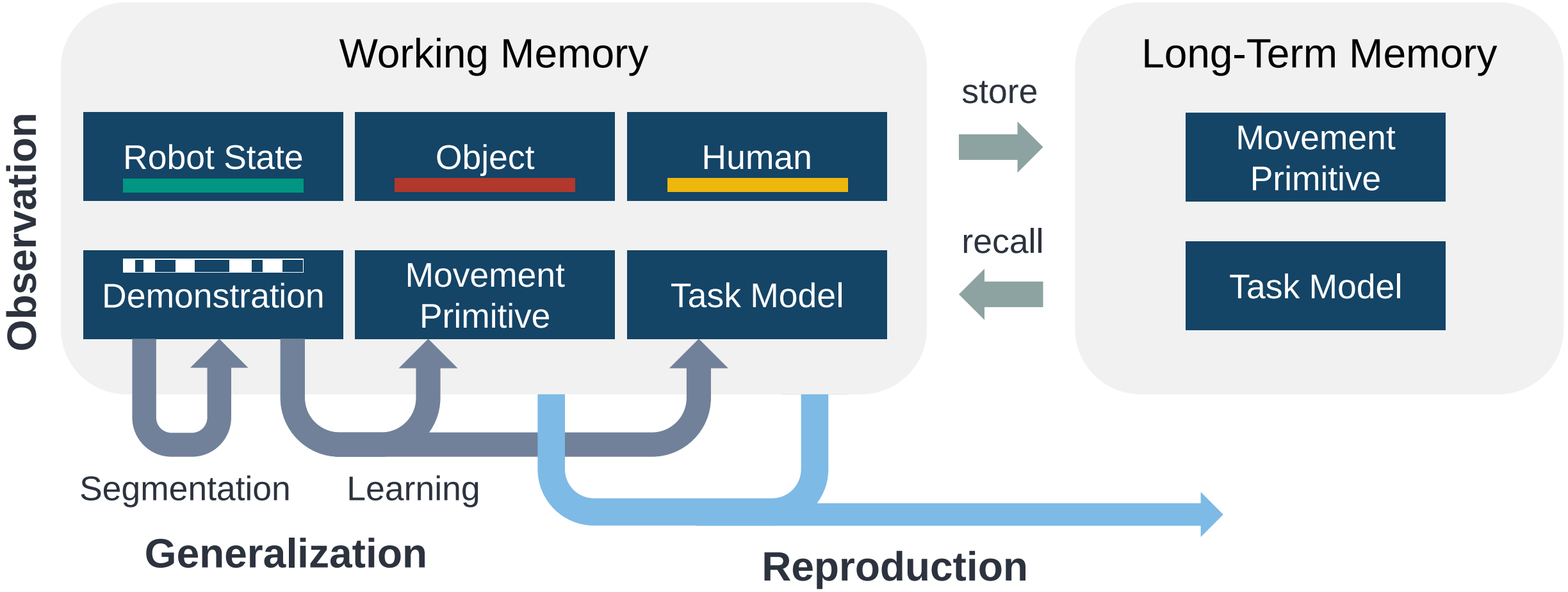
Retarget VMPs to object
parts in current scene

6-D Object Part Pose Estimation Pipeline
using Fast-FoundationStereo, CNOS, FoundationPose
⇒ 6-D pose of each object part



Programming by Demonstration Interface

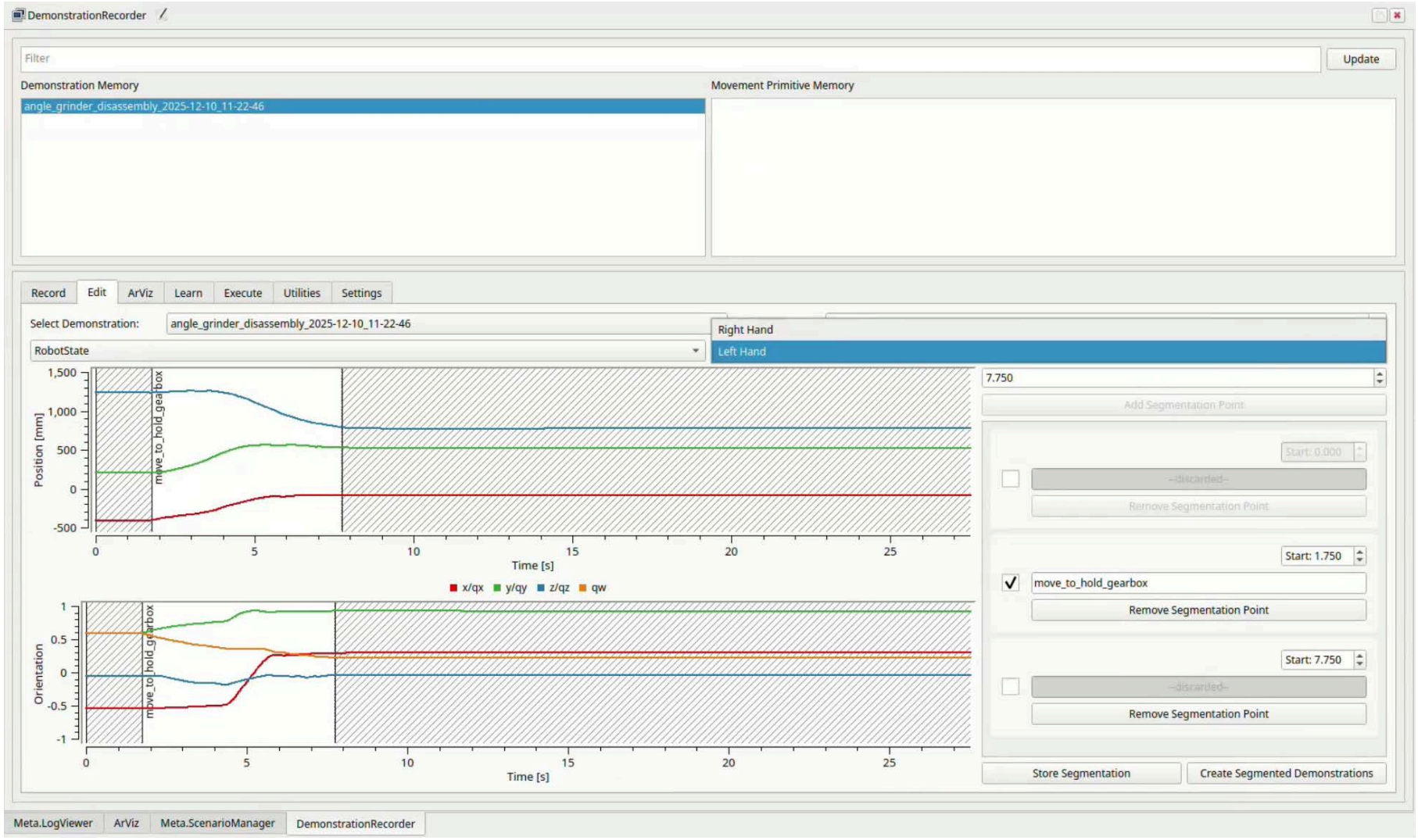
Enabled by our cognitive architecture in ArmarX



F. Peller-Konrad, R. Kartmann, C. Dreher, A. Meixner, F. Reister, M. Grotz, and T. Asfour. A Memory System of a Robot Cognitive Architecture and Its Implementation in ArmarX. Robotics and Autonomous Systems (RAS), page 104415, 2023.

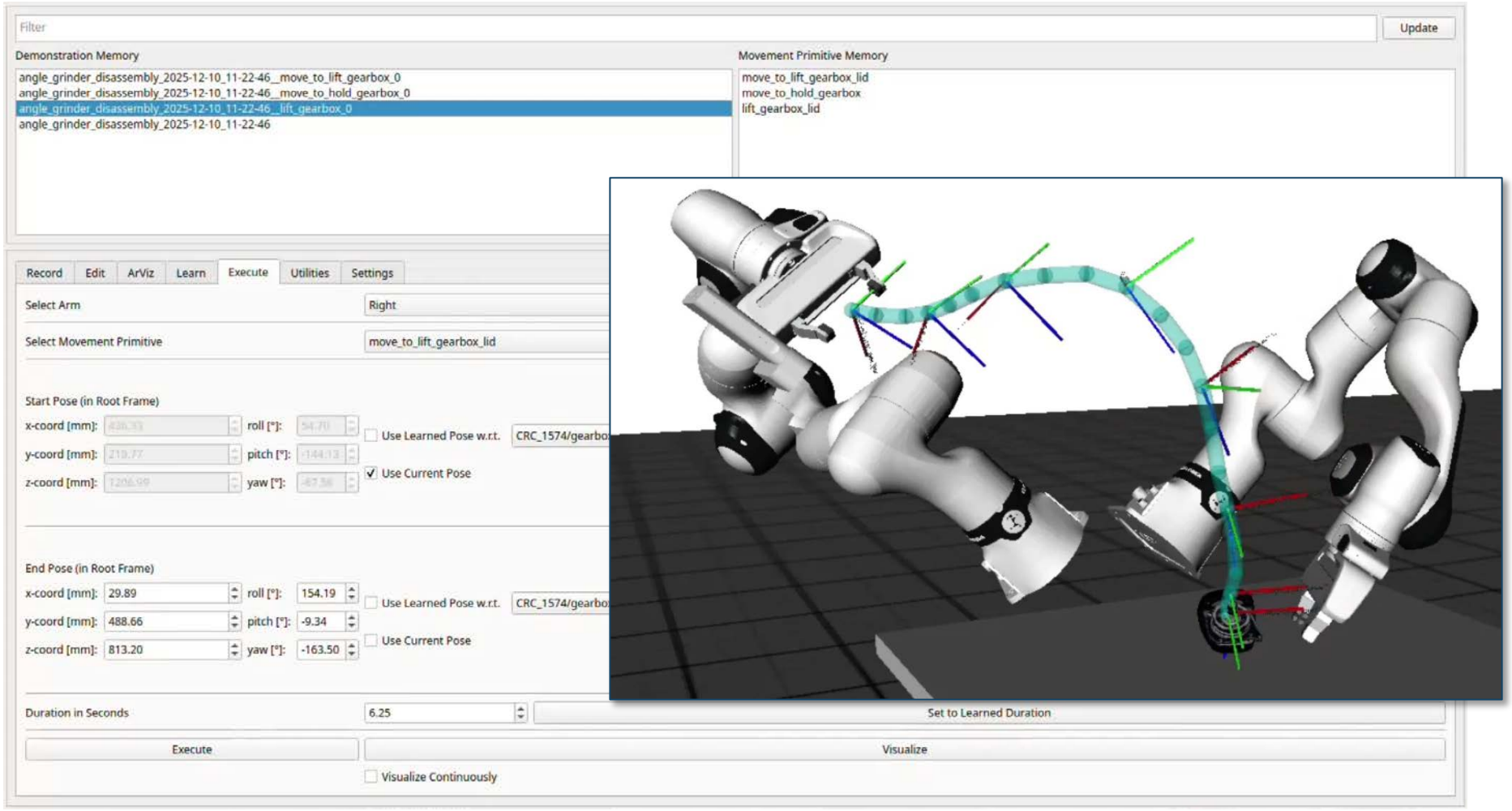
Programming by Demonstration Interface

Learn new VMPs or update existing



Programming by Demonstration Interface

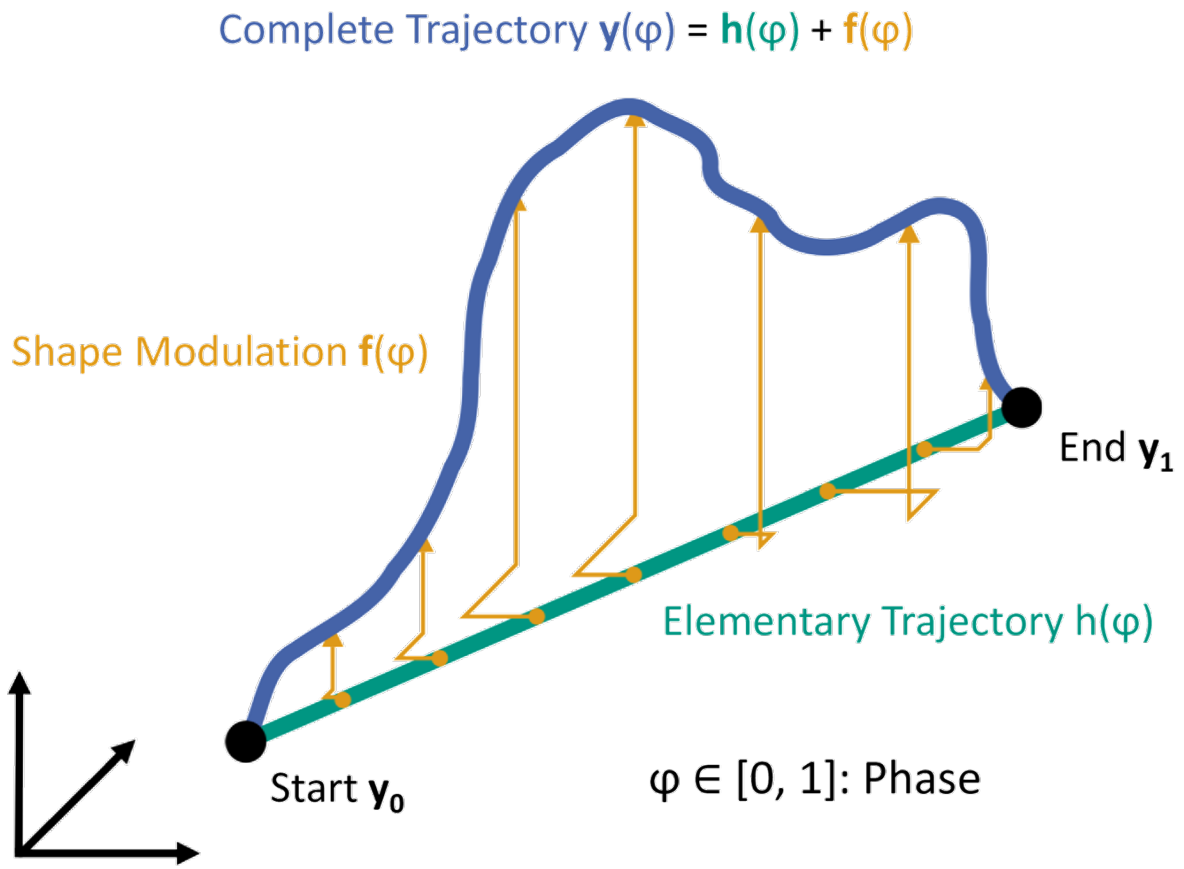
Introspection of movement primitive library by visualization and execution



Via-Point Movement Primitives (VMPs)

Properties

- **Trajectory model**, consisting of
  - Elementary trajectory to connect start with end
  - Shape modulation to represent motion characteristics
- Can be **retargeted** to new end poses …
- Can be forced to go through **via-points** …
- … while **keeping** the original trajectories' shape



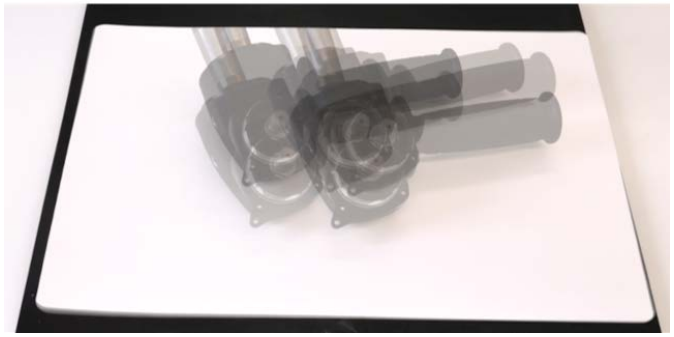
T. Daab, N. Jaquier, C. Dreher, A. Meixner, F. Krebs, and T. Asfour. Incremental Learning of Full-Pose Via-Point Movement Primitives on Riemannian Manifolds. In International Conference on Robotics and Automation (ICRA), pages 2317–2323, 2024.

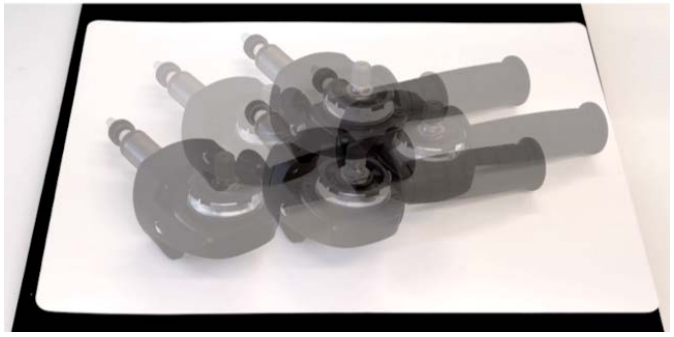
Y. Zhou, J. Gao, and T. Asfour. Learning Via-Point Movement Primitives with Inter- and Extrapolation Capabilities. In International Conference on Intelligent Robots and Systems (IROS), pages 4301–4308, 2019.

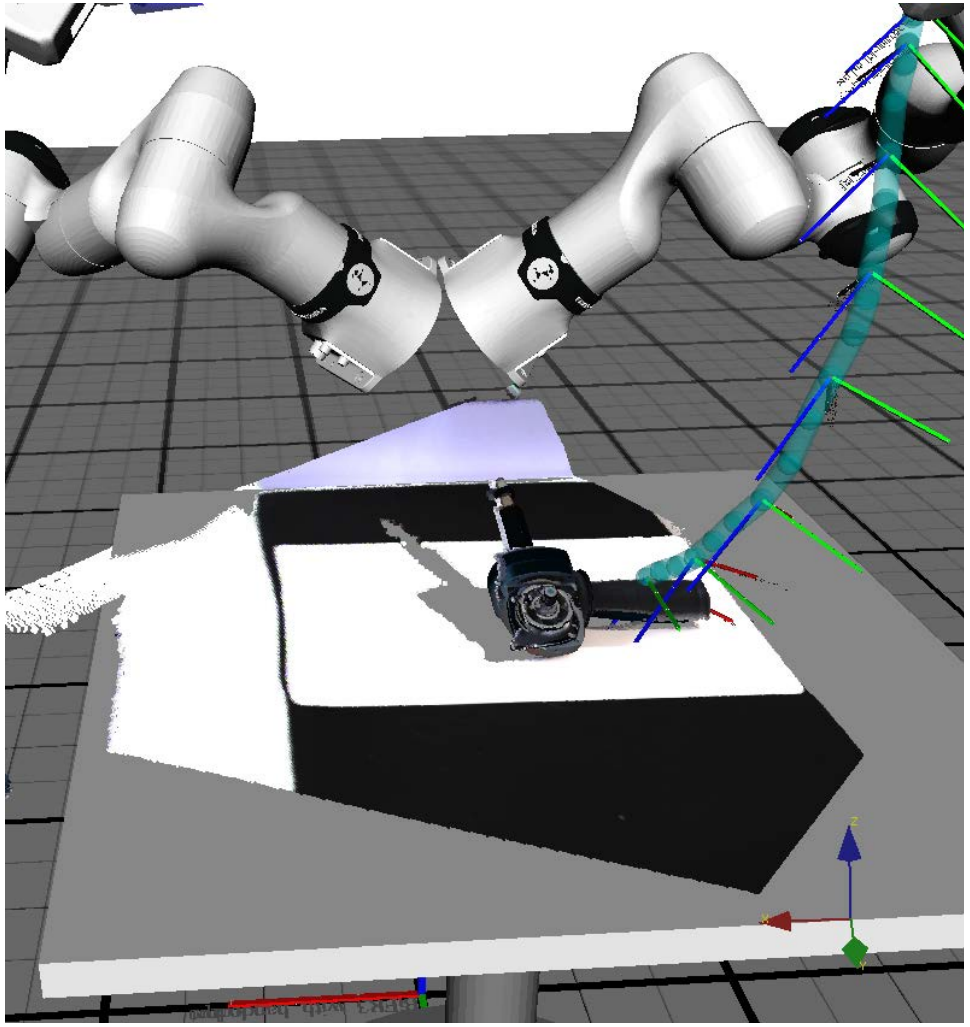
Trajectory End Pose Estimation

What is required?

- Robot needs to be able to …
  - … **identify**, to which objects in the scene a demonstration correlates to
  - … **perceive** the objects in new scenes to retarget learned motions



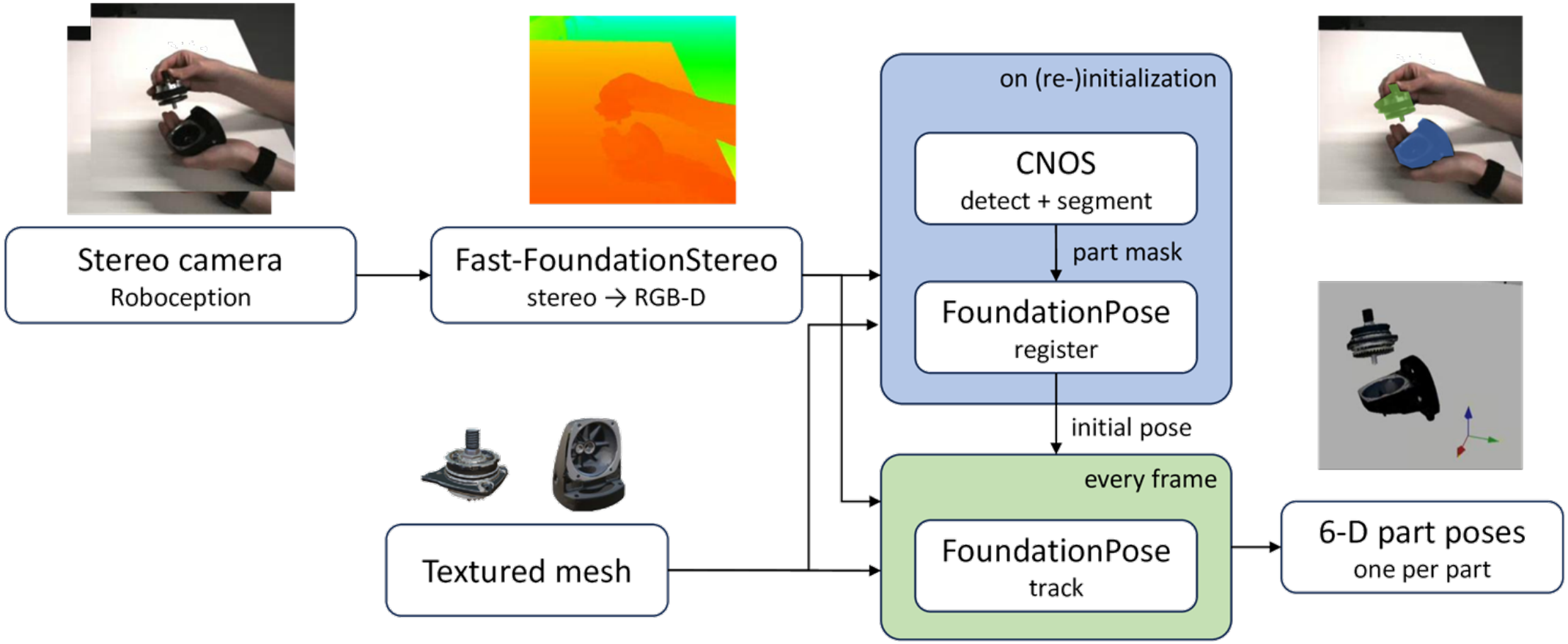




➔ Thus, a **6-D object part pose estimation** is needed

6-D Object Part Pose Estimation Pipeline

Schematic overview



B. Wen, S. Dewan, and S. Birchfield. Fast-FoundationStereo: Real-Time Zero Shot Stereo Matching. In Proceedings of the Conference on Computer Vision and Pattern Recognition (CVPR), pages 7513–7524, 2026.

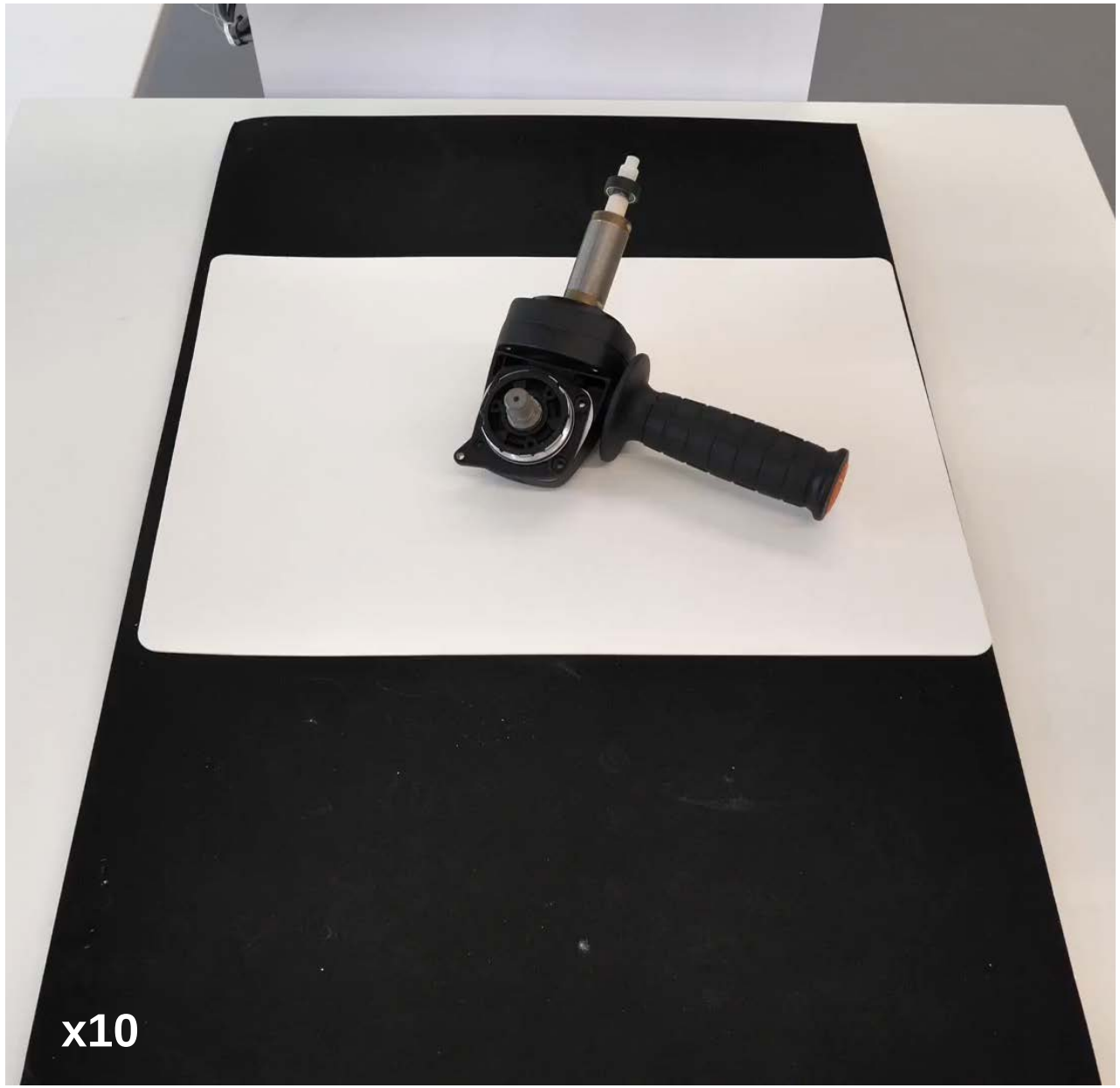
V. Nguyen, T. Groueix, G. Ponimatkin, V. Lepetit, and T. Hodan. CNOS: A Strong Base-line for CAD-Based Novel Object Segmentation. In International Conference on Computer Vision (ICCV) Workshops, pages 2134–2140, 2023.

B. Wen, W. Yang, J. Kautz, and S. Birchfield. FoundationPose: Unified 6D Pose Estimation and Tracking of Novel Objects. In Conference on Computer Vision and Pattern Recognition (CVPR), pages 17868–17879, 2024.

Robot Experiments

Experimental setup

- 6 different settings
  - 3 different orientations on the table
  - Lying on gearbox vs. lying flat
- 5 retries per setting
- Report on:
  - Hold success rate ➔ object fixated
  - Grasp success rate ➔ object lifted
  - Place success rate ➔ object placed at target
  - Attempts of executing vision pipeline (min once)



Results (I)

Disassembly scenario

- Azimuthal orientation: 0° = angle grinder's drive train perpendicular to robot; +/- 30°
- Polar orientation: Angle grinder's drive train parallel to table = 0°; tilted on gearbox = -30°
- *: Recorded before recalibration

Setting (azimuthal, polar)	Hold Success %	Grasp Success %	Place Success %	Pose estimation tries	
				median	mean
ca. (0°, -30°) *	100%	80%	60%	1	1.0
ca. (+30°, -30°) *	100%	60%	40%	1	1.0
ca. (-30°, -30°)	100%	100%	100%	1	3.8
ca. (0°, 0°)	100%	80%	80%	1	1.0
ca. (+30°, 0°)	100%	100%	100%	1	1.4
ca. (-30°, 0°)	100%	100%	100%	3	10.2

Results (II)

6-D object part pose estimation pipeline benchmarks

- Per-component latency in isolation and under full system load (two tracked parts) on a single RTX 4090, reported as median (p_{50}) / tail latency (p_{95})
- Components compete for GPU resources, settle at ca. 16 Hz while tracking

Component	Isolated p_{50} / p_{95} (ms)	Under load p_{50} / p_{95} (ms)
Stereo (per frame)	25.6 / 30.9	30.7 / 47.0
Tracking (two parts)	13.4 / 17.3	57.1 / 72.8
CNOS detection (per part)	— / —	291.8 / 304.4
Registration (per part)	547.7 / 563.2	1071.5 / 1098.0

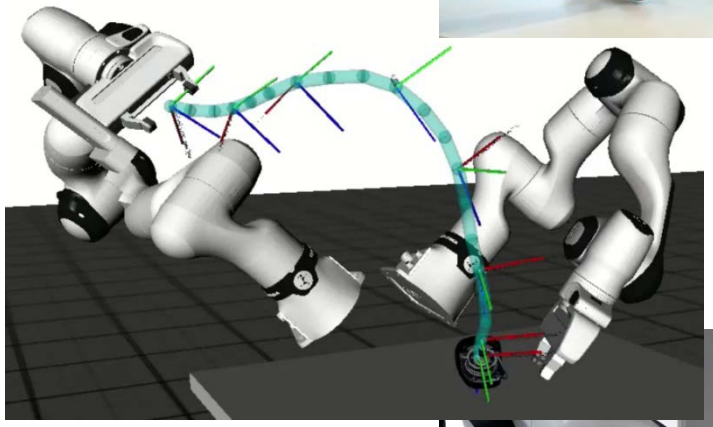
Conclusion and Future Work

- Presented a **system for learning VMPs with end pose estimators w.r.t. object part poses** using an intuitive and interactive interface

- Object part poses are estimated using a novel **6-D object part pose estimation pipeline** that only requires CAD models of objects

- **Future works** include
  - More complex actions that require tool use
  - Learning from visual observations



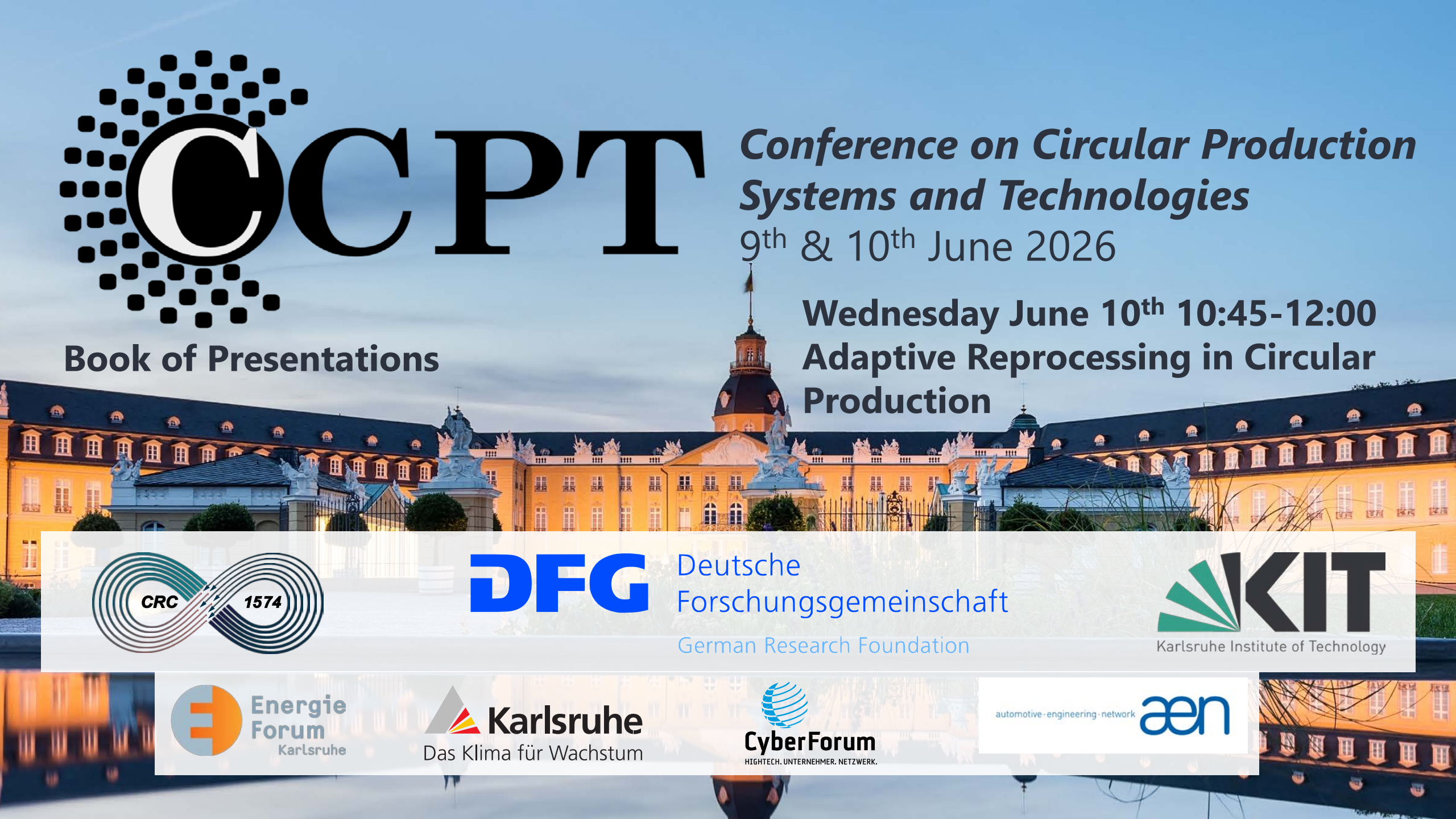




Thank you!

Questions?

The research leading to these results has received funding from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – SFB 1574.



CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 10:45-12:00
Adaptive Reprocessing in Circular Production

CRC 1574

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

KIT Karlsruhe Institute of Technology

Energie Forum Karlsruhe

Karlsruhe Das Klima für Wachstum

CyberForum HIGHTECH. UNTERNEHMER. NETZWERK.

automotive · engineering · network aen

Karlsruhe Institute of Technology

Institute of Production Science

Detection of Nozzle Wear in High-Speed Directed Energy Deposition through Powder Stream Caustic Analysis

Helena Wexel, Patrick Gajek, Luca Thober, Frederik Zanger



Reprocessing in Circular Production

Unique products

Variable condition of used products

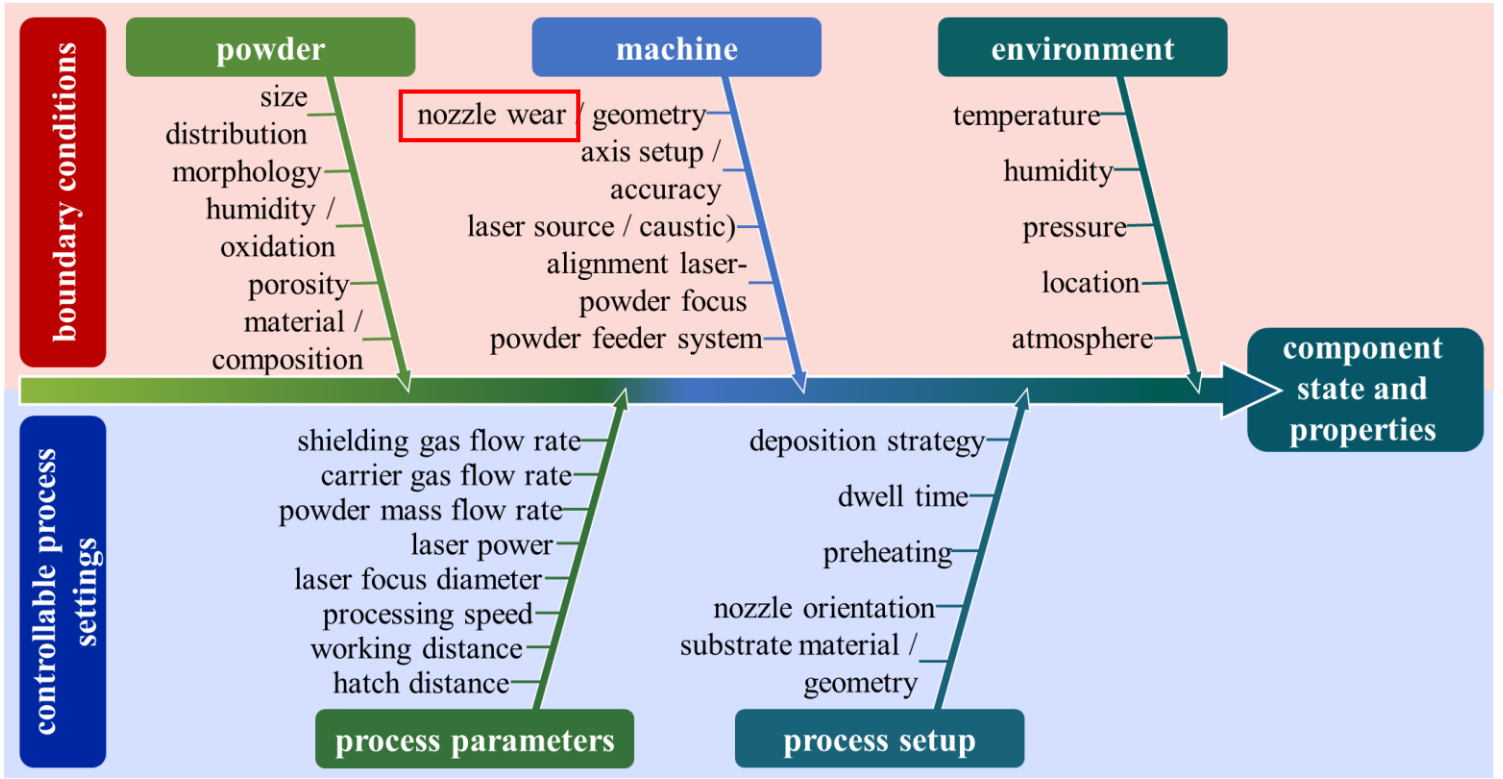


High number of variants



High geometric and material divergence

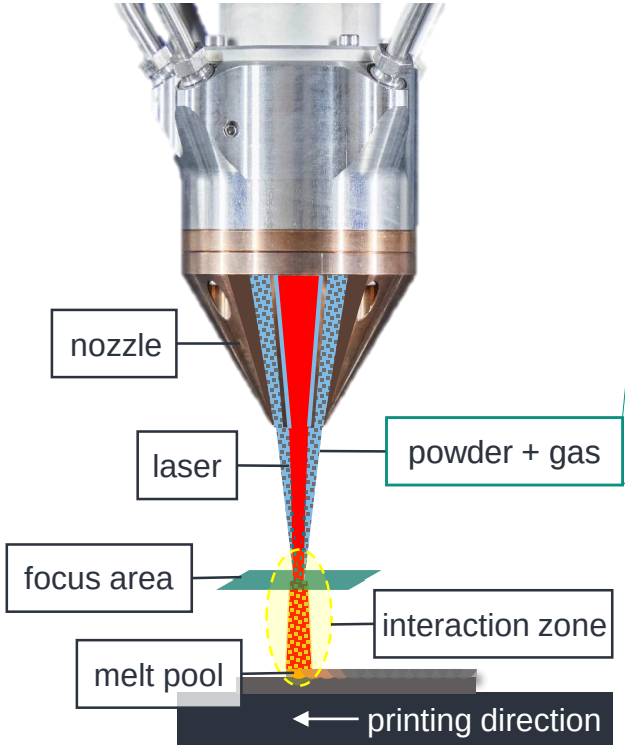
Numerous influencing factors



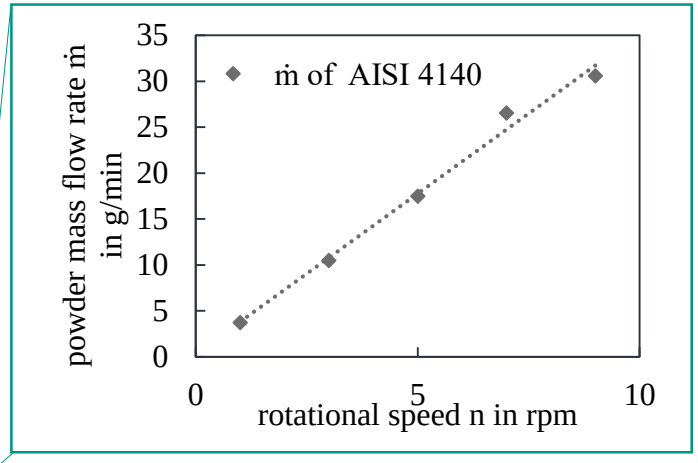
Stable boundary conditions are required

Experimental realization

AM process



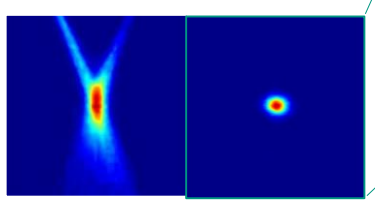
Parameter variation



Optical analysis powder-gas flow

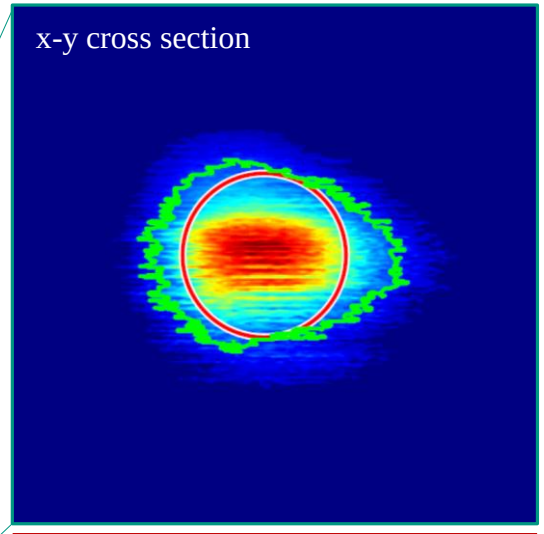


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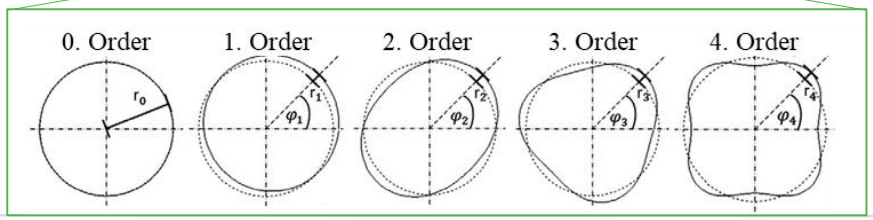


- Ideal 86% powder focus diameter
- Powder focus position

Fourier transformation – circularity assessment

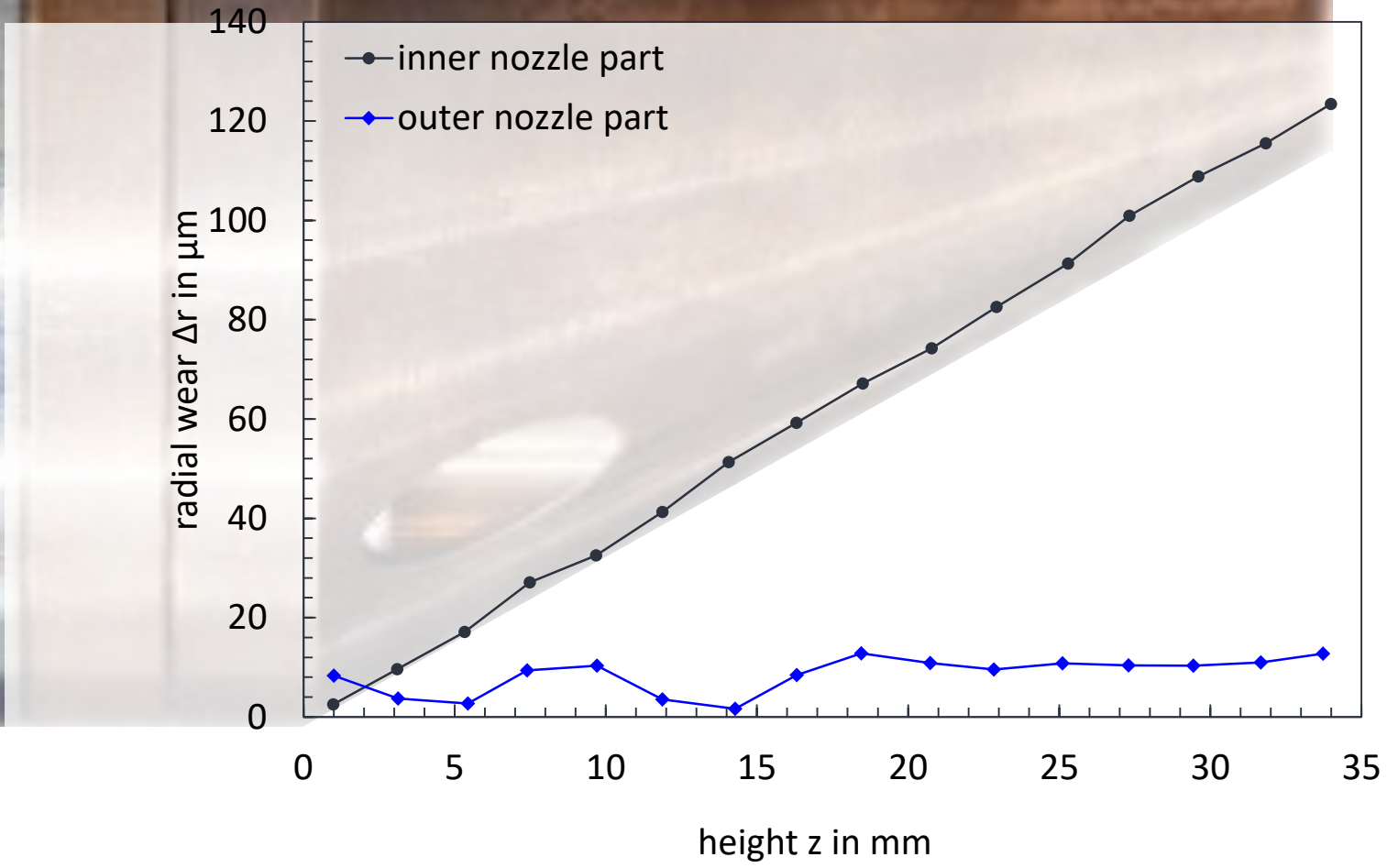


- ideal 86% powder focus diameter $d_{PF,86,ideal}$
- actual 86% powder focus contour $d_{PF,86,actual}$



Nozzle wear

Quantitative characterization worn nozzle

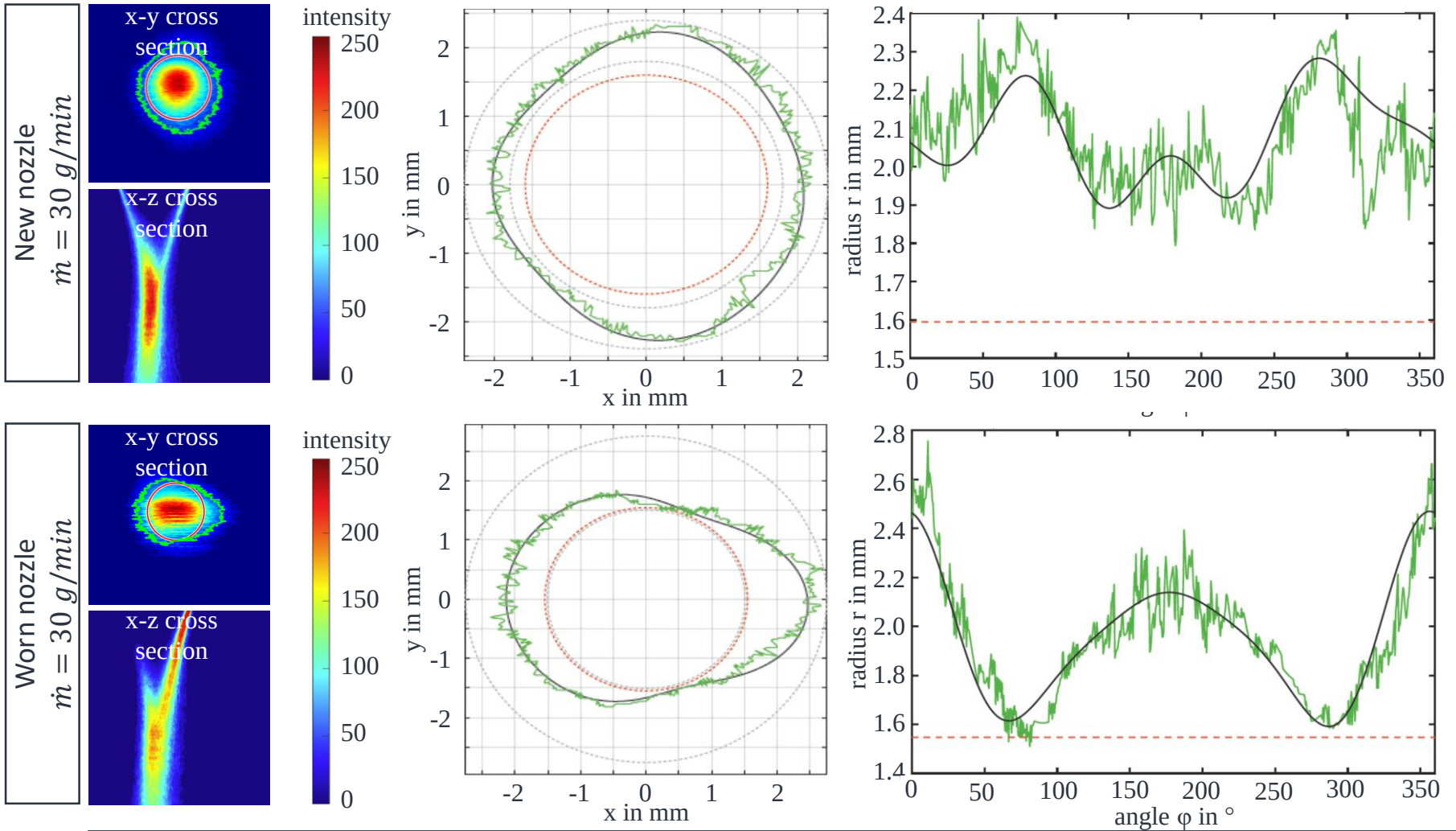


outer nozzle part:
- moderate material removal
- minimal axial wear progression

inner nozzle part:
- pronounced monotonic increase in material removal towards nozzle tip
- progressive erosion in the direction of powder flow
- suggesting non-uniform powder-wall interaction

Results and Discussion

Powder caustic measurements



ideal 86% powder focus diameter and position:
correlations with powder mass flow rate known from literature also apply to worn nozzle:

- ↑ powder mass flow rate → ↑ powder focus diameter increases
- powder focus position remains largely unaffected

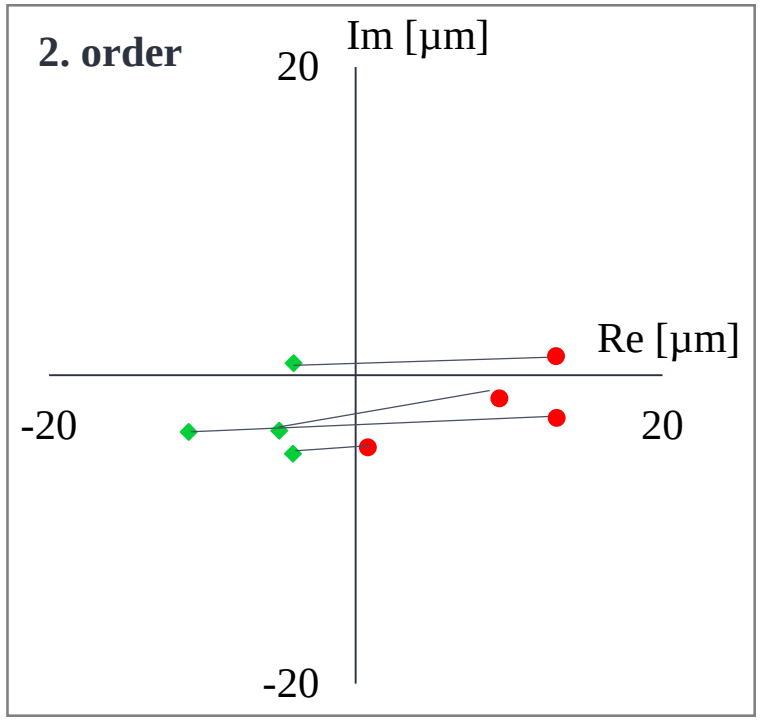
→ Conventional scalar caustic descriptors primarily reflect process-parameter-induced changes.

actual 86% powder focus contour:
worn nozzle shows deviated focus contour and inhomogeneous powder cone

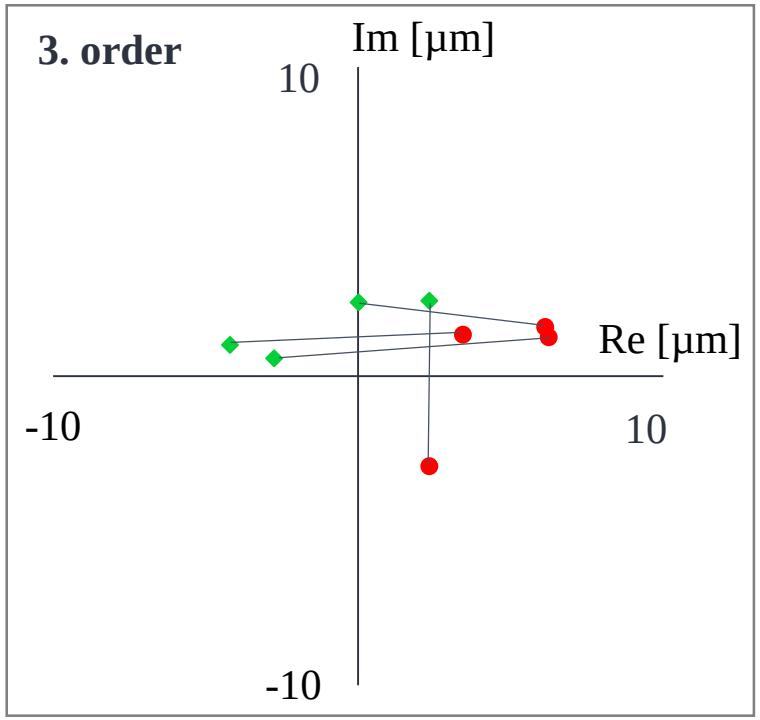
Results and Discussion

Fourier analysis

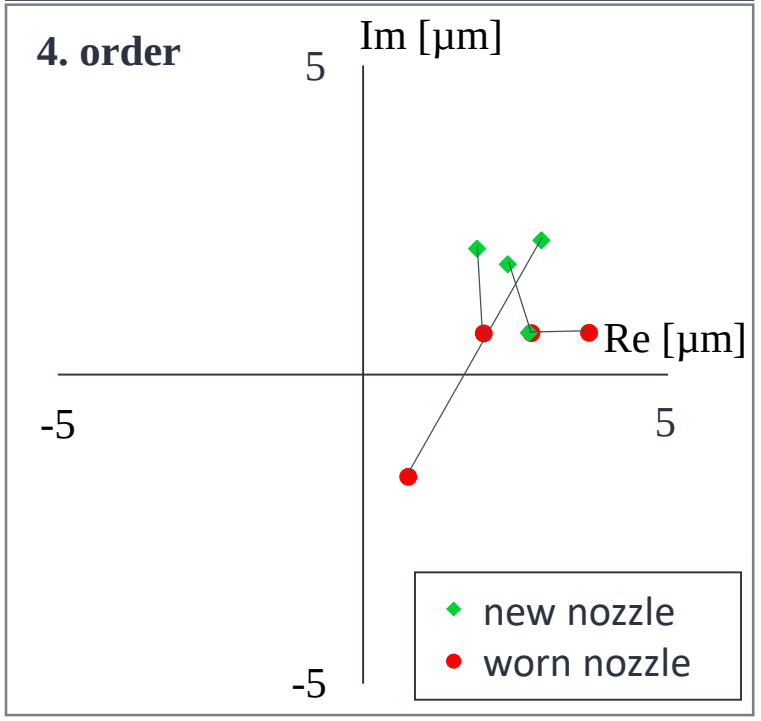
Ovality



Triangularity



Quadrangularity



Abrasive nozzle wear exerts substantial influence on ovality

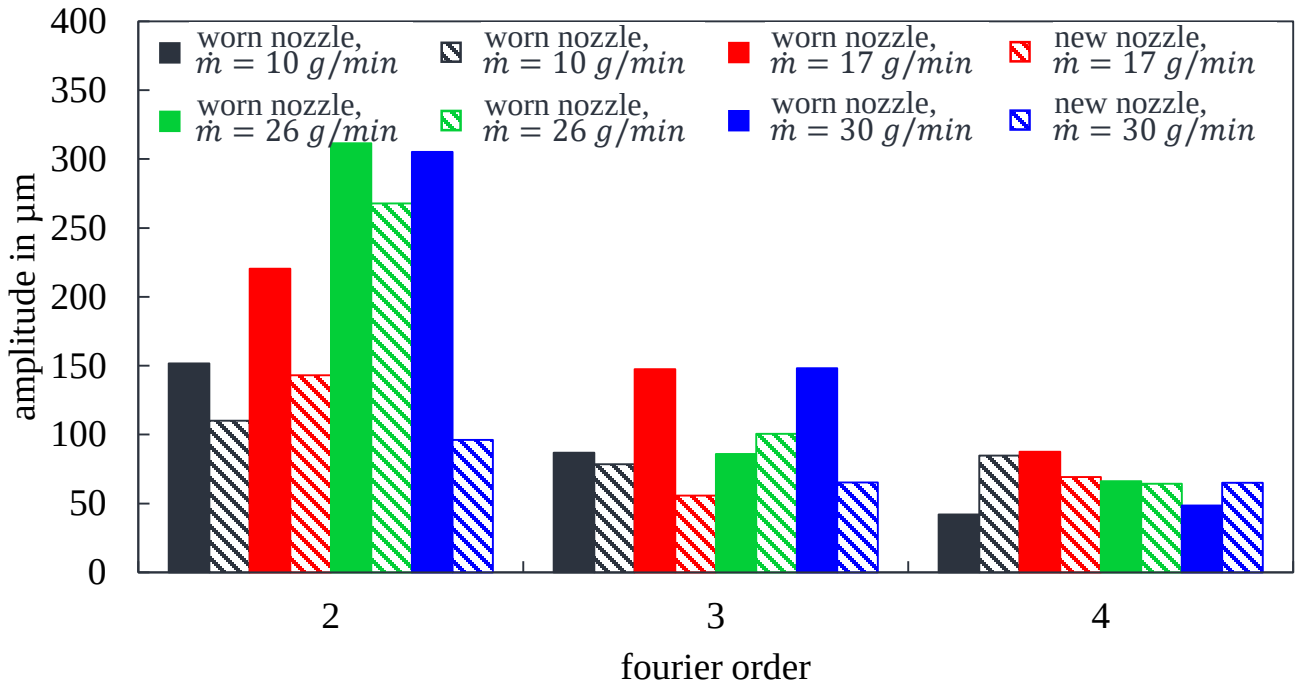
Minor alterations in triangularity are observable

No substantial contribution for either nozzle condition

Scalar descriptors capture global powder stream characteristics
Fourier descriptors additionally reveal wear induced directional asymmetries in the powder distribution

Results and Discussion

Fourier analysis



- no discernible trend
- Geometric deviation of the powder focus is dependent on the nozzle geometry rather than on the process parameter

Conclusion and Outlook

1. Nozzle wear significantly alters powder stream symmetry, while conventional characteristic parameters such as powder focus diameter and focal position continue to follow expected trends with increasing powder mass flow rate.

2. Fourier-based analysis of the 86% powder focus contour enables a quantitative description of wear-induced distortions, allowing the actual powder stream contour to be decomposed into characteristic geometrical deviations such as ovality, triangularity, and quadrangularity.

3. The second Fourier order (ovality) proved to be the most sensitive indicator of nozzle wear, showing a clear increase for the worn nozzle across all investigated powder mass flow rates.

4. The observed geometric deviation was primarily dependent on nozzle condition rather than process parameters, as no systematic correlation between powder mass flow rate and the magnitude of the Fourier amplitudes was identified. This highlights the suitability of the method for condition monitoring independent of the selected operating point.



- **Extend** the presented caustic-based monitoring approach to further investigate the **relationship between nozzle wear, powder stream deviation,** and **resulting deposition quality**.
- **Fourier descriptors** will be **correlated with track geometry** and component **properties** to evaluate the **impact of nozzle degradation on reprocessing quality**

Thank you – questions?

Funded by the German Research Foundation (DFG, German Research Foundation) - SFB-1574 – 471687386.



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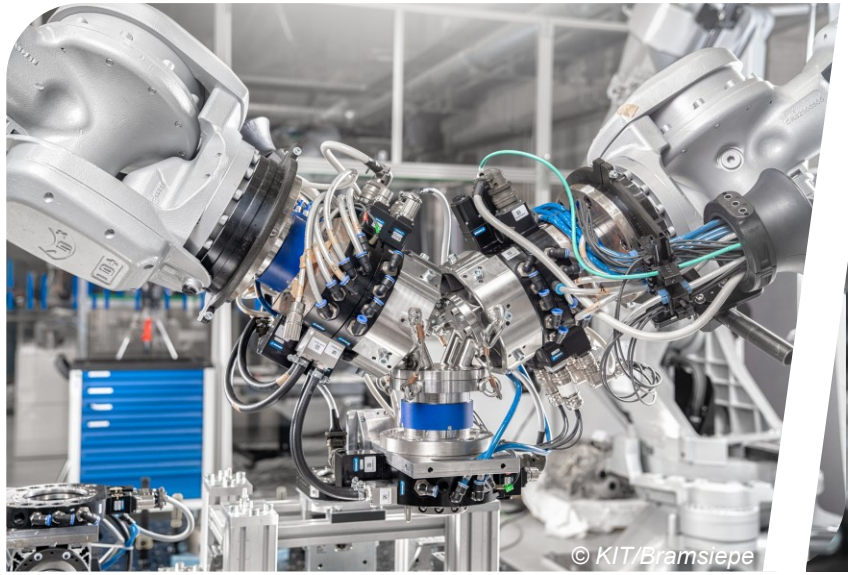
Karlsruhe Institute of Technology

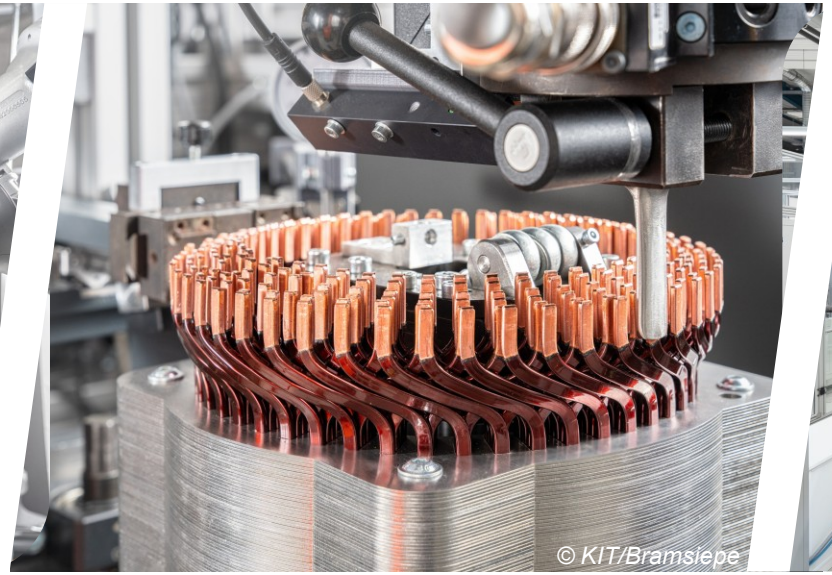
FAKT

wbk Institute of Production Science

A simulation-based approach to address planning challenges in electric traction motor remanufacturing

10. June 2026 | CCPT 2026 | Nicolaus Klein, Martin Jestädt, Jörg Drees, Sebastian Henschel, Jürgen Fleischer







Environmental impact of EV manufacturing

CO_2 and greenhouse gas emissions

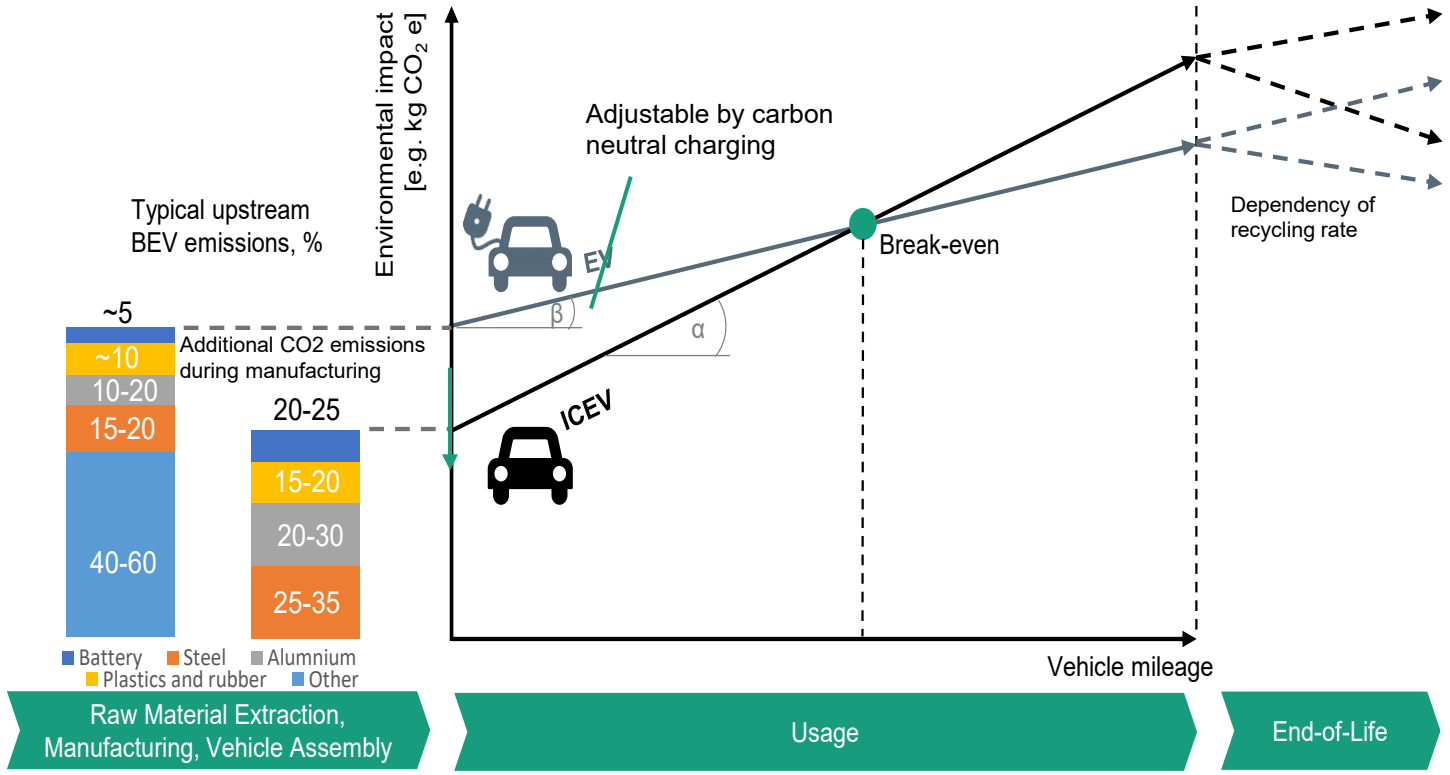
More CO_2 by EV than ICE during manufacturing

Break-even-point during usage

Circular economy to reduce lifecycle impact of EV

EVs contain critical raw materials* and rare earth materials*

* e.g. NMC, platinum, neodym (Dependency on foreign countries)

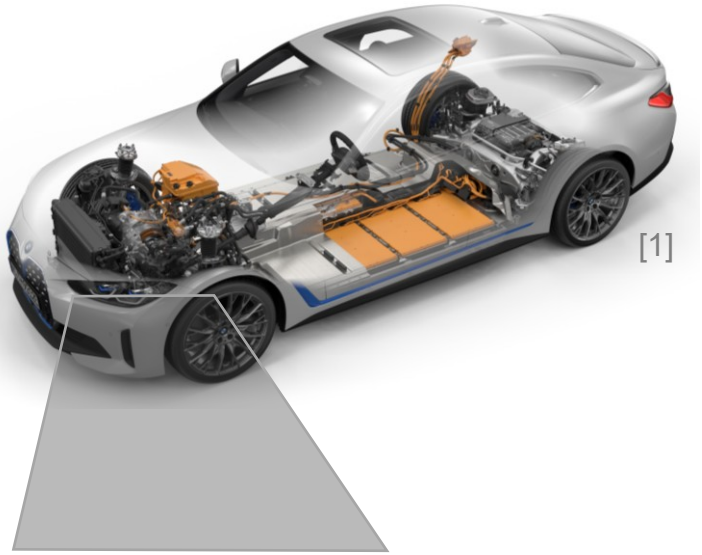


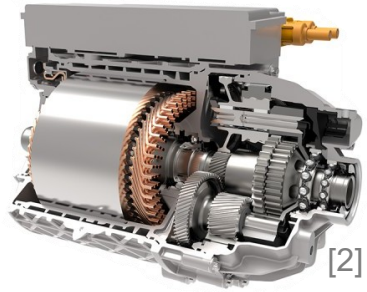
Circularity approaches necessary to reduce environmental impact.

Fleischer (2025); Cerdas; McKinsey

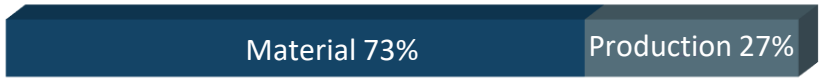
Unlocking Circular Value in EVs

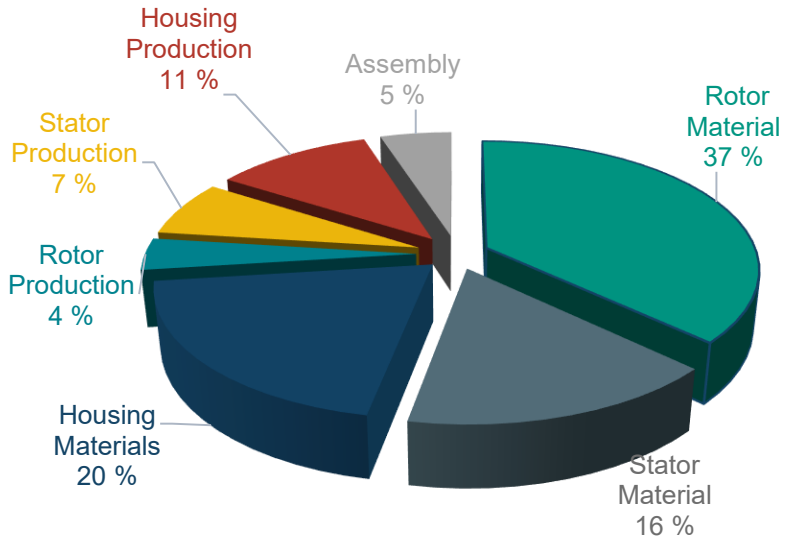
Electric Traction Motors as core elements of EVs


[1]


[2]

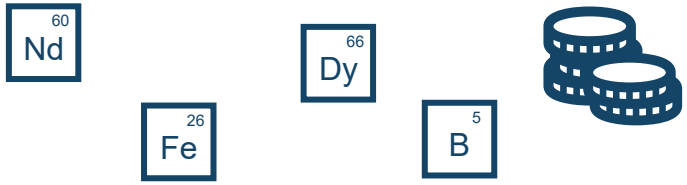
Distribution of the value creation potential of PMSM





Raw material prices for NdFeB magnets

Element	Mass share	Cost/kg in €	Cost/kg share in €
Neodymium	25 %	135,8	33,9
Iron	69 %	0,1	0,07
Boron	1 %	3,3	0.03
Dysprosium	5 %	526,1	26,3
			60,3
Magnet mass per rotor		**~ 2 kg**	**120,7 €**

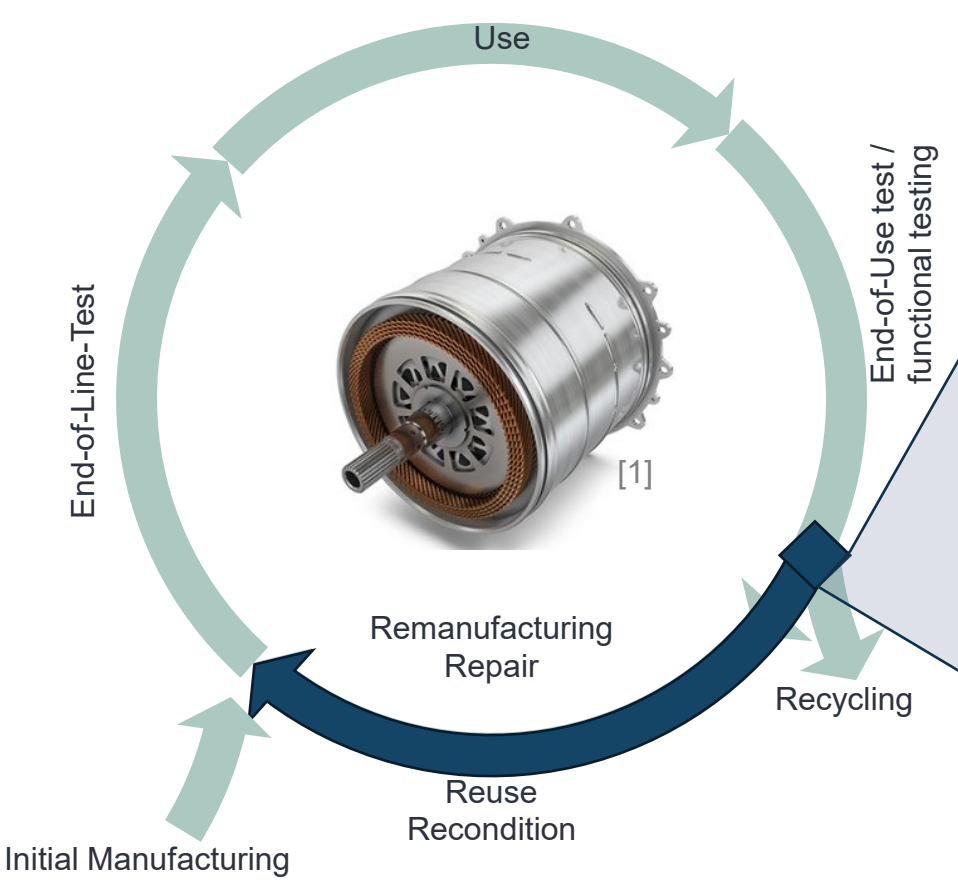


Electric traction motors contain several raw materials that must be recovered.

[1] BMW; [2] Schaeffler

Vision

End-of-life treatment

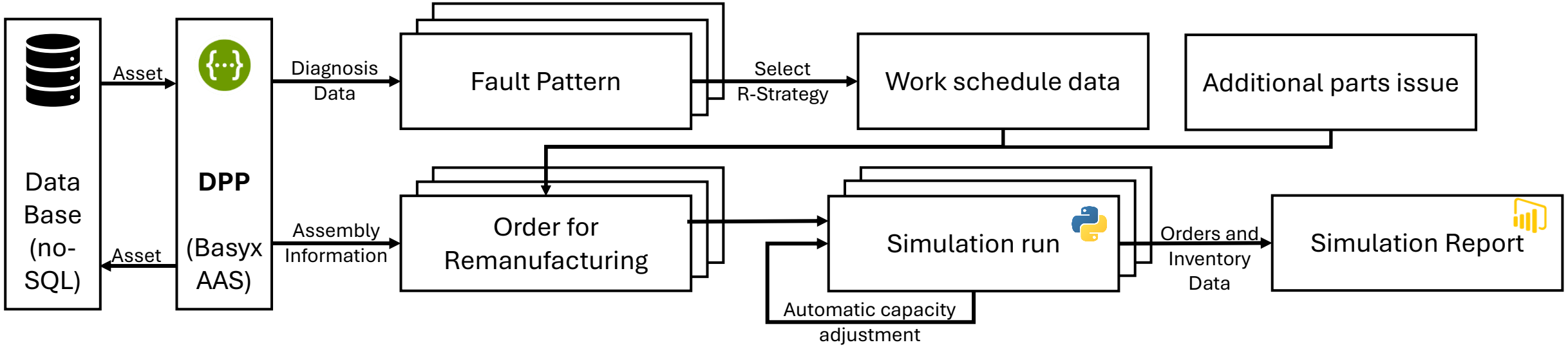


Approach for end-of-life-treatment

Assessment	Decision	Evaluation	Execution
Perform End-of-Use Test	Select R-Strategy	Capacity Planning	Perform R-Strategy
Initial inspection	1. Reuse 2. Remanufacture 3. Refurbish	Simulation and Planning Tools	Proceed with dedicated R-Strategy

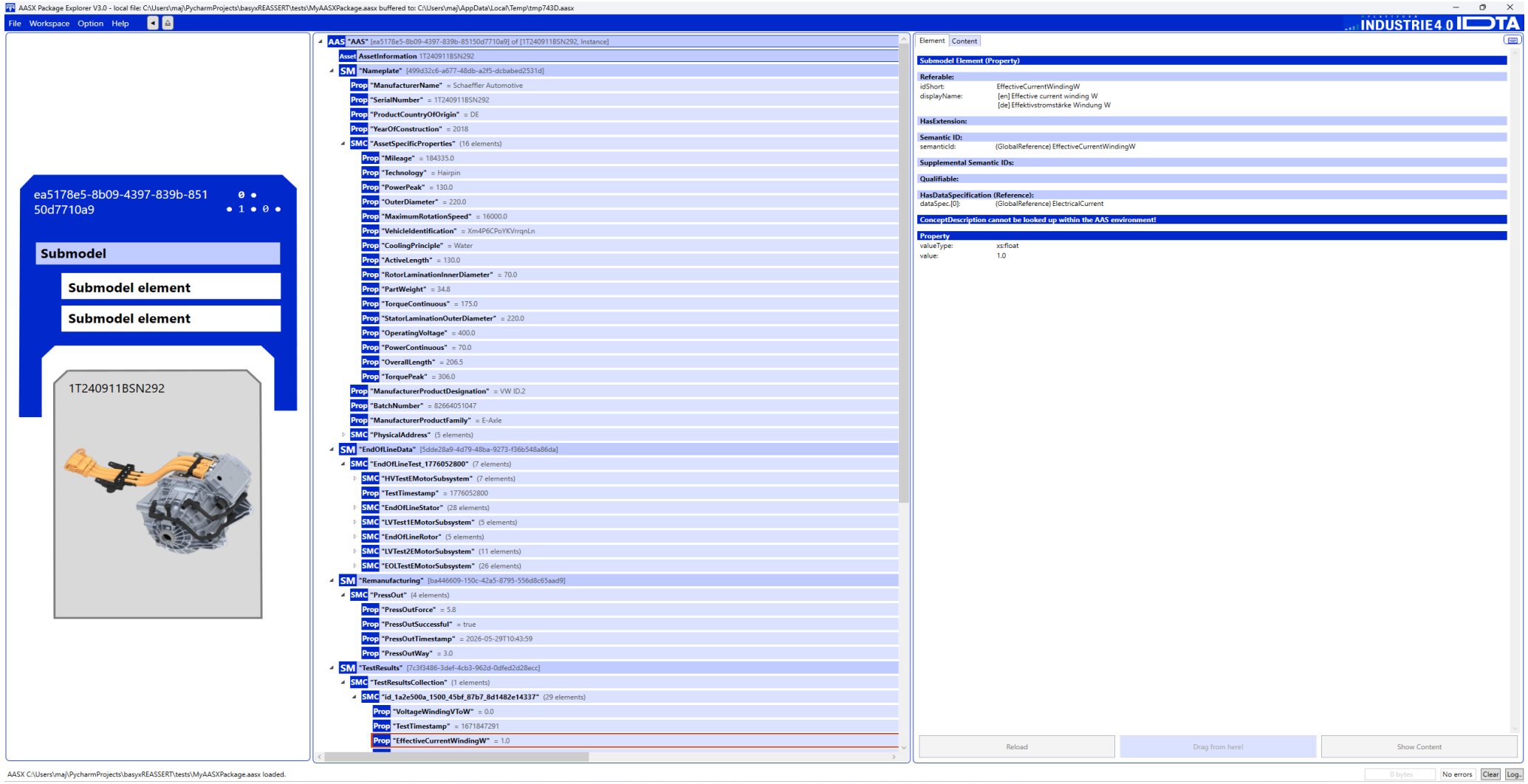
[1] Schaeffler

System architecture for DPP-based remanufacutring



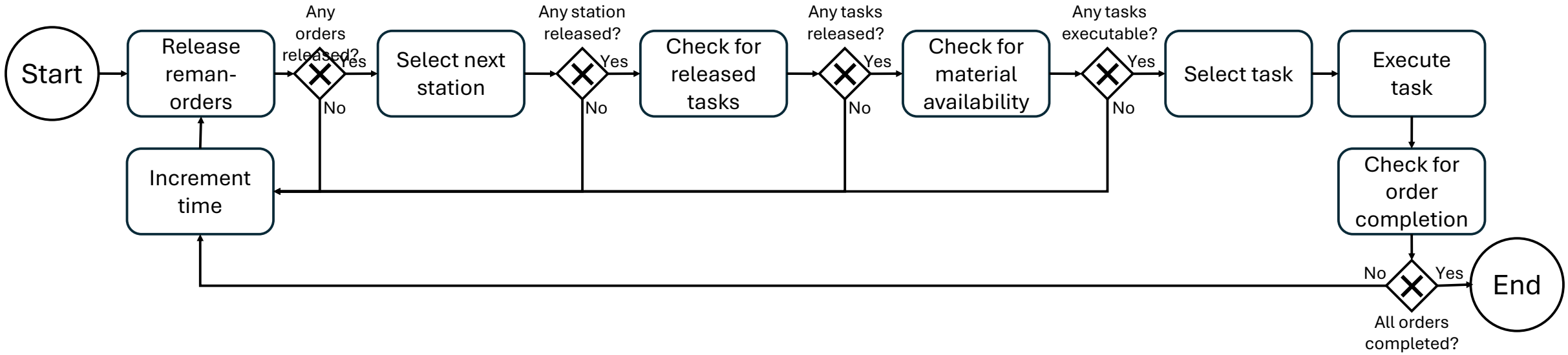
Case Study

Digital Product Passport

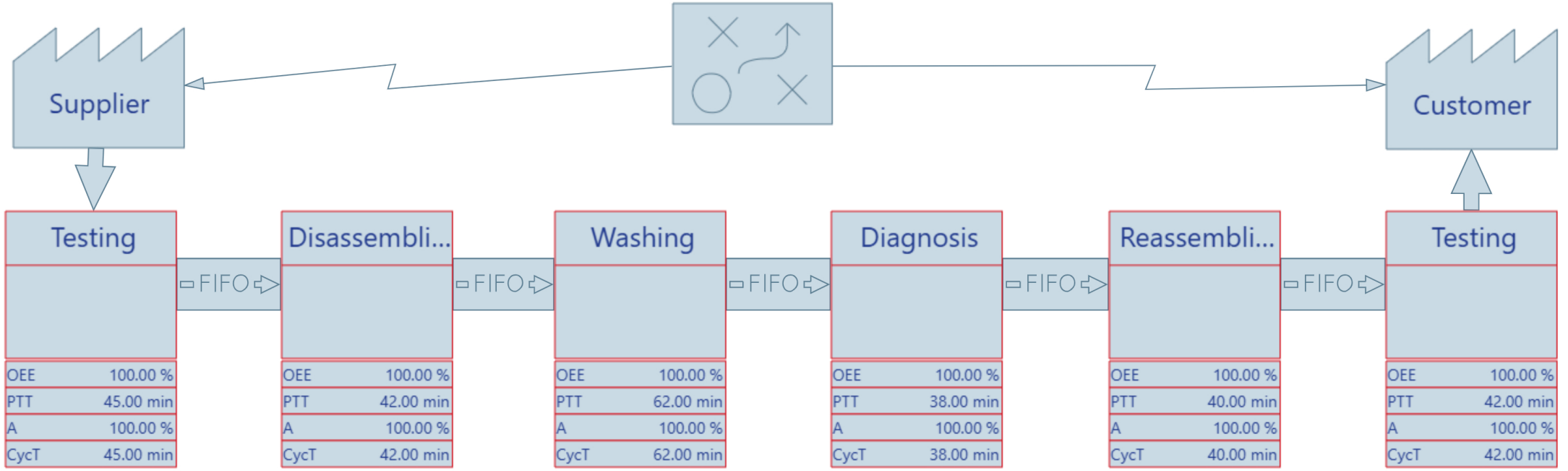


Simulation Flow

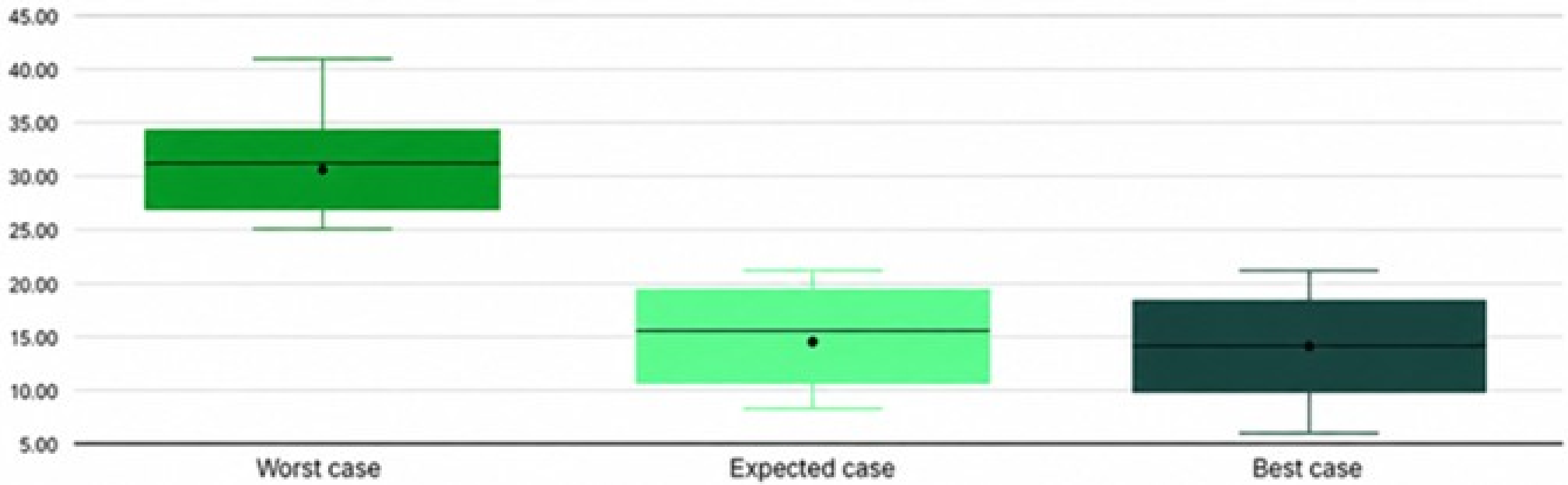
Ticker-based simulation execution logic with iterative task selection and material availability checking at each discrete time step



Case Study


Supplier
Customer
Testing
FIFO
Disassembli...
FIFO
Washing
FIFO
Diagnosis
FIFO
Reassembli...
FIFO
Testing
OEE 100.00 %
PTT 45.00 min
A 100.00 %
CycT 45.00 min
OEE 100.00 %
PTT 42.00 min
A 100.00 %
CycT 42.00 min
OEE 100.00 %
PTT 62.00 min
A 100.00 %
CycT 62.00 min
OEE 100.00 %
PTT 38.00 min
A 100.00 %
CycT 38.00 min
OEE 100.00 %
PTT 40.00 min
A 100.00 %
CycT 40.00 min
OEE 100.00 %
PTT 42.00 min
A 100.00 %
CycT 42.00 min

Casestudy



	Worst Case	Expected Case	Best Case
Min. throughput time [h]	28	11	10
Average throughput time [h]	31	16	14
Max. throughput time [h]	34	19,5	19

Conclusion

A simulation-based approach to address planning challenges in electric traction motor remanufacturing

[1] Schaeffler

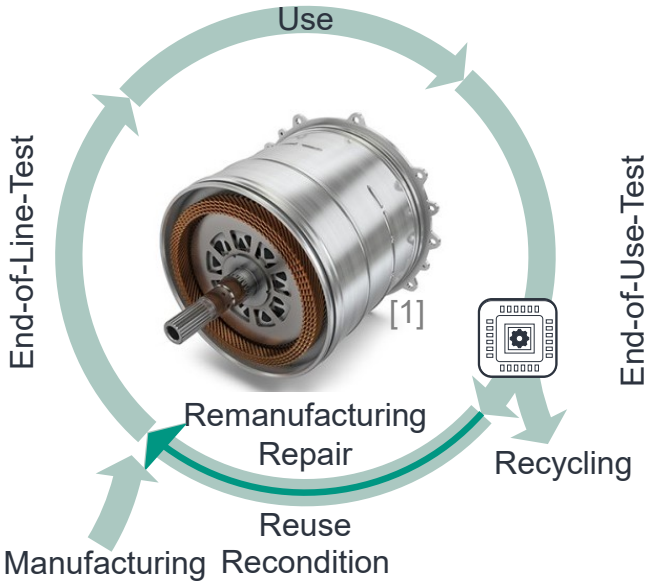
Motivation

Increasing demand for electric traction motors

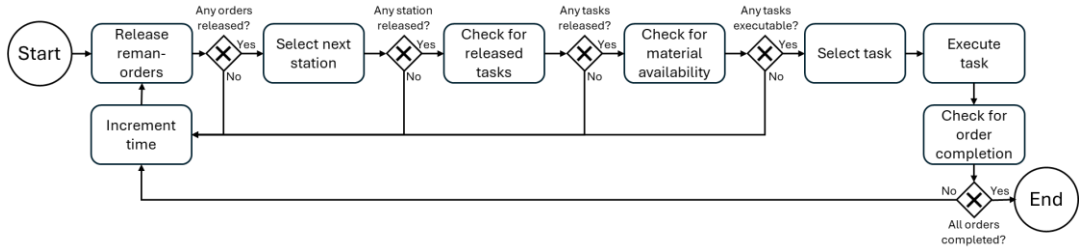
High material costs & high environmental impact

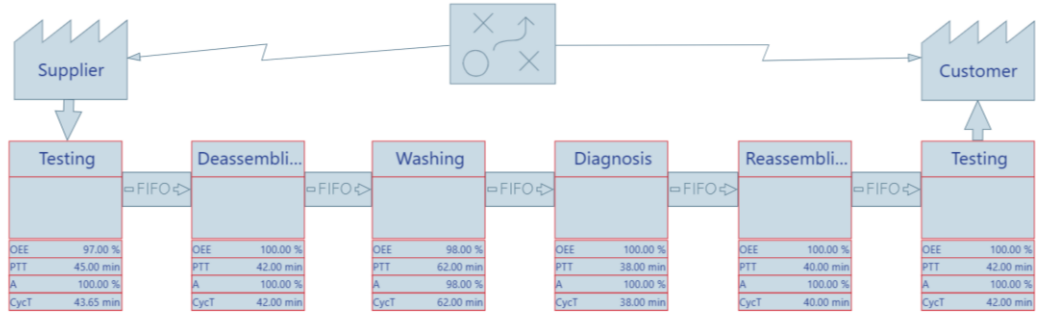
Identification of appropriate value retention strategy

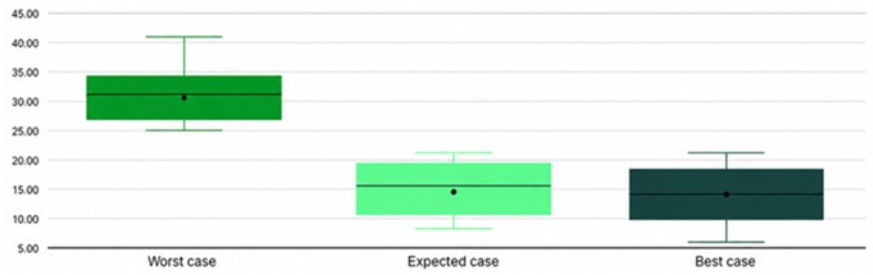
Vision



Results







Thank you!

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REASSERT

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WELCOME

CASCADED WEAR INSPECTION OF GEAR HOB TOOLS USING DEEP LEARNING MACHINE VISION

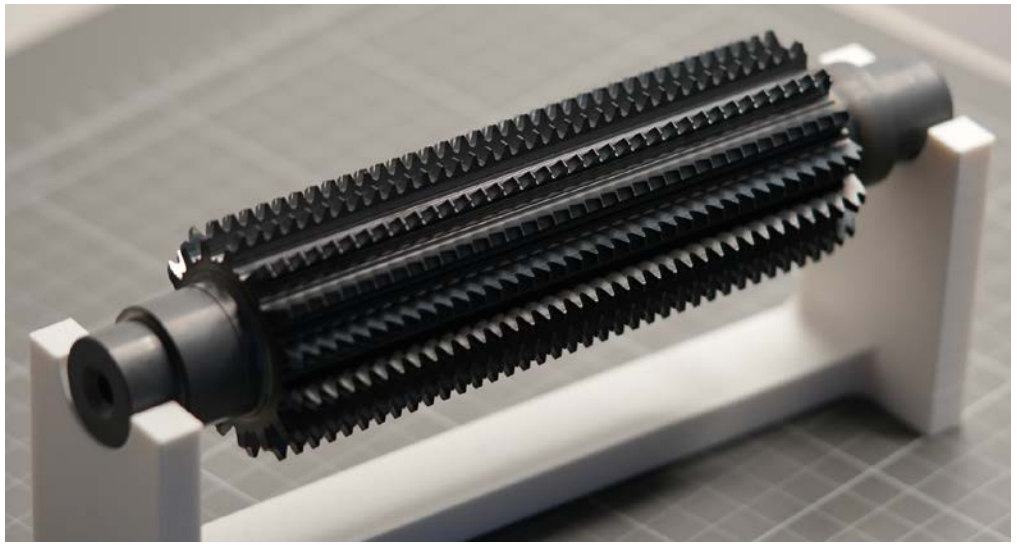
ALEXANDER MOLTSCHANOV, STEFAN SCHULTE AND JOACHIM METTERNICH

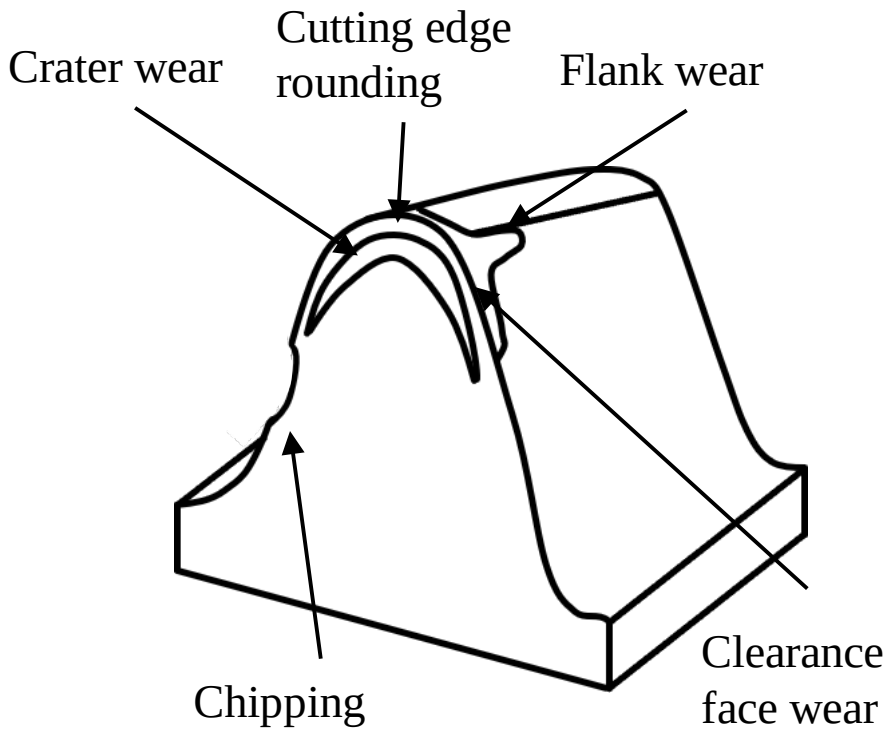
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THE GEAR HOB AND THE MOTIVATION TO REGRIND

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Institut für Produktionsmanagement, Technologie und Werkzeugmaschinen





Gear hobs are precision tools used for efficient gear cutting and are typically made from cemented carbide, a costly and wear-resistant material. To extend tool life in an economical and sustainable way, regrinding is commonly applied to remove wear and restore functionality. The objective is to re-establish a clean cutting edge on every tooth. [1,2,3,4]

MANUAL INSPECTION

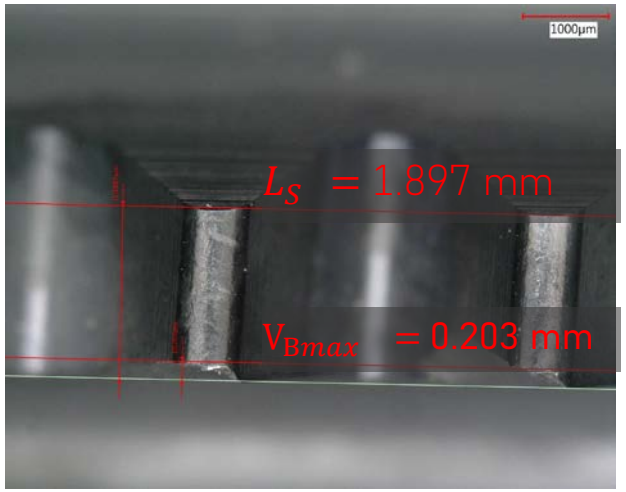
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Successful regrinding of a hobbing tool requires accurate detection of the maximum wear mark, as the entire worn region must be removed to restore full cutting performance and tool integrity.

Currently, to determine whether a new regrind is feasible, the following features are inspected for each tooth:

- For every tooth (up to 500):
  i. Is enough tooth left $L_S > L_{Smin}$?
  ii. Measure local wear V_{Bmax}
- Regrind all teeth for $\max V_{Bmax}$

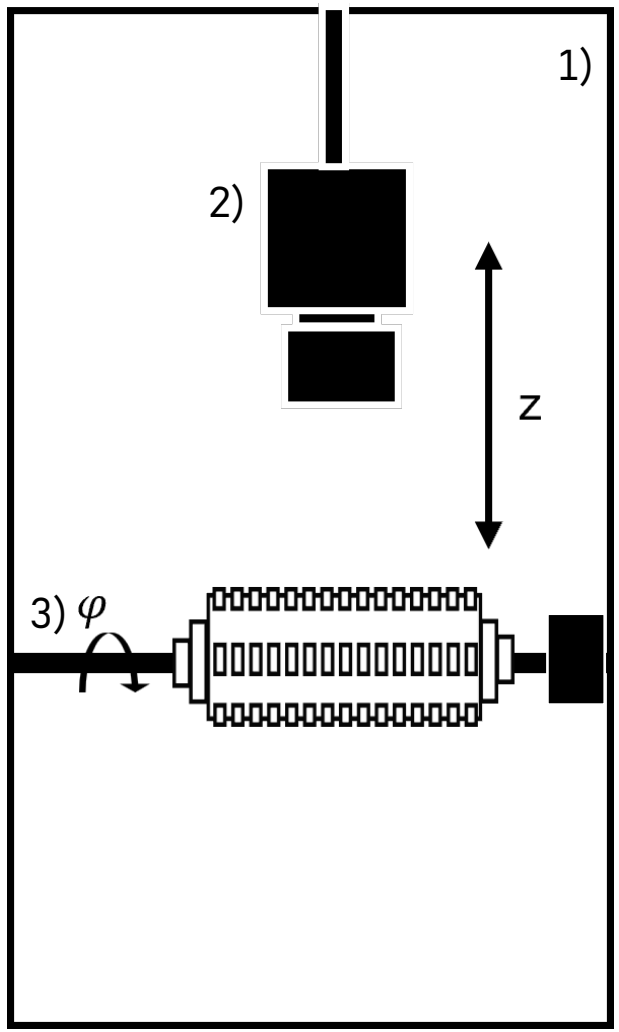
$$T = \begin{bmatrix} t_{1,1} & \cdots & t_{1,M} \\ \vdots & \ddots & \vdots \\ t_{N,1} & \cdots & t_{N,M} \end{bmatrix} \text{ with } t_{i,j} = \begin{bmatrix} L_{S_{i,j}} \\ V_{Bmax_{i,j}} \end{bmatrix}$$

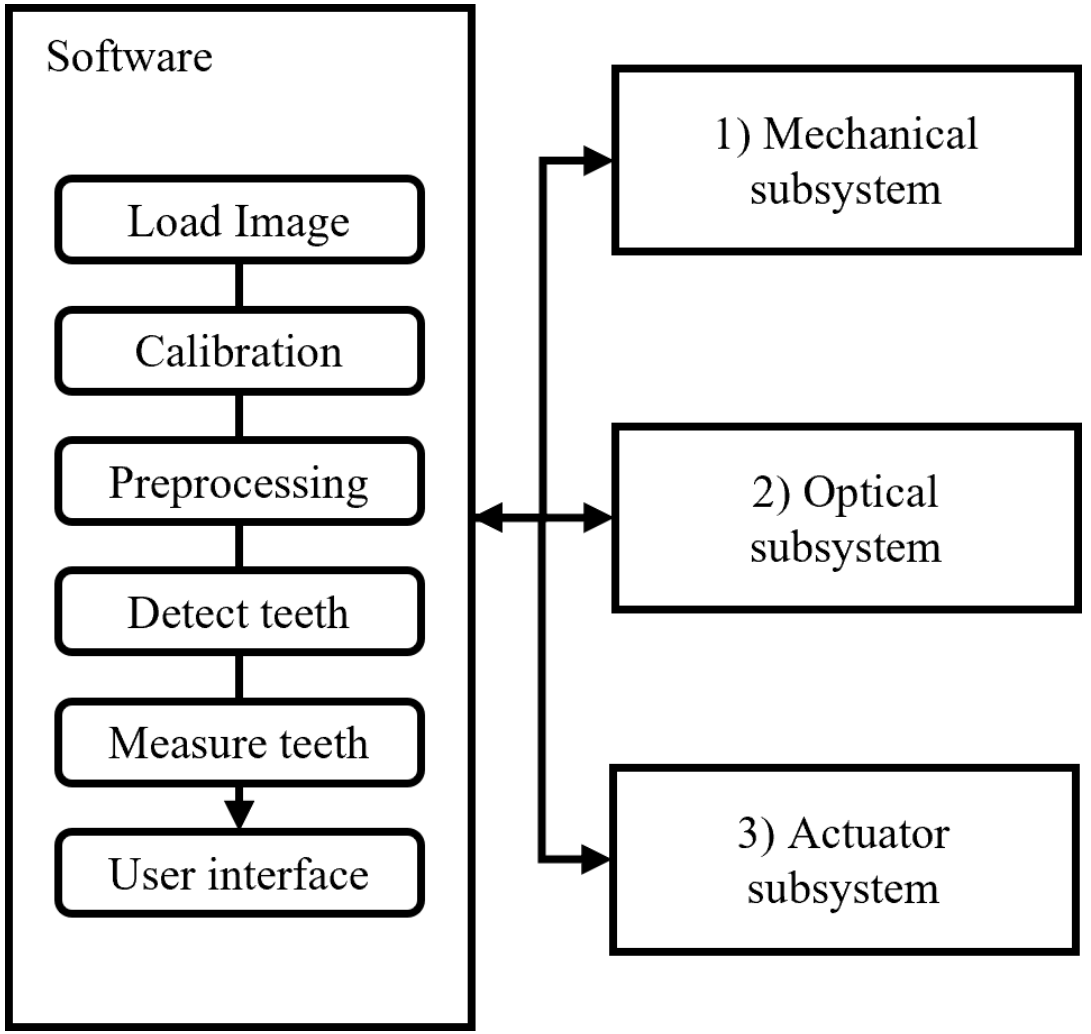


Is it possible to automate this process?

AUTOMATED SYSTEM DEVELOPED WITH MODULAR SUBSYSTEM

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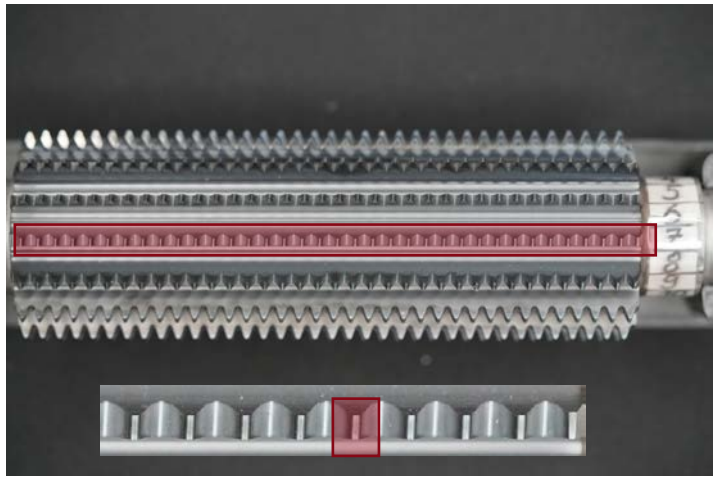




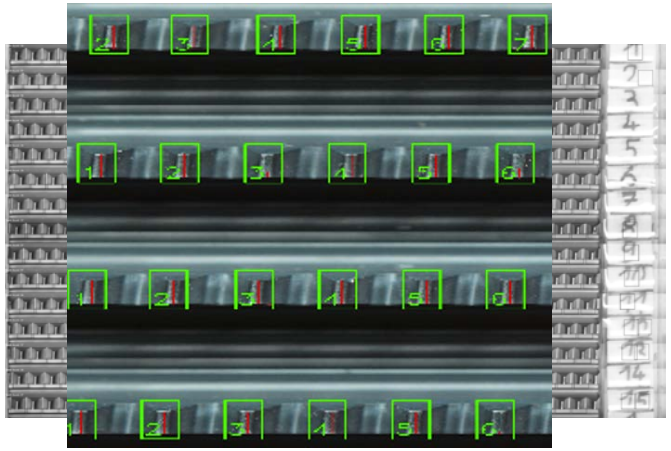
STATUS QUO: FINDING ALL TEETH WITH HIERARCHICAL TEMPLATE MATCHING AND ROTATION

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Step 1: Rotate tool in N steps and capture N images around full circumference.

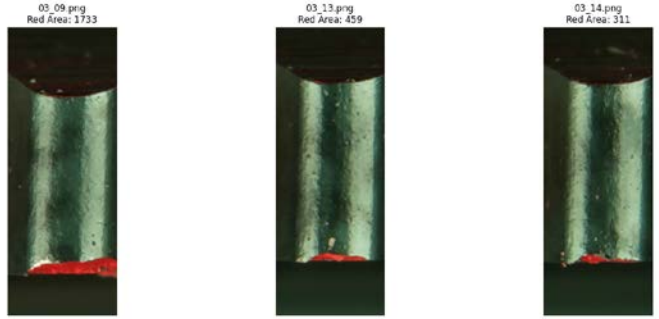


Step 2: Interactively choose one row and tooth from first image as matching template..



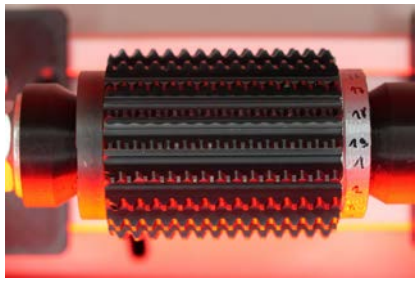
Step 3: Unwrap & Match. Stitch images into 2D roll-up.
Detect and mark all corresponding teeth across rotations.

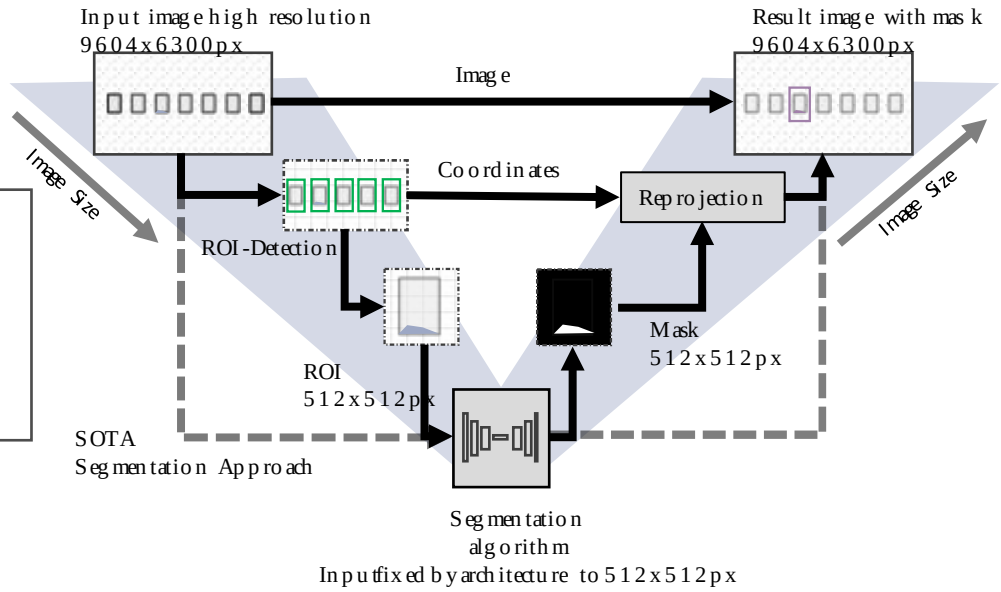
Step 4: Analyze each tooth individually. Map results back onto 2D roll-up for visual evaluation.

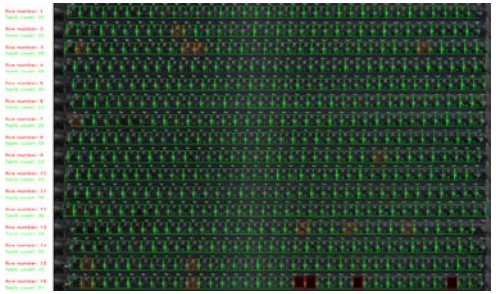


This has limitations: Need for manual ROI selection and manual thresholding for detection and segmentation.

TO OVERCOME MANUAL THRESHOLDING BUT STAY TRUE TO RESOLUTION, WE PROPOSE A CASCADED DEEP LEARNING APPROACH FOR MEASUREMENT







Teeth detection

$\{b_{i,m}\}_{i=1}^{N_m}$

Wear mark size

$V_{Bmax_{i,m}} = \mathrm{h}(M_{i,m}^{wear})$

ROI



Segmentation

$M_{i,m}^{tooth}$



$M_{i,m}^{wear}$

DEEP LEARNING BASED TOOTH DETECTION AND WEAR SEGMENTATION RESULTS

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Tooth Detection (YOLOv8n)

test set results on 728 tooth instances

0.94
Precision

0.95
Recall

Tooth finding is robust; errors occurred due to label inconsistencies.

Wear Segmentation (YOLOv8m-Seg)

On the test set of the detection task at 80/10/10 split: test results

0.95
mAP50

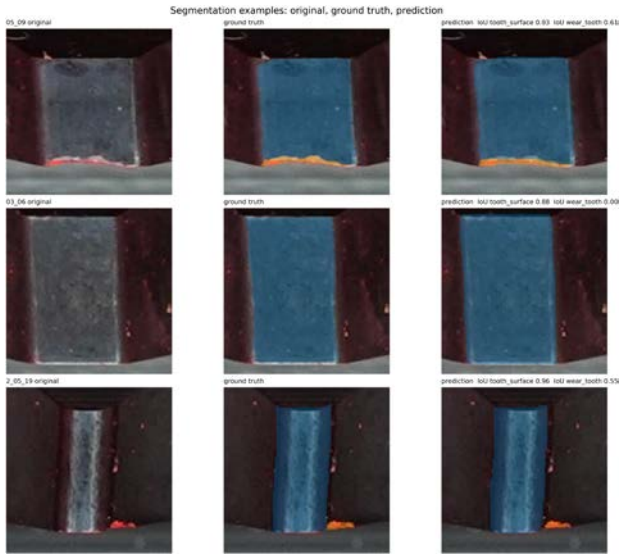
0.70
mAP50-95

0.93
Precision

0.90
Recall

Confusion matrix: predicted vs. ground truth

	Tooth (GT)	Wear (GT)	Background (GT)
Tooth surface (pred.)	74	0	0
Wear (pred.)	0	16	3
Background (pred.)	0	5	0



Geometric agreement (wear)

0.55
Mean IoU (median 0.52)

0.22–0.89
IoU range

1.3 px
Mean error (σ ≈ 1.2 px)

0–5 px
Wear-height error range

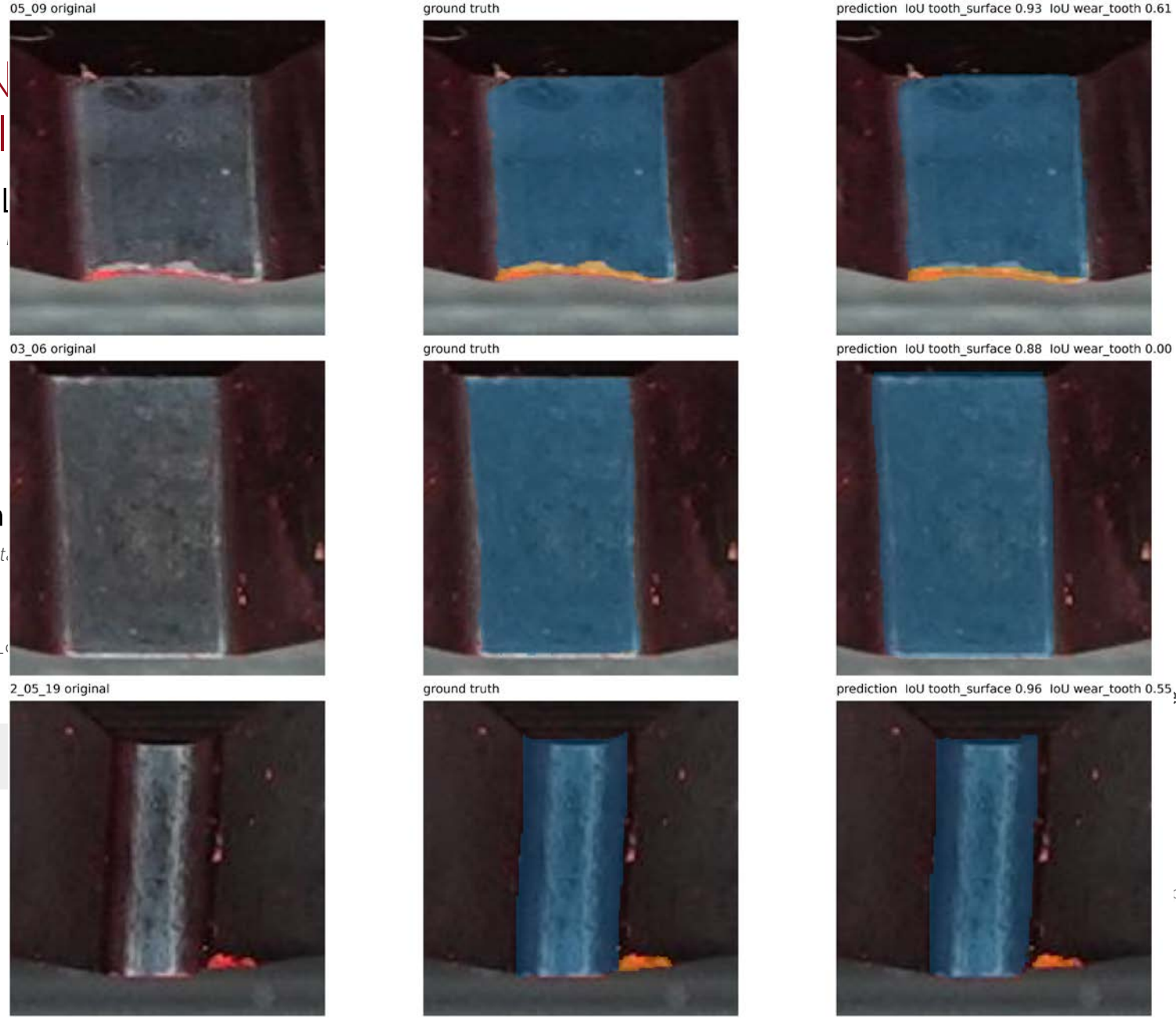
DEEP LEARN
SEGMENTATI

Tooth Detection (YOl

test set results on 728 tooth

0.94
Precision

Segmentation examples: original, ground truth, prediction



Wear Segmentation

On the test set of the detection t

0.95
mAP50

0.70
mAP50-

Confusion matrix: predicted vs.

Tooth surface (pred.)	
Wear (pred.)	
Background (pred.)	

ement (wear)

0.52)

0.22–0.89
IoU range

ox)

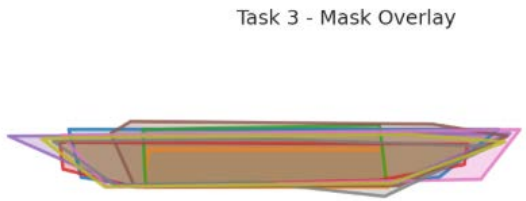
0–5 px
Wear-height error range

LIMITATIONS AND OUTLOOK

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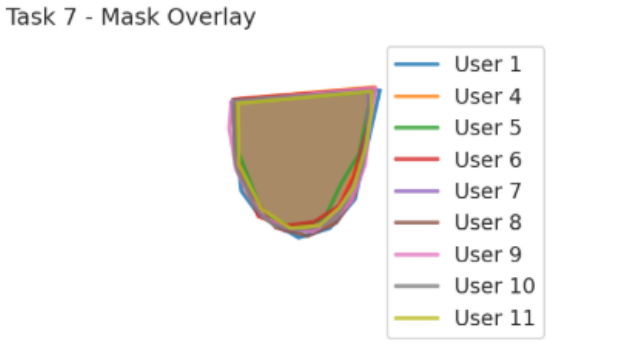
While results show promising results, there are still topics to work on:

Segmentation results remain sensitive to subjective human ground-truth masks and class imbalance
Dataset size and variability may also remain limiting factors for full generalization



Pairs=45, IoU=0.6316, MAP50=0.8222, MAP50-95=0.3311, HeightDiff=2.45

Medium agreement (IoU = 0.63)



Pairs=45, IoU=0.9087, MAP50=1.0000, MAP50-95=0.8578, HeightDiff=1.38

High agreement (IoU = 0.91)

REFERENCES USED IN THIS PRESENTATION

- [1] Pieter Johannes Theron Conradie, Gert Adriaan Oosthuizen, and Dimitri Dimitrov, “On the effect of regrinding cutting tools for high performance milling of titanium alloys.”
- [2] B. Denkena, T. Grove, M. Theuer, and Y. Liu, “Resource efficient regrinding of cemented carbide milling tools,” Procedia CIRP, vol. 69, pp. 882–887, 2018.
- [3] B. Karpuschewski, “Influence of the tool profile on the wear behaviour in gear hobbing,” 2017.
- [4] M. Köchig, “Analyse geometrischer einflüsse auf die werkzeugbelastung beim wälzfräsen,” 2019.

THANK YOU

CASCADED WEAR INSPECTION OF GEAR HOB TOOLS USING DEEP LEARNING MACHINE VISION

ALEXANDER MOLTSCHANOV, STEFAN SCHULTE AND JOACHIM METTERNICH

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TECHNOLOGY AND MACHINE TOOLS
TECHNICAL UNIVERSITY OF DARMSTADT



TOOTH DETECTION AND WEAR SEGMENTATION

Institut für Produktionsmanagement, Technologie und Werkzeugmaschinen
TU DARMSTADT

Tooth Detection (YOLOv8n)

37 images · test set on 728 tooth instances · stabilized after ~10 epochs

0.94
Precision

0.95
Recall

Confusion matrix: predicted vs. ground truth

	Tooth (GT)	Background (GT)
Tooth (pred.)	703	35
Background (pred.)	25	0

Wear Segmentation (YOLOv8m-Seg)

On the test set of the detection task at 80/10/10 split: test results

0.95
mAP50

0.70
mAP50-95

0.93
Precision

0.90
Recall

Confusion matrix: predicted vs. ground truth

	Tooth (GT)	Wear (GT)	Background (GT)
Tooth surface (pred.)	74	0	0
Wear (pred.)	0	16	3
Background (pred.)	0	5	0

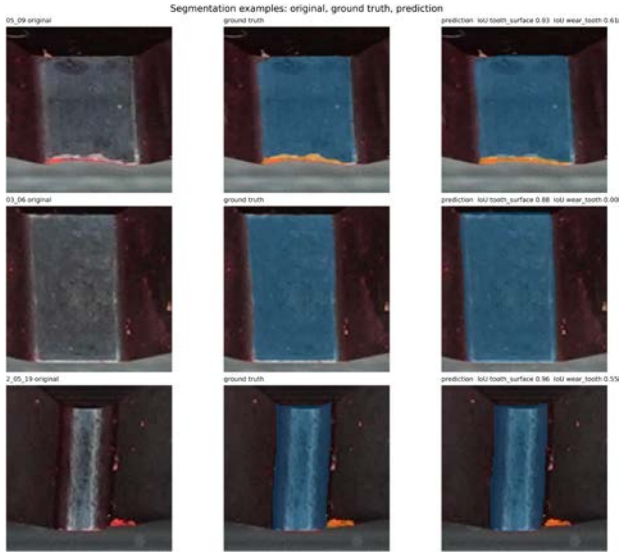


Fig. 1 — Example detection / segmentation result

Geometric agreement (wear samples)

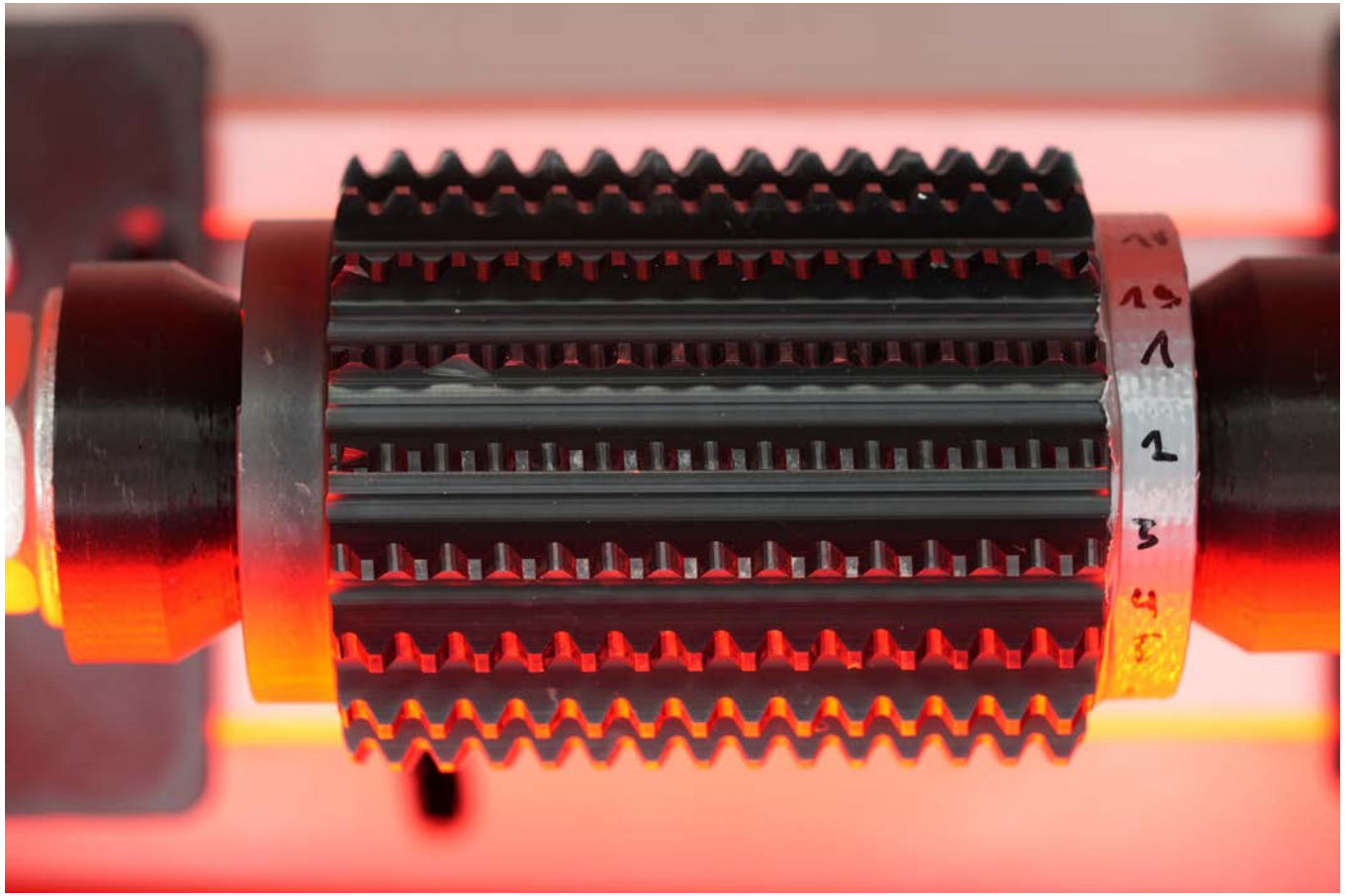
0.55
Mean IoU (median 0.52)

0.22–0.89
IoU range

1.3 px
Mean error (σ ≈ 1.2 px)

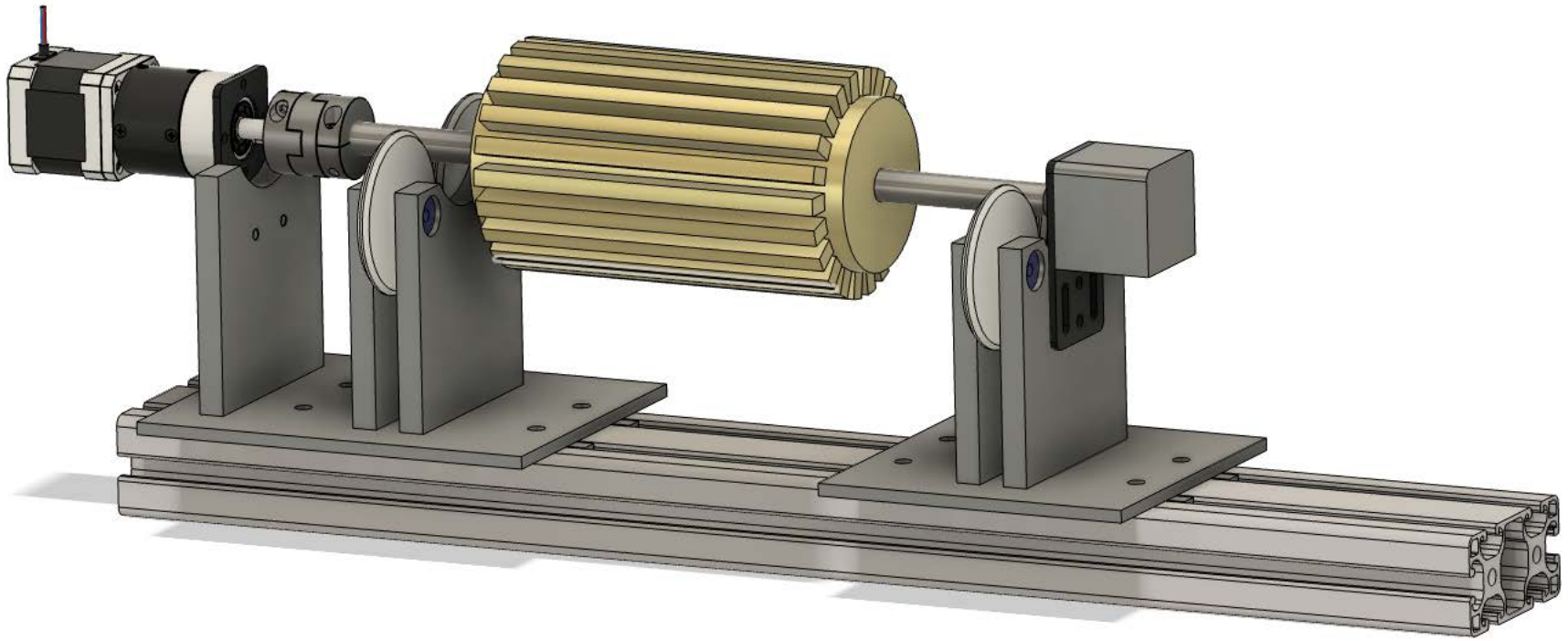
0–5 px
Wear-height error range

BACKUP

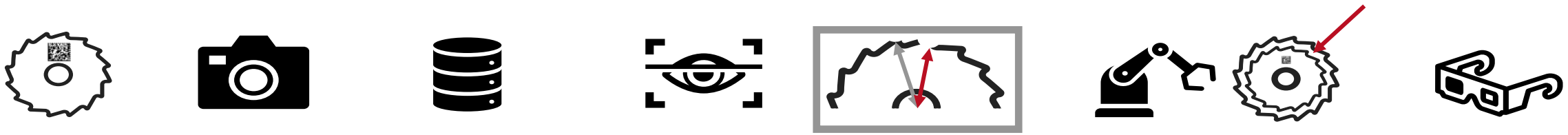


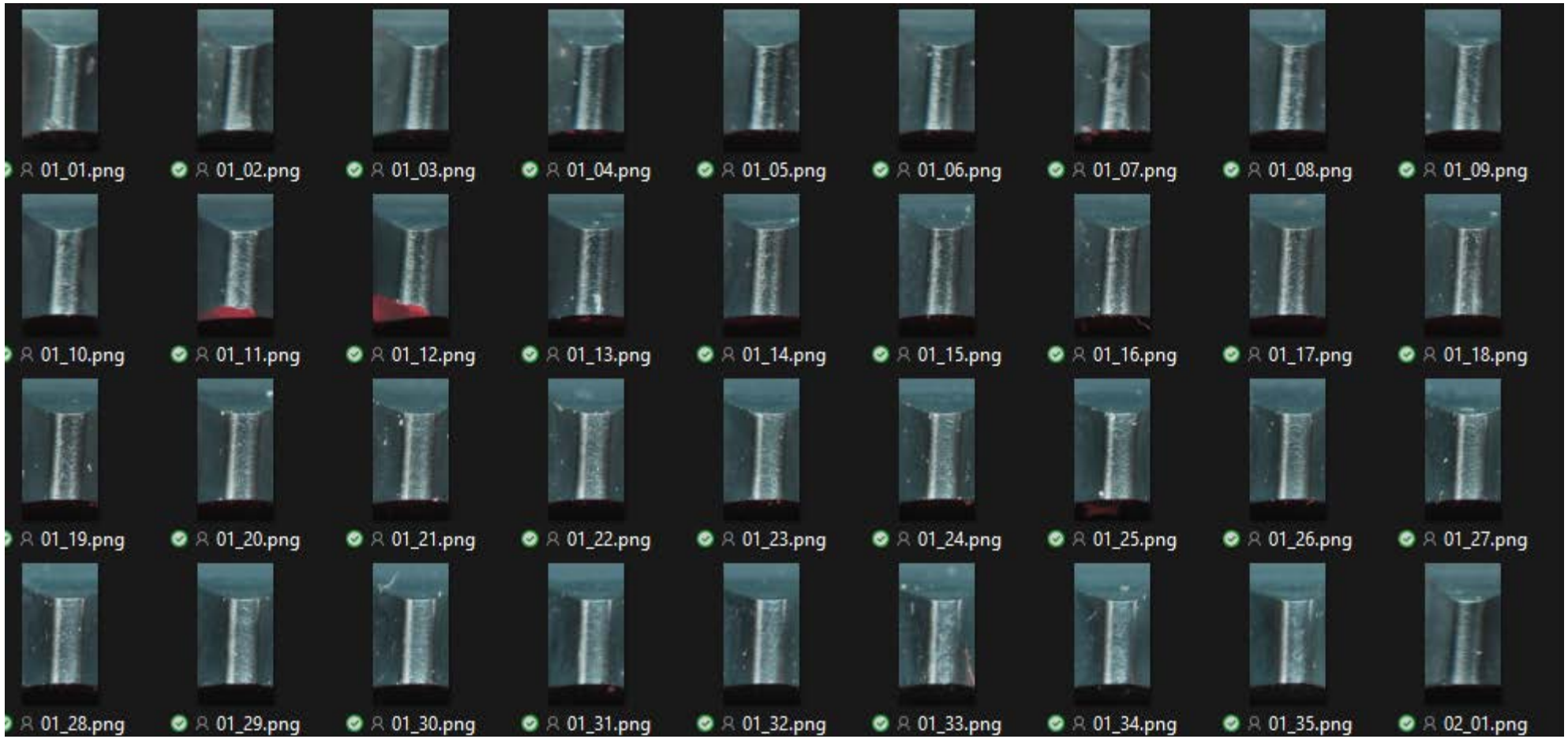
ROTATION SYSTEM FOR DIFFERENT TYPES OF HOBBING TOOLS

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MANUAL REFERENCE PROCESS




01_01.png
01_02.png
01_03.png
01_04.png
01_05.png
01_06.png
01_07.png
01_08.png
01_09.png
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01_34.png
01_35.png
02_01.png

RED AREA FILTER ALGORITHM AND TEMPLATE MATCHING

1.Enhance contrast using **CLAHE** in LAB color space, then **split RGB channels** to isolate red regions via **thresholding** (R > R_min).

2.Morphological operations (opening/closing with a 5×5 kernel) clean the binary mask, and **contour detection** filters regions by area (A_min ≤ area ≤ A_max).

3.Sort all images by detected wear area, then **overlay the top 5** with semi-transparent red (60% original + 40% red) for visualization.

4.Save the top 3 as fully red-highlighted images, using **non-zero pixel counting** to quantify wear in each case.

1. Preprocess images:
   - Convert both the full image and the tooth template to grayscale.

2. Compute similarity map:
   - Apply OpenCV's cv.matchTemplate using the normalized correlation coefficient (TM_CCOEFF_NORMED (LINK)).

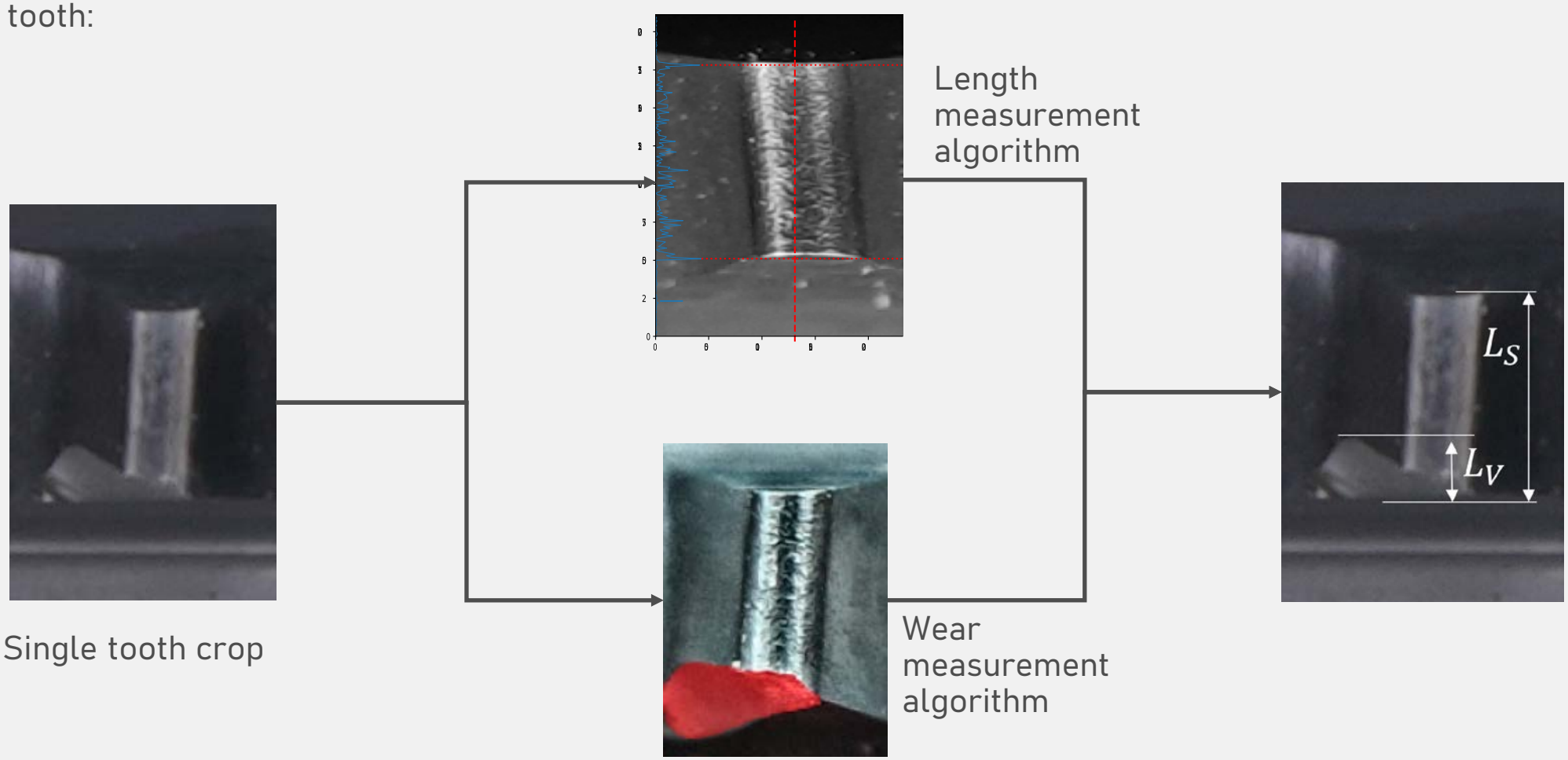
3. Select candidate matches:
   - Threshold the similarity map to keep only strong responses above a chosen value.

4. Refine detections:
   - Merge overlapping bounding boxes with cv.groupRectangles to produce stable tooth positions.

SOFTWARE 2: LENGTH AND WEAR MEASUREMENT SUBPROCESS

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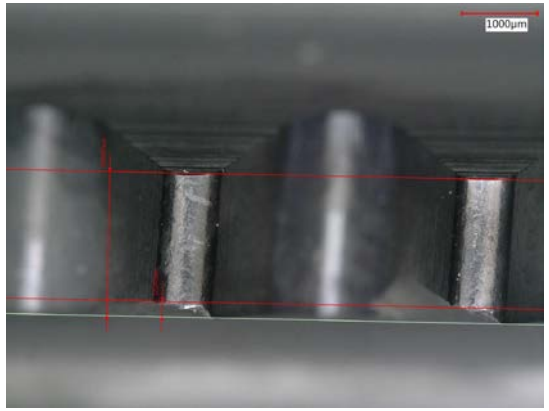
For every tooth:

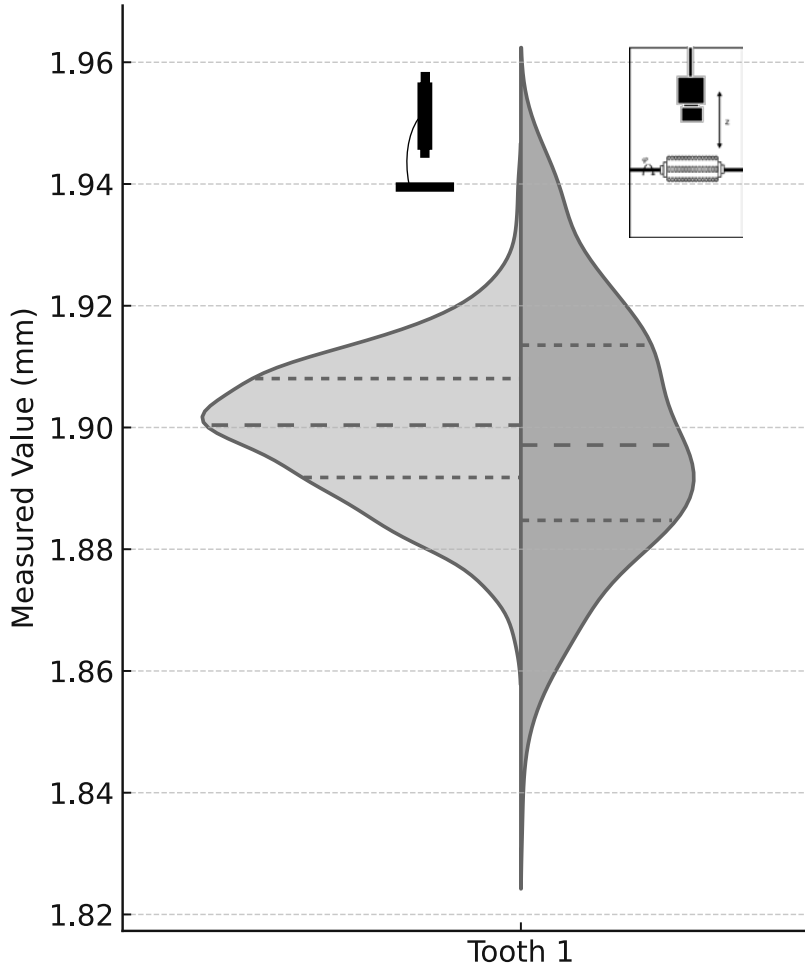


SOFTWARE 2A: FIRST VALIDATION OF OUR LENGTH MEASUREMENT APPROACH

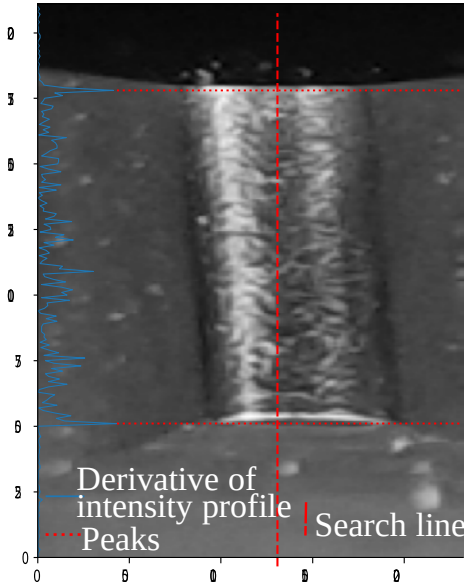
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Left: manual method via microscope





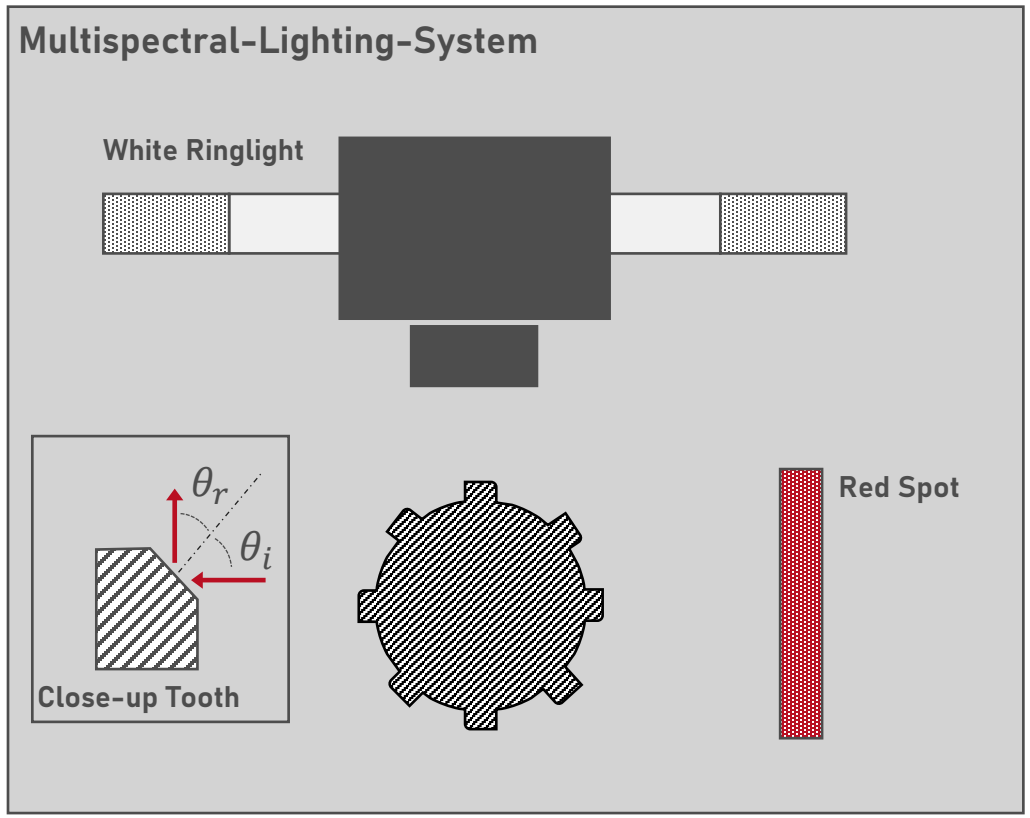
Right Side: Our method



The length is calculated by detecting the two main peaks in the derivative of the intensity profile taken from the center of each tooth image. Results closely match those from the manual method. Average Error: 0.47 px – 1.00 px and standard deviation: 0.73 px – 1.31 px.

SOFTWARE 2B: MULTISPECTRAL LIGHTING SYSTEM FOR HIGHLIGHTING WEAR

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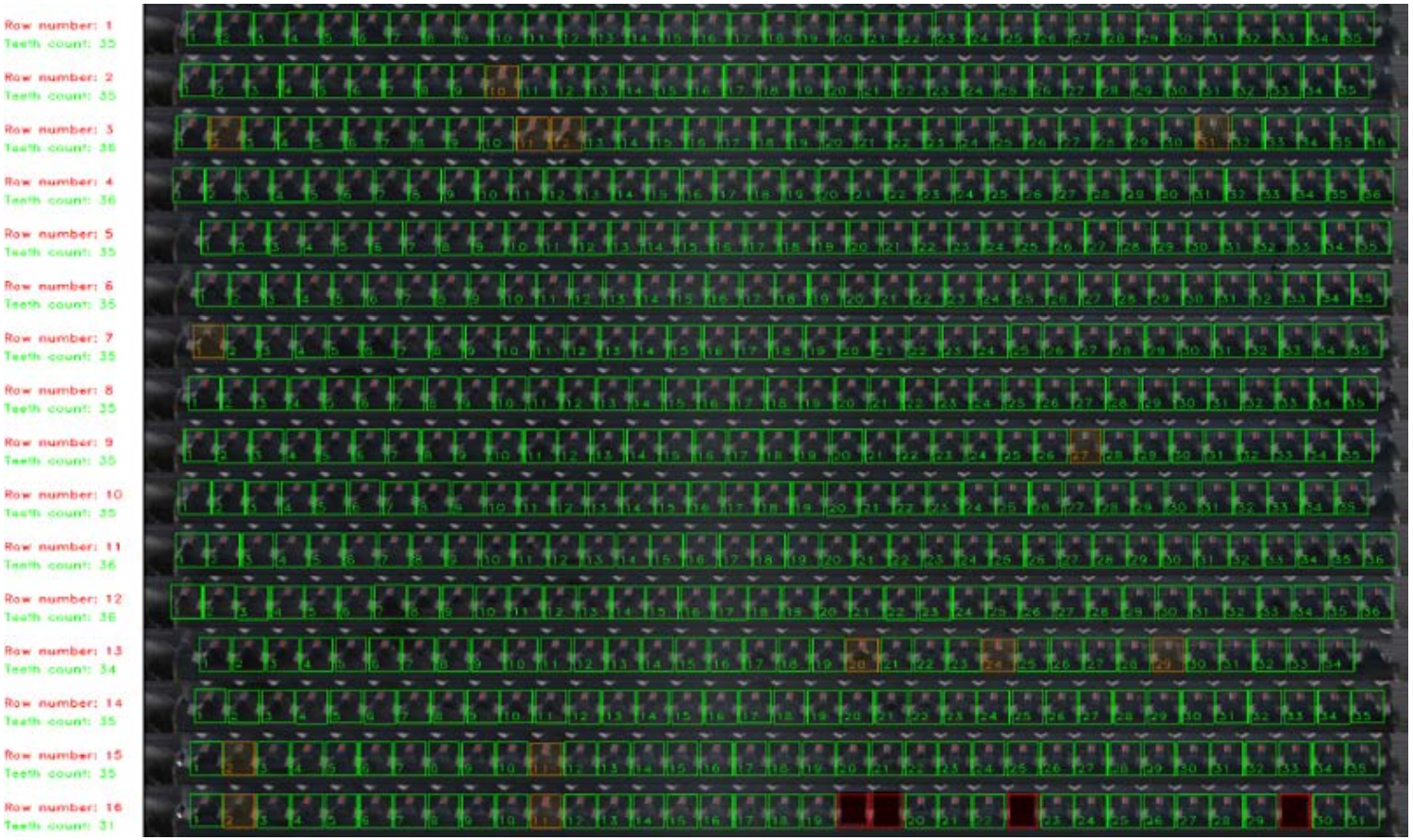


Algorithm:

1. Illuminate tool with dark field red light.
2. Filter single tooth image for red features.
3. Measure area and length of segment.

SOFTWARE 3: WORKERS ASSISTING 2D RESULT INTERFACE

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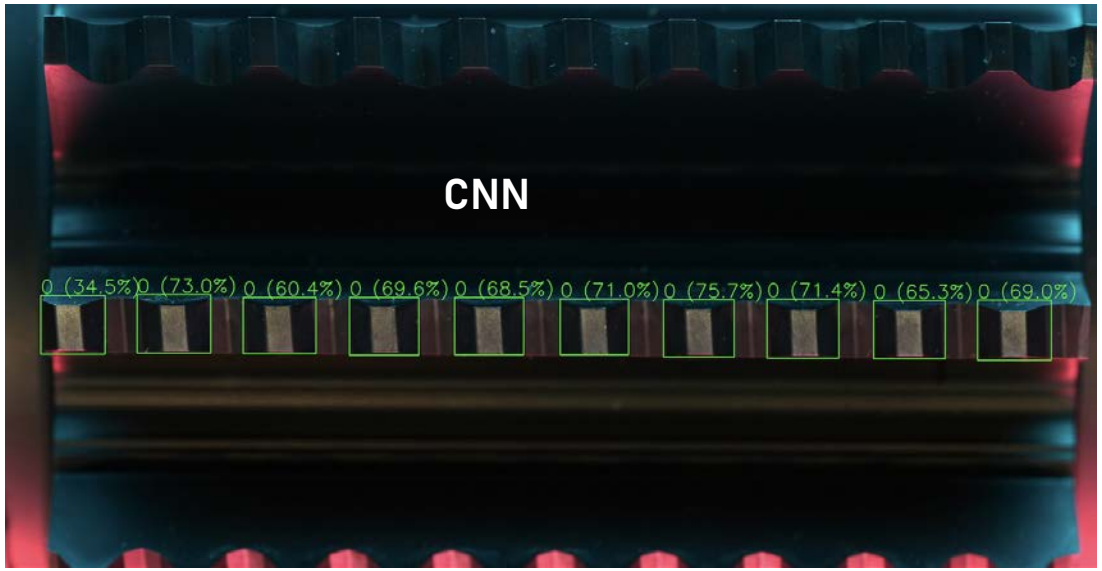


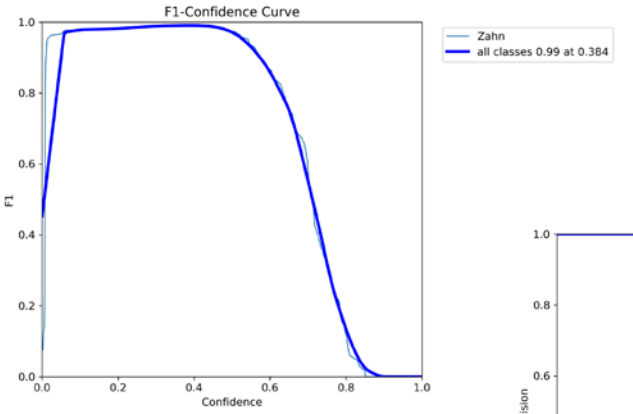
The calculated inspection results are presented to the operator using a 2D roll-up view. This visualization includes:

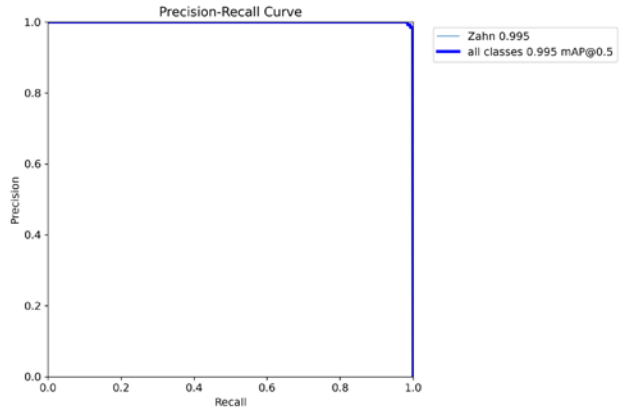
- All gear rows stitched together vertically with corresponding tooth bounding boxes.
- Highlighted outliers based on length or wear deviation.

SUMMARY AND OUTLOOK

- Future work will focus on formal uncertainty quantification following the Guide to the expression of Uncertainty in Measurement (GUM) framework [5].
- Further integration of machine learning for aligning, object recognition and automated tooth classification is foreseen.
- Extending the approach to more complex tool geometries, such as helical or non-uniformly pitched gear hob tools.







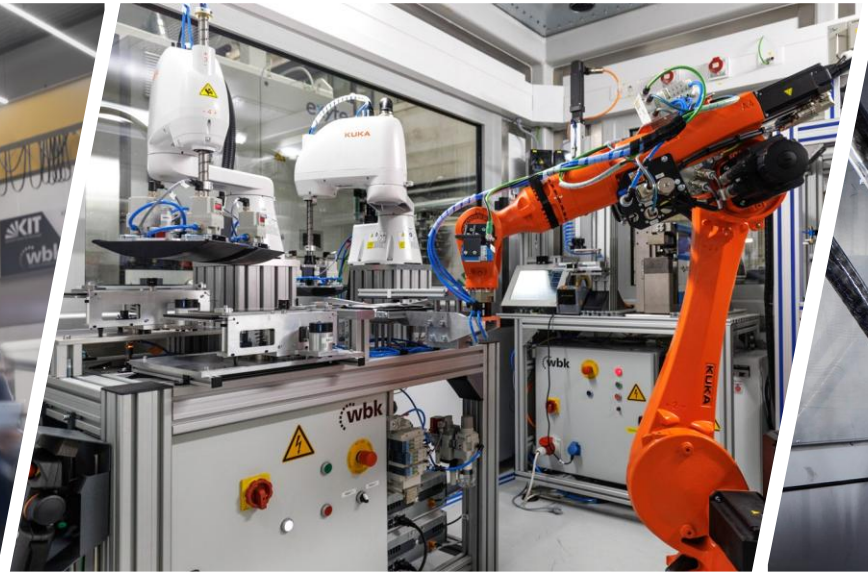
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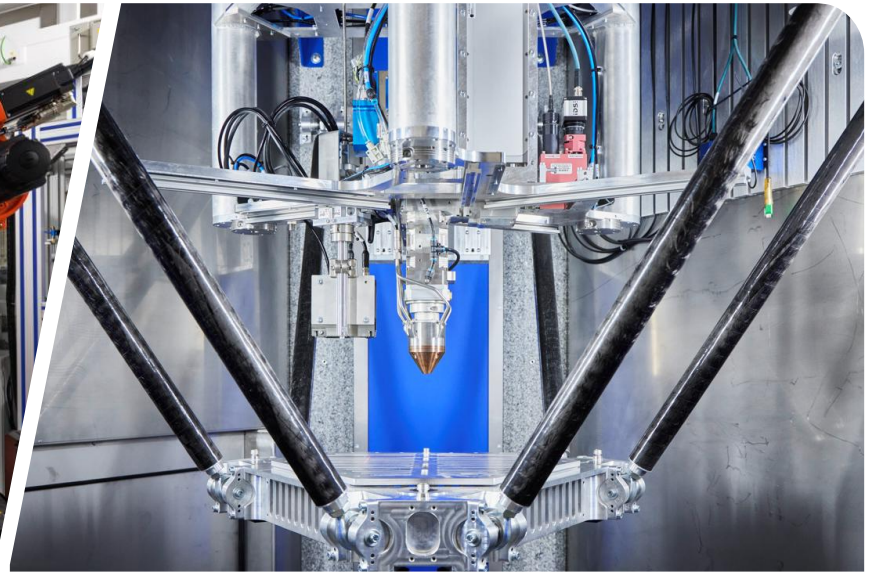
Institute of Production Science

Effects of the recycling of fine copper powder in the binder jetting process

Daniel Mayer and Frederik Zanger | CCPT Conference Karlsruhe | 10.06.2026







Agenda

1 Motivation

2 Materials and Methods

3 Results and Discussion

4 Conclusion



1. Motivation

challenges for todays production
- limited natural resources
- increasing material costs
- mounting environmental requirements



demand new technologies

potential additive manufacturing
- significant reduction in material waste
- reuse of production waste
- flexible on-demand-production



promising for middle quantities

binder jetting
- high printing speed
- scalable production
- large variety of materials



ensuring part quality

fine powders
- higher sinter density achievable
- enhanced sintering activity



recycling is more complex

challenges of recycling powders
- consistent particle size distribution (This work)
- management of impurities
- wear of particles



knowledge about the changes is essential
for a circular binder jetting process chain

Agenda

1 Motivation

2 Materials and Methods

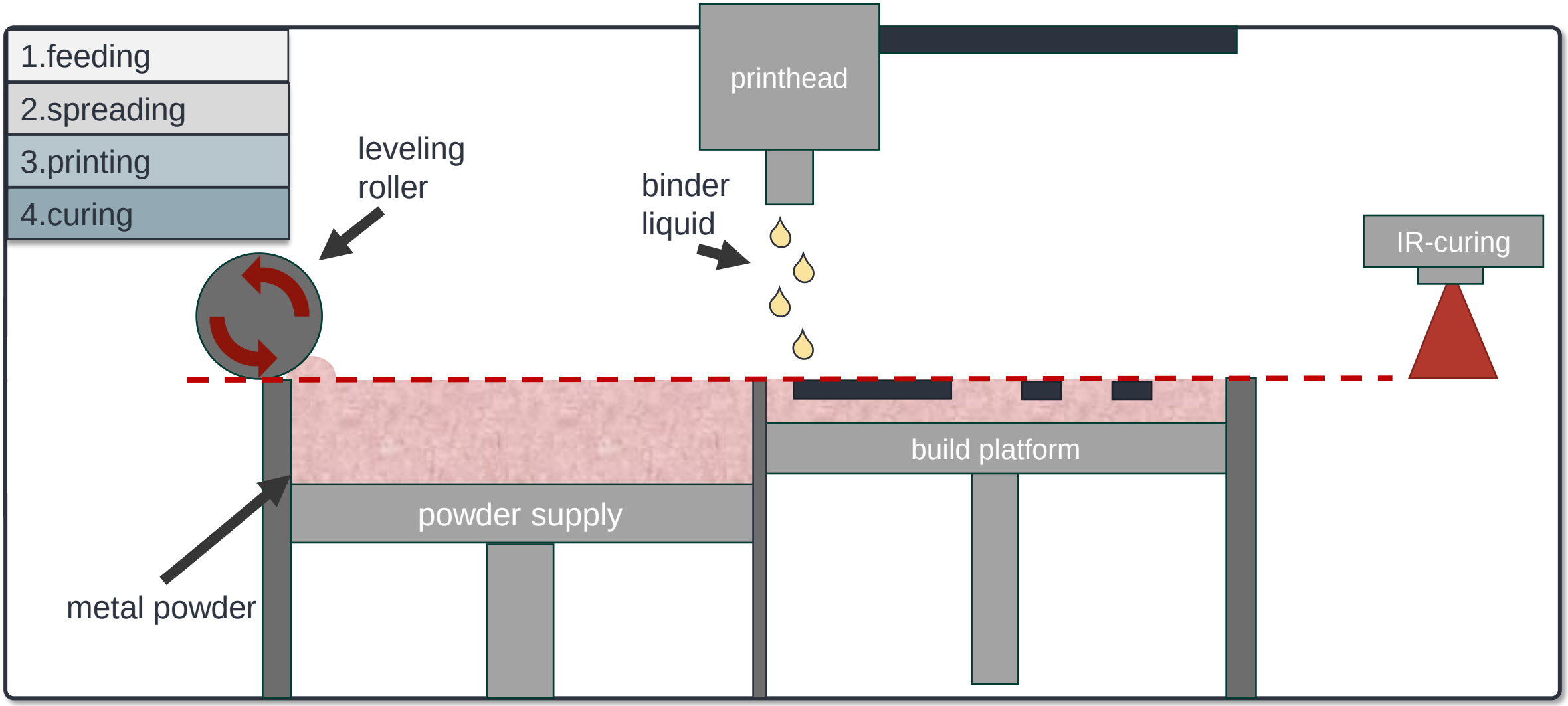
3 Results and Discussion

4 Conclusion



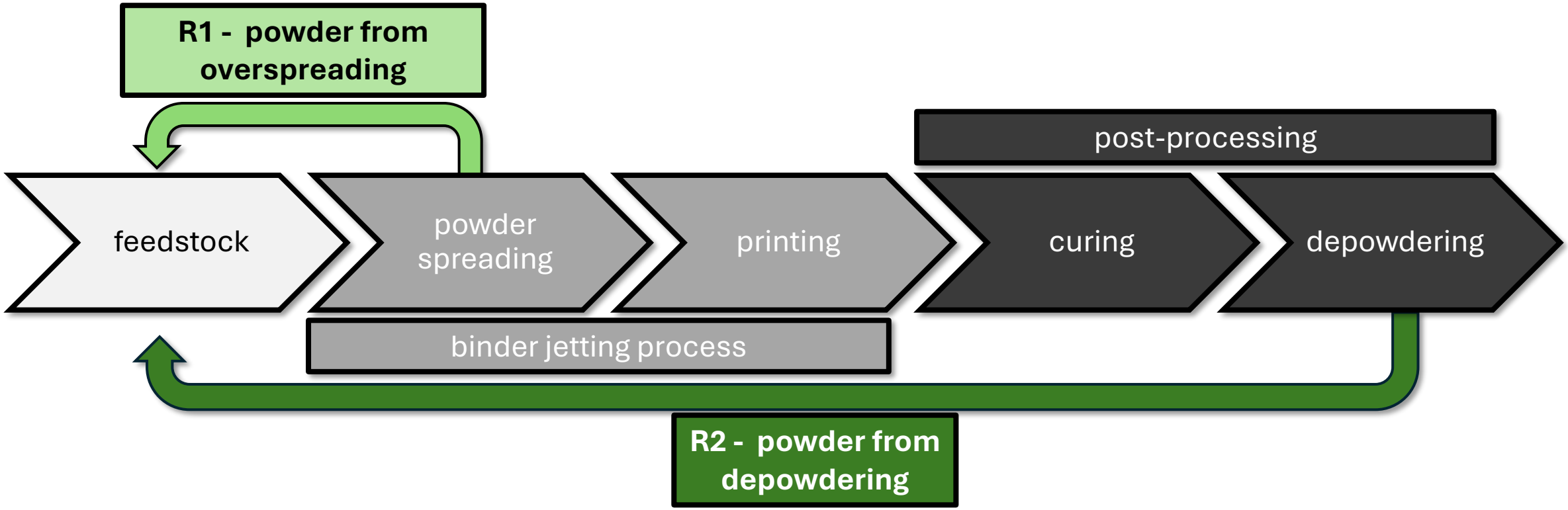
2. Materials and Methods

Process Fundamental



2. Materials and Methods

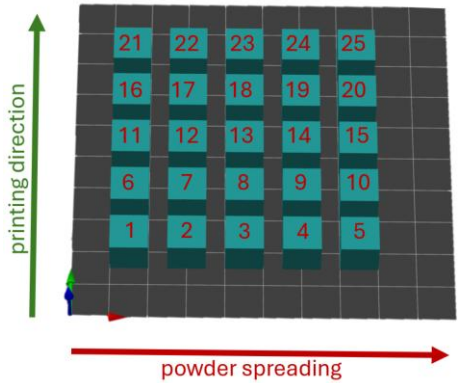
Powder recycling within first cycle

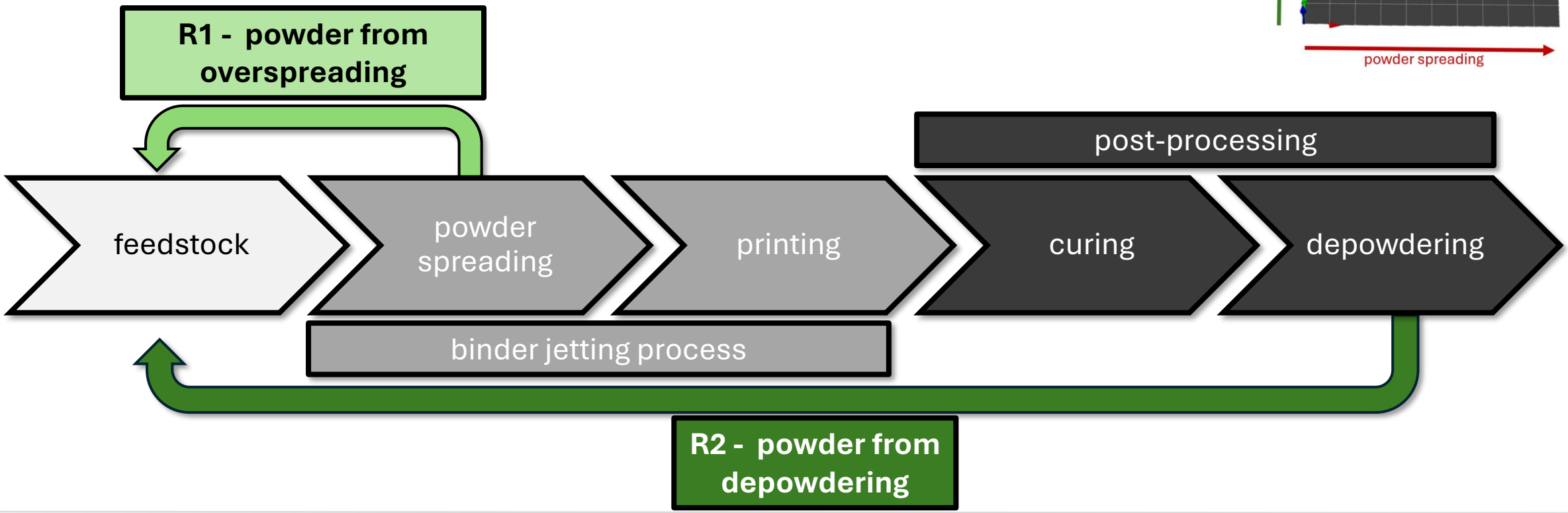


2. Materials and Methods

Powder recycling within first cycle

- observation of **particle size changes** within the **first cycle**
- **printing** experiments and **density measurements**
- **5 x 5 matrix** of cubes → revealing possible allocation of particle



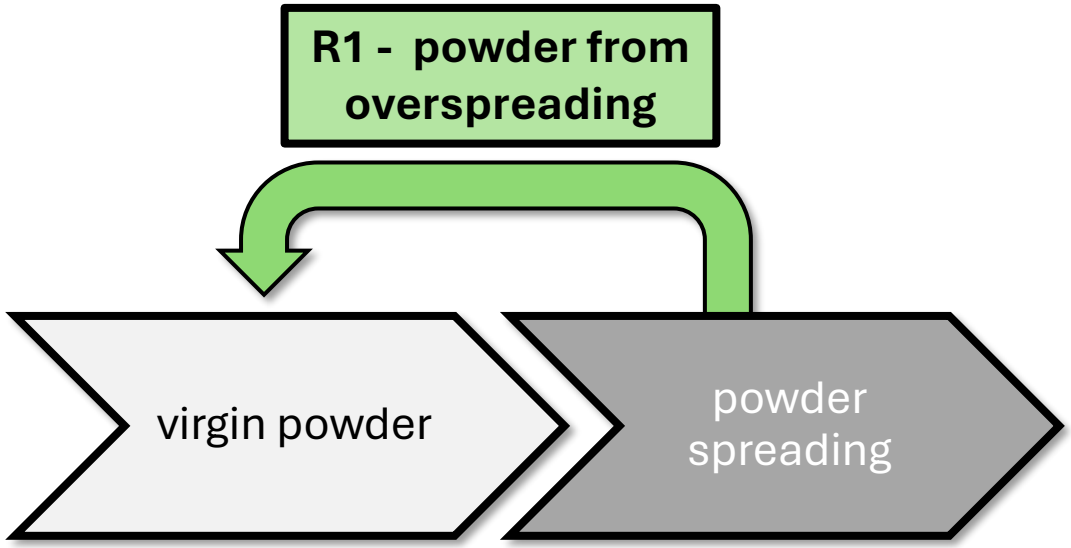


2. Materials and Methods

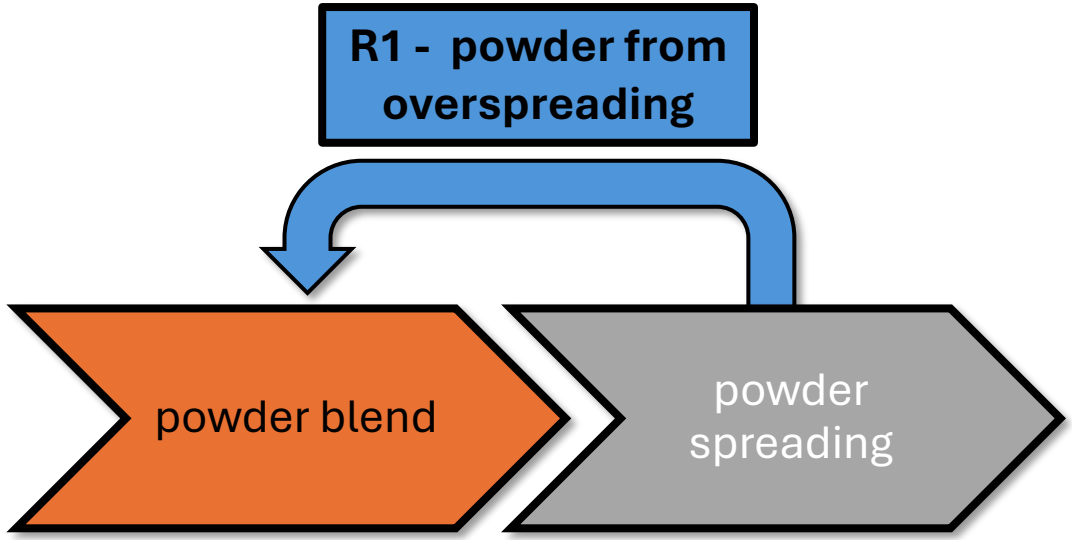
Powder recycling over multiple cycles

- **spreading experiments** up to **10 cycles,** same setup, identical parameter
  - **isolated view** on the **particle loss,** coarse particles are not formed in spreading
- measurement of the **changes in the particle size distribution**
- **two different powders** are used

- **virgin powder**



- **powder blend:** virgin powder + fine particles



Agenda

1 Motivation

2 Materials and Methods

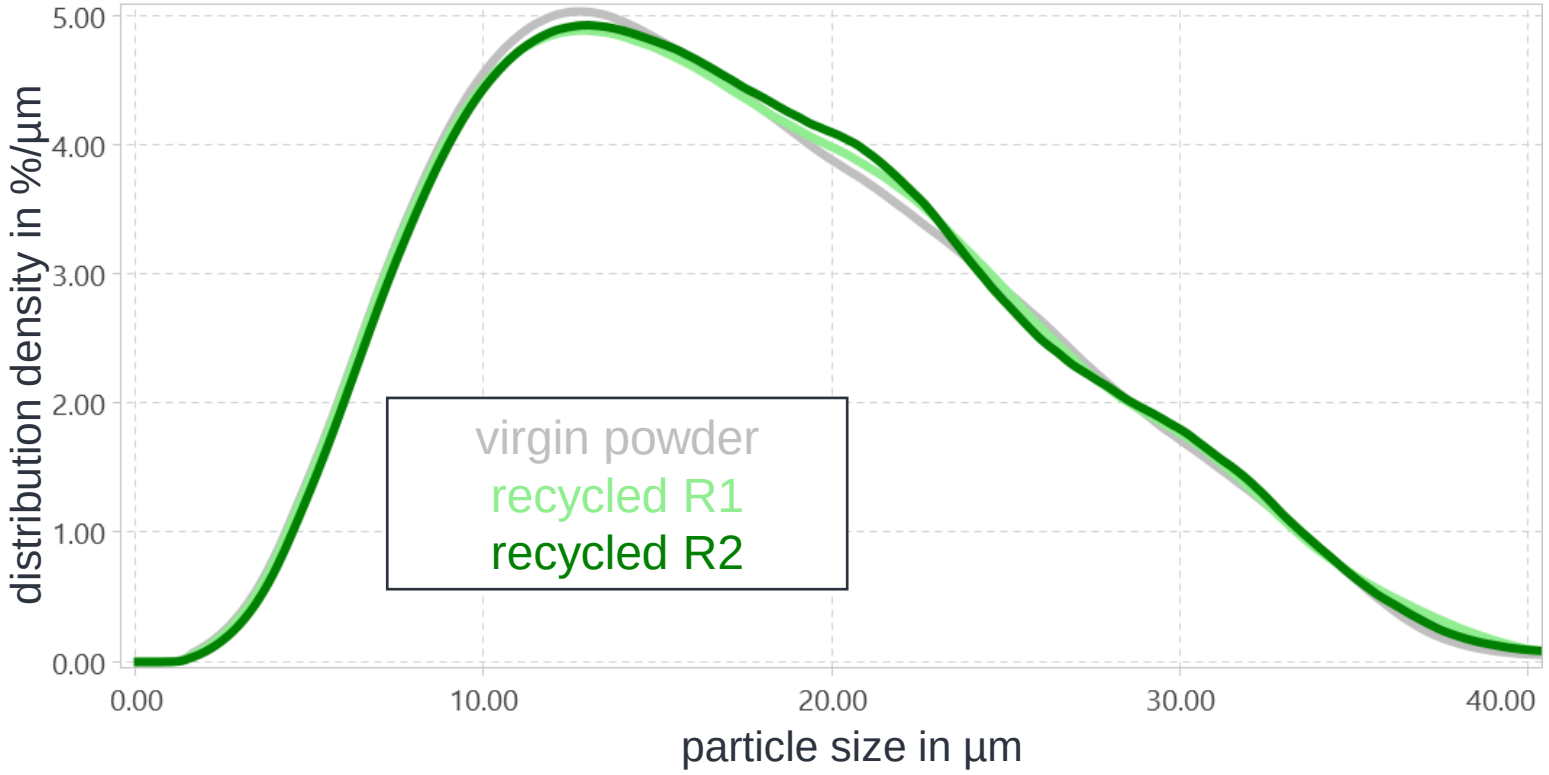
3 Results and Discussion

4 Conclusion



3. Results and Discussion

Powder recycling within first cycle



		Virgin	R1	R2
	<10 µm	17.25	16.99	16.34
10 µm	15 µm	25.10	24.32	24.48
15 µm	20 µm	21.77	21.82	22.07
20 µm	25 µm	17.07	17.78	18.02
25 µm	30 µm	11.52	11.05	11.04
30 µm	50 µm	7.28	8.02	7.96
>50µm		0.01	0.02	0.09

Changes in particle size within 1 cycle stay small, however a decrease in fine particle is seen in R1 and R2 while an increase in coarse particle is seen for R2

3. Results and Discussion

Powder recycling within first cycle

absolute density in g/cm³	virgin powder				
	7.96	7.94	7.92	7.93	7.94
	7.76	7.60	7.51	7.54	7.73
	7.67	7.58	7.50	7.56	7.68
	7.78	7.74	7.56	7.53	7.63
	7.87	7.70	7.62	7.65	7.78

7.94 / 7.50

	R2 - powder from depowdering				
	7.53	7.49	7.45	7.52	7.63
	7.53	7.21	7.13	7.17	7.32
	7.47	7.22	7.16	7.13	7.26
	7.53	7.27	7.06	7.09	7.23
	7.57	7.26	7.32	7.35	7.31

7.63 / 7.06

rel. density in %					
	88.8	88.6	88.3	88.5	88.7
	86.6	84.8	83.9	84.2	86.2
	85.6	84.6	83.7	84.3	85.7
	86.8	86.3	84.3	84.0	85.2
	87.8	86.0	85.1	85.4	86.9

88.8 / 83.7

	84.1	83.6	83.2	83.9	85.2
	84.1	80.5	79.6	80.0	81.7
	83.3	80.6	79.9	79.6	81.1
	84.0	81.1	78.8	79.2	80.7
	84.4	81.0	81.6	82.0	81.6

85.2 / 78.8

- **colorized by highest and lowest values** of each job
- **similar pattern** are shown
  - lowest density in the middle
  - highest densities in first column and row → spreading, printing

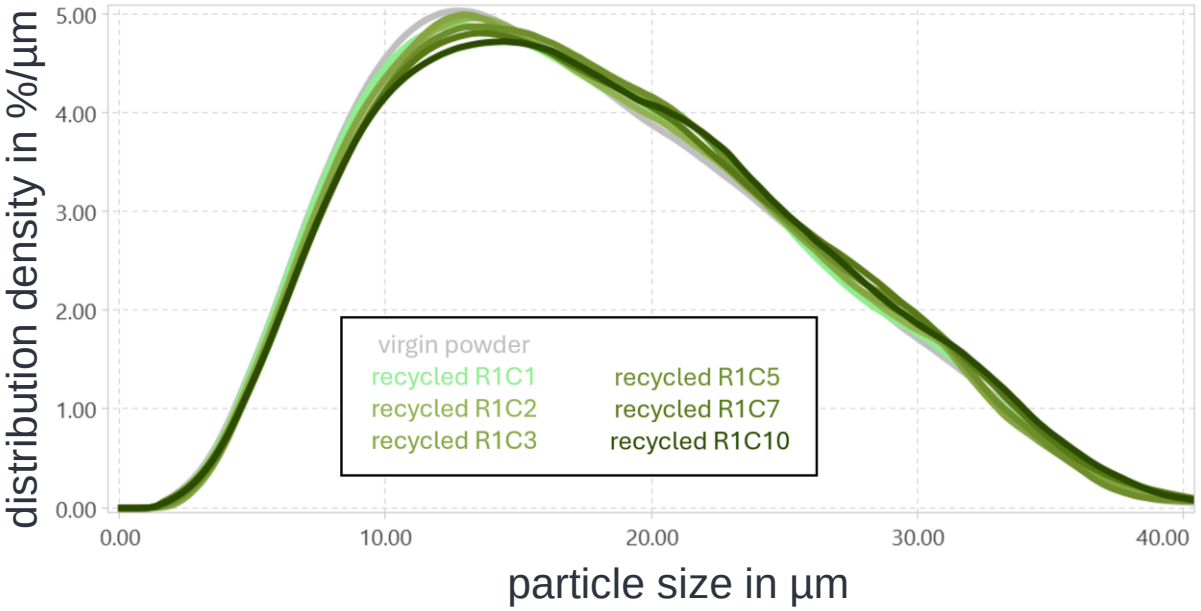
No accumulation of fine or coarse particle is visible

- difference in the achievable density
  - **-4.2 % in rel. density** through **1 cycle**
  - indication of additional **oxidation** in curing step

Significant influence on achievable sintered density.

3. Results and Discussion

Powder recycling over multiple cycles / initial powder



initial powder shows a **steady loss of fine particles over cycles**

- **maximal loss after 10 cycles -3.6%**
- **PSD shifted to higher values over cycles**

absolute values

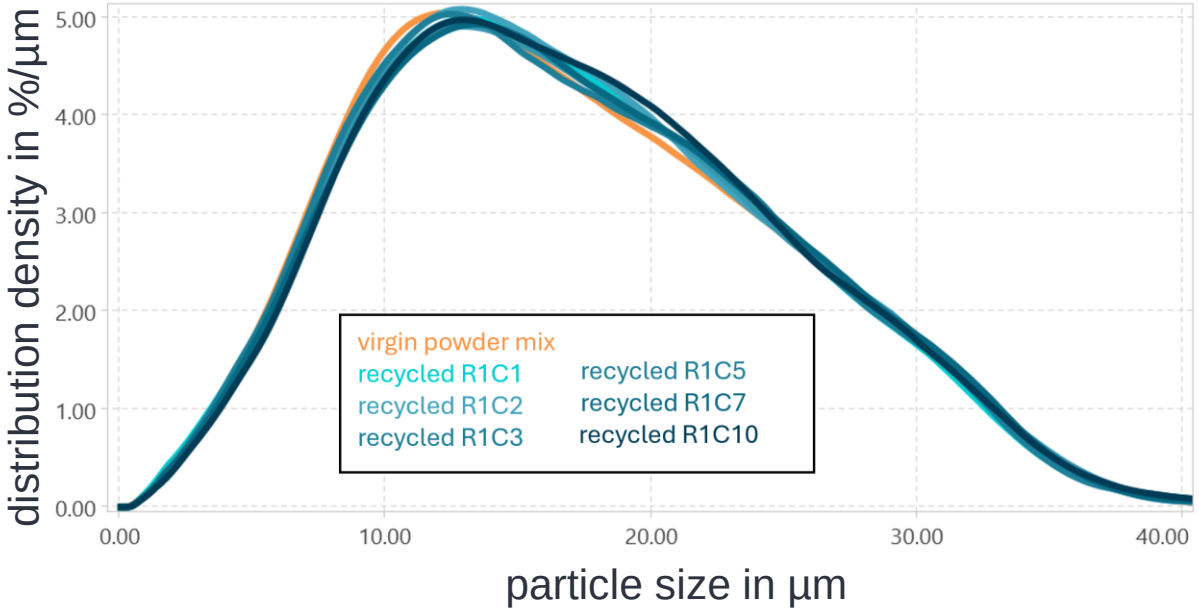
		virgin	R1 C1	R1 C2	R1 C3	R1 C5	R1 C7	R1 C10
	<10 µm	17.25	16.99	16.39	16.1	15.47	15.53	15.62
10 µm	15 µm	25.1	24.32	24.56	24.32	23.93	23.71	23.1
15 µm	20 µm	21.77	21.82	21.77	22.34	22.56	22.2	22.08
20 µm	25 µm	17.07	17.78	17.55	17.98	18.23	17.73	18.42
25 µm	30 µm	11.52	11.05	11.49	11.58	12.06	12.4	12
30 µm	50 µm	7.28	8.02	8.22	7.66	7.73	8.41	8.76
>50 µm		0.01	0.02	0.02	0.02	0.02	0.02	0.02

		virgin	R1 C1	R1 C2	R1 C3	R1 C5	R1 C7	R1 C10
	<10 µm	0	-0.26	-0.86	-1.15	-1.78	-1.72	-1.63
10 µm	15 µm	0	-0.78	-0.54	-0.78	-1.17	-1.39	-2
15 µm	20 µm	0	0.05	0	0.57	0.79	0.43	0.31
20 µm	25 µm	0	0.71	0.48	0.91	1.16	0.66	1.35
25 µm	30 µm	0	-0.47	-0.03	0.06	0.54	0.88	0.48
30 µm	50 µm	0	0.74	0.94	0.38	0.45	1.13	1.48
>50 µm		0	0.01	0.01	0.01	0.01	0.01	0.01
0 µm	15 µm	0	-1.04	-1.4	-1.93	-2.95	-3.11	-3.63
15 µm	>50 µm	0	1.04	1.4	1.93	2.95	3.11	3.63

changes to virgin

3. Results and Discussion

Powder recycling over multiple cycles / powder blend



absolut values

		blend	C1	C2	C3	C5	C7	C10
	<10 µm	19.12	18.47	17.83	18.49	18.48	17.95	17.49
10 µm	15 µm	25.25	24.9	25.3	24.58	24.47	24.36	24.46
15 µm	20 µm	21.19	22.1	22.36	21.63	21.60	21.83	22.38
20 µm	25 µm	16.78	17.19	16.74	17.16	17.37	17.42	17.60
25 µm	30 µm	11.24	10.94	11.16	11.42	11.08	11.48	11.29
30 µm	50 µm	6.37	6.36	6.59	6.7	6.58	6.58	6.76
>50 µm		0.05	0.04	0.02	0.02	0.02	0.03	0.02

		blend	C1	C2	C3	C5	C7	C10
	<10 µm	0	-0.65	-1.29	-0.63	-0.64	-1.17	-1.63
10 µm	15 µm	0	-0.35	0.05	-0.67	-0.78	-0.89	-0.79
15 µm	20µm	0	0.91	1.17	0.44	0.41	0.64	1.19
20µm	25 µm	0	0.41	-0.04	0.38	0.59	0.64	0.82
25 µm	30 µm	0	-0.3	-0.08	0.18	0.24	0.09	0.05
30 µm	50 µm	0	-0.01	0.22	0.33	0.21	0.71	0.39
>50 µm		0	-0.01	-0.03	-0.03	-0.03	-0.02	-0.03
0	15 µm	0	-1	-1.24	-1.3	-1.43	-2.06	-2.42
15 µm	>50 µm	0	1	1.24	1.3	1.43	2.06	2.42

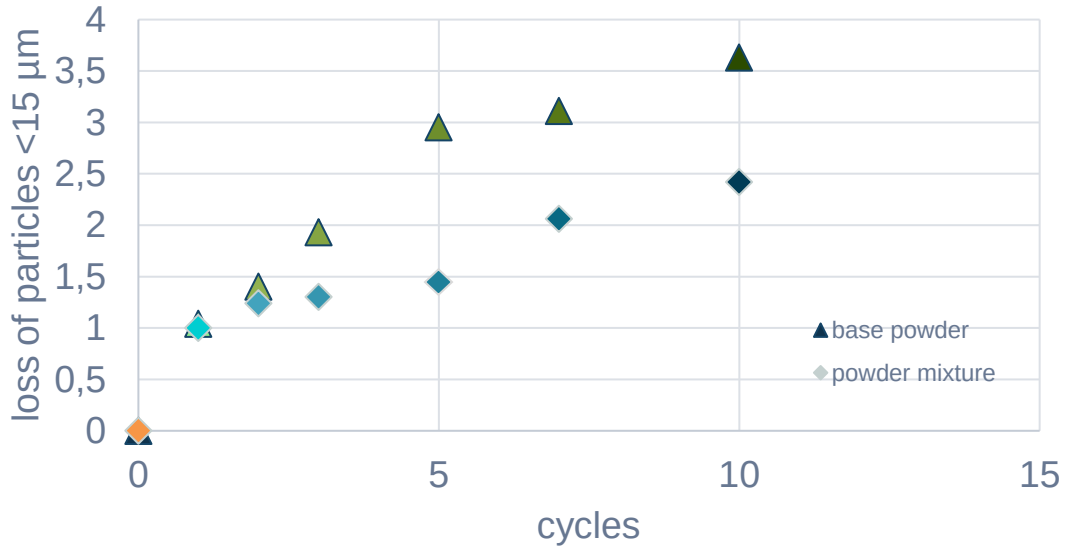
changes to virgin

powder blend shows a **steady loss of fine particles over cycles**

- **maximal loss after 10 cycles -2.4%**
- **PSD shifted to higher values over cycles**

3. Results and Discussion

Powder recycling over multiple cycles / comparison



virgin	C1	C2	C3	C5	C7	C10
blend	C1	C2	C3	C5	C7	C10

after **10 cycles** both powder show **still a lose fine particle** content

→the number of cycles are to low for a final value

both powder show a loss of fine particles, however the powder with higher fine particle content has a lower loss

Agenda

1 Motivation

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4 Conclusion



4. Conclusion

Focus of this work

- **changes in particle size distribution** in fine powder inside the binder Jetting process

powder recycling within first cycle

1

- **R1**: **decrease** in **fine particles (>10 µm)**
- **R2**: additionally **increase** in **coarse paritcel (<50 µm)**
- **changes** in the PSD are **overall small**
  → amount of recycle cycles

- same spatial pattern was observed for the density
  → **no allocation of particles** was found

- **recycling decreases** sintered **density sigificantly**
  → indication of oxidation

powder recycling over multiple cycles

10

- change in powder composition
  → **particle** content up to **15 µm decreased**
- **increasing loss** of **fine particles over cycles**
  → spreading and handling powder

- **virgin powder:** maximum **loss of 3,6%**
- **powder blend:** higher fine content, but **lower loss (2,4%)**

for a circular binder jetting process chain the changes per cycle must be determined

Thank you!



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A Virtual Reality Framework for Collecting Demonstrations of Fine Manipulation Tasks

David Waidelich, Aleksandar Taranovic, Emiliyan Gospodinov, Gerhard Neumann

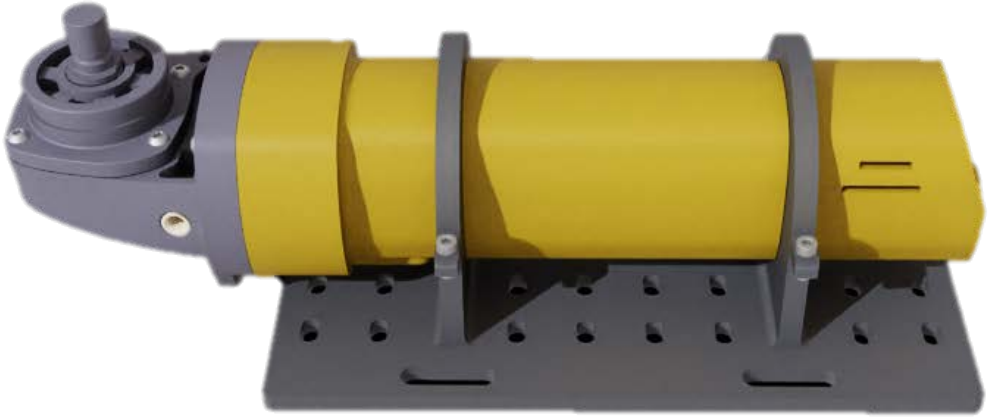
9th June 2026

Conference on Circular Production Systems and Technologies (CCPT)

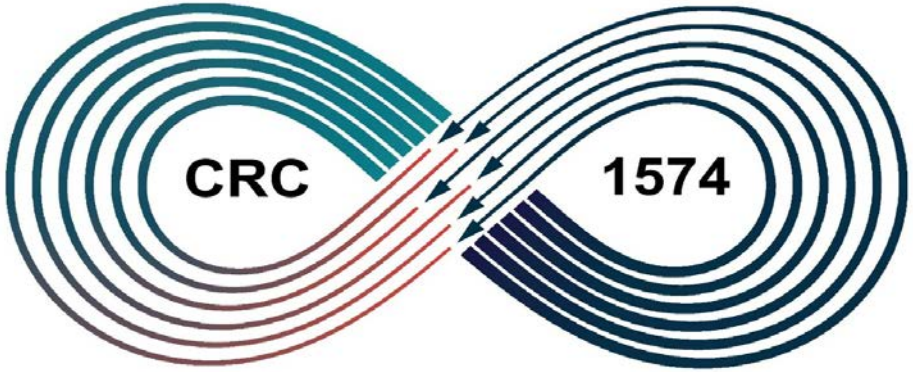


Introduction

- **Circular manufacturing** repairs, upgrades, and restores earlier-generation products.
- **Imitation Learning** trains robot policies from expert demonstrations.
- **Demonstration quality and diversity** are critical.
  - But **collecting** demonstrations is **difficult and costly**, especially in industry.
- Our solution is an **intuitive VR framework** using bare-hand tracking with no controllers.



Angle Grinder © Jan Baumgärtner

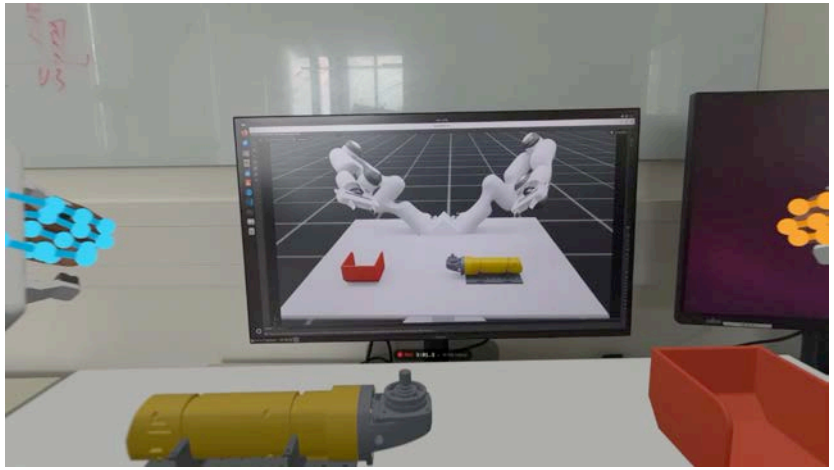


Circular Factory for the Perpetual Product

VR Framework Foundation

- **Apple Vision Pro**
  - High-fidelity bare-hand tracking with good visual representation of the scene.
  - Direct interaction with no controllers or extra devices, removing friction for novice demonstrators.
- **Hand-tracking teleoperation** (built on [1])
  - Raw hand skeleton mapped to a 6-DOF end-effector pose.
  - Each hand individually controls one arm for bimanual tasks.
- **NVIDIA Isaac Lab simulation**
  - Photo- and physics-realistic environment for training and evaluation.





[1] https://github.com/Improbable-AI/VisionProTeleop

Contribution

Two assistive mechanisms:

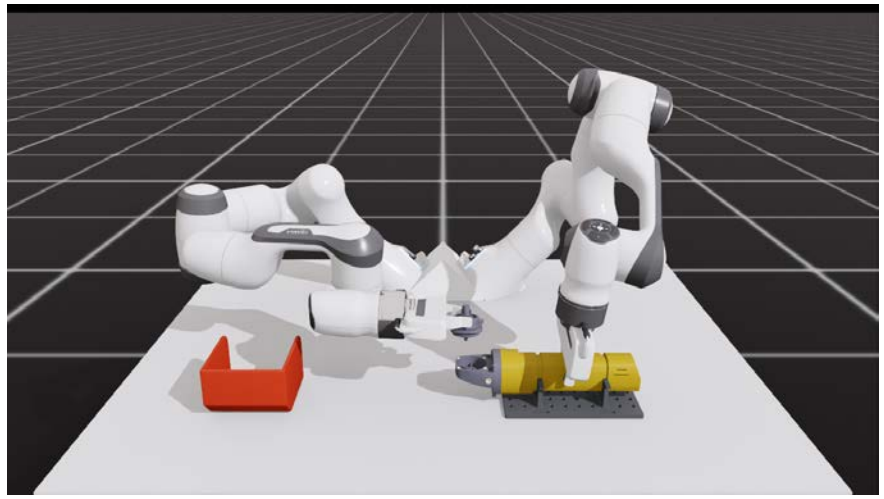
- **Snapping alignment**, which removes the fine-manipulation burden by automatically aligning the end-effector with the target when within a small proximity threshold.
- **Hold position**, which locks a stabilizing arm in place during bimanual manipulation to reduce demonstrator strain and prevent unintended drift.

Evaluation on two angle grinder disassembly tasks:

- **Screw-loosening** Task

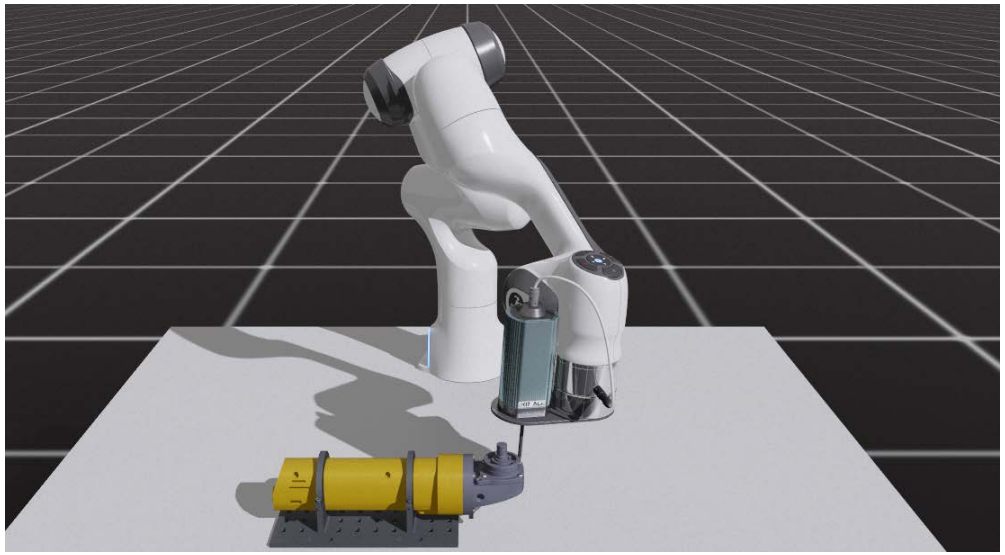


- **Ring-Gear-Removal** Task

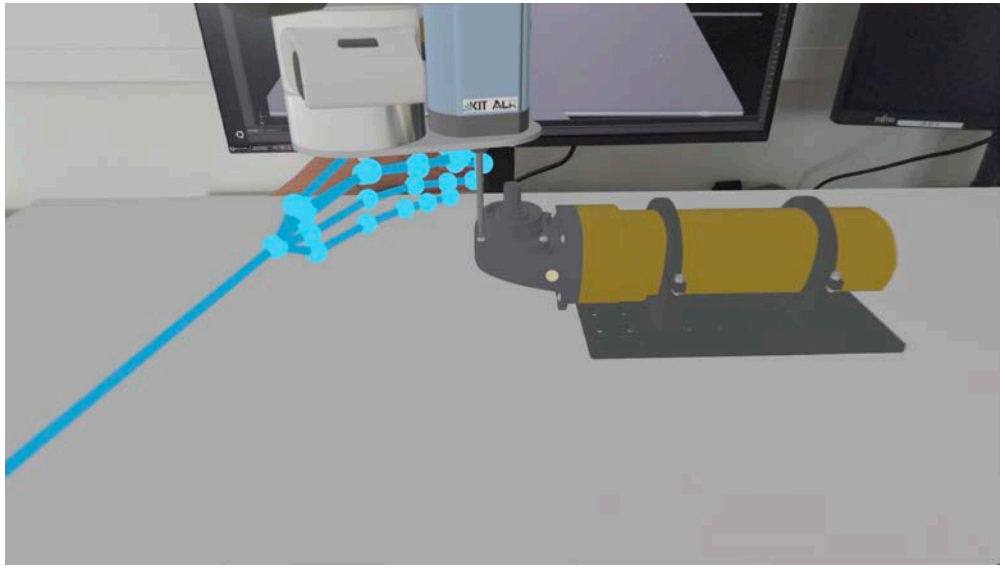


Snapping Alignment in the Screw-loosening Task

- **Setup**:
  - Single Franka Emika Panda arm with a screwdriver end-effector.
  - Angle grinder in holder on the table.
- **Goal**:
  - Reach a target screw on the angle grinder housing and loosen it.
- **Challenge**:
  - Requires precise alignment of the screwdriver bit with the screw head.



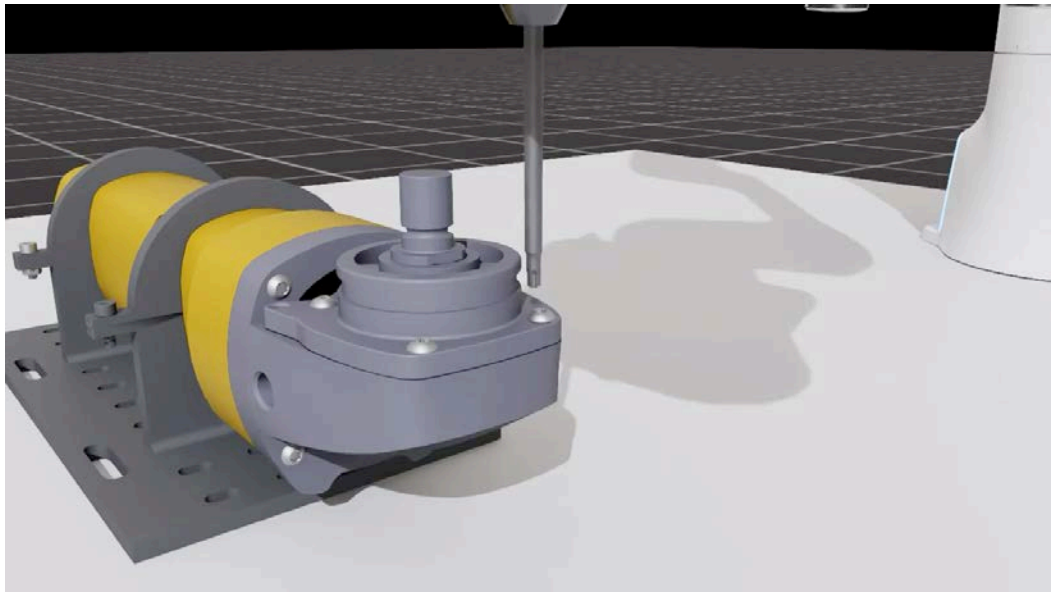
- **Simulation** Visualization



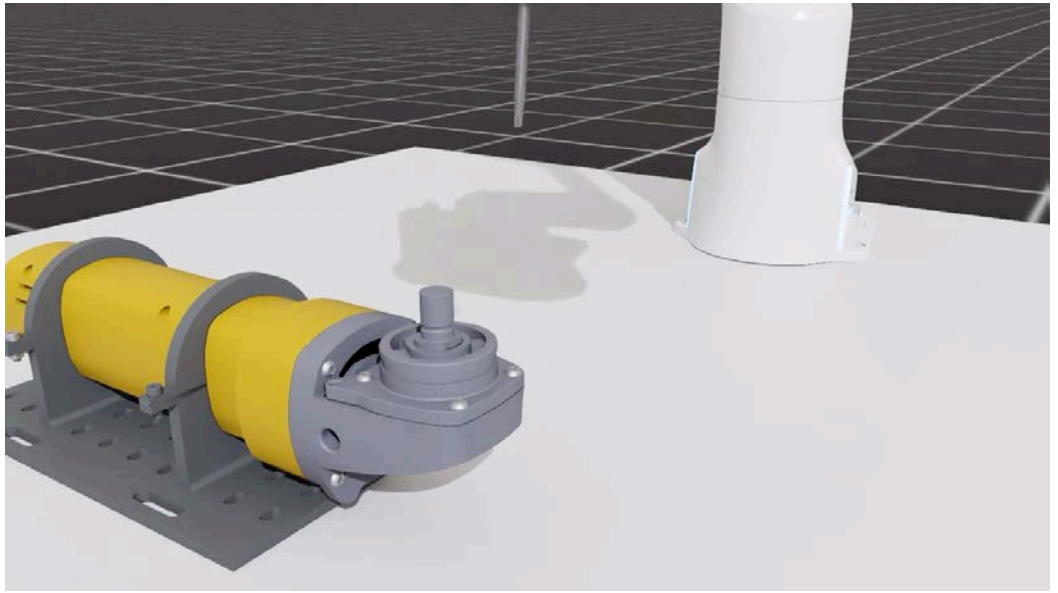
- **VR** View

Snapping Alignment in the Screw-loosening Task

- System **continuously measures the distance** between the end-effector and the target screw.
- While **far away**, the robot **follows the hand exactly**, so the demonstrator keeps full control.
- Once the end-effector **crosses a proximity threshold**, its commanded position **snaps** to the screw's known pose.
- **Small threshold** means snapping only triggers in the final approach, where precision is hardest.
- **Summary**:
  - Natural motion is preserved over the rest of the trajectory, while fine alignment error at contact is eliminated.



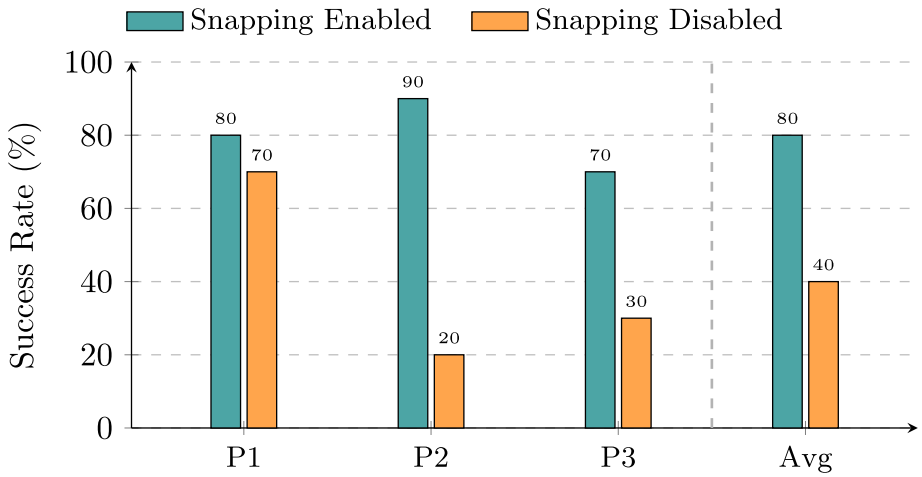
- **Without** Snapping Alignment



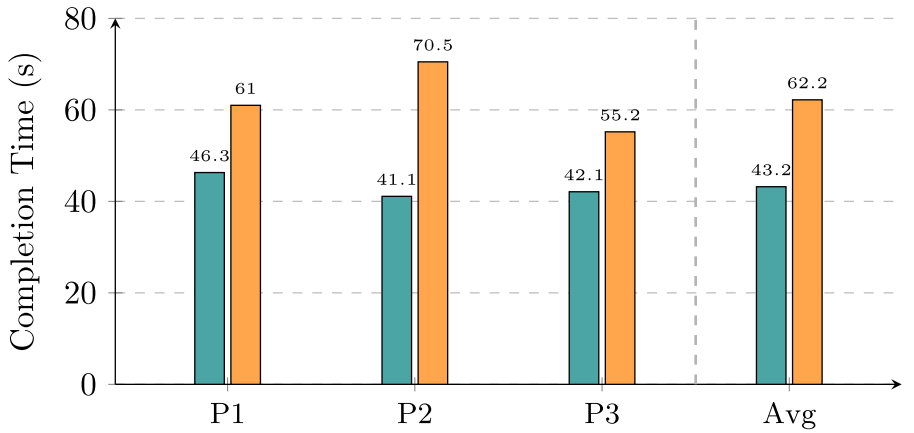
- **With** Snapping Alignment

Snapping Alignment in the Screw-loosening Task

- **Participants**:
  - **3** users,
  - each collected **10 demonstrations** with snapping and 10 without snapping alignment mechanism.
- **Randomized order** to control for learning effects.
- **With Snapping Alignment**
  - **Higher Success Rate** (80% vs 40%)
  - **Shorter Completion time** (43.2 vs 62.2 *seconds*)



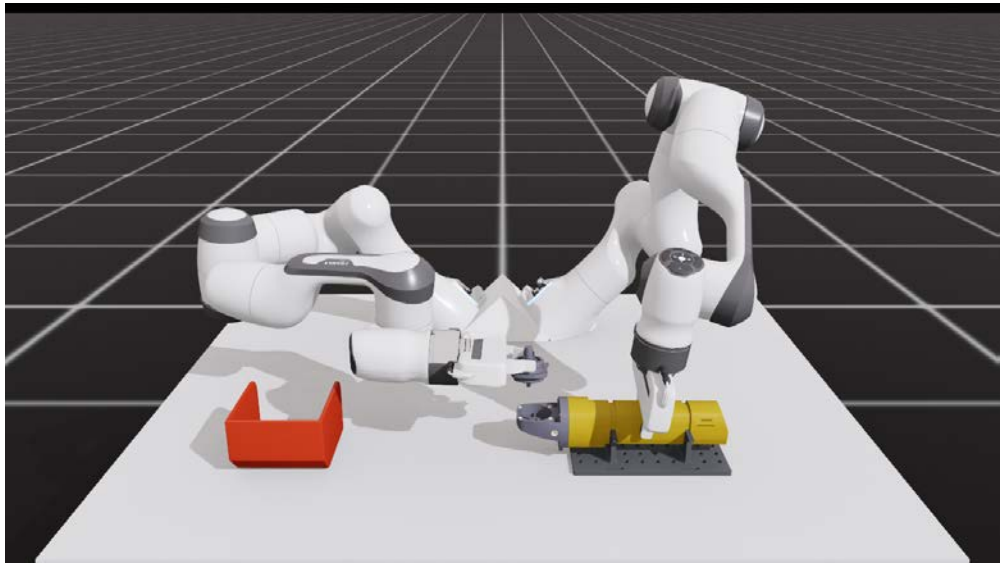
(a) Success rate (↑ higher is better).



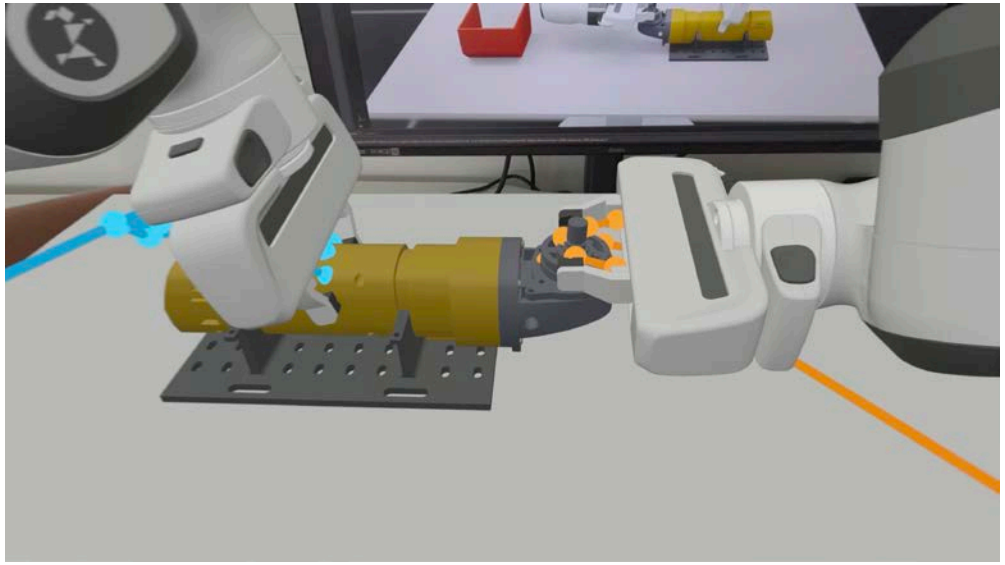
(b) Completion time (↓ lower is better).

Hold Position in the Ring-Gear-Removal Task

- **Setup**:
  - Two Franka Emika Panda arms, one stabilizing and one manipulating.
  - Angle grinder body held by the stabilizing arm.
- **Goal**:
  - Grasp and remove the ring gear from the gearbox while the other arm holds the body steady.
- **Challenge**:
  - Prolonged bimanual teleoperation is physically and cognitively demanding, and the holding hand drifts without force feedback.



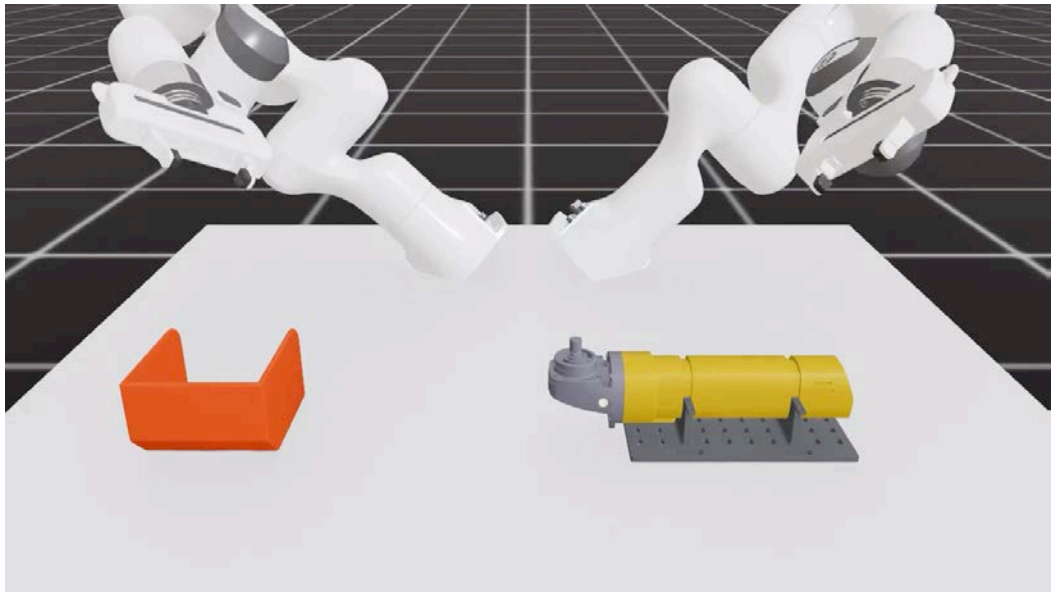
- **Simulation** Visualization



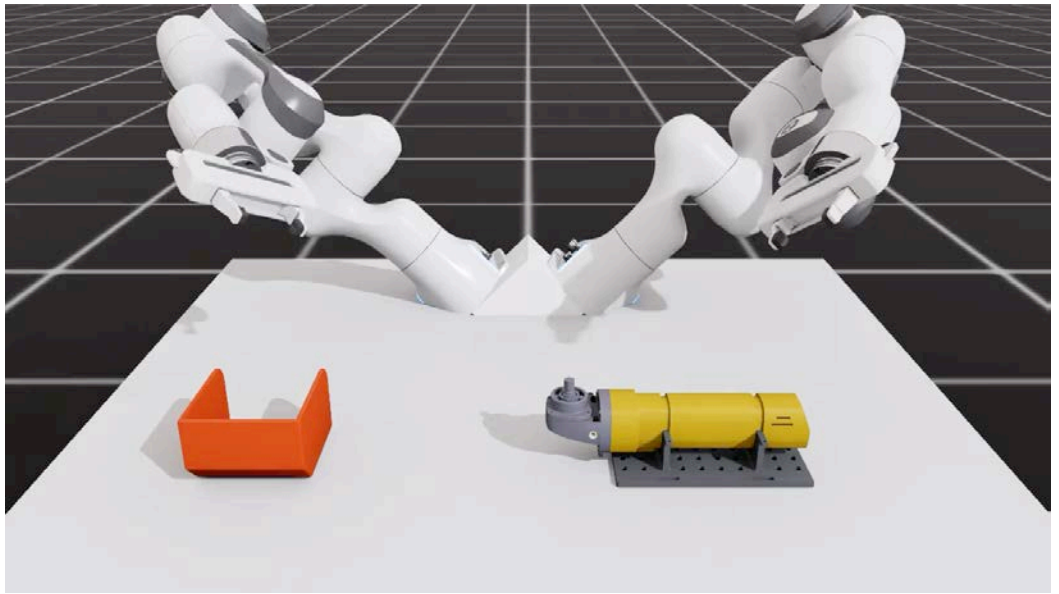
- **VR** View

Hold Position in the Ring-Gear-Removal Task

- Demonstrator first **positions the stabilizing arm** at the desired pose using hand tracking.
- A dedicated finger gesture (pinch past the threshold) **locks the arm** at its current pose.
- While locked, the **arm stays fixed** and ignores hand motion, so the demonstrator can relax that hand.
- The demonstrator then **focuses** entirely on the **manipulating arm** to remove the ring gear.
- **Summary**:
  - Physical strain and unintended drift are minimized, so demonstration quality stays high over long bimanual sessions.



- **Without** Hold Mechanism



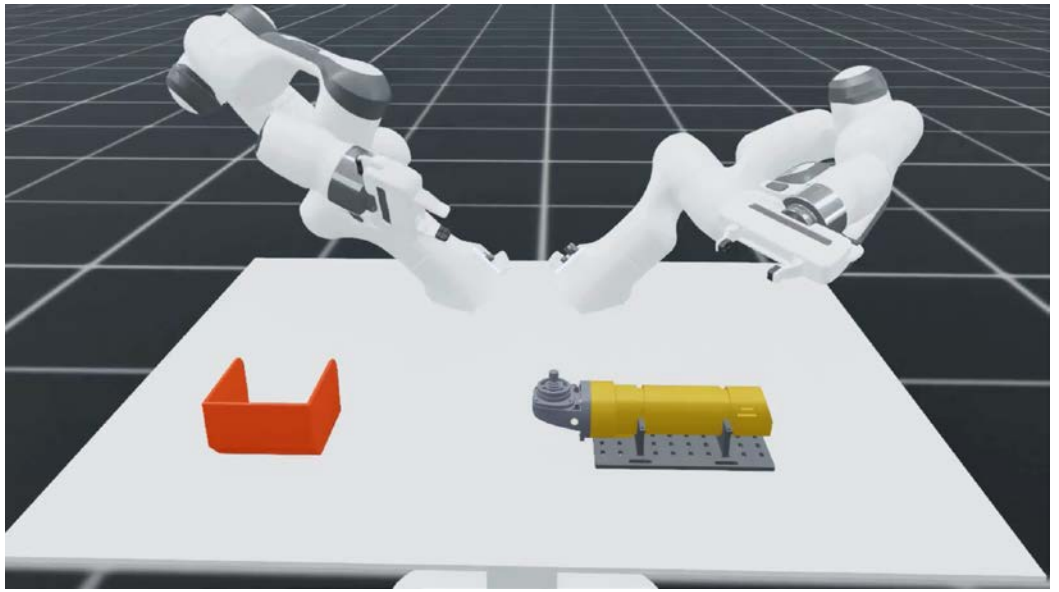
- **With** Hold Mechanism

Hold Position in the Ring-Gear-Removal Task

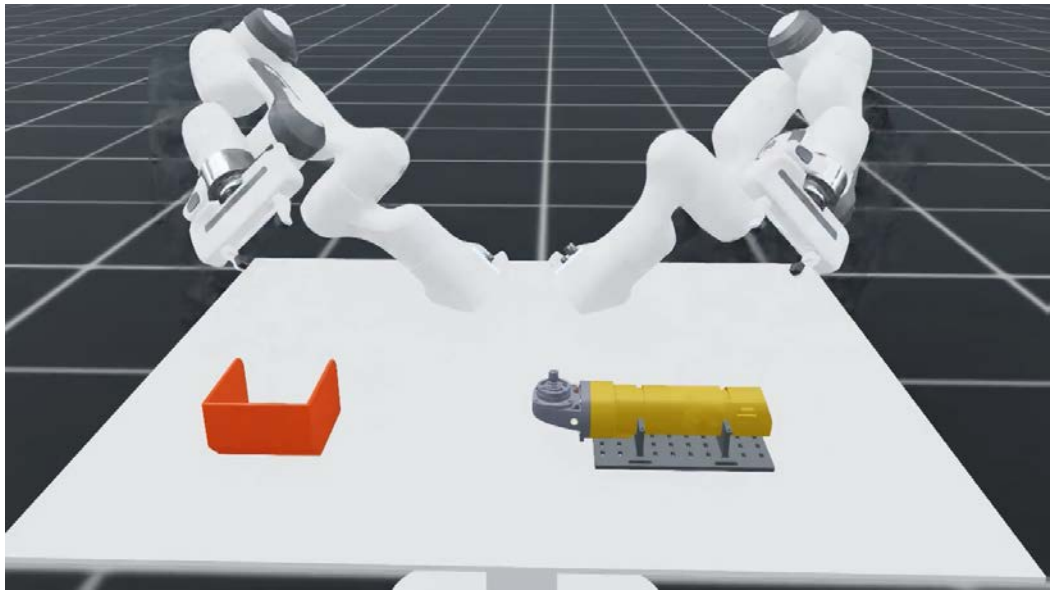
- Collected 50 demonstrations with hold position enabled and 50 with it disabled.
- Evaluation on 2 state-of-the-art Imitation Learning Baselines.
- Hold position gives consistent gains across both baselines.

Success Rate [%]

Algorithm	w/o Hold	w/ Hold
Diffusion Policy	75	**90**
ACT	80	**95**



- **Failed** rollout

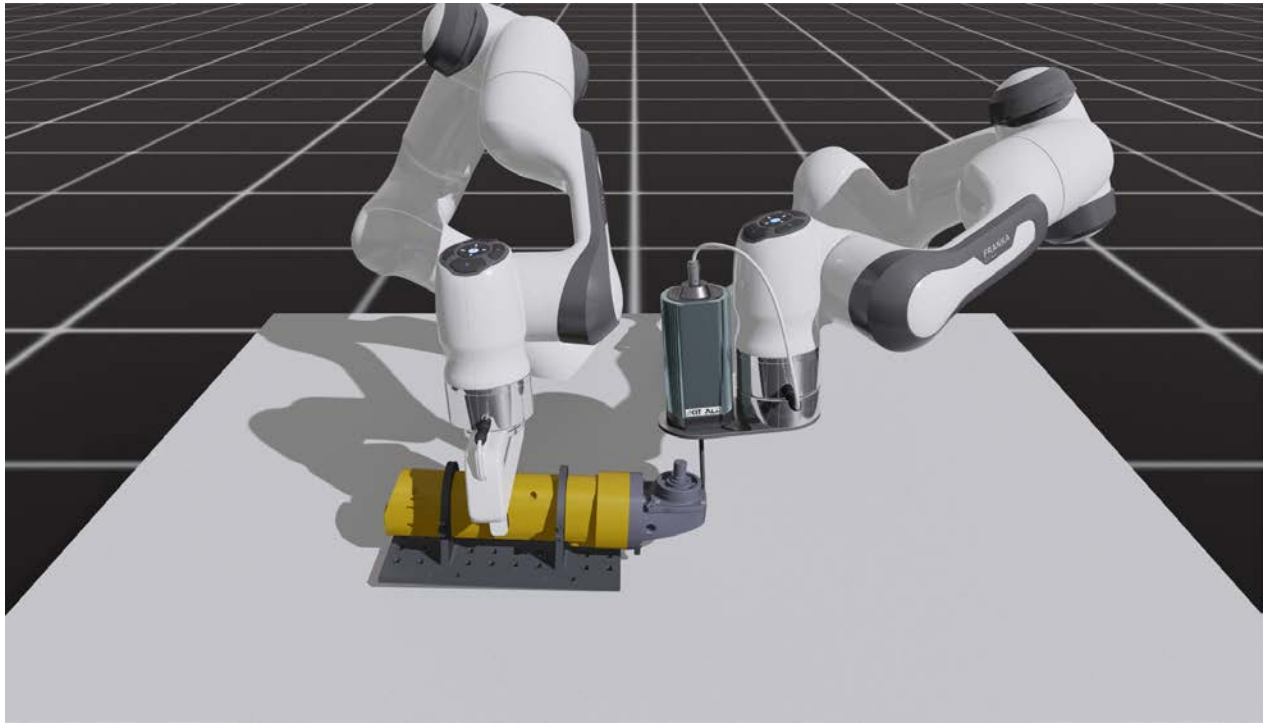


- **Successful** rollout

Conclusion

We extend a **VR-based demonstration collection framework** so that users can more easily collect higher-quality demonstrations:

- **Snapping alignment mechanism** aligns the end-effector with the target object, benefiting tasks such as screw loosening.
- **Hold position mechanism** fixes the pose of one arm in a bimanual setup, reducing demonstrator effort.

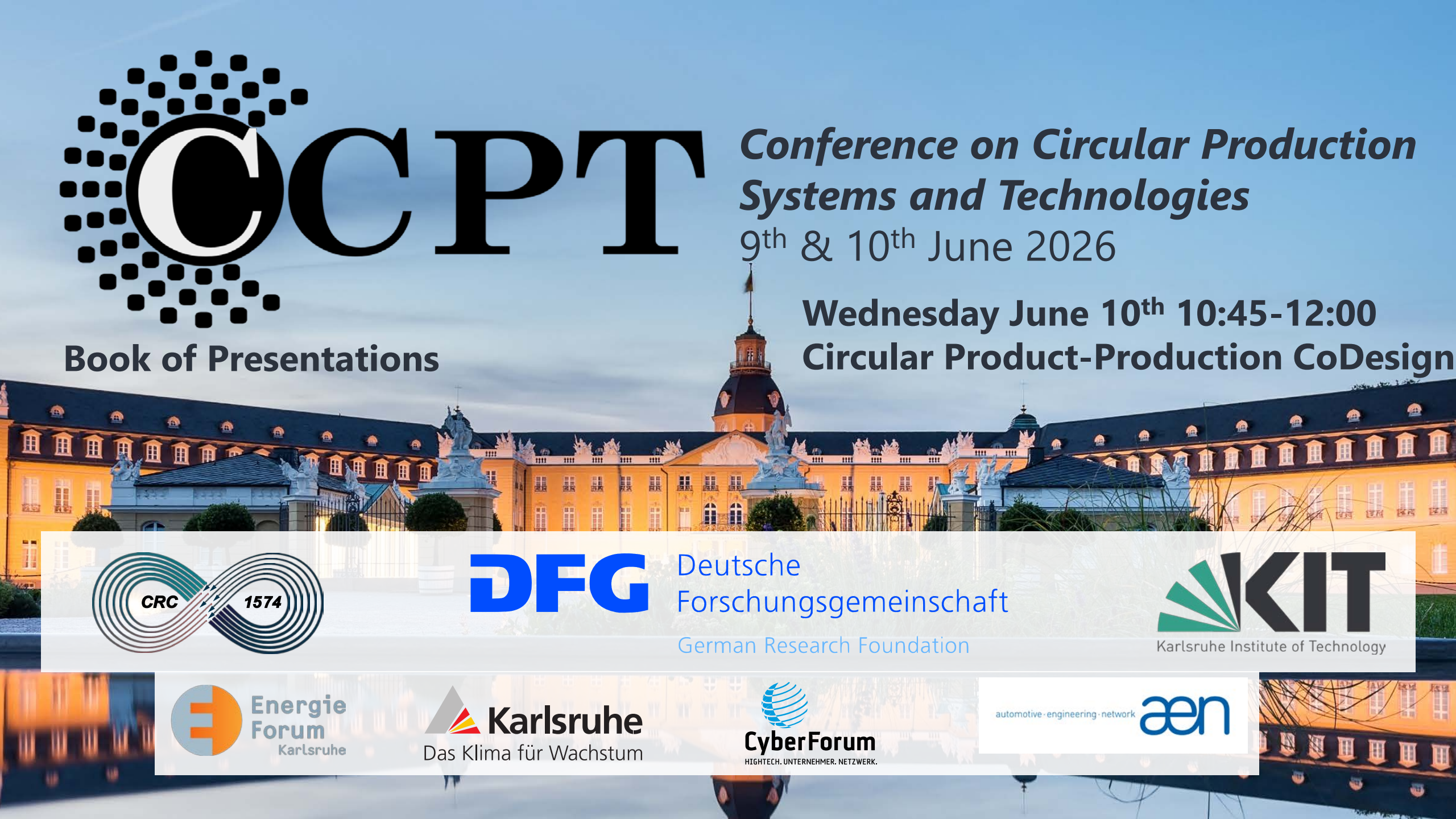


- Bimanual Manipulation with both mechanisms

Future Work

- Evaluate the mechanisms on a **wider range of tasks.**
- Explore tasks that require combining **both mechanisms.**
- Assess the framework through a **larger user study.**
- Evaluate the trained policies on a **real physical robot system.**





CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 10:45-12:00
Circular Product-Production CoDesign

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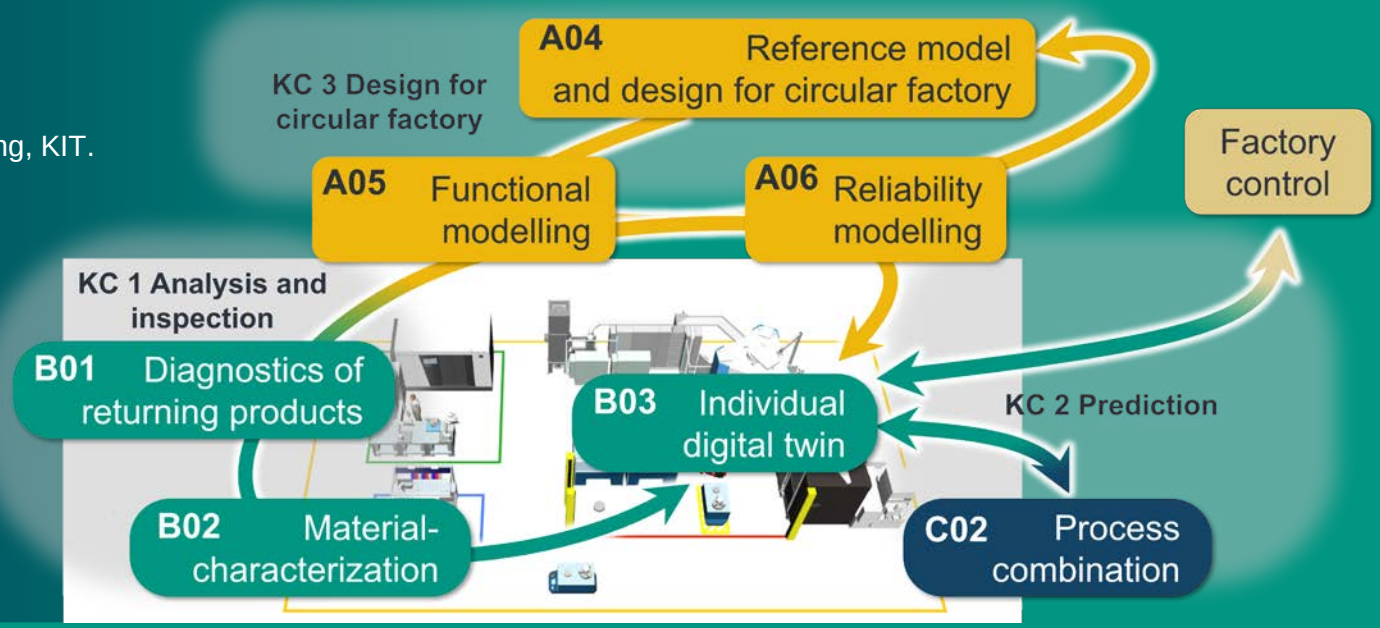
automotive · engineering · network aen

Bringing the vision of perpetual innovative products to life – challenges and opportunities at the circular factory for angle grinders

Patric Grauberger, Jonas Hemmerich, Nehal Afifi, Victor Mas, Dominik Koch, Edwin Blum, Luisa Hoffmann, Ali Darijani, Gabriel Moser, Kristian Vlajic, Mehdi Khabou, Helena Wexel, Gisela Lanza, Albert Albers, Tobias Düser, Volker Schulze, Michael Heizmann, Jürgen Beyerer, Frederik Zanger, Stefan Dietrich, Sven Matthiesen

IPEK - Institute of Product Engineering, KIT.
wbk Institute of Production Science, KIT.
IAM-WK Institute for Applied Materials – Materials Science and Engineering, KIT.
IIIT-Institute of Industrial Information Technology, KIT.
Fraunhofer-Gesellschaft, Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB .
Vision and Fusion Laboratory (IES), KIT.
All KIT-affiliated institutes are located at Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany.

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Challenges in a circular factory – how can the vision come to life?

Focus on the functional aspects

How can subsystems and components be **diagnosed**, **reprocessed** and **technologically updated** in order to establish value-adding products from circular value creation on the **primary market**?

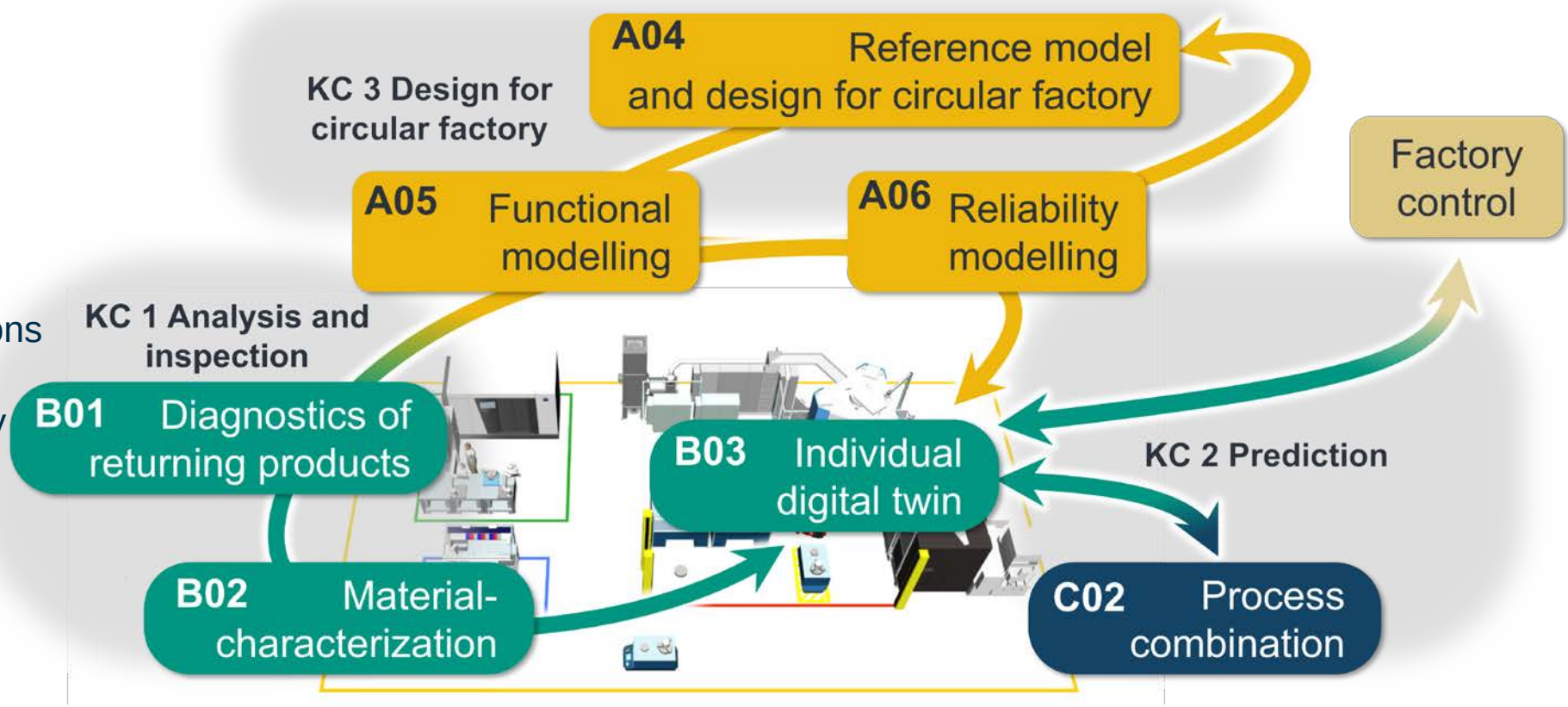
Prediction of the product function

Subprojects from areas **A**, **B** and **C** create **instance-specific models** of the product in order to

I enable target-oriented diagnostics,

II define concrete specifications for **reprocessing**, taking into account the reliability and

III support **Design for Circular Factory** (D4CF).



What happens to the product entering the Circular Factory?

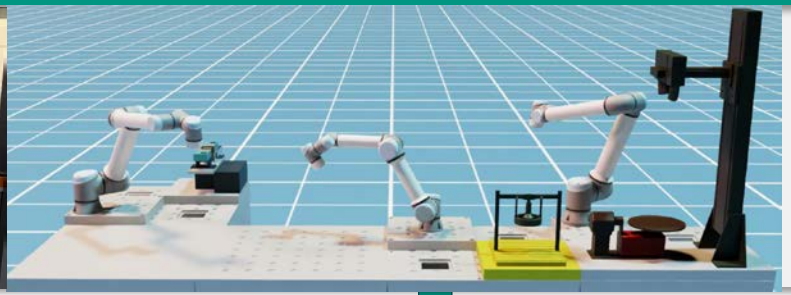
Diagnostics – what do we have here?

Individually worn down Product

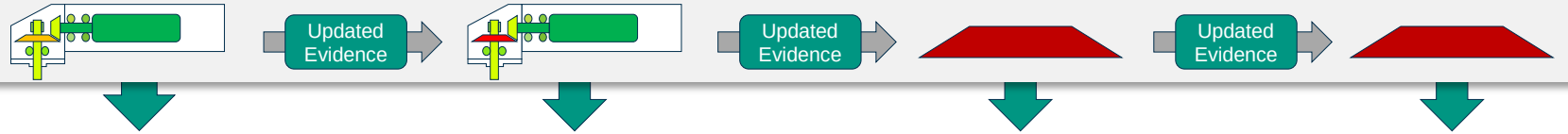
Measurement Strategies

Adaptive determination of optimal **measurement-process sequences** for unical products under **competing objectives** such as minimal disassembly depth, minimal inspection time, and maximum diagnostic precision.

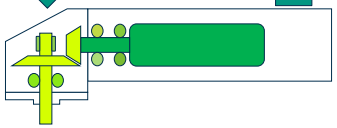




Digital Representation – Gaussian Mixture Model (GMM) based representation of assemblies and components

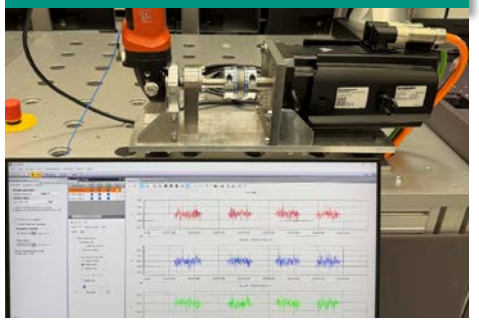


A priori Knowledge

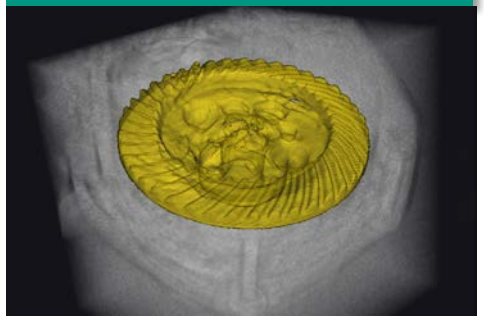


Initial hypothesis

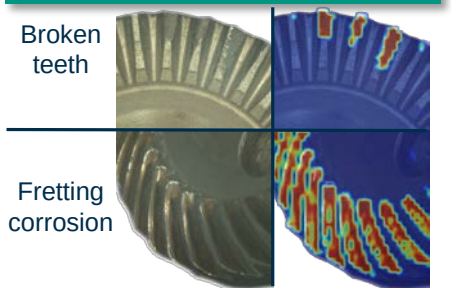
Functional Behaviour Testing



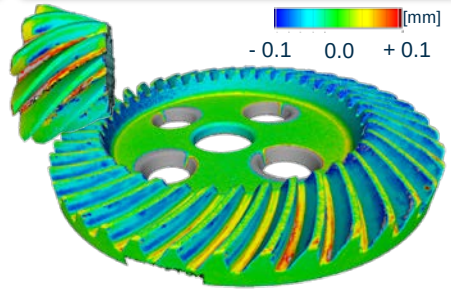
CT Inspection



Surface defect detection

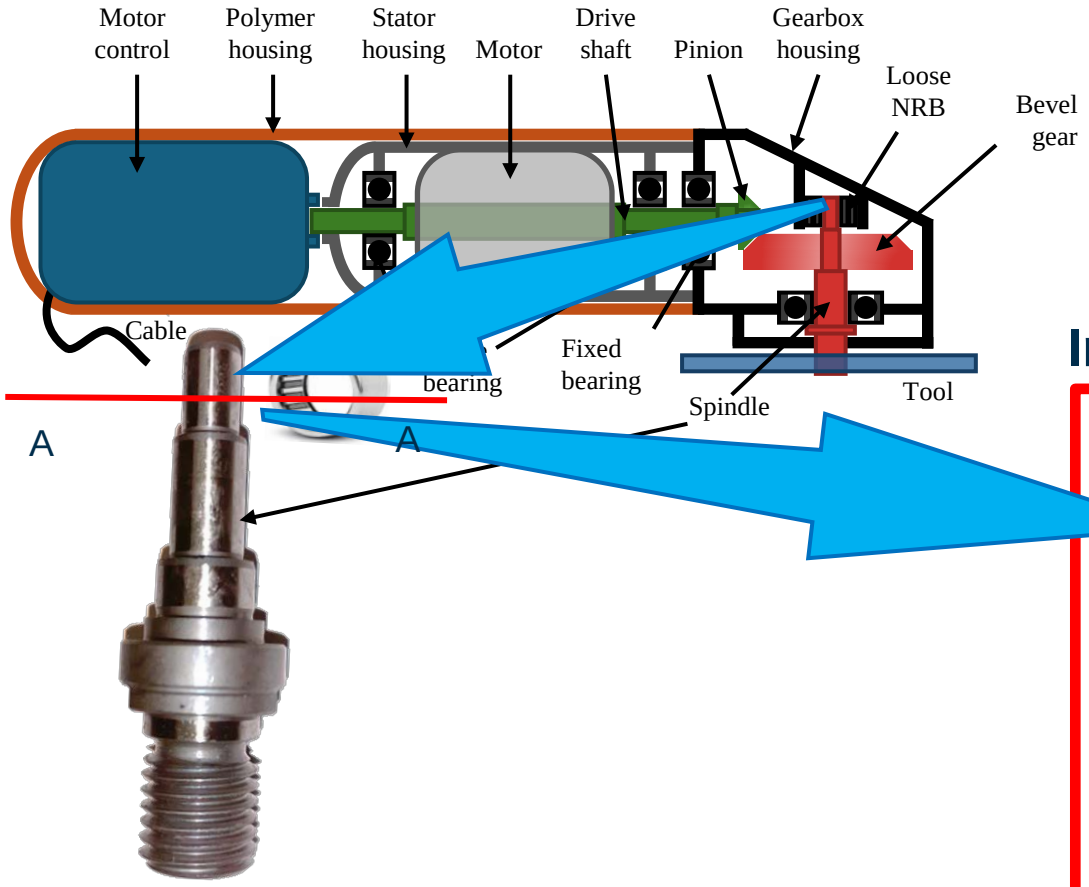


Geometric measurement



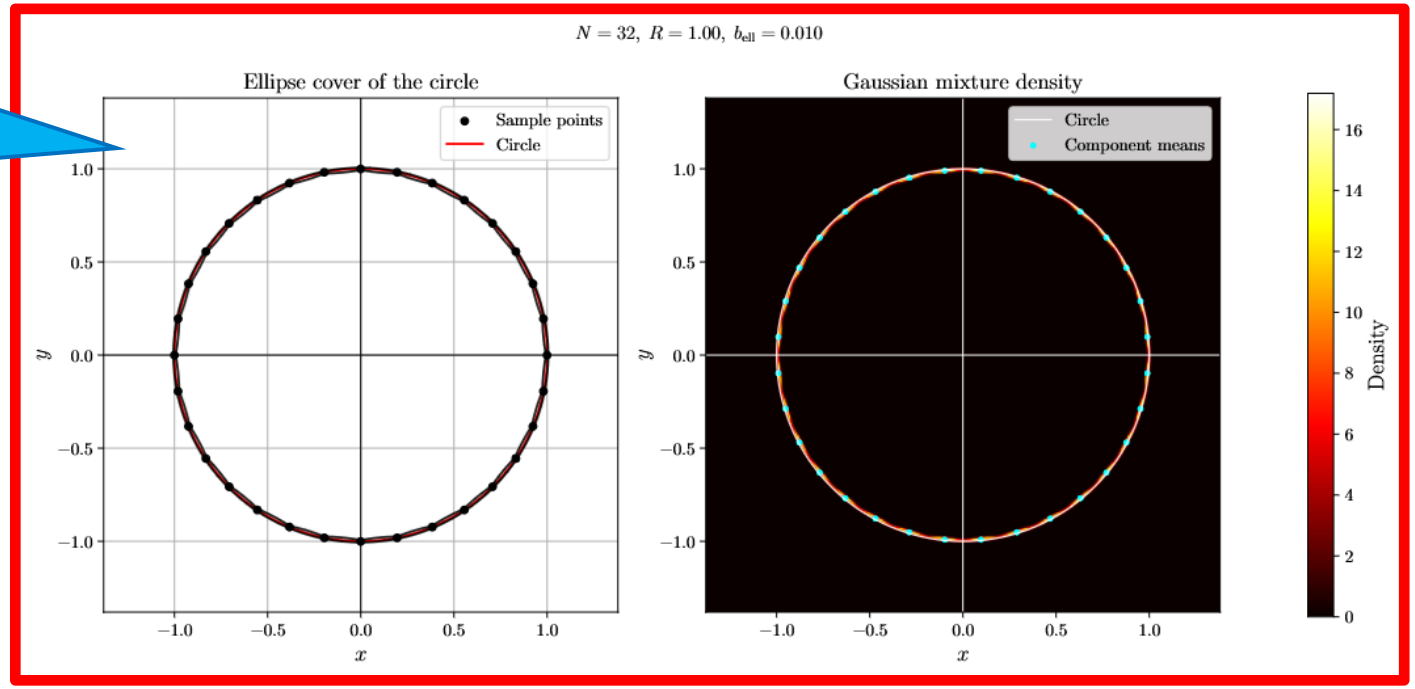
Spotlight on a detail – how to model uncertainty

Individually worn down products bring up to now unknown amounts of uncertainty with them



Uncertainty added to the geometric description via Gaussian mixture modelling

Intersection A-A



What to do with the identified products?

Reprocessing of the subsystems for perpetual innovative products

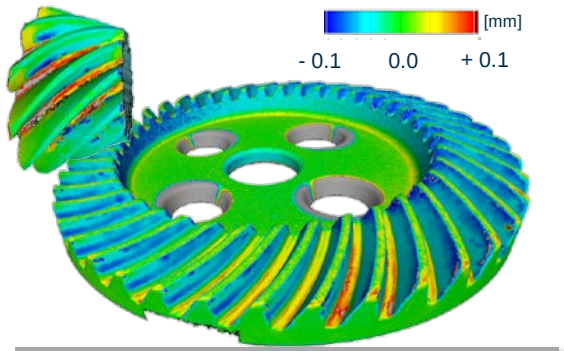
Coordination of **additive and machining manufacturing technologies** for the **reprocessing** of unique metallic components, alongside the conclusions drawn from **multi-sensor process monitoring** regarding the **resulting properties** of these components.



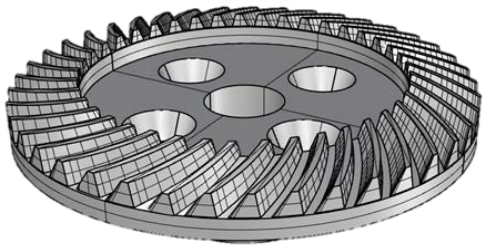


Input CAD/CAM path planning

Geometric measurement

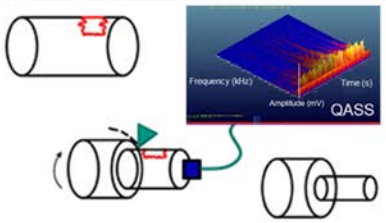


CAD data

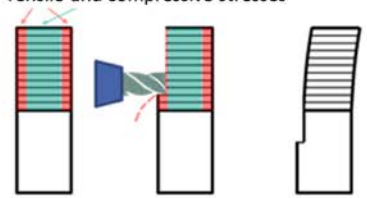


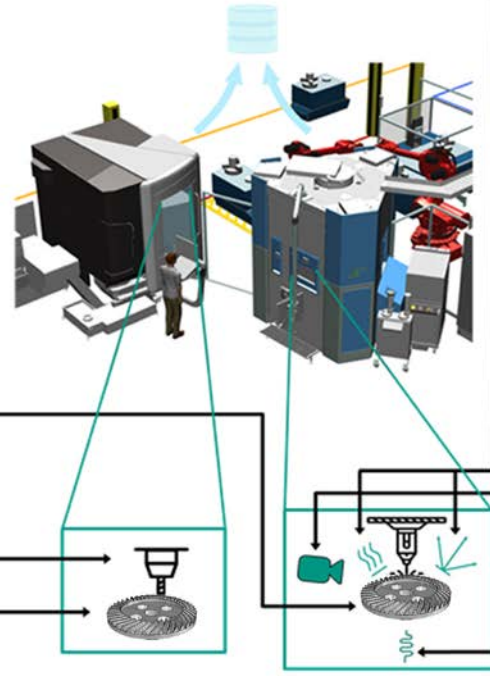
Process monitoring

Process monitoring in pre-machining

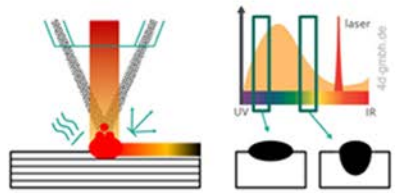


Monitoring the interactions in the additive-subtractive process chain

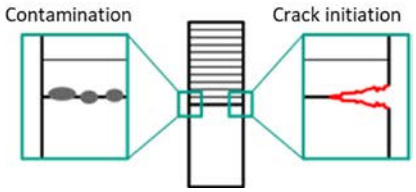




Process monitoring in additive manufacturing



Monitoring the interactions in hybrid additive manufacturing



How to design for the Circular Factory?

Reference Architecture Model for "Design for Circular Factory"

Ontology and System Model
Traceable and consistent cross-generational product and production information.

Stakeholder objectives
…
System Requirement
Task
Product Ontology
User & Customer Scenarios
Use Case
Product Generation

User and Customer Scenarios
Scenario-based representation of future usage & procurement contexts to derive requirements.

Scenario Elements
- Actor
- Device
- Location
- Acivity

Core Factors
Geometry, Material, Surface, Interface, Principle

$G_{i=n-1}$



$R_{i=n}$ { … }

$\{CV_n \mid AV_n \mid PV_n\}$

Analysis

Production-relevant information linked to system model



$R_{i=n+1}$ { … }

$G_{i=n}$

$\{CV_n \mid AV_n \mid PV_n\}$

Synthesis

e.g. *Interfaces, planned variations, reuse and reprocessing paths, future value-retention potential*

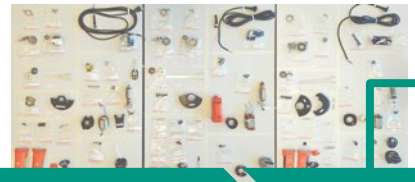
$G_{i=n+1}$



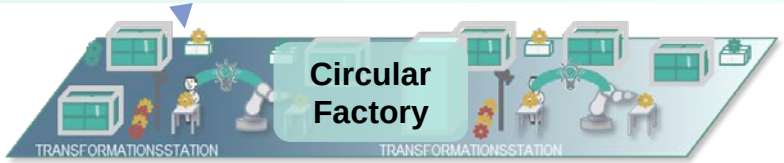


Cross-Generational Product Analysis
Systematic analysis of variation paths and circularity potentials across product generations.

Information from inspection, steering, and planning of the CF



$f\left(\begin{matrix}Extent\\Relevance\\Impact\end{matrix}\right)$



Recommendations from testing observation
Functional behavior and reliability-related information

Decision making with tolerance scheme
Instance-specific criteria for reuse, pairing, and reprocessing

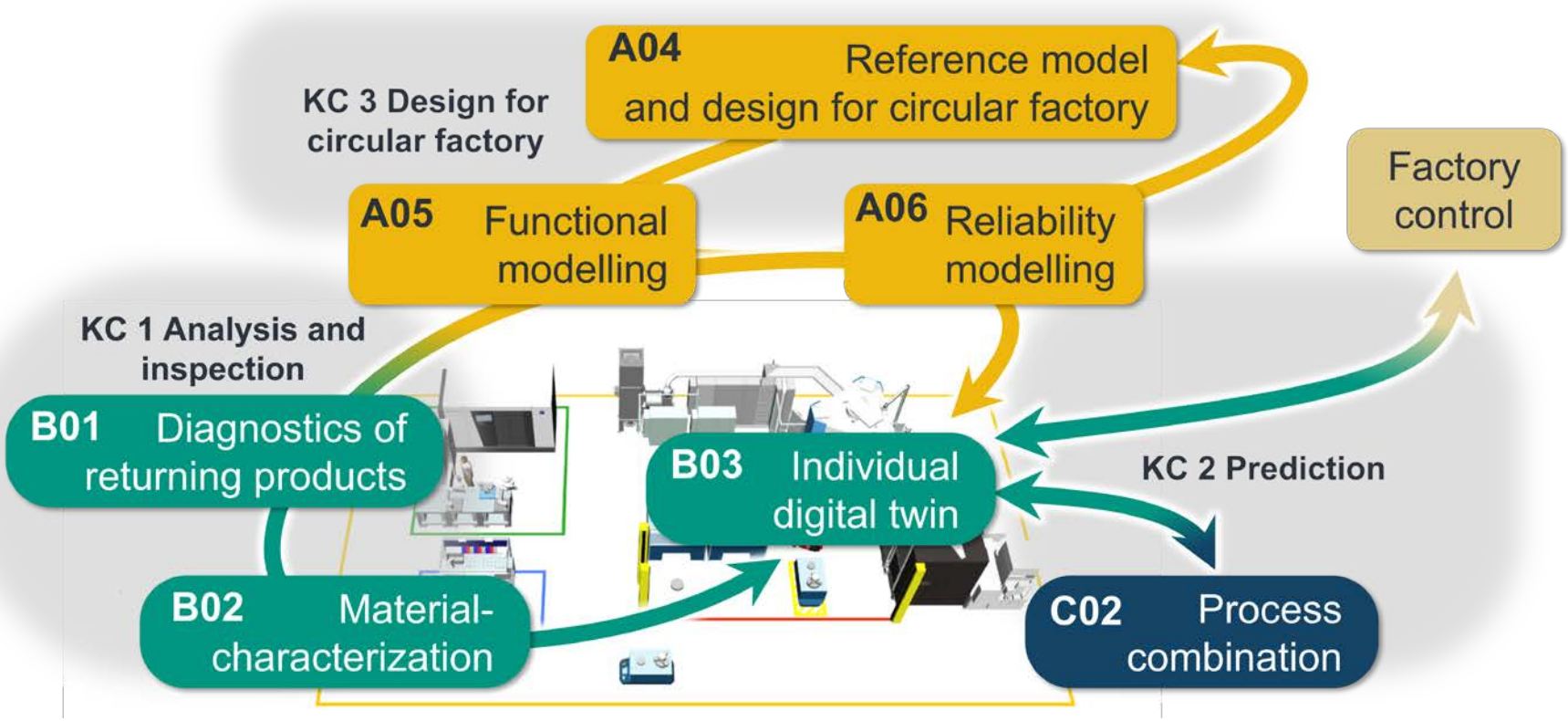
Planning and Decomposition → Intra- & CG-Analysis → Synthesis: Prioritize Sub-Systems

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

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Patric.grauberger@kit.edu



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(In Print) Vlajic, K., Tang, Y., Dreher, J.H., Schwarz, S.E., Moser, G., Düser, T., Albers, A.: Developing an Ontology for User and Customer Scenarios to Support Model-Based Cross-Generational Modelling of Products and Production Systems in Circular Economy. Procedia CIRP (2026)

(In Print) Moser, G., Weber, D.L., Spekker, M.W., Schwarz, S.E., Schlegel, M., Düser, T., Albers, A.: Cross-Generational Variation Analysis to Identify Circularity Potentials based on the Model of SGE – System Generation Engineering. Procedia CIRP (2026)

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POLITECNICO MILANO 1863 | DIPARTIMENTO DI MECCANICA

Adaptive Cost-Optimized Process Planning for Automated Disassembly of Electric Motors

Eng. Matteo Zanovello, Eng. Giorgio Terraneo, Prof. Haluk Akay, Prof. Tullio Tolio

Contents



Giorgio Terraneo
Presenting author
PhD student



Matteo Zanovello
First author
PhD student
Politecnico di Milano –
Depatement of Mechanical Engineering

1. Introduction and Motivations
2. Research Gap and Objectives
3. Methodology
4. Use Case: CIRC4ME Lab
5. Results and Discussion
6. Conclusions and Future Work

Introduction and Motivations

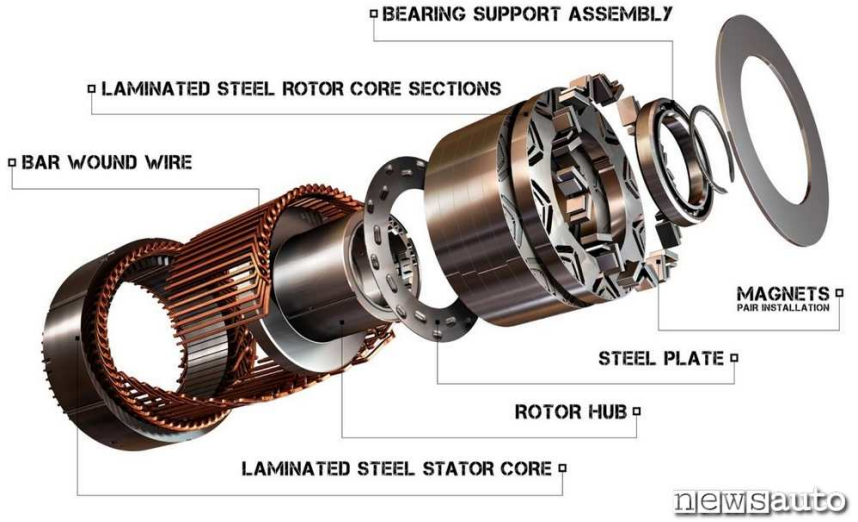
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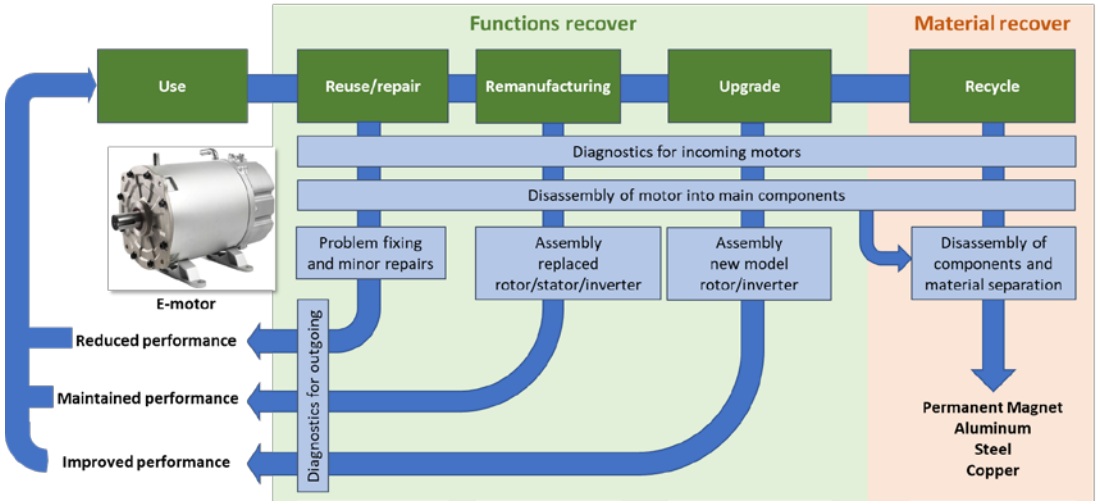
Circular Economy applied to e-motors: an urgent need

As the adoption of electric vehicles accelerates, the **number** of **electric motors** reaching **end-of-life** is expected to **grow dramatically**.

Conventional waste treatment approaches are **inadequate**, as these components contain **high residual functional value** and **critical materials** such as rare earth elements, high-grade steel, and sophisticated electronics. More than **75% of EVs use rare earth permanent magnet traction motors** [1].

Developing **effective de-remanufacturing processes** for electric motors will generate substantial **environmental**, **economic**, and **competitive benefits**, supporting both the **sustainability** of the automotive industry and the strategic autonomy of Europe in securing critical raw materials [1].





Source: McDonough W. and Braungart M., 2002. Cradle to Cradle: Remaking the Way We Make Things. North Point Press, New York. 208 pp.

The Process Planning Problem

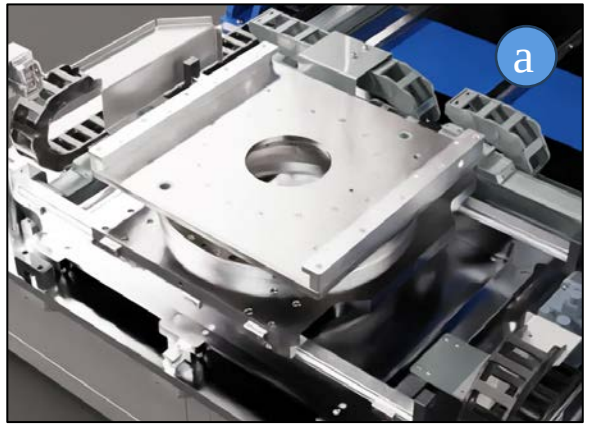
Process plan is the systematic set of instructions that details **how a product will be manufactured**. It acts as the vital bridge connecting product design to physical production.

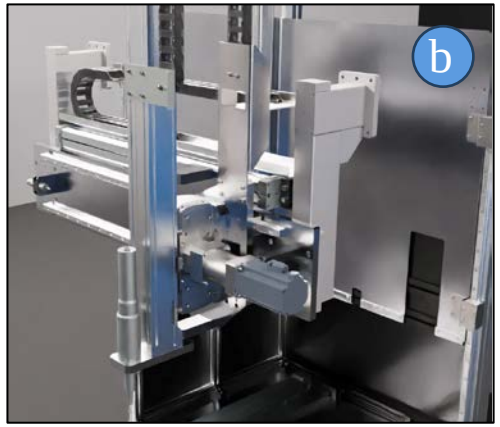
Problem	Need
Selectivness and operational costs are critical for industrial feasibility: complete disassembly is often economically unfeasible; tool changes and repositioning between consecutive operations add execution time without removing any component → the ***chosen technology and operation sequence directly impacts operational costs downstream***	**Selective disassembly** and minimization of **non-value-adding operations** (tool changes, repositioning).
Multiple ways to execute the same operation (optimization): each disassembly action may be performable by different resources, tools, and access directions → the planner must ***choose among alternatives, not just sequence operations***	Select **technology, resource, tool, and access direction** for each operation.
Each removal changes what can be done next: after a component is removed, new components become accessible → the set of ***executable operations evolves continuously*** and cannot be pre-computed statically	Dynamically recompute which operations are **currently executable.** Non-Static plans that track the **evolving product state** after each removal.
End-of-life units exhibit ***heterogeneous wear, degradation, and configuration differences***	**Quality state based** dynamic planning.

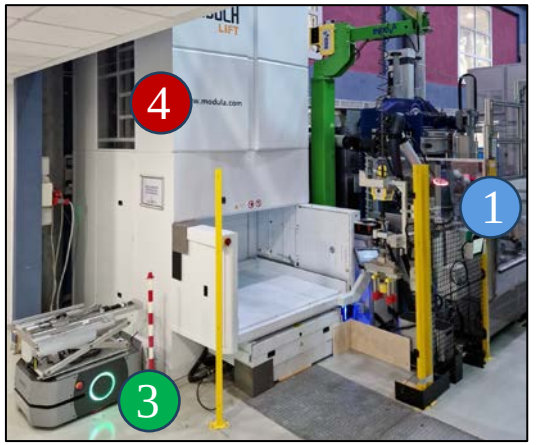
Introduction to the CIRC4ME Lab

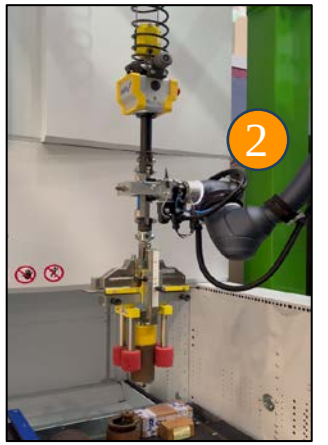












CIRC4ME-Lab is a pilot plant at Politecnico di Milano, for testing the ***feasibility of automated e-motors disassembly*** operations. *Resources* are:

1. *Custom multi-axis Disassembly Machine* ← *main station for this work.* Its **tool-change and repositioning behavior** directly drives the **cost model.**
   a) Movable and rotating table for product positioning. Rotating table enables access-direction changes between operations.
   b) Multiple axes: screwing/unscrewing, pressing/pulling, measurement tasks.
   c) Integrated pull-press for force-intensive operations (bearing/rotor extraction).
2. *Collaborative robot* with interchangeable tools.
3. *Autonomous Mobile Robot (AMR)* for logistics.
4. *Vertical warehouse.*

Research Gap & Objectives

02

Research Gap and Objectives

Research gaps:

Graph-based sequence planning: feasible precedence-based sequences, but no automated cell cost model [2,3,4]	**Automated disassembly**: adaptive task execution, but not integrated with technology-resource-tool selection [5,6]	**Cost-based & selective planning:** multi-attribute optimization, but often learning-based, data-demanding [7,8,9]

Requirements to close the gap between these research areas in one integrated module:

- **product-state tracking** after each removal
- **dynamic update of the feasible frontier** preserving predefined precedence
- **technology–resource–tool**–access-direction constraints
- **cost optimization** including ancillary tool changes and repositioning

OBJECTIVE: Propose an adaptive cost-optimized process planning module for automated de-remanufacturing of electric motors that:

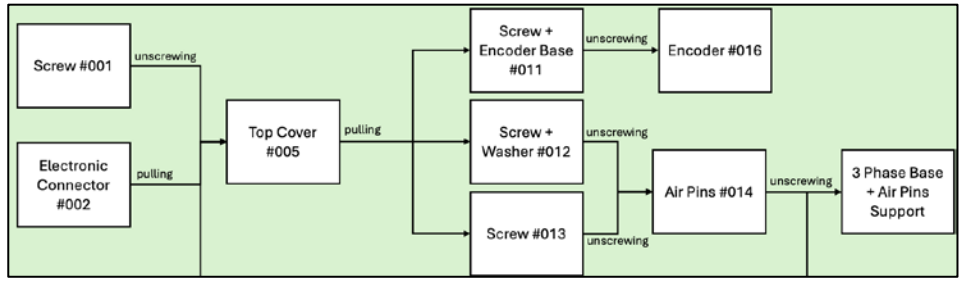
- Generates structurally correct, technologically executable, and cost-optimized disassembly plans
- Acts as an intermediate layer between product-level knowledge and shop-floor execution

Methodology

03

Methodology – Product Model and Precedence Graph

Three inputs to the planner:





Formalization:

Bill of Materials – components involved in disassembly

→ **Bill of Materials**: set of components $C = \{c_1, c_2, \dots, c_n\}$
Product state s: subset of components still present

Precedence description – sequence of operations that allow to reach a specific product state, for which a component become accessible.

→ **Precedence description**: $P(c_i)$ set of predecessor of components c_i
$R(s)$ is the set of components already removed in state s

Technological table – each operation → resource, tool, access direction

→ **Operation** a_i: $s \rightarrow s'$ (removes one component until → s^{goal})

Feasibility condition: set of operations executable at the current state s

The precedence graph is static. The feasible frontier $A_f(s)$ is dynamic and recomputed after every removal.

Methodology – Technological Alternatives and Cost Model

Each feasible operation can be executed through one or more alternatives: $\tau_{ij} = (p_{ij}, r_{ij}, t_{ij}, d_{ij})$

- $p = process$
- $r = resource$
- $t = tool\ required$
- $d = access\ direction$

j is the **alternative technology for the same operation** a_i – it distinguishes different combinations of resouce, tool and direction to remove the same component

Cost Model:

$$Cost(a_i, \tau_{ij}, s) = w_0 + w_t * \Delta Tool + w_d * \Delta Direction$$

- $w_0 = base\ operation\ cost$
- $w_t * \Delta Tool = penalty\ if\ tool\ change\ vs. previous\ operation$
- $w_d * \Delta Direction = penalty\ if\ access\ direction\ changes$

Tool changes and repositioning **increase execution time without advancing the process plan**

Weights **calibrated experimentally** from actual **shop-floor execution time and effort**.

Methodology: Branch & Bound

Minimization Objective Function:

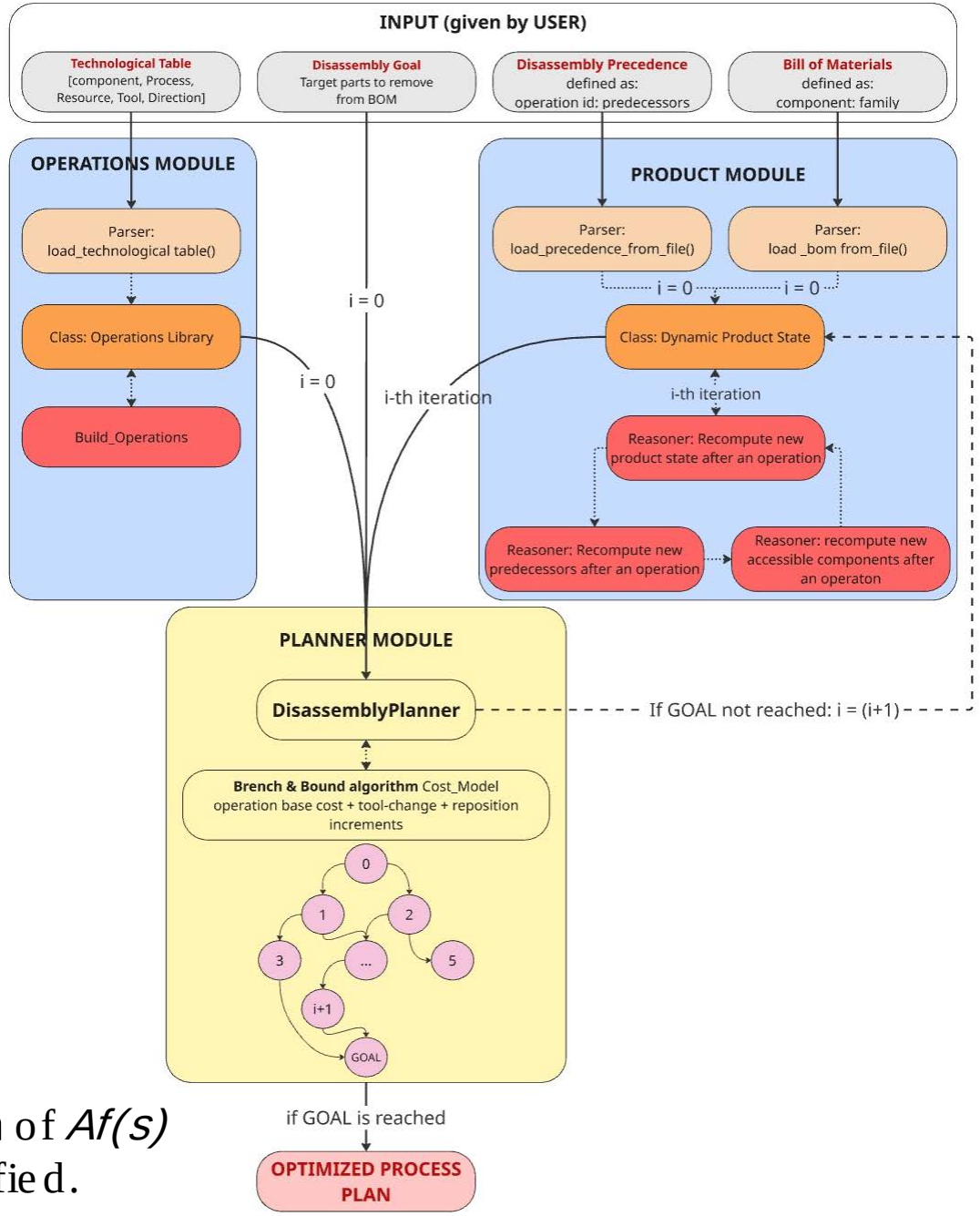
Find the **sequence of operations** among technological alternatives, from s^0 to s^g, that **minimizes the total accumulated process cost**, including increments for tool changes and repositioning.

$$\min_{\pi} \ \Sigma_{a_i,\tau_{ij}\epsilon\,\pi} Cost(a_i, \tau_{ij}, s)$$

Subject to:

- $Precedence\ feasibility: P(c_i) \subseteq R(s)$
- $Geometric\ accessibility: c_i accessible\ in\ state\ s$
- $Technological\ feasibility: \tau_{ij}\ available\ in\ the\ table$

```
best_cost ← ∞,  π* ← ∅
Push (s₀, π=∅, cost=0) onto frontier
while frontier not empty do
    extract (s, π, cost)
    if cost ⩾ best_cost: continue          ▷ prune branch
    if s = sᵍ: best_cost ← cost, π* ← π, continue
    for each aᵢ ∈ Af(s) do                 ▷ recompute feasible frontier
        for each τᵢⱼ available for aᵢ do
            push (s\{cᵢ}, π∪{(aᵢ,τᵢⱼ)}, cost + Cost(aᵢ,τᵢⱼ,s))
return π*
```



Note on Adaptivity: **state tracking + repeated recomputation** of *Af(s)* at every iteration as the precedence graph itself is never modified.

Testing and Results

04



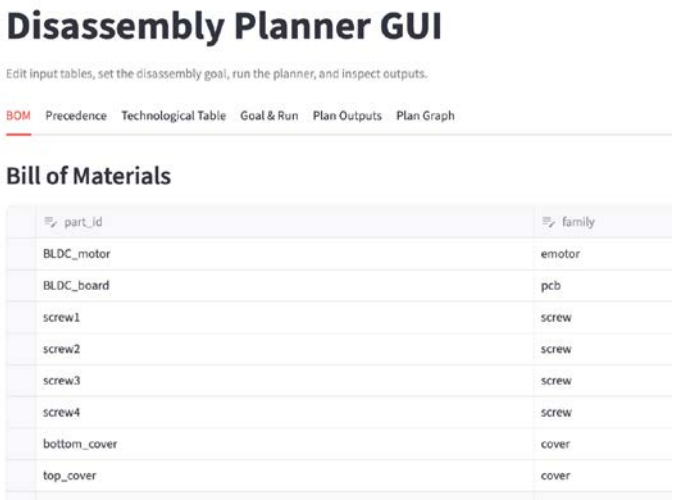
Use Case: Testing on Electric Motor Disassembly

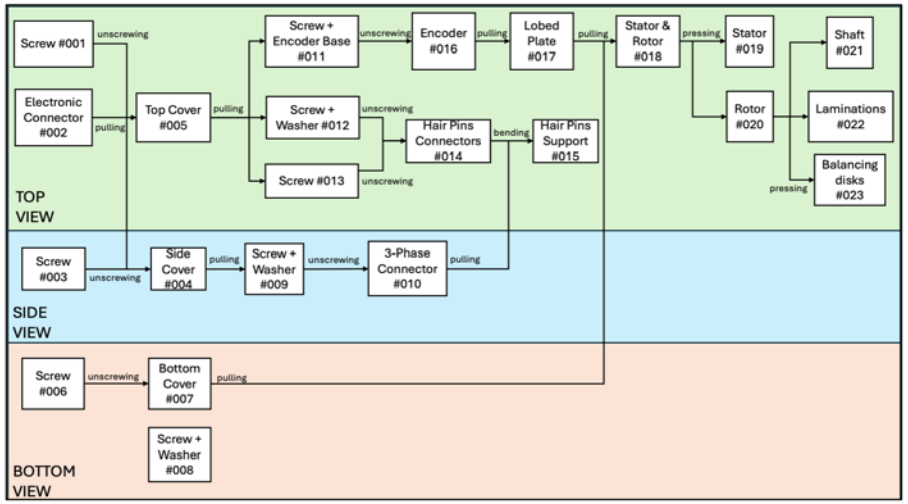
Disassembly tasks considered:

- Screw removal
- Top cover removal
- Rotor extraction
- Balancing disk disassembly
- Permanent magnet extraction (after induction heating for demagnetization)

Input preparation:

- BOM company product documentation
- Precedence relations derived from manufacturing BOM + technical product knowledge
- Technological table defined from actual CIRC4Me Lab capabilities
- Tool-change costs: estimated from shop-floor experience *(vary per tool)*
- Repositioning costs: estimated from Disassembly Machine axis performance

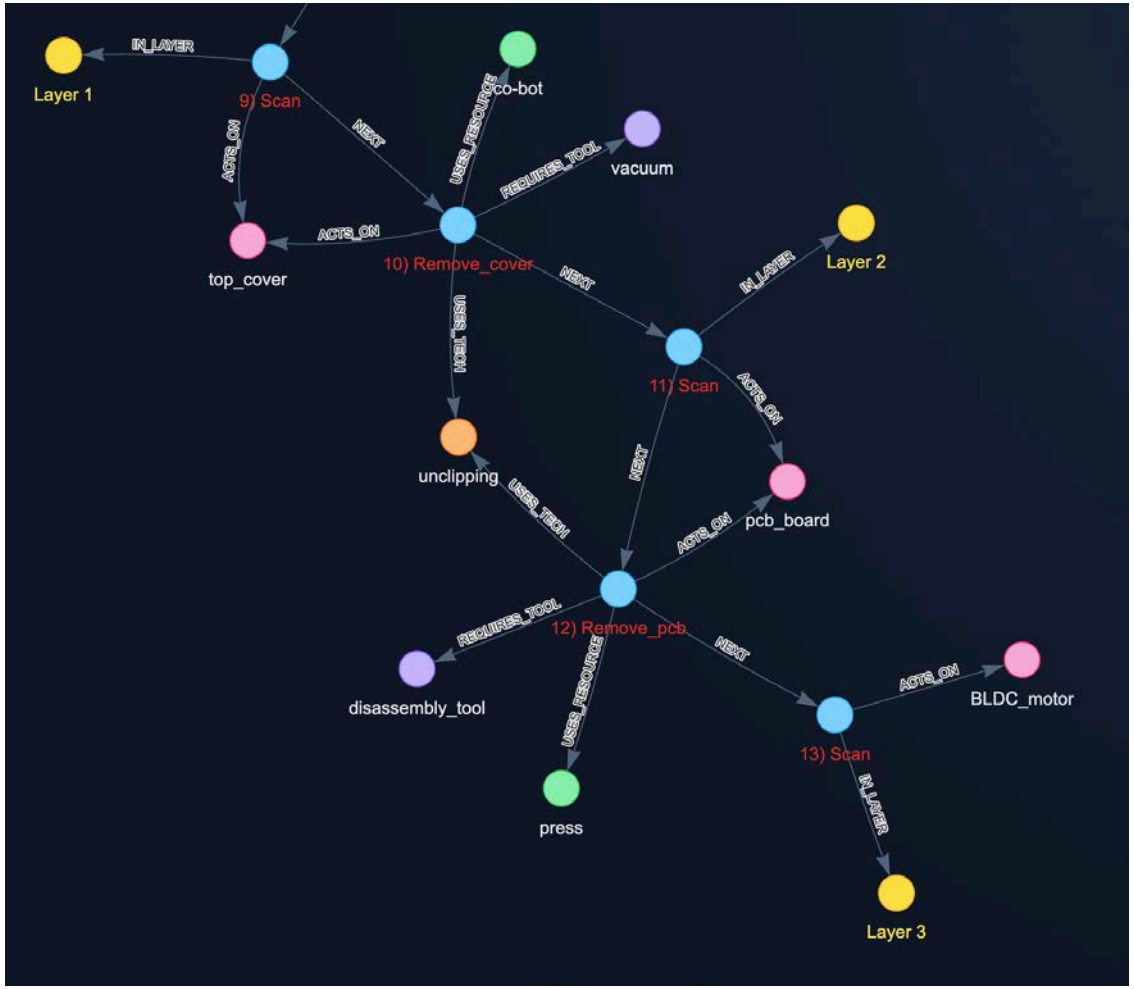






Technological alternatives are **not generic**: shop-floor-specific capabilities linked to actual resources and tools installed in the pilot plant.

Testing Results



The module was tested for:

Generate process plans satisfying all **precedence, accessibility, and technological constraints** across tested scenarios

Produce different **ordered sequences** depending on target goal and cost configuration, while preserving structural correctness

Reduce **tool changes and access-direction changes** vs. precedence-only baseline whenever alternative feasible branches were available

Scenarios generated by varying:

- **Target disassembly goal** - selective recovery of specific components vs. broader disassembly
- **Available technological alternatives** - different resource–tool–direction combinations
- **Cost weights** w_0, w_t, w_d - different penalty configurations for tool changes and repositioning

Baseline: **precedence-only planning**; satisfies structural constraints, ignores sequence-dependent costs.

Conclusions and Future Work

Results:

- Proposed an **adaptive cost-optimized process planning** module for automated de-remanufacturing of electric motors
- Product formalized as a **dynamic object** evolving **through disassembly states**
- Feasible frontier $A_f(s)$ recomputed after each removal → plans remain **structurally consistent** throughout execution
- Cost model integrates **base operation cost** + **tool-change** and **repositioning penalties**
- **Branch-and-bound search** identifies the **minimum-cost plan**
- Verified on a real automotive PM motor at CIRC4Me Lab – confirmed role as intermediate layer between product knowledge and shop-floor execution

Future Work:

- **Condition-aware planning**: Integrate EoL quality assessment; connect inspection results and component quality classes to disasembly strategy selection
- **Real-time replanning**: Use sensor and execution-monitoring feedback to detect deviations from nominal conditions and regenerate the plan on unexpected accessibility issues or operation failures

Thank you for your attention

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PERMANET

CIRC4ME TEAM

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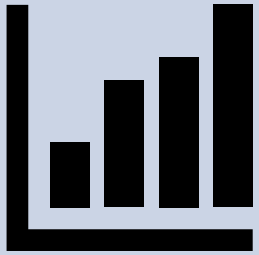
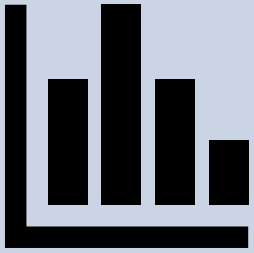
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Life Cycle Assessment of Remanufactured Products: A Framework Proposal

Jens Becker[1], Robin Fürst[1] , Finn Bail[2] , Maurice Engels[2] , Kristian Vlajic[3], Gabriel Moser[3], Tobias Düser[3], Albert Albers[3], Gisela Lanza[2] , and Nicole Stricker[1]

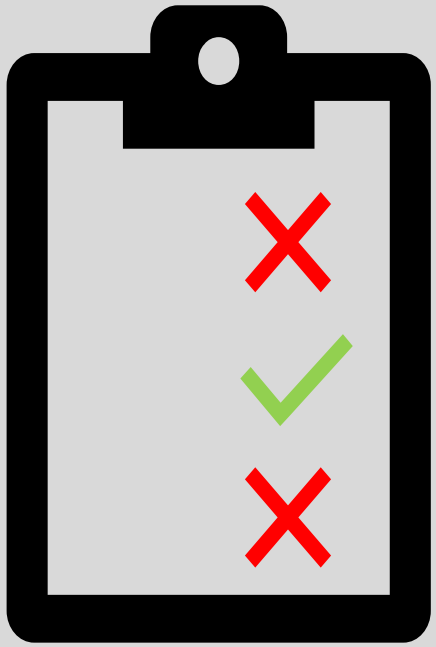
1 ReLab, Aalen University of Applied Sciences, Aalen, Germany
2 wbk Institute of Production Science, Karlsruhe Institute of Technology, Karlsruhe, Germany
3 IPEK Institute for Product Development, Karlsruhe Institute of Technology, Karlsruhe, Germany

Literatur

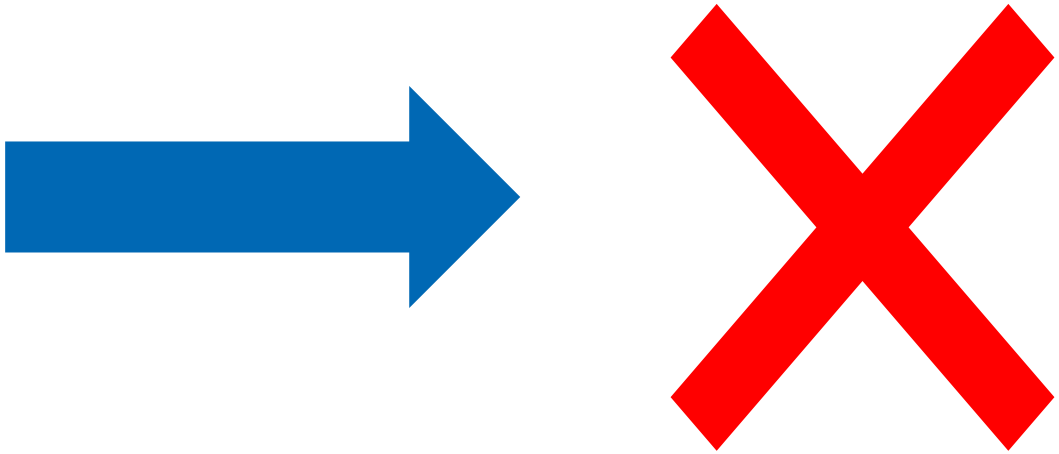
	**Extreme approaches** (0:100 / 100:0) include the traditional substitution-approach [3] and the cut-off approach [3,24].
	**Symmetric approaches** (50:50) consist of approaches, that share environmental burdens and benefits equally between the systems, implying an even distribution of responsibility and credit.[3,24]
	**Advanced approaches** include more complex models such as the “linearly degressive” approach, which assumes that the environmental credit associated with recycling decreases with the number of life cycles.[3]

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Literatur



Allacker et. al [3] evaluate current approaches with 3 criteria. No approach can satisfy all three.



[3]

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CFF (Circular Footprint Formula)

$$\textbf{Material:}\quad (1-R_1)\,E_V + R_1\left(A\,E_{\text{recycled}} + (1-A)\,E_V \cdot \frac{Q_{S_{\text{in}}}}{Q_p}\right) + (1-A)R_2\left(E_{\text{recyclingEoL}} - E_V^* \cdot \frac{Q_{S_{\text{out}}}}{Q_p}\right) \quad \text{(based on [24])}$$

R_1	Percentage of recycled material used
E_V	Environmental impact of new materials that are used
A	„[...]Allocation factor used to allocate the costs and savings associated with secondary materials between users and suppliers (it can take values ranging from 0.2 to 0.8)[...]“[9, own translation p.76]
E_{recycled}	Impact of the usage of recycled material
$Q_{S_{\text{in}}}$	„[...] quality of the ingoing secondary material [...]“[24, p.69]
Q_p	„[...] quality of the primary material [...]“[24, p.69]
R_2	„[...] Percentage of material recycled in the process [...]“[9, own translation]
$E_{\text{recyclingEoL}}$	Environmental impact of material recycling after usage
E_V^*	Environmental impact if virgin materials that would be used
$Q_{S_{\text{out}}}$	„[...] quality of the outgoing secondary material [...]“[24, p.69]

- Virgin material
- Recycled content material
- Recycling process minus credit for avoided primary material

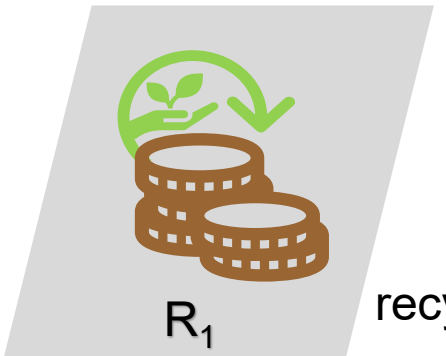
Adapted from [25]

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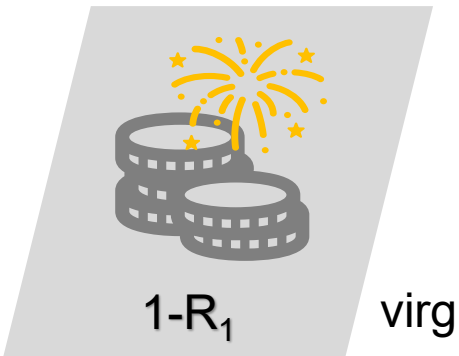
CFF (Circular Footprint Formula)

Input

Output

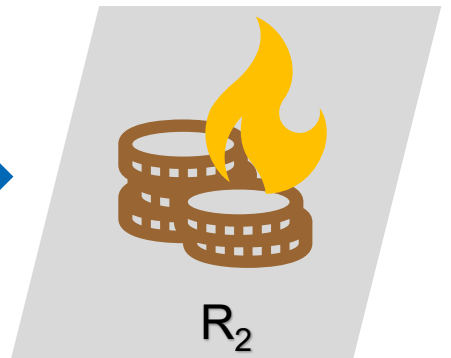


recycled material



virgin material





„[...] Percentage of material recycled in the process [...]“ [9, own translation]

CFF focuses on recycling, thereby ignoring remanufacturing, recondition, and repair

$$\textbf{Material:}\quad (1-R_1)\,E_V + R_1\left(A\,E_{\text{recycled}} + (1-A)\,E_V \cdot \frac{Q_{S_{\text{in}}}}{Q_p}\right)$$
$$+\,(1-A)R_2\left(E_{\text{recyclingEoL}} - E_V^* \cdot \frac{Q_{S_{\text{out}}}}{Q_p}\right) \quad \text{(based on [24])}$$

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CFF Remanufacturing

CFF Original

$$\begin{aligned}\mathbf{Material}_{\mathrm{New}} &= (1 - R_1 - R_{\mathrm{reman}}) \cdot E_V \\ &+ R_1 \left(A\, E_{\mathrm{recycled}} + (1 - A)\, E_V \frac{Q_{S_{\mathrm{in}}}}{Q_p} \right) \\ &+ R_{\mathrm{reman}} \left(A_{\mathrm{reman}}\, E_{\mathrm{reman}} + (1 - A_{\mathrm{reman}})\, E_V \frac{Q_{S_{\mathrm{in}}\mathrm{reman}}}{Q_p} \right) \\ &+ (1 - A) R_2 \left(E_{\mathrm{recyclingEoL}} - E_V^* \cdot \frac{Q_{S_{\mathrm{out}}}}{Q_p} \right) \\ &+ (1 - A_{\mathrm{reman}}) \cdot R_{\mathrm{remanEoL}} (E_{\mathrm{remanEoL}} - E_V^* \cdot \frac{Q_{S_{\mathrm{out}}\mathrm{reman}}}{Q_p})\end{aligned} \quad (2)$$

$$\mathbf{Material}: \quad (1 - R_1)\, E_V + R_1 \left(A\, E_{\mathrm{recycled}} + (1 - A)\, E_V \cdot \frac{Q_{S_{\mathrm{in}}}}{Q_p} \right) + (1 - A) R_2 \left(E_{\mathrm{recyclingEoL}} - E_V^* \cdot \frac{Q_{S_{\mathrm{out}}}}{Q_p} \right) \quad \text{(based on [24])}$$

R_{reman}	Percentage of remanufactured material used
E_{reman}	Impact of usage of remanufactured material
A_{reman}	„|...|Allocation factor used to allocate the costs and savings associated with secondary materials between users and suppliers|...|“ [9, own translation p.76]
$R_{remanEoL}$	Percentage of remanufacturing material in the process
E_{remanEoL}	Environmental impact of remanufactured material after usage
$Q_{S_{\mathrm{in}}\mathrm{reman}}$	Quality of the remanufactured output material
$Q_{S_{\mathrm{out}}\mathrm{reman}}$	Quality of the remanufactured output material

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DESIGNING LITHIUM-ION BATTERY PACKS FOR END-OF-LIFE: INSIGHTS FROM LITERATURE AND INDUSTRIAL STAKEHOLDER INTERVIEWS

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Delphine Pinto
Hélène Porthault
Peggy Zwolinski

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Context

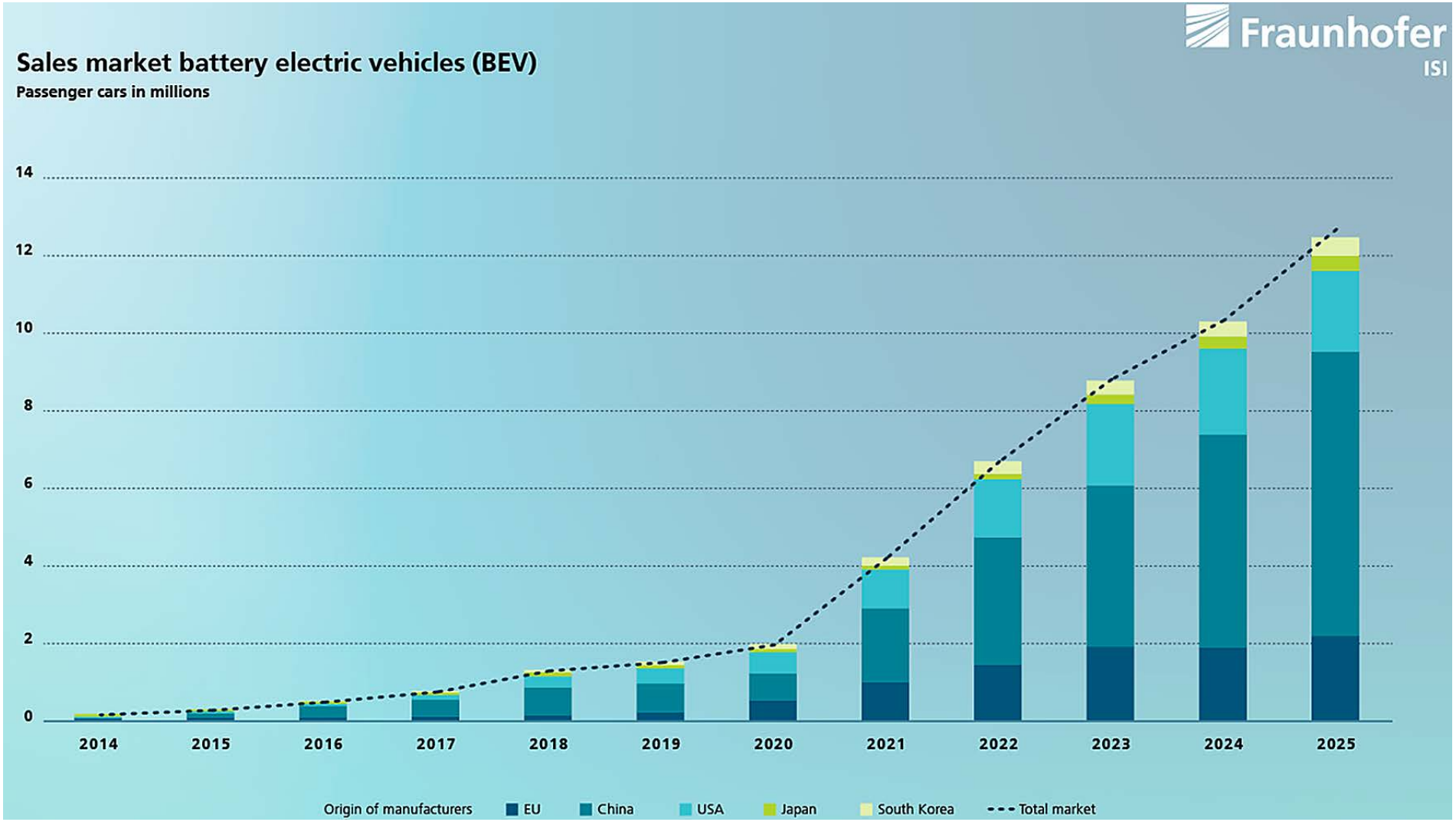
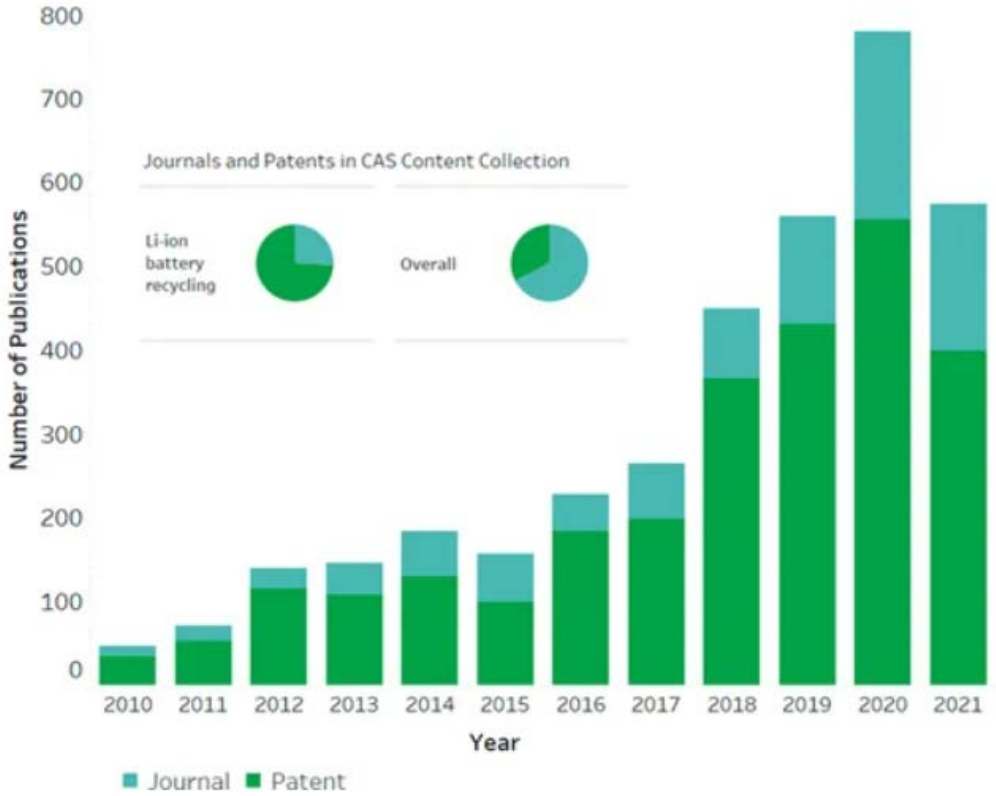


Figure 1: Global BEV sales market broken down by origin (headquarters) of the manufacturers (Fraunhofer Institute for Systems and Innovation Research ISI)

Literature

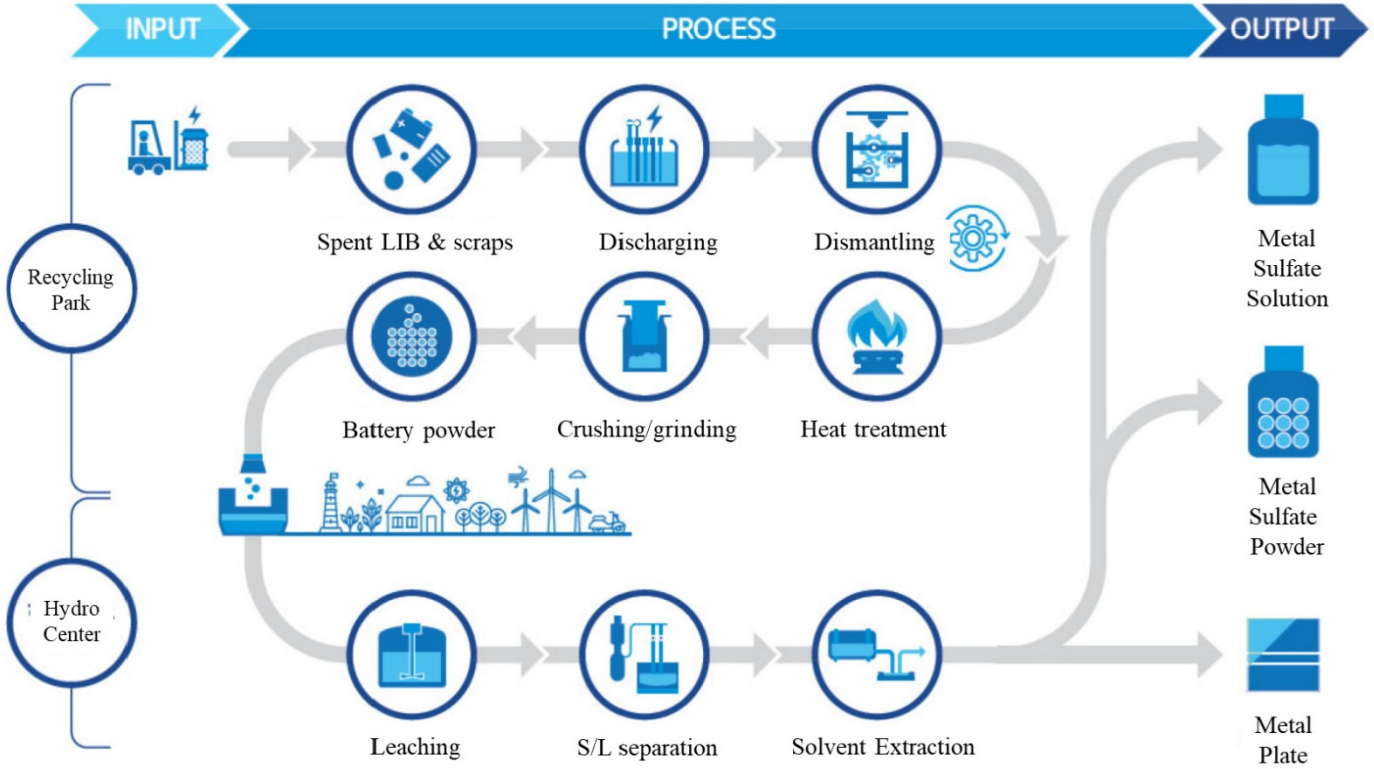
Literature-based issues

- Circularity pathways
- Design for disassembly and recycling
- Safety and SOC management
- Product / process data requirements



J. Baum et al., 2022
(doi: 10.1021/acsenergylett.1c02602)

Industrial observations

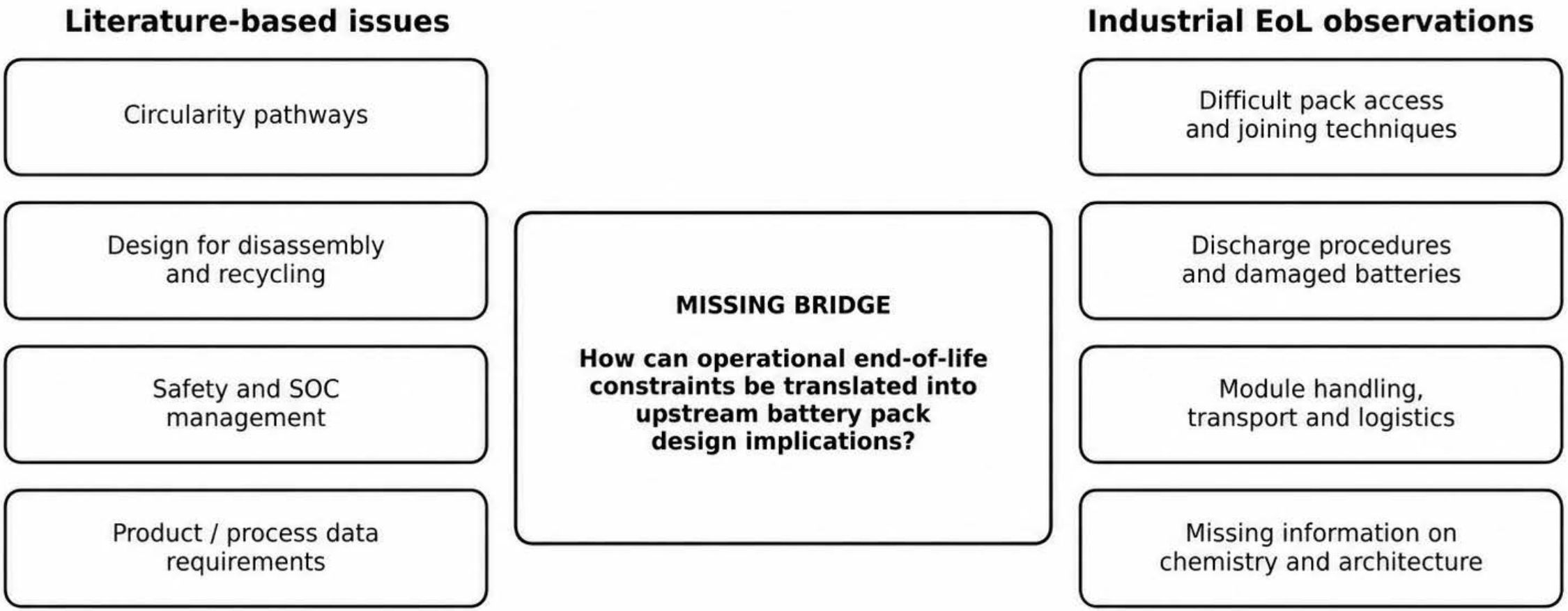


Industrial EoL observations

- Difficult pack access and joining techniques
- Discharge procedures and damaged batteries
- Module handling, transport and logistics
- Missing information on chemistry and architecture

Kyoungkeun Yoo (2023)
https://doi.org/10.7844/kirr.2023.32.1.13

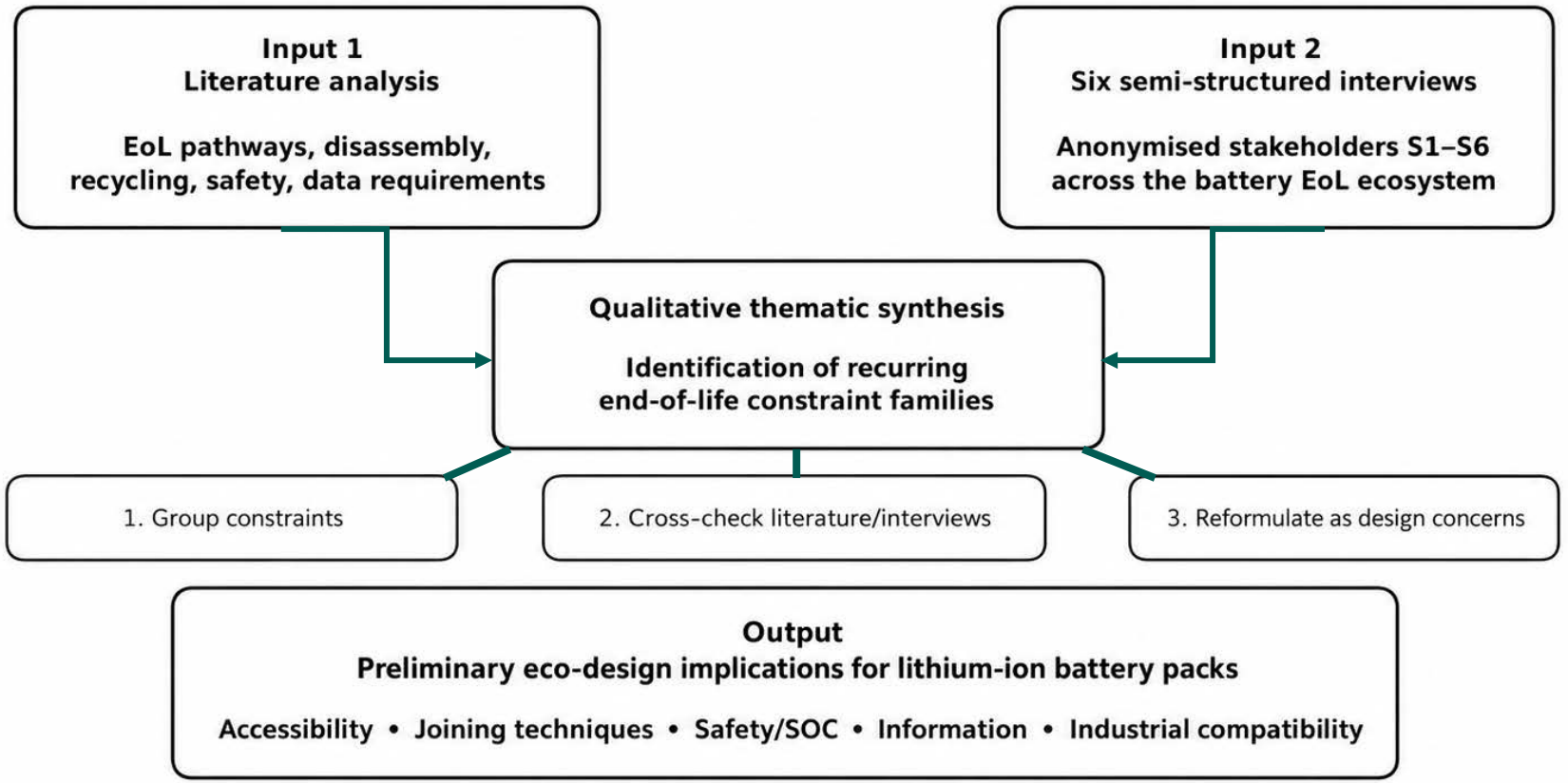
Knowledge gap



Research methodology

Methodology: exploratory qualitative study

Cross-analysis of literature and industrial stakeholder interviews



Purpose: not to validate a complete method, but to derive exploratory design orientations from converging evidence.

Stakeholders ecosystem

Interviewed stakeholders across the battery EoL ecosystem

Anonymised stakeholder sample (S1–S6)

S1
Battery recycling actor

Role: Recycling operations

Focus: discharge strategy, shredding, black mass quality

S2
Battery training and technical expertise actor

Role: Cross-cutting support for battery handling and dismantling

Focus: training, safety, repairability, discharge procedures

S3
Vehicle dismantling and battery extraction actor

Role: First EoL step after vehicle collection

Focus: battery removal, risk classification, secure storage, module extraction

S4
Eco-organisation / EoL coordination actor

Role: Collection, logistics and regulatory coordination

Focus: traceability, transport organisation, regulatory targets

S5
Waste management and battery preparation actor

Role: Safety preparation and pre-recycling operations

Focus: regulatory constraints, damaged batteries, discharge, secure handling

S6
Battery recycling actor

Role: Recycling and cell treatment

Focus: chemistry separation, cell formats, recycling economics

The sample covers complementary positions across the battery end-of-life ecosystem, from vehicle dismantling and logistics coordination to battery preparation and recycling operations.

Main constraints

Main end-of-life constraints identified

Recurring constraint families from literature and stakeholder interviews

1. Physical design constraints

- Sealed housings and encapsulation
- Adhesives, thermal paste, non-standard fasteners
- Difficult access to modules, connectors and internal components

2. Safety and SOC management

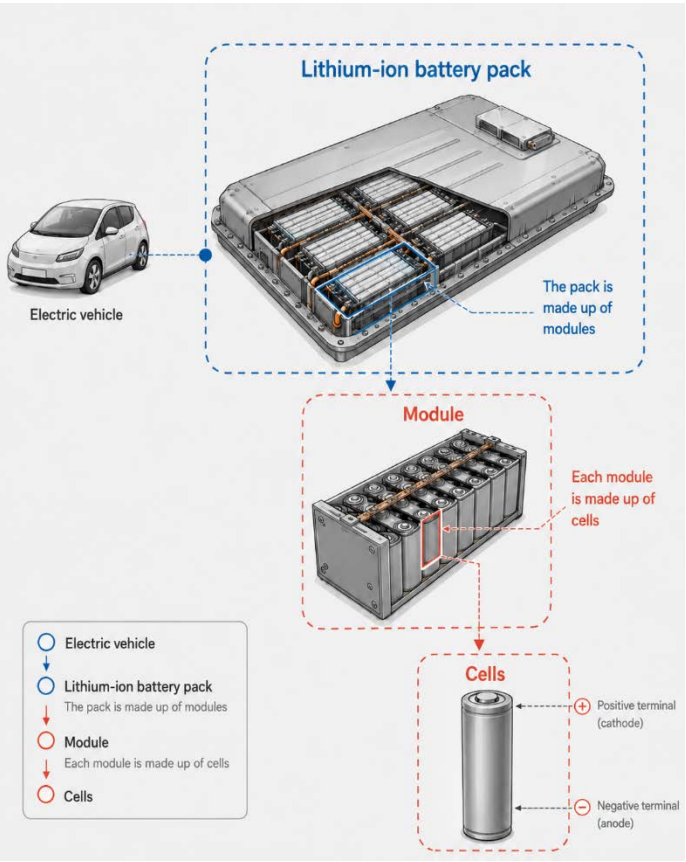
- Discharge procedures remain variable
- Industrial compromise around 20–30% SOC
- Damaged batteries require specific handling and storage

3. Information and process constraints

- Missing data on chemistry and pack architecture
- Limited traceability and disassembly-relevant information
- Variability reduces compatibility with industrial processes

Key observation

The module emerges as a central operational unit for discharge, transport and recycling preparation, but module weight and handling remain important constraints.



Eco-design implications

Preliminary eco-design implications

From operational end-of-life constraints to upstream battery pack design concerns

1. Accessibility

- Facilitate access to modules, connectors and safety devices
- Support safe diagnosis and non-destructive disassembly

2. Joining techniques

- Limit irreversible bonding, sealing and encapsulation
- Favour standardised and removable fastening solutions

3. Safe diagnosis and discharge

- Provide reliable access to SOC and battery status
- Reduce dependence on inaccessible or manufacturer-specific systems

4. Information availability

- Provide structured data on chemistry, architecture and component location
- Include safety status and disassembly-relevant information

5. Industrial compatibility

- Design modules for handling, transport and discharge operations
- Improve compatibility with sorting, recycling preparation and industrial equipment

Conclusion + PhD

Takeaway

Battery pack design should be evaluated not only for use-phase performance,
but also for accessibility, safety, information and end-of-life process compatibility.

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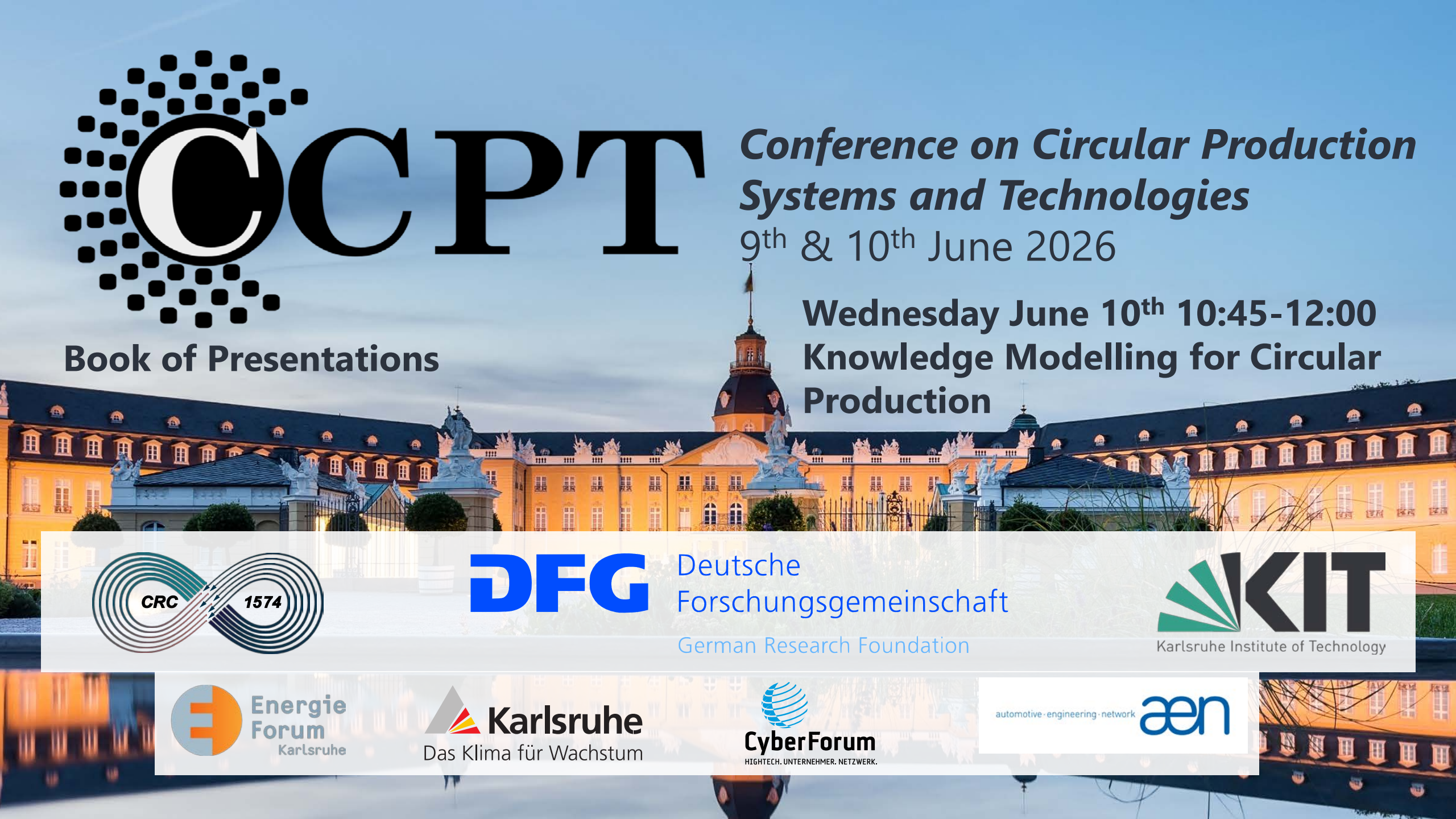
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G-SCOP SCIENCES POUR LA CONCEPTION, L'OPTIMISATION ET LA PRODUCTION

THANK YOU

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CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 10:45-12:00
Knowledge Modelling for Circular Production

CRC 1574

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CCPT 2026 Karlsruhe – Patrick Alexander Schmidt, Dr. Uwe Frieß, Prof. Dr. Steffen Ihlenfeldt

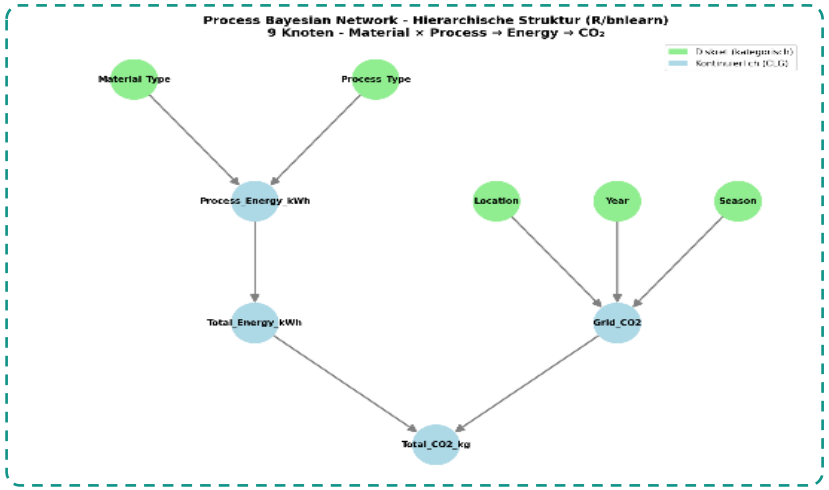
Probabilistic Assessment of Repurposing Processes Using Bayesian Networks: CO_2e Evaluation of Tie Rod Manufacturing from End-of-Life Components

Motivation

Starting point, challenge, approach

Starting point

- **CO_2e** increasingly drives manufacturing and end-of-life decisions
- **Circular economy** new production, remanufacturing and repurposing compete
- **Classical LCA** needs complete inventories, uses Monte Carlo for uncertainty
- **Uncertainty** of component history leads to missing data



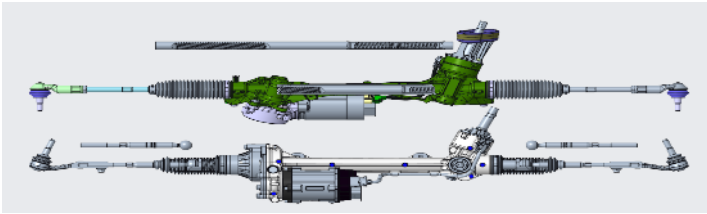
Challenge

- **Unknown history** place, year, steel route and electricity mix are missing
- **Context-bound savings** reported figures transfer only to a limited extent
- **A robust decision** needs the benefit as a probability, not a point value

My approach — Bayesian networks

Graph-based causal modelling
Inference under missing evidence
Modular structure for process changes

Use case gear rack



Goal: assess the CO_2e potential of remanufacturing under uncertainty

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What we do

A methodical application test, not just an energy proof

We test a graph-based probabilistic method on a real tie-rod process. The method is the goal. The energy comparison is the application.

01

Build a CLG Bayesian network

Discrete + continuous nodes for material route, location, energy and CO_2e, coupled in one conditional linear Gaussian graph.

02

Couple two process paths

Shared context new production and remanufacturing share location, year, season, grid factor and material route, compared under identical conditions.

03

Quantify the benefit

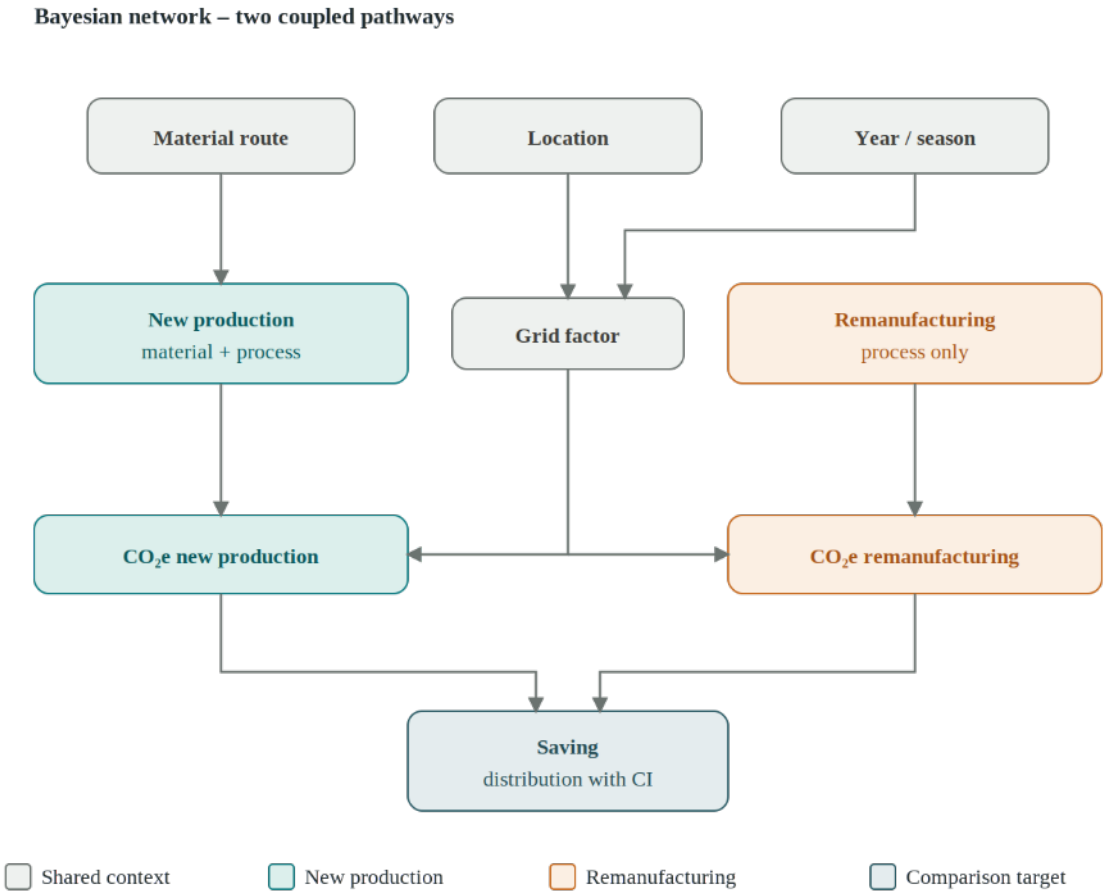
A distribution uncertain inputs give a 95 % interval, not a point value; unknown component history is marginalized away.

The energetic result is the demonstration that the method yields interpretable decision information.

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The graph is the difference

Network architecture and what it enables



Works under missing evidence

unknown parameters such as the steel route or build year are marginalized, so the model still returns a result instead of failing.

Dependencies stay explicit

the directed graph makes the causal structure visible and checkable, so every influence on the result can be traced.

Output is a distribution

each query returns an expected value plus a 95 % uncertainty interval, so the decision carries its own confidence.

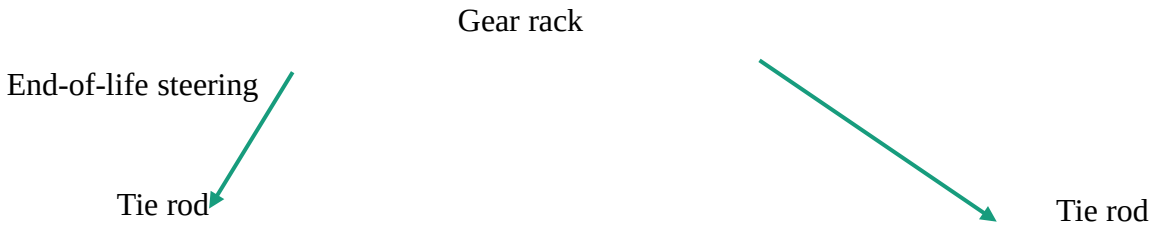
Two target quantities

- energy saving (location-independent) and
- CO_2e factor hierarchy (location-dependent)

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Use case: rack bar to tie rod

A real repurposing process from EKODA



Next generation steering





Forging



Turning

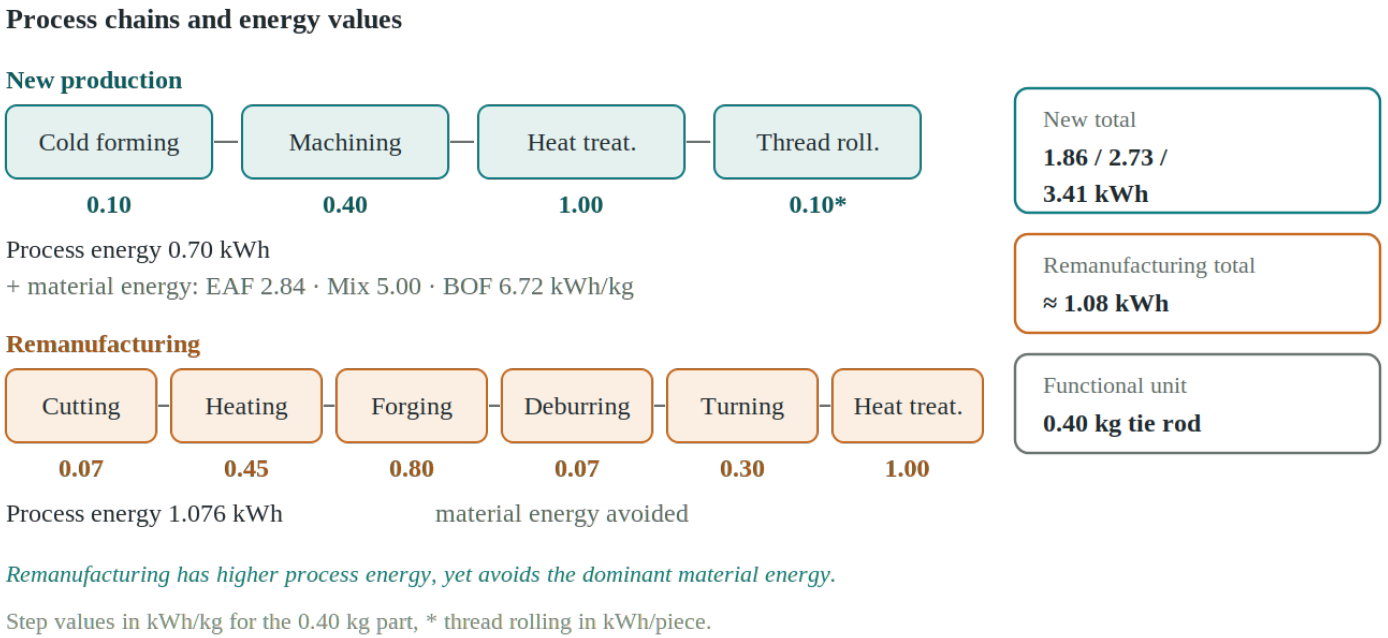


Finished tie rod

- **Rack bar** from an end-of-life steering gear
- **Converted** into tie rods for new vehicles
- **Functional repurposing** modelled as a component-level remanufacturing process
- **Functional unit** 0.40 kg tie rod

Two processes are modelled

New production with higher material energy and remanufacturing with higher process energy



Remanufacturing has higher process energy, yet avoids the dominant material energy.

Step values in kWh/kg for the 0.40 kg part, * thread rolling in kWh/piece.

Reading the comparison

Process energy new 0.70 kWh vs remanufacturing 1.076 kWh, so remanufacturing needs more.

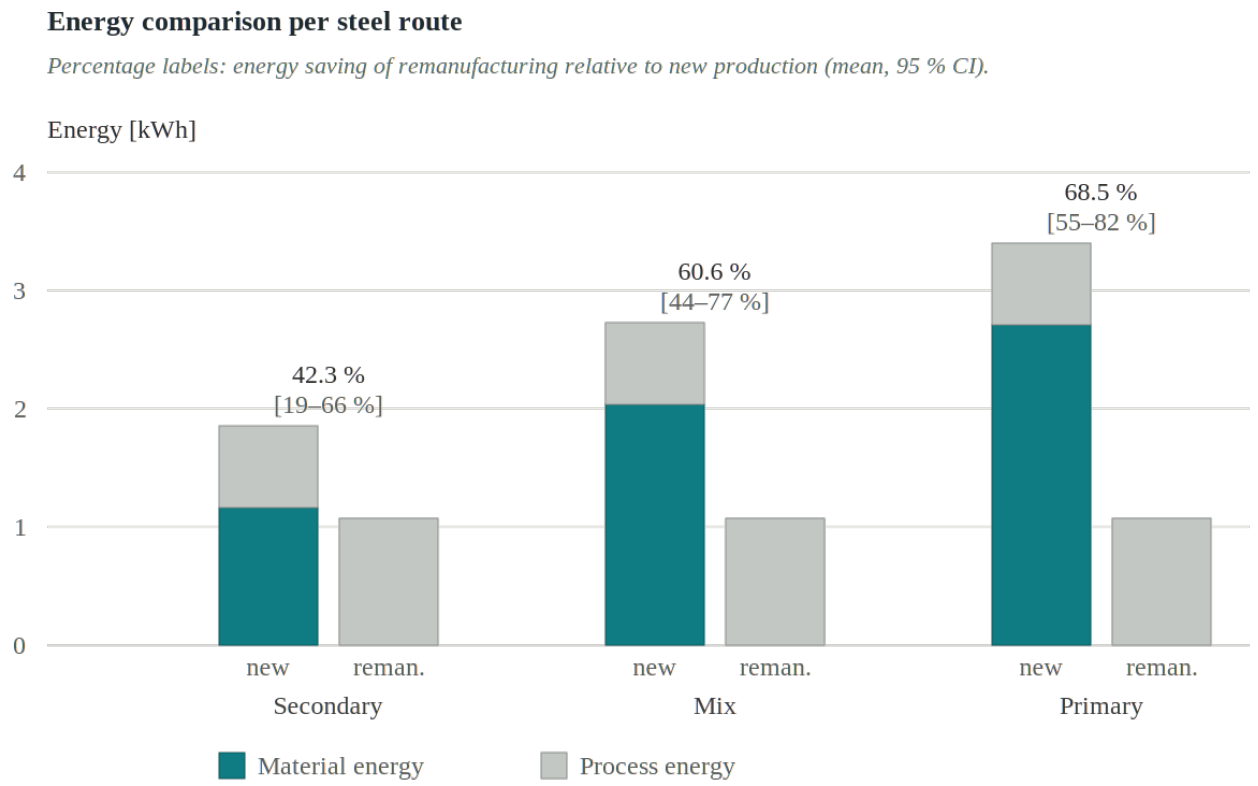
Material energy dominates new production (EAF 2.84 / Mix 5.00 / BOF 6.72 kWh/kg) and is fully avoided.

The trade-off extra process energy, but no new steel provision.

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Energy comparison for different material routes

Saving depends on the displaced steel route



Reading the result

Secondary 42.3 % [19–66]

Mix 60.6 % [44–78]

Primary 68.5 % [55–82]

Material share of new production rises 61 % → 73% → 79 %, so the benefit grows with the avoided material energy.

For parts with low material energy, the extra process energy could offset the saving.

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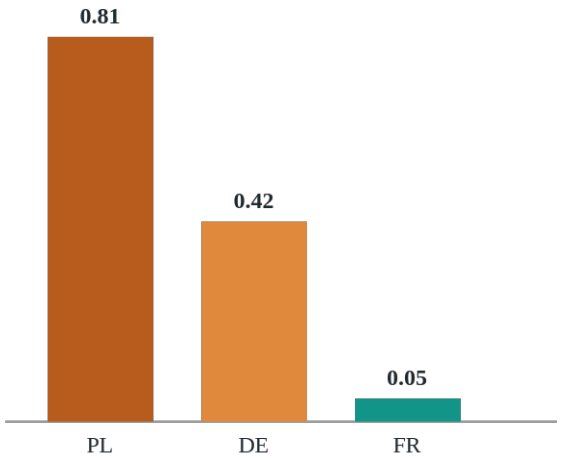
Location dominated the CO_2e balance

Factor dominance hierarchy

From grid factor to CO_2e factor hierarchy

A Grid factor by location

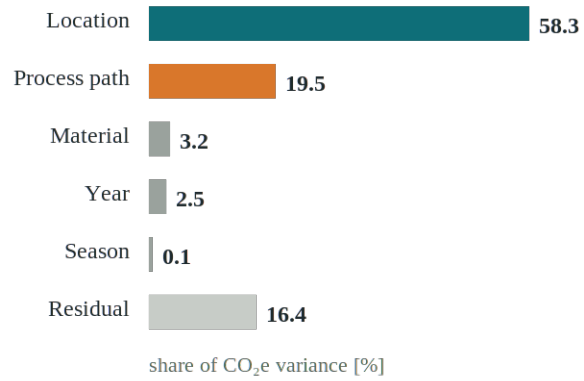
kg CO_2e / kWh, annual mean 2015 / 2020 / 2025



Grid spread drives the location dominance.

B η^2 of modelled CO_2e

variance pooled over new production and remanufacturing



Location and process path explain most of the variance.

What this means

Location ≈ 58 % process path ≈ 20 %, material, year and season stay minor.

Within one location the material energy of new production is the lever.

Across locations the grid factor can overlay the material and process difference.

A cross-location decision must control the grid factor first — exactly the job of the scenario analysis.

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What the model adds

Validation, limits and next steps

A distribution, not a point

The result carries its own 95 % uncertainty interval, so you read the confidence, not just a single number.

The drivers are visible

The graph shows which assumptions move the result, so sensitivities are explicit and auditable rather than hidden.

Validated, not just applied

Tested end-to-end on a real EKODA process, energy first and then CO_2e, not only demonstrated in theory.

Limitations

- **System boundary** material provision, process energy, grid factor
- **Not included** use phase, logistics, full cost model
- **Process-specific** not a general remanufacturing quota

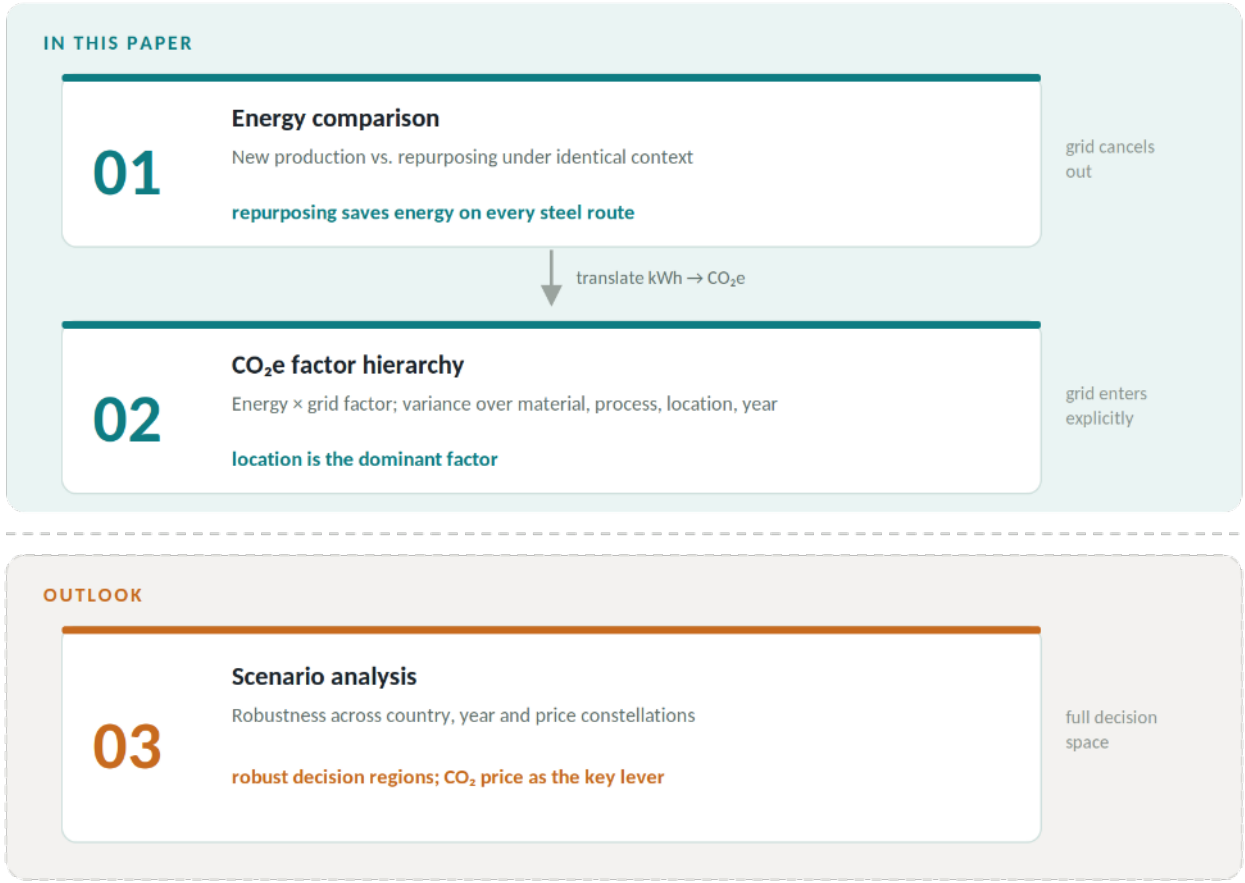
Next steps

Scenario analysis location, year, electricity and CO_2 price decide robustness, 27 settings explored.

BN vs. Monte Carlo same distributions, plus conditional independence, inverse queries and local updates.

Outlook: scenario analysis

From the paper’s two steps to the open question



The same factors, a new question.

Steps 1 and 2 are the paper. The scenario analysis re-uses the same factors and asks not what drives the result, but when the decision holds across countries, years and prices.

- **Not new factors** the same drivers, now tested for decision robustness
- **Decision regions** the constellations in which repurposing stays the better choice
- **Status** the scenario space is currently being analysed in the dissertation

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Testing Environments for Data-Driven Prediction of Functional Behavior and Reliability in the Circular Factory

Victor Leon Mas, J. Hemmerich, A. Klesen, M. Münch, N. Afifi, P. Grauberger, S. Matthiesen
Institute of Product Engineering (IPEK) · Karlsruhe Institute of Technology (KIT)

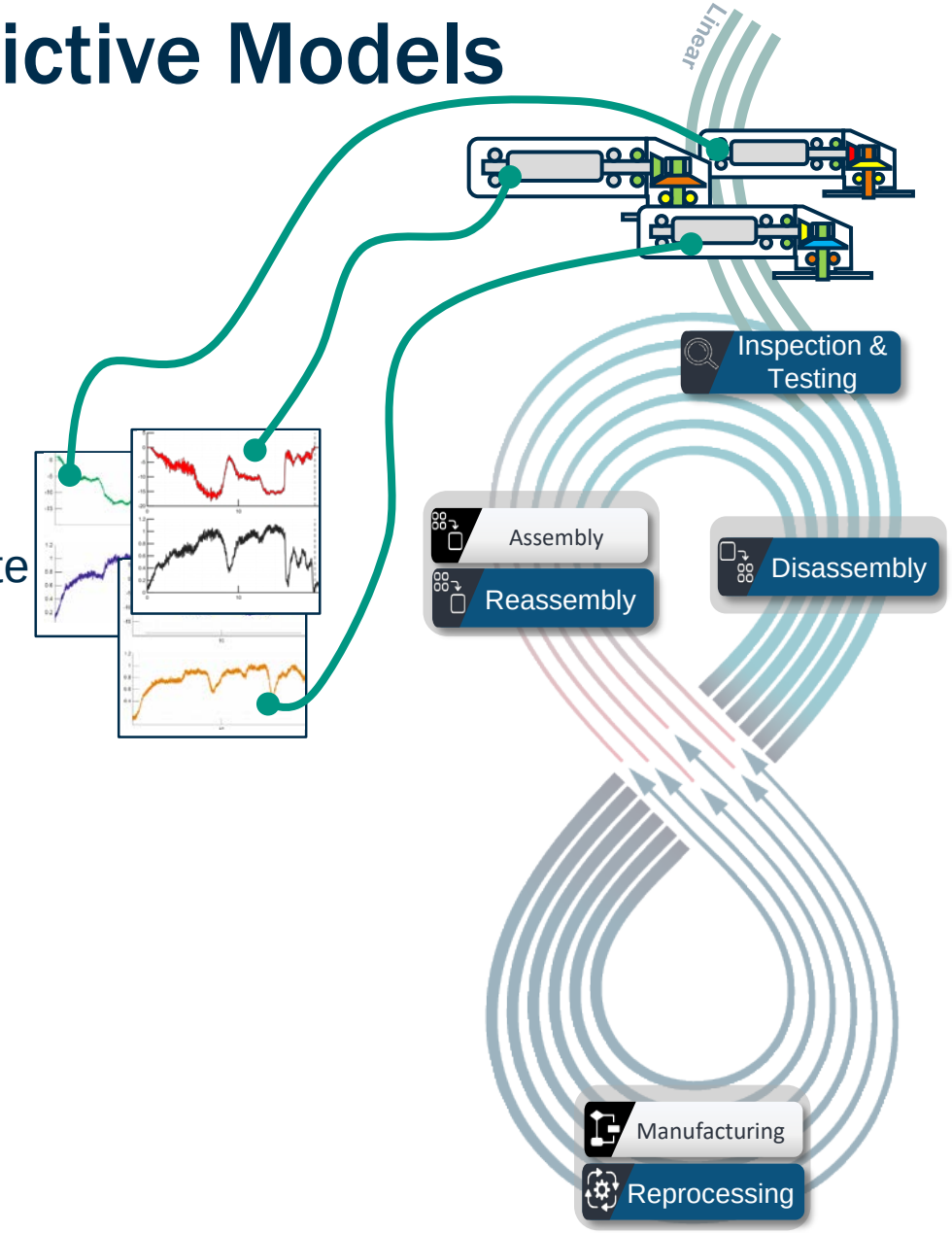
[CCPT 2026 · Karlsruhe]



Why the Circular Factory needs Predictive Models

Motivation: From an Operational Check to a Lifetime Prediction

- The Circular Factory (CF) reprocesses and recombines used products into **new product generations** instead of discarding them.
- **Returned products differ** in loading history and degradation state even when nominally identical.
- A subsystem that **still works at inspection** may **not deliver** the required function and reliability in its **next life**.
- CF remanufacturing decisions therefore become **prediction problems**, not simple pass/fail checks.

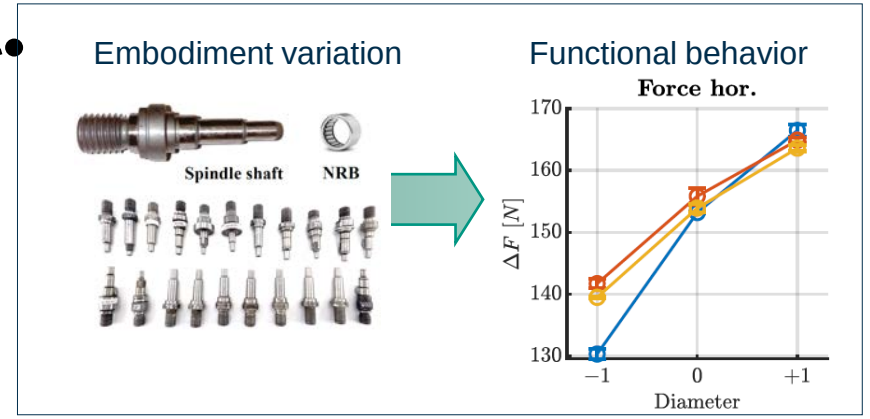


Two Predictive Models Drive Recombination Decisions

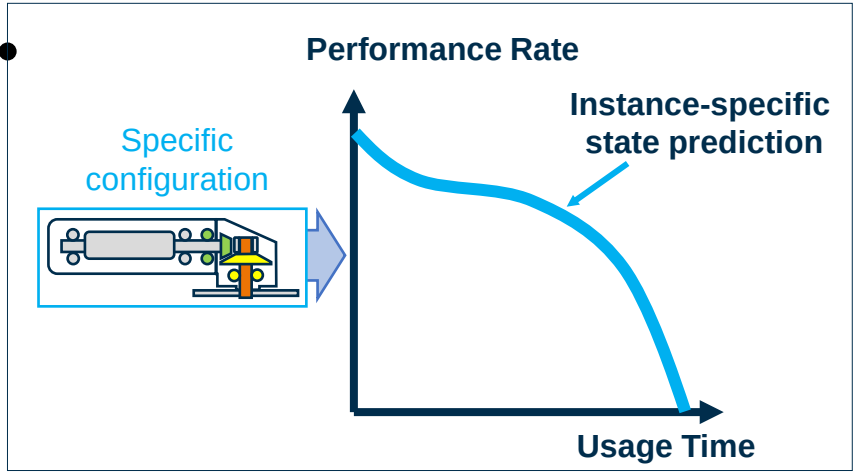
Motivation: Different Models have Different Data Requirements

- **Functional Behavior Model (FBM):**
  - Maps embodiment variation to measurable performance
- **System Reliability Model (SRM):**
  - Describes instance specific degradation trajectories

→ Different data requirements for model building!



Functional Behavior Model (from [4])



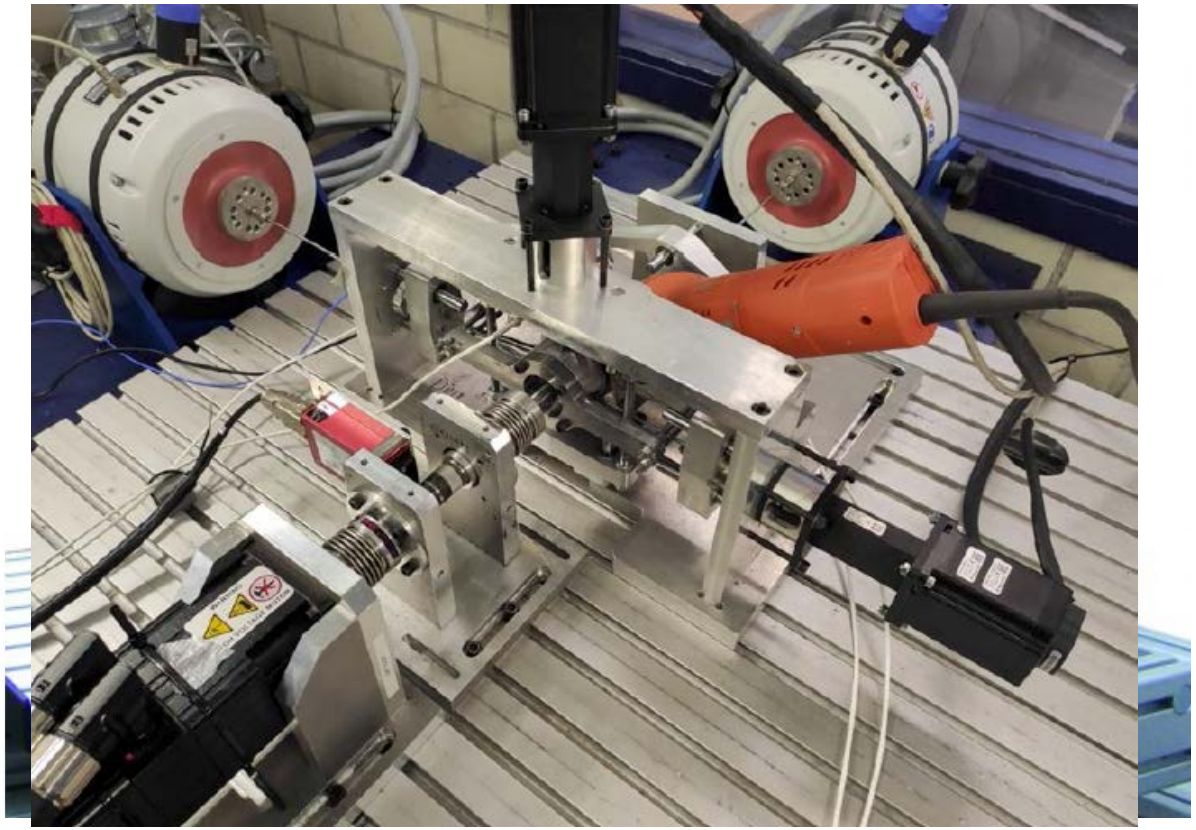
System Reliability Model

Existing Test Benches

Related Work / Research Gap

- **Industrial brake test benches** (Weinmann [5], SCS): simplified loading, but no access to embodiment or degradation quantities.
- **Matthiesen et al.** [1]**:** load-equivalent subsystem testing for angle grinder drive trains
- **Dörr et al.** [2]**:** dynamic multi-axial angle-grinder bench (torque + radial/axial loads up to 200 Hz).

- **Gap:** These test benches target loading reproduction and failure mechanisms — **not** the separate **generation** of **embodiment-sensitive data** for **FBM** and **degradation data** for **SRM**.



It is unclear how to translate the model requirements into testing environments capable of producing data in a systematic, repeatable, and configuration-specific manner.

A VDI 2221 Based Design Process for Testing Environments

Methodology

- Testing-environment development treated as an engineering design task following **VDI 2221**.
- Combined with extended Matthiesen & Grauberger's testing-environment dimensions. [3]

1 Clarification of the Development Task
- Problem statement
- System boundaries
- Operating conditions



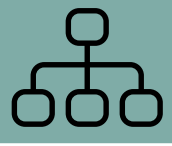
2 Derivation of Requirements
- Model needs
- Data needs
- Testing environment requirements



3 Categorization of the Design Space
- Testing dimensions / Characterization



4 Derivation of Functional Structures and Concepts
- Required functions
- Solution principles
- Concept selection



5 Implementation
- Embody and detail the testing environments



One Task Splits into Two Testing Environments

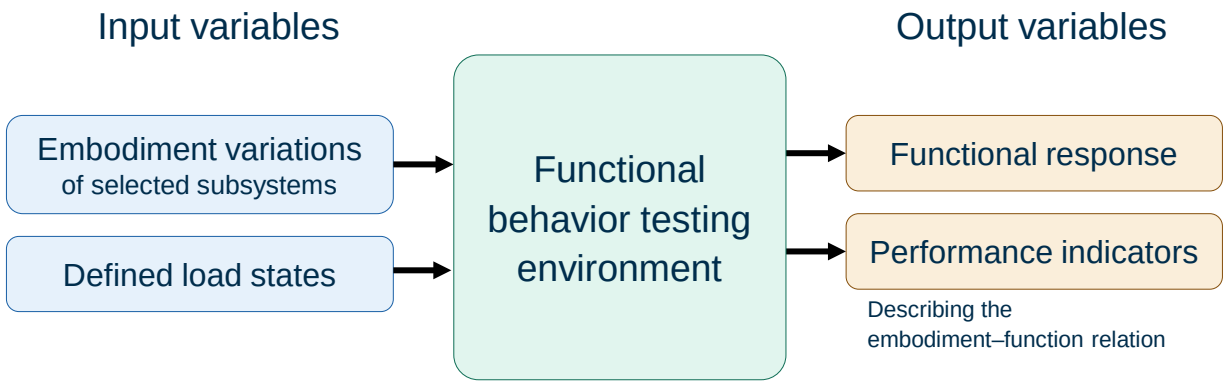
1 2 Results: Clarification of the Development Task & Derivation of Requirements

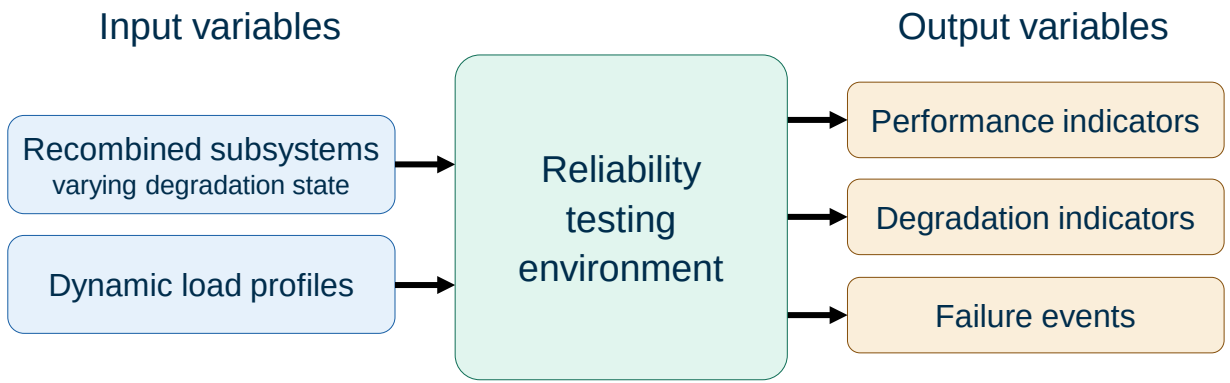
Functional Behavior Testing Environment

- Embodiment variations & defined load states
- Short, repeatable experiments
- Fast reconfiguration & exchange of subsystems
- High-resolution embodiment-function data

Reliability Testing Environment

- Recombined, degraded Systems & realistic load profiles
- Long-term continuous or accelerated-life tests
- Automated monitoring, minimal intervention
- Long-term degradation & failure time-series





Positioning Both Environments in the Design Space

3 Results: Categorization of the Design Space

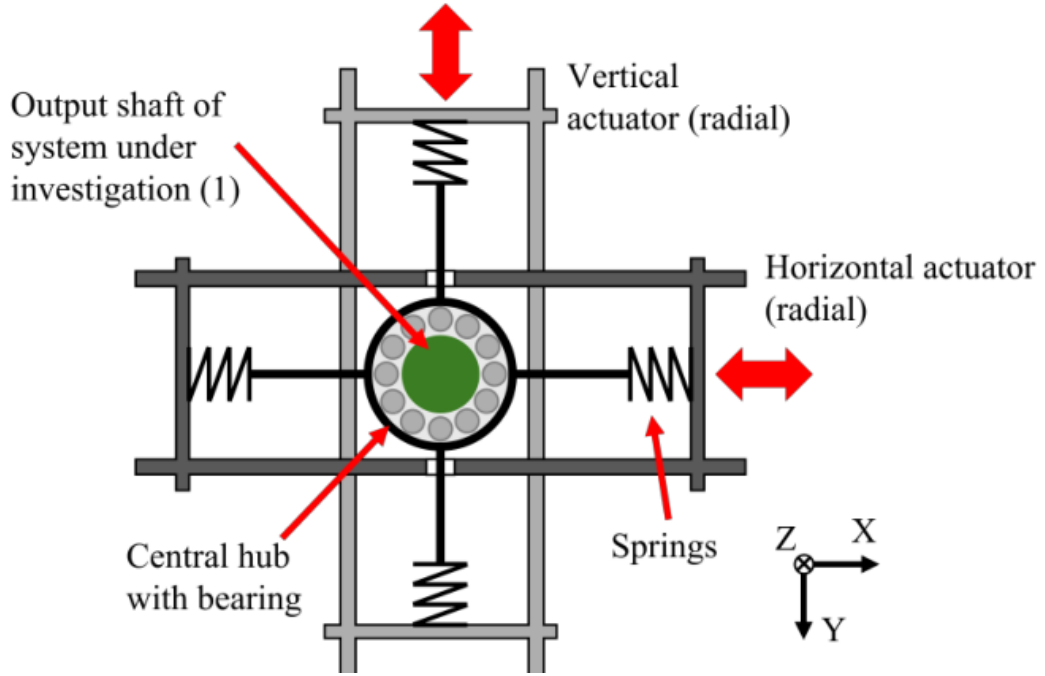
	Dimension	Functional Behavior Testing Environment	Reliability Testing Environment
Matthiesen & Grauberger [3]	**Characterization**	Physical	Physical–virtual
	Functional integration	Relevant subsystem interactions	Realistic system-level behavior
	Fidelity	Controlled, partly abstracted	Realistic loading conditions
Extended	**Stationarity**	Repeatable between experiments	High long-term stability
	Flexibility	High – rapid reconfiguration	Moderate – stable operation
	Automation	Semi-automated	Highly automated
	Observability	Functional-change detection	Continuous degradation monitoring

Functional Behavior Test Bench: Flexibility & Observability

4 5 Results: Derivation of Functional Structures and Concepts & Implementation

- **Superimposed** radial **loads** (vertical + horizontal) & torque

Working principle:
Superimposed force loads via disc springs and a torque motor.

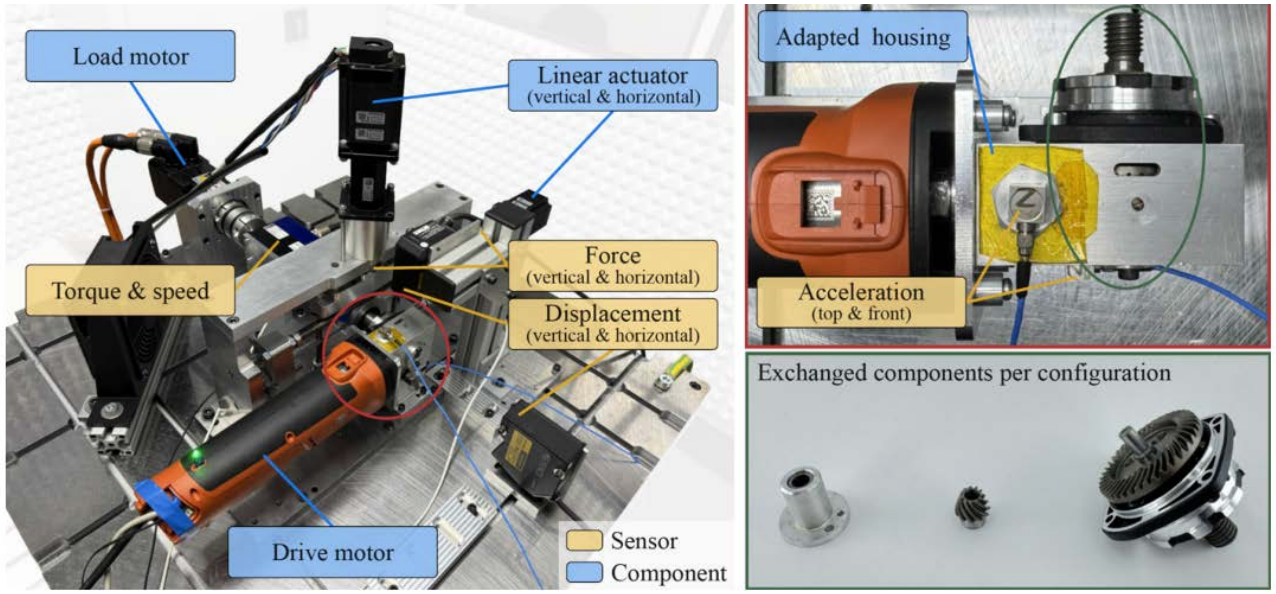


Working principle: load superposition (after [1,2])

Functional Behavior Test Bench: Flexibility & Observability

4 5 Results: Derivation of Functional Structures and Concepts & Implementation

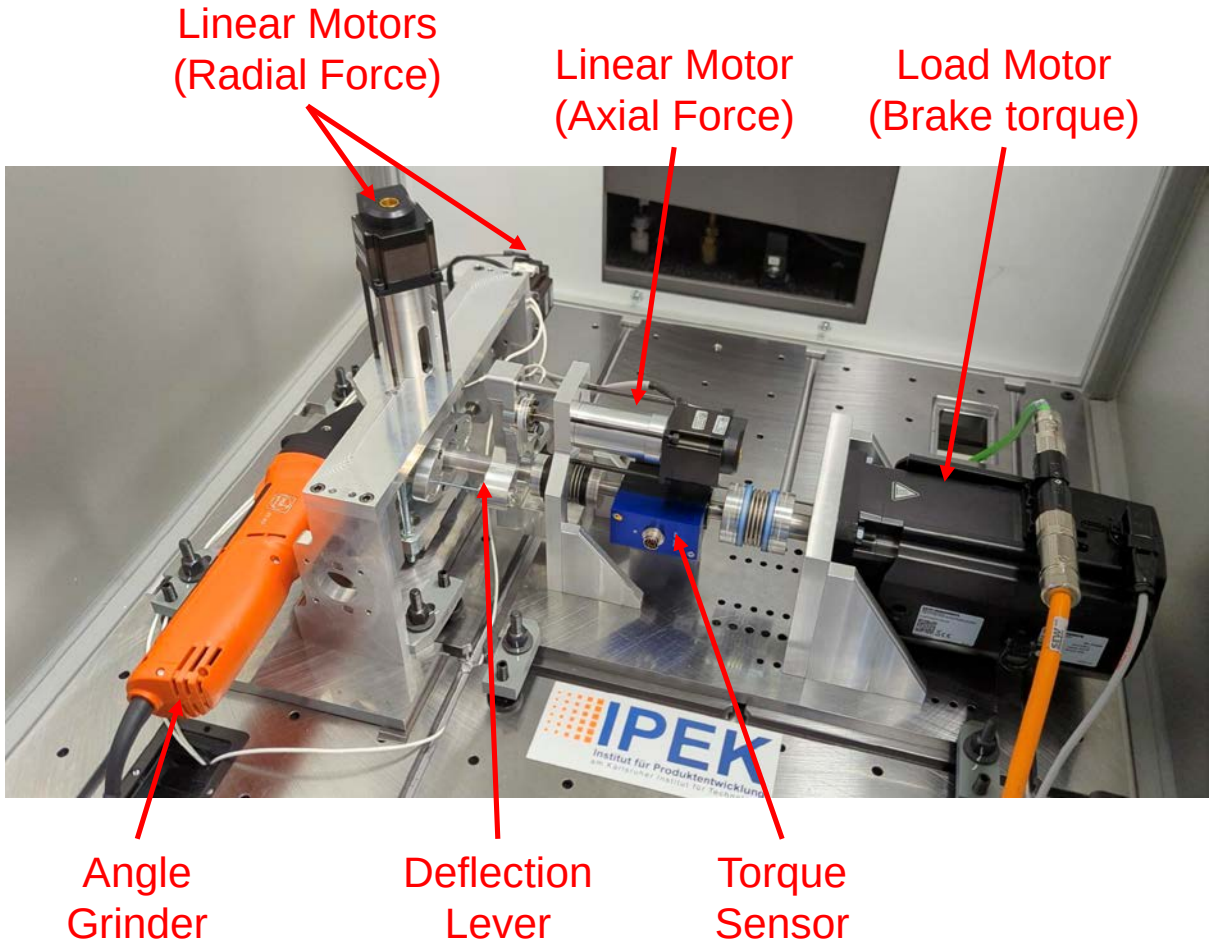
- **Superimposed** radial **loads** (vertical + horizontal) & torque
- **Replica gearbox housing** – bearing swap without press-fit + slots for online laser shaft-deflection measurement.
- **Subsystem exchanged as a unit** (spindle shaft, gear, bearing plate) – preserves the run-in state.
- No lubrication, no climate control → **short tests.**



Realized functional behavior test bench

Reliability Test Bench: Endurance & Degradation Monitoring

- **Three linear actuators** load a disc-spring package – controlled radial + axial loads on the output-shaft bearing.
- **Deflection lever** redirects the axial actuator – the rear of the grinder stays fully accessible.
- **Online embodiment measurement** (line laser) through minor housing modifications.
- **Damped, acoustically insulated & climate-controlled enclosure** – high signal quality over long runs.



Realized multi-axial reliability test bench

No Single Setup can Generate all the Required Data

Conclusion & Outlook

- **A VDI 2221-based method translates abstract data requirements into two concrete testing environments.**
- **Requirements of testing environments for FBM and SRM pull in opposite directions:** flexibility & observability vs. stability, fidelity & endurance.
- No single generic setup can produce all the required data – **two purpose-specific environments** are needed.
- This **enables data-driven recombination decisions**
- **Next steps:** experimental validation of both testing environments and building the prediction models.

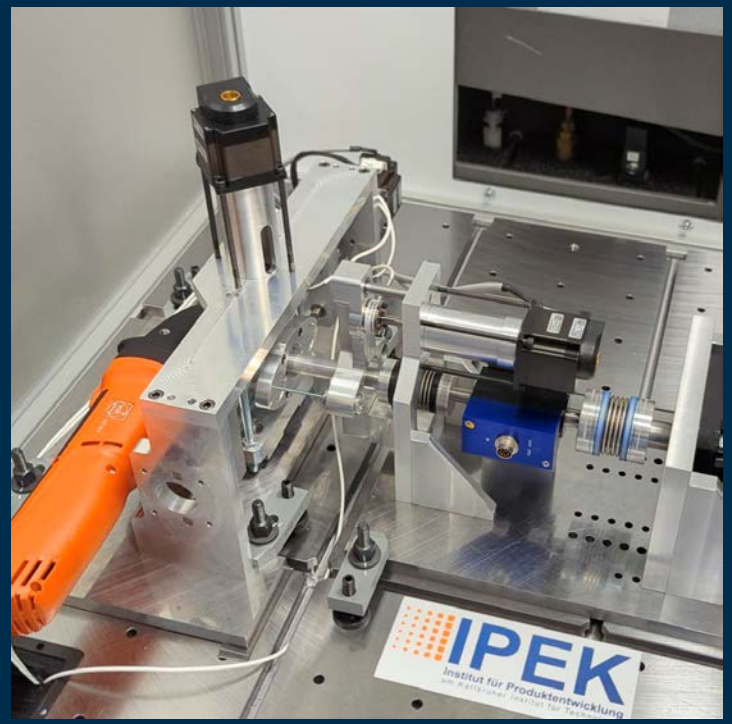
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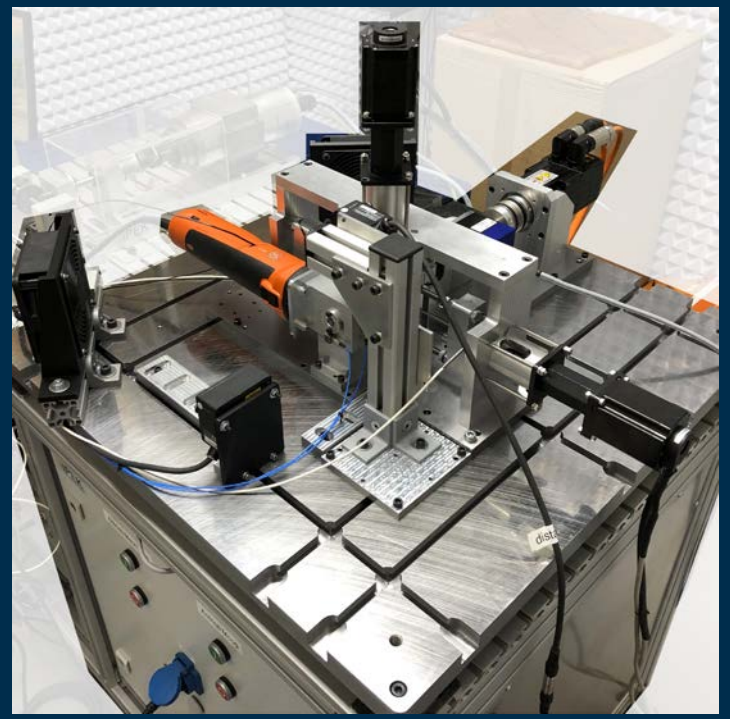
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This research was funded by the German Research Foundation DFG in the collaborative research center 1574 “Circular Factory for the Perpetual Product” with the project ID 471687386.

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[3] Matthiesen, S., Grauberger, P. (eds.): Konstruktionswissen Für Ingenieure: Innovative Produkte Zielgerichtet Entwickeln. Springer, Berlin, Heidelberg (2024). https://doi.org/10.1007/978-3-662-68986-8

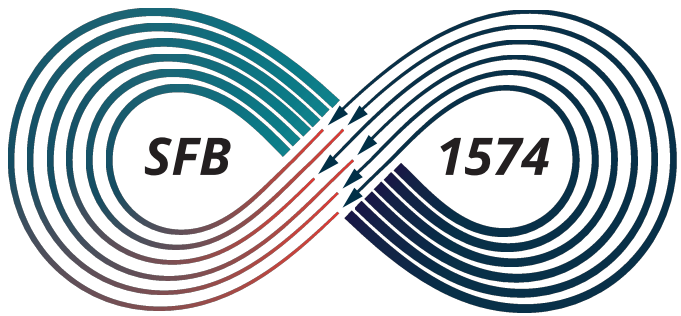
[4] J. Hemmerich, D. Koch, V. Mas, N. Afifi, E. Blum, G. Lanza, S. Matthiesen, and P. Grauberger, “Unified embodiment description for functional evaluation of used components in circular manufacturing systems,” [in publication]

[5] Prüftechnik Weinmann https://www.weinmann-online.de/produkt/leistungspruefstand-fuer-handgefuehrte-elektrowerkzeuge/ Accessed 2026-04-08

Automatic Gaussian Mixture Sampling for Uncertainty Management in Circular Factories

Zahra H.S Nasrollah, Ali Darijani et al. [1]

[1] KIT-IES / Fraunhofer IOSB



10th of June, 2026
Conference on Circular Production Systems and Technologies (CCPT)
Karlsruhe

Problem

Circular factories do not receive one homogeneous input stream.

returned parts
$\Downarrow$
different histories
$\Downarrow$
different condition regimes
$\Downarrow$
multimodal uncertainty

Problem: a single Gaussian can hide rare but decision-relevant regimes.

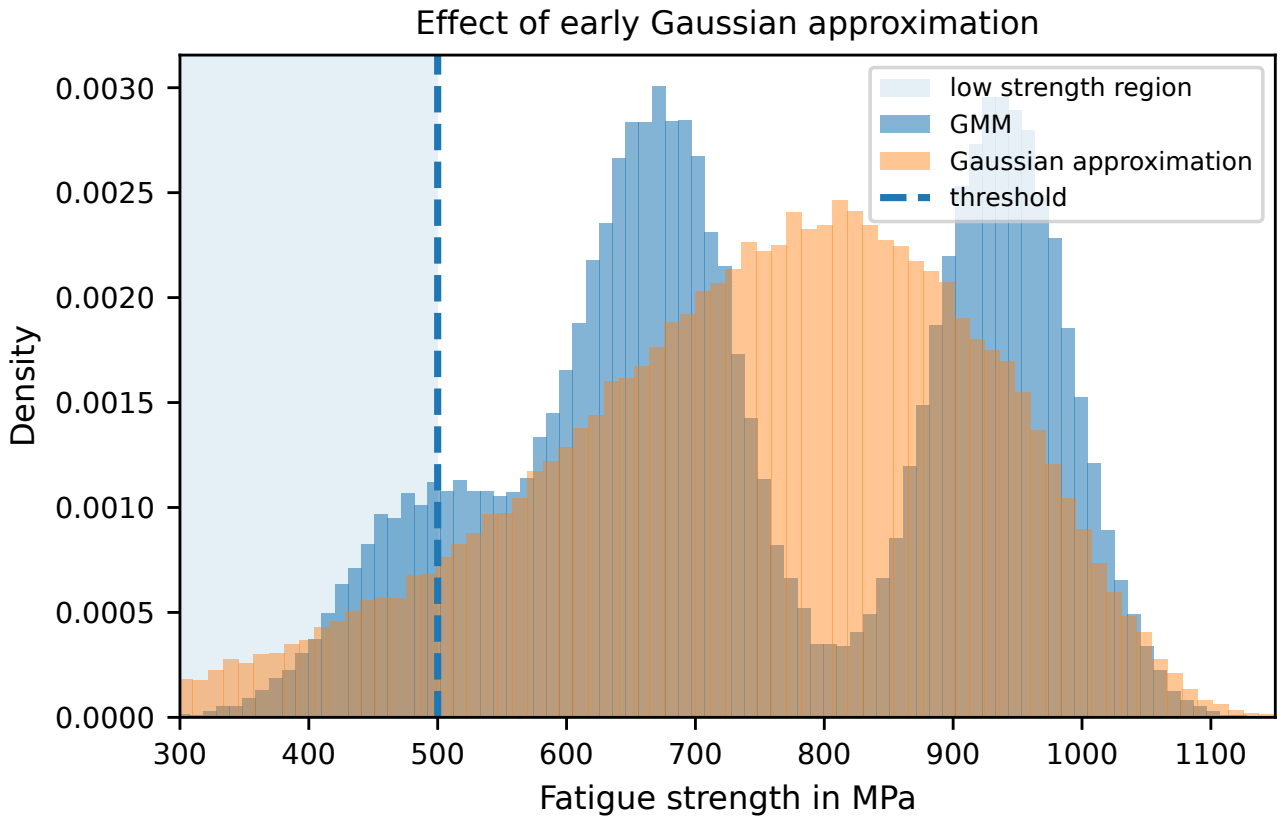
Idea

Do not collapse returned part uncertainty too early.

$$X \sim \text{GMM} \qquad \longrightarrow \qquad Y = g(X)$$

- GMM components represent condition regimes.
- The model g can be nonlinear or algorithmic.
- Monte Carlo is used only when closed-form propagation is not available.

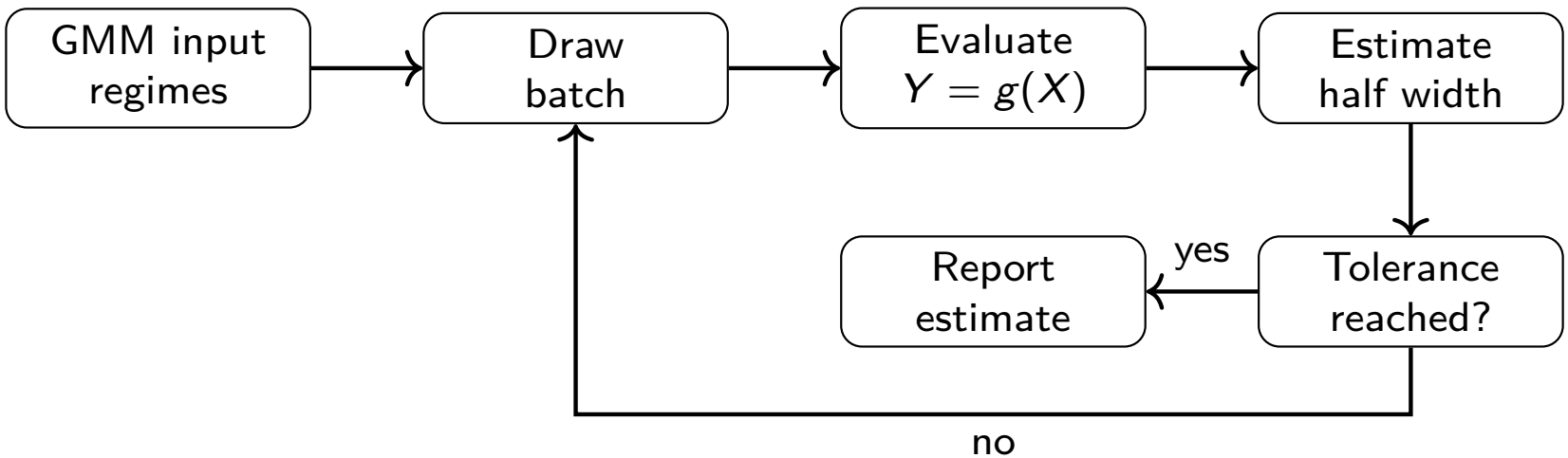
Why preserving the mixture matters



Early Gaussian approximation smooths the propagated distribution and can change the estimated low-strength probability.

Automatic sampling layer

Keep the GMM, sample only as much as needed.



- Draw samples from the GMM in batches.
- Propagate them through the nonlinear model.
- Stop when the requested precision is reached.

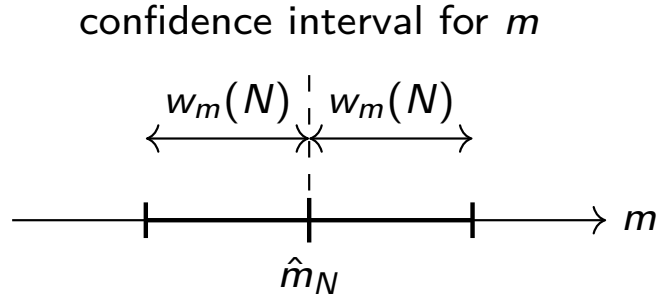
Stopping rule

Stop when the estimate is accurate enough.

For a scalar output $Y = g(X)$:

$$\hat{m}_N = \frac{1}{N} \sum_{j=1}^{N} Y_j$$

$$w_m(N) \approx z_{1-\alpha/2} \frac{\hat{s}_N}{\sqrt{N}}$$



Stop when $w_m(N) \leq \varepsilon_m$

Same idea for Y^2 and threshold probabilities.

Use case: Can a returned or treated metallic component still be reused?

We use a simplified fatigue strength assessment as nonlinear test model.

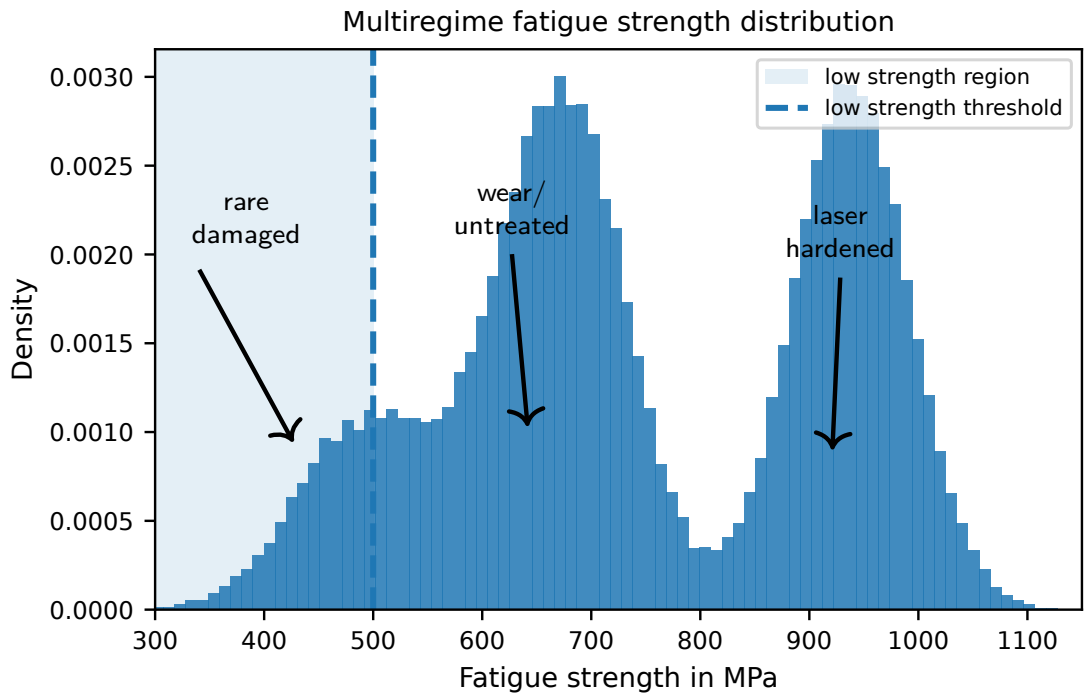
$$X = (HV, \sigma_{\mathrm{ES}}, R_z) \qquad \longrightarrow \qquad Y = R_w$$

- HV: local hardness
- σ_{ES}: residual stress
- R_z: surface roughness
- R_w: estimated local fatigue strength

The fatigue relation is not the contribution; it is the nonlinear engineering mapping used to test the sampling layer.

Multimodal surface state uncertainty by GMM

Regime	Interpretation	Expected effect
1	wear affected/untreated	medium strength
2	laser hardened	higher strength
3	rare damaged	low-strength tail



The components are coupled regimes over hardness, residual stress, and roughness.

Nonlinear fatigue strength relation

The model maps surface state to fatigue strength.

$$X = (HV, \sigma_{\mathrm{ES}}, R_z) \qquad \longrightarrow \qquad R_w = g(X)$$

$$R_w = \omega R_w^0 n(z) \left(1 - \frac{\sigma_{\mathrm{ES}}}{R_m}\right)$$

- hardness affects R_m and R_w^0
- roughness affects ω
- residual stress shifts the strength estimate

The fatigue relation is not the contribution; it is the nonlinear engineering mapping used to test the sampling layer.

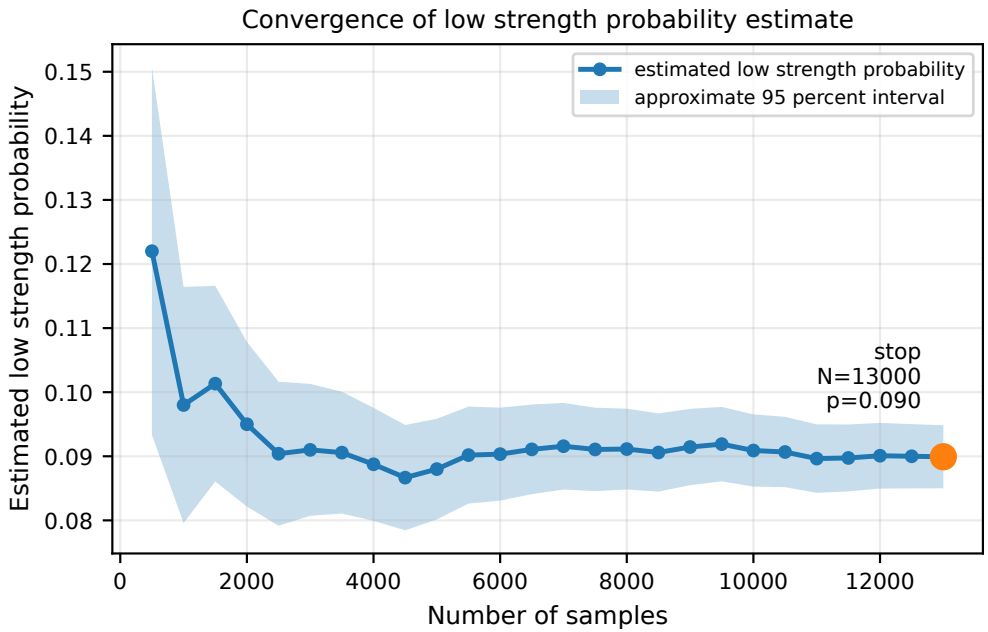
Result 1: Automatic stopping for decision risk

How many samples are enough for p_{low}?

Decision relevant event:

$$R_w < R_{\text{crit}}$$

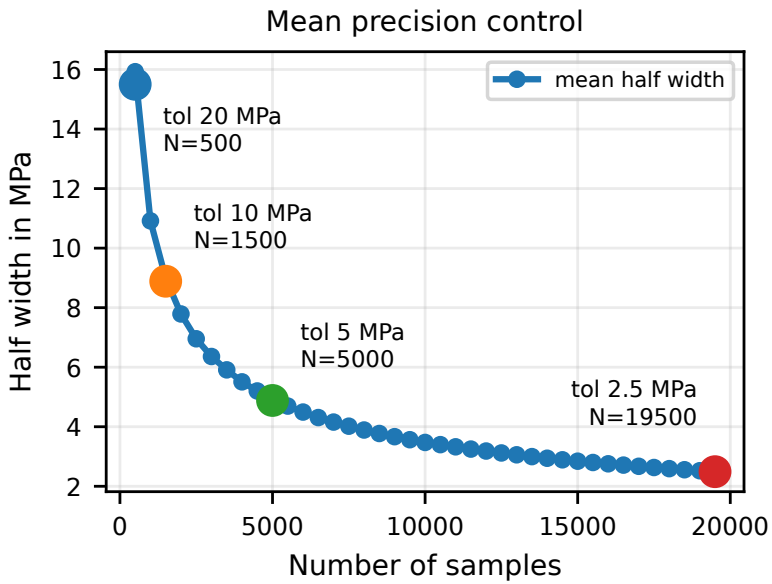
$$p_{\text{low}} = \mathbb{P}(R_w < R_{\text{crit}})$$

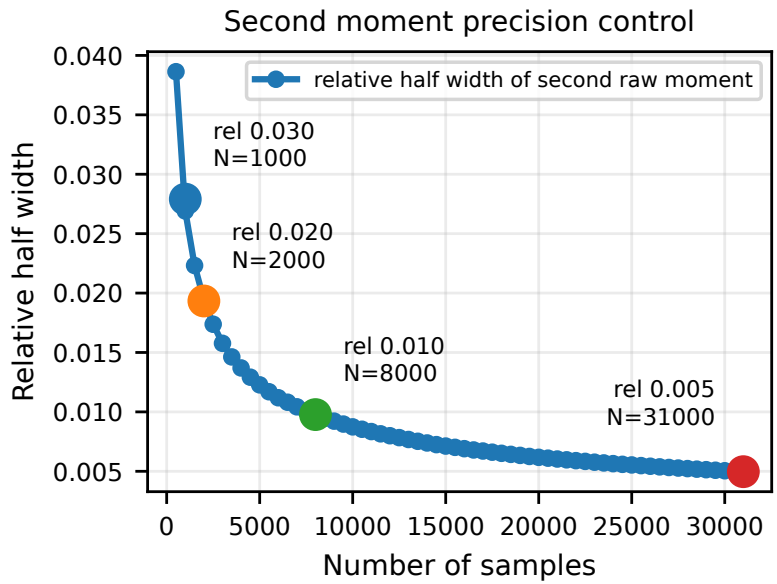


The sample size is not fixed in advance. It is selected when the probability interval is narrow enough.

Result 2: Sample size follows requested precision

Stricter tolerance requires more samples.





The final sample size becomes an output of the analysis: coarse precision stops early, stricter precision continues longer.

Conclusion

Fatigue assessment should describe the full strength distribution, not only a nominal strength value.

The sampling analysis determines the required number of fatigue test samples for precise estimation of

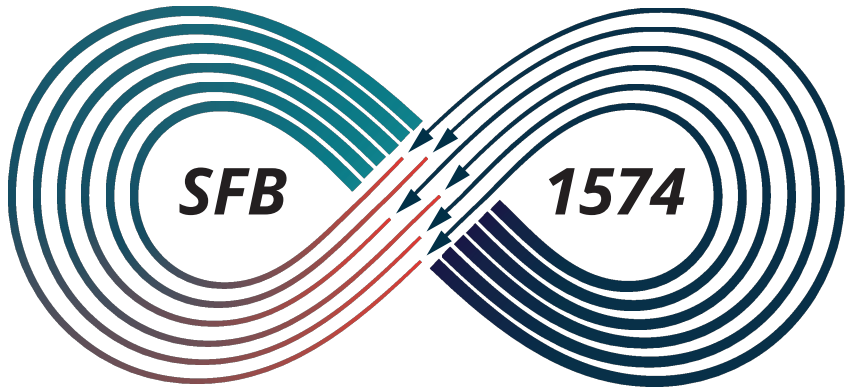
$$\mathbb{E}[R_w] \quad \text{and} \quad \mathrm{Var}(R_w).$$

This precision is important because uncertainty in the mean and variance directly affects the estimated lower tail:

$$p_{\mathrm{low}} = P(R_w < R_{\mathrm{crit}}).$$

Main conclusion: Sample size estimation provides the practical link between precise distribution characterization and reliable low strength risk assessment.

Fortis fortuna adiuvat



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REUMAN
SMART HUMAN-CENTRIC REMANUFACTURING

Structuring Information Flows in Circular Production

A Conceptual Framework based on the Battery Value Chain

10.06.2026 | Ludovica Bina, Abdelrahman Abdalla and Marcello Colledani

Conference on Circular Production Systems and Technologies

Funded by the European Union under the Horizon Europe Framework Programme as part of the REUMAN project, Grant Agreement No. 101138930

Contents

01 Introduction

02 Research Gap and Objective

03 Methodology

04 Results

05 Contributions, Implications and Future Work

Introduction: Why It Matters

150M

EOL battery units by 2035

80%

Capacity retained at end of first life

- The information gap between actors is one of the main barriers to circular economy implementation.
- Batteries are recycled prematurely because post-use actors lack the data they need.
- The DPP is mandated by 2027 but does not yet prescribe the granularity that second-life actors require.

Without structured information, circular value is lost.

Research Gap and Objective

What we know

The **Digital Product Passport** creates a regulated infrastructure to collect and share **battery lifecycle data**. It improves **traceability**, **transparency** and **compliance** across the value chain.

What is missing

Current approaches do not clearly show which actor needs which **information**, at which **lifecycle stage**, and at which **granularity level**: pack, module or cell.

What this paper does

An **actor-level framework** that maps battery value chain **actors**, DPP **data requirements**, and **information exchanges** needed to support second-life and circular strategies.

The challenge is not only in collecting data but also in structuring it so that each actor can use it for circular decision-making.

Methodology

Development of a conceptual mapping approach combining value-chain and DPP data perspectives.

1

Identification of EV battery lifecycle phases

Cradle-to-cradle battery value chain

2.

Catalogue of DPP data requirements

EU Battery Regulation + Battery Pass Consortium guidance

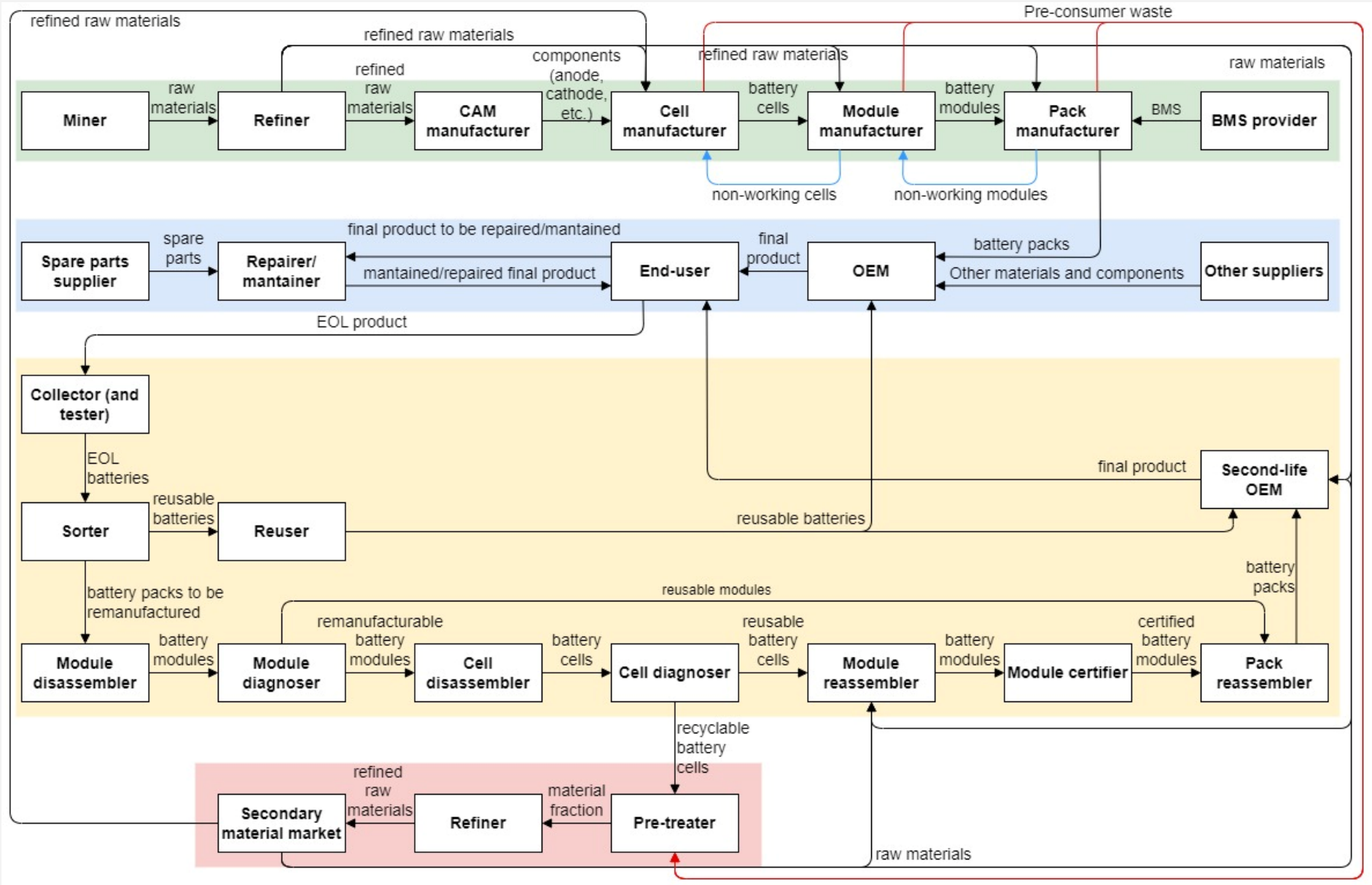
3.

Mapping of data against lifecycle actors

Input data required + output data generated

The Battery Value Chain

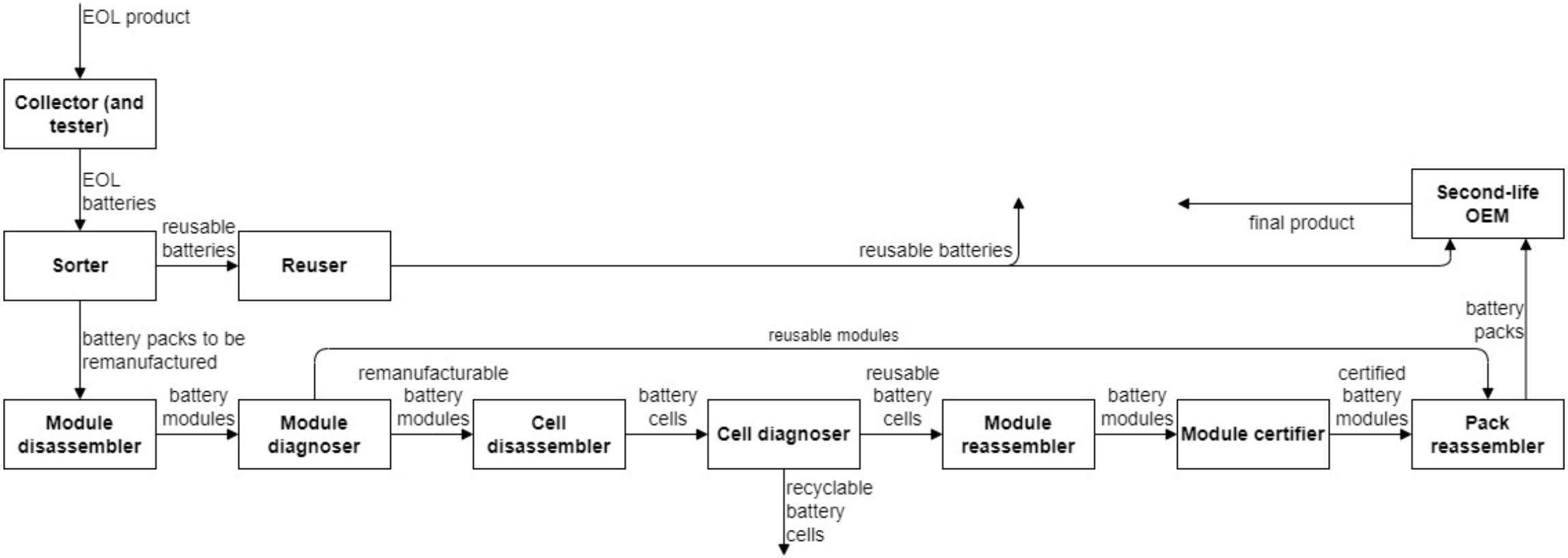
From resource extraction (cradle) to the use phase and the reintroduction of materials into the cycle (cradle).



- Pre-Use Phase
- Use Phase
- Post-Use Phase
- Recycling

Focus on Second-life Actors

The second-life segment is where information becomes most critical and most deficient.



Information Flows

Every actor is both a data consumer and a data producer.

Actor	Input Data	Output Data
Collector/tester	Specifications, safety, product data, performance data	Test reports, incidents, product data, performance data
Module Disassembler	Manuals for disassembly, wiring diagram, safety	Battery status, component health, applied procedure
Cell Disassembler	Manuals for disassembly, wiring diagram, safety	Battery status, component health, applied procedure
Cell Tester	Performance data, geometry and chemistry	Health status, benchmark
Module Reassembler	Spare parts information, performance data, safety	Performance data, composition, reassembly procedure
Module Diagnoser and Certifier	Safety, performance data, testing and reassembly records	Performance data, safety and reliability reports
Pack Reassembler	Safety, design and performance requirements, specifications	Status, performance data, composition, reassembly procedure
Second-life OEM	All information of previous actors	Battery status, new DPP, reference to old battery's data

Source: simplified from Table 1

Key Finding: Information must mirror product granularity

Pack-level data alone supports compliance, but not efficient inner-loop circular strategies.

CELL	Cell SoH, chemistry, geometry, performance thresholds, manuals Needed by: Cell disassembler, cell tester, module reassembler
MODULE	Module SoH, damages, manuals, certification Needed by: module disassembler, module diagnoser, pack reassembler, module certifier
PACK	Compliance, identity, carbon footprint, durability Needed by: collector and tester, reuser, all other actors

Without granular data, remanufacturers must repeat tests already performed during manufacturing, increasing costs and destroying circular value.

Contributions, Implications and Future Work

CONTRIBUTIONS

Granularity principle
Information flows must mirror the physical battery architecture: pack, module and cell to support inner-loop circular strategies.

Second-life actor mapping
The framework identifies where information is most critical and most deficient.

DPP repositioning
The DPP is not only a compliance tool, but an enabler of circular value creation.

IMPLICATIONS

POLICYMAKERS
Mandate module- and cell-level data exchange and define rules for data sharing across the value chain.

COMPANIES
Understand the DPP as a shared information backbone for the entire circular value chain.

FUTURE WORK

Empirical validation through expert interviews
Extension to international supply chain dimensions
Quantitative cost-benefit analysis of information exchange

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Thank you for the attention!

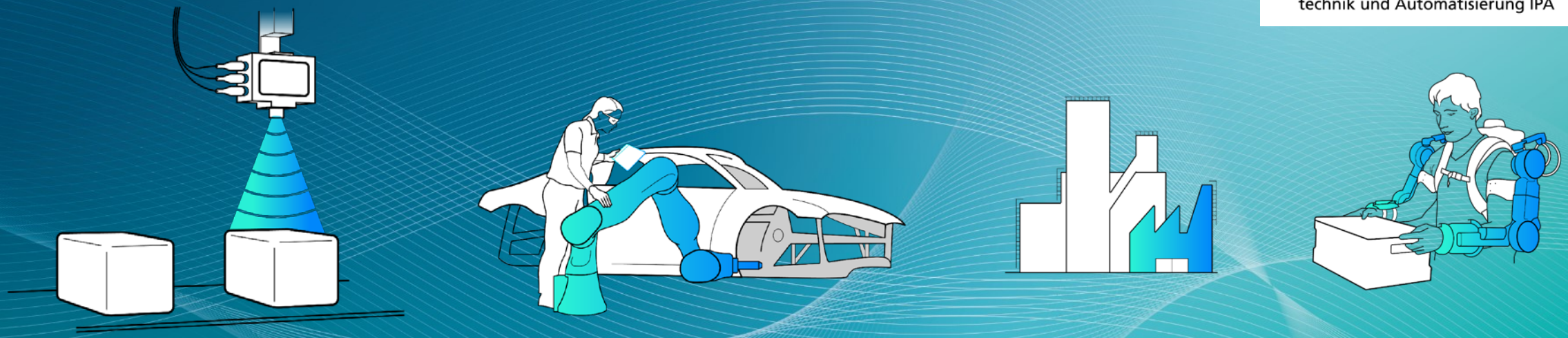
Questions?

Contatti

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Fraunhofer IPA

Fraunhofer-Institut für Produktions-technik und Automatisierung IPA



Conference on Circular Production Systems and Technologies (CCPT)



Sovereign Data Spaces and Interoperable Digital Twins for Automated Product Carbon Footprint Integration in Circular Production Systems

Presented by Sowjanya Krishna et al. · Fraunhofer IPA / IOSB / IESE / ISST

Table of contents

Agenda

1. Motivation
2. Introduction
   - Product Carbon Footprint
   - Dataspaces
3. Approach
4. Reference Architecture
   - Value Network
   - System Overview
5. Implementation
6. Results
7. **Conclusion**

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Motivation

Cross-Border Data Exchange for Product Carbon Footprint : A Real-World Use Case

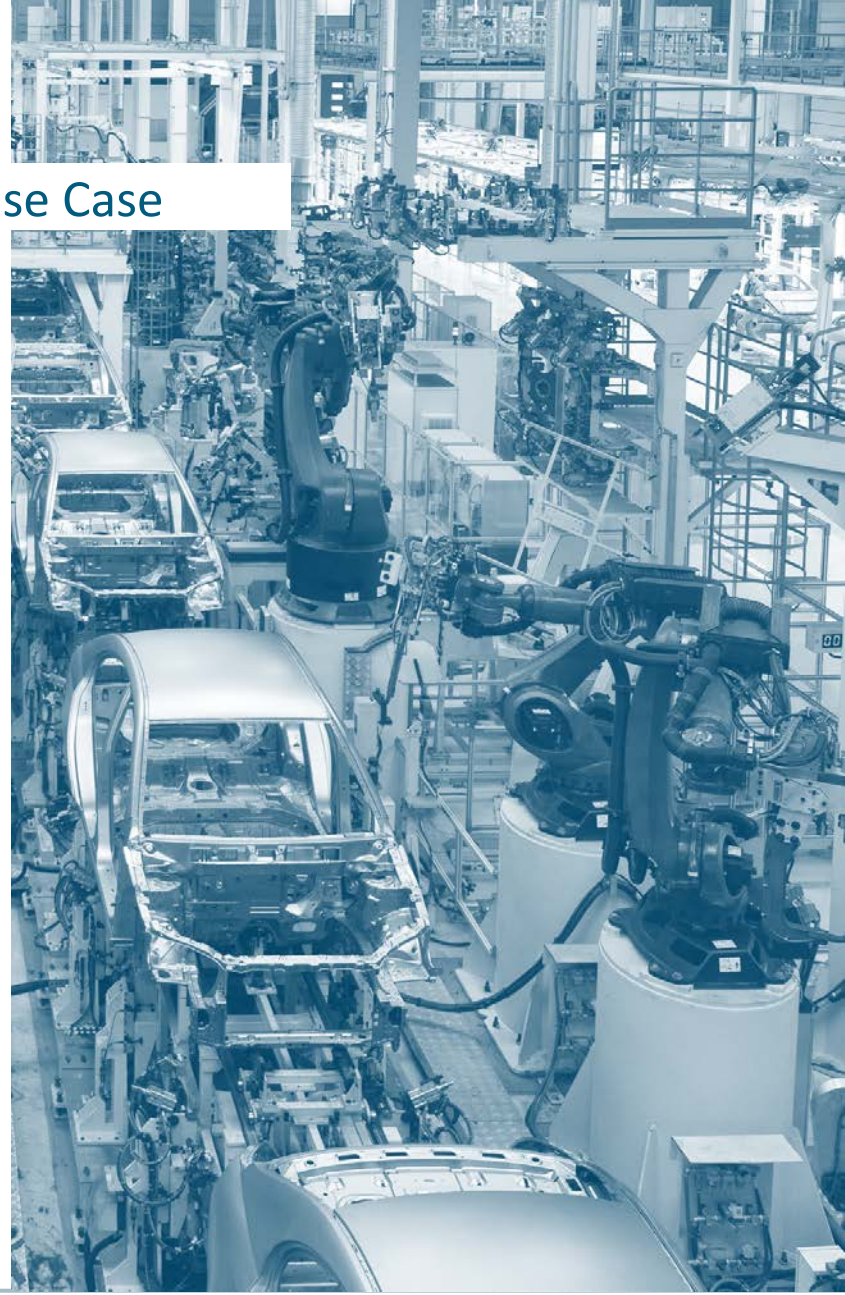
Global supply chains require trusted, standardized Product Carbon Footprint (PCF) data exchange. Differing laws and technical standards between China and Germany limit transparency and compliance. A unified, interoperable solution is needed.

Implementation: Ensuring the interoperability of different digital twin standard implementations and integrating them into a data space framework.

- Reviewed PCF regulations and compliance requirements
- Prototyped two digital twin frameworks and the PCF solution tailored to stakeholder needs
- Deployed the solution in a cross-border data space infrastructure
- Demonstrated results through PoC setups in Stuttgart and Shanghai

Benefits achieved: Cross-border interoperability of PCF data between China and Germany; Trusted and secure data exchange using AAS and Data Space technologies

Fraunhofer Institutes (ISST, IOSB, IESE, IPA) are involved in the development of a technical solutions.



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Introduction
Product Carbon Footprint

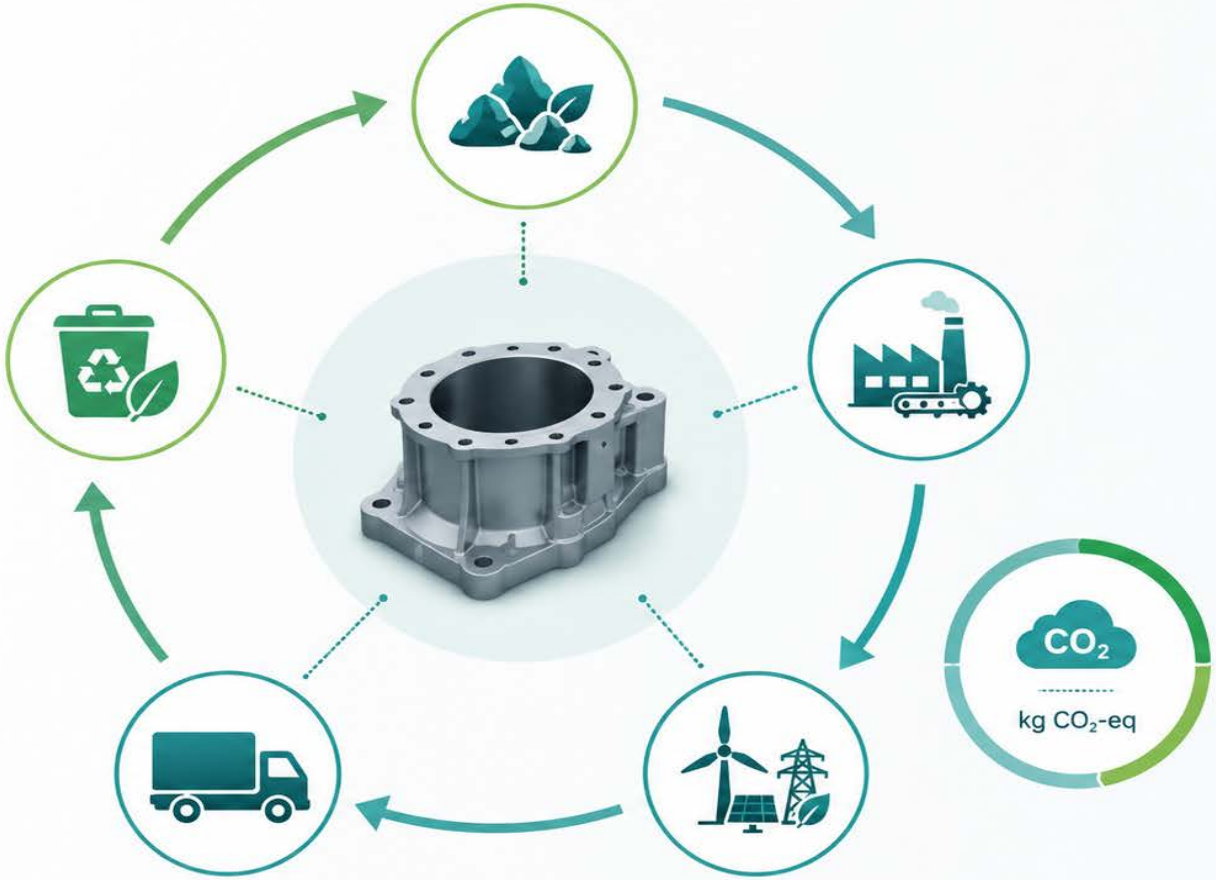
What is PCF?

A Product Carbon Footprint quantifies the greenhouse gas emissions associated with a product within a defined life-cycle boundary. It is expressed as **kg CO_2-eq** and links product, process, material, energy and transport data.

Why it matters

- supports customer reporting and supplier comparison
- guides low-carbon product and process decisions
- creates a basis for circularity measures and compliance
- needs to be machine-readable, updateable and exchangeable

Key message
PCF becomes valuable when it can be updated from production data and shared under controlled conditions.

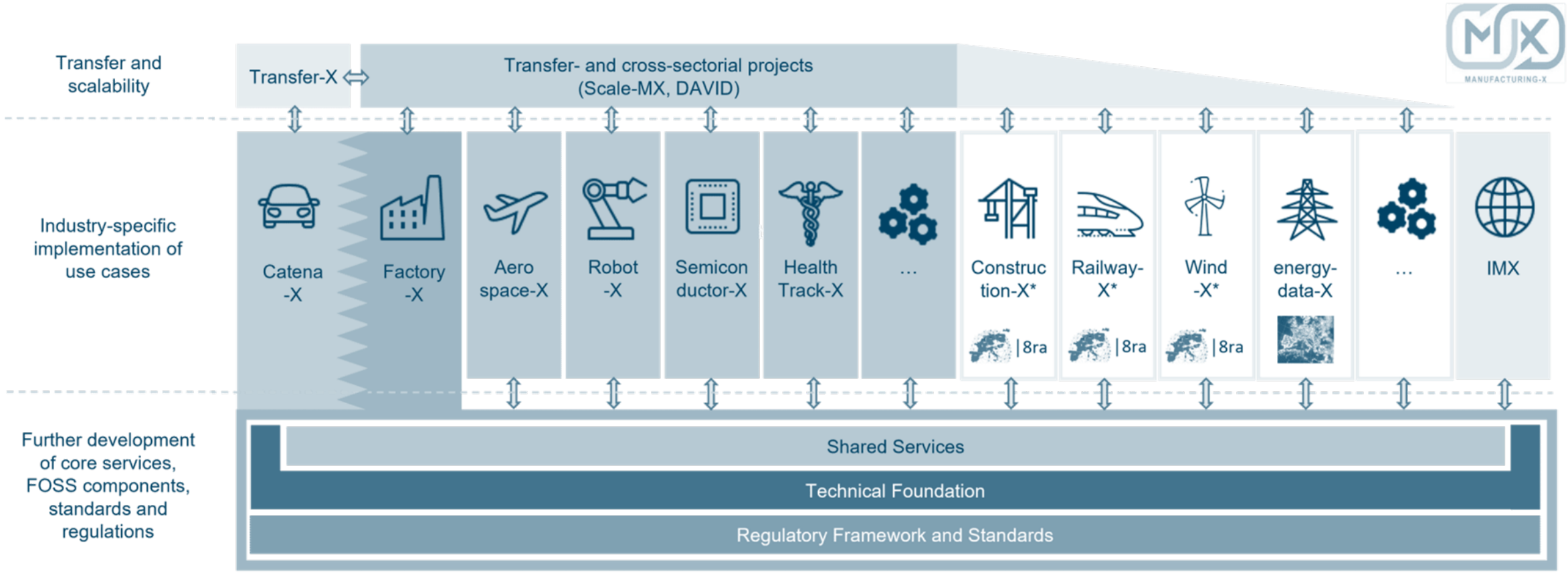


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Introduction

DataSpaces Manufacturing-X

Manufacturing-X is Germany's largest initiative that creates cross-industry data rooms to enable the use of shared services, technology infrastructure, and standardized frameworks and regulations across companies.



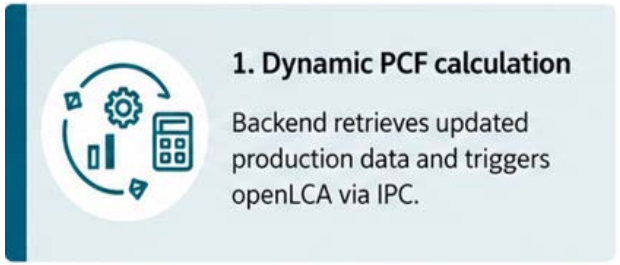
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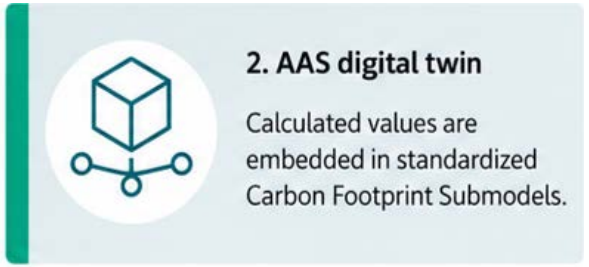
Approach

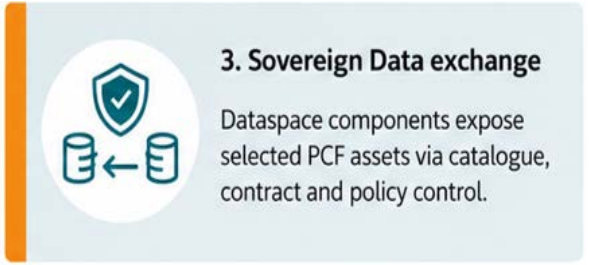
Research question and contribution

Research question

How can dynamically updated PCF information be integrated into interoperable digital twins and exchanged through sovereign Data Spaces?







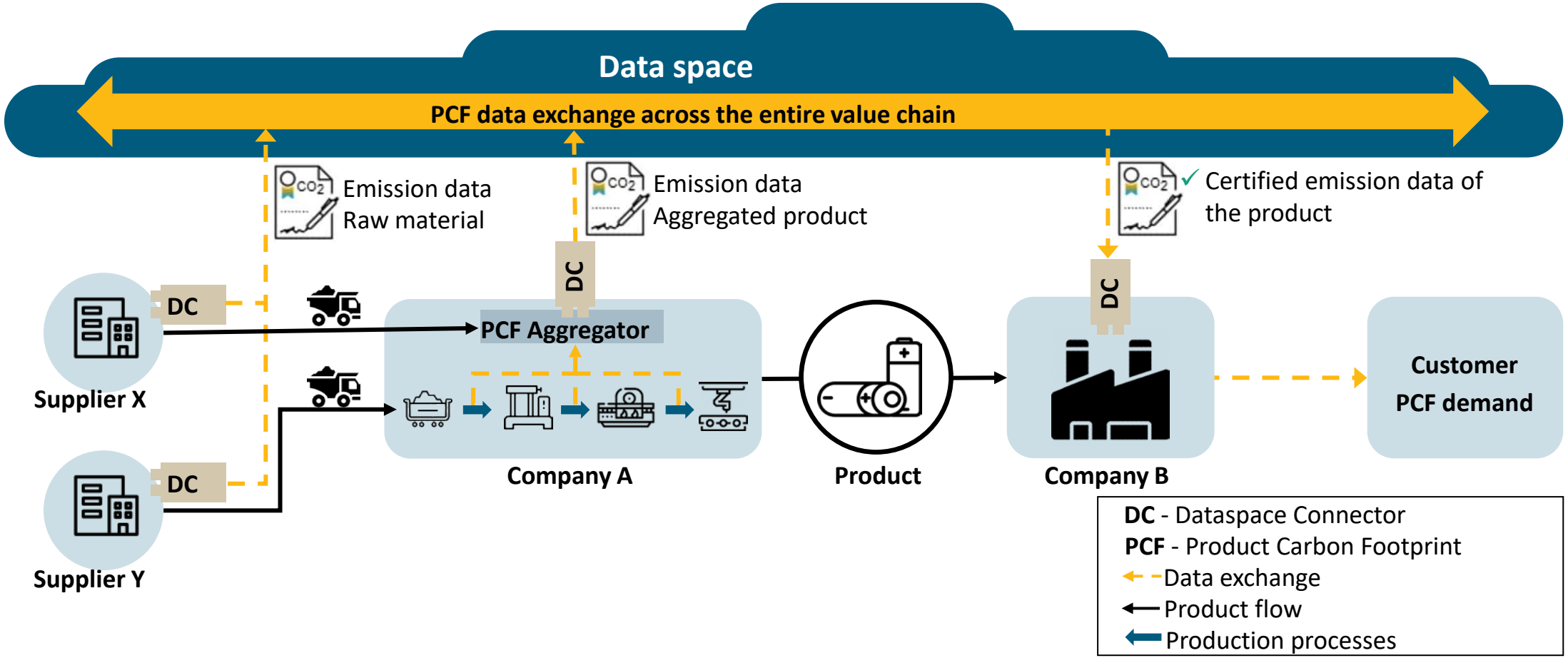
Contribution

A modular reference architecture and demonstrator linking production data, openLCA, AAS, BaSyx/FA³ST interoperability and EDC-based data exchange.

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Reference architecture - Value network

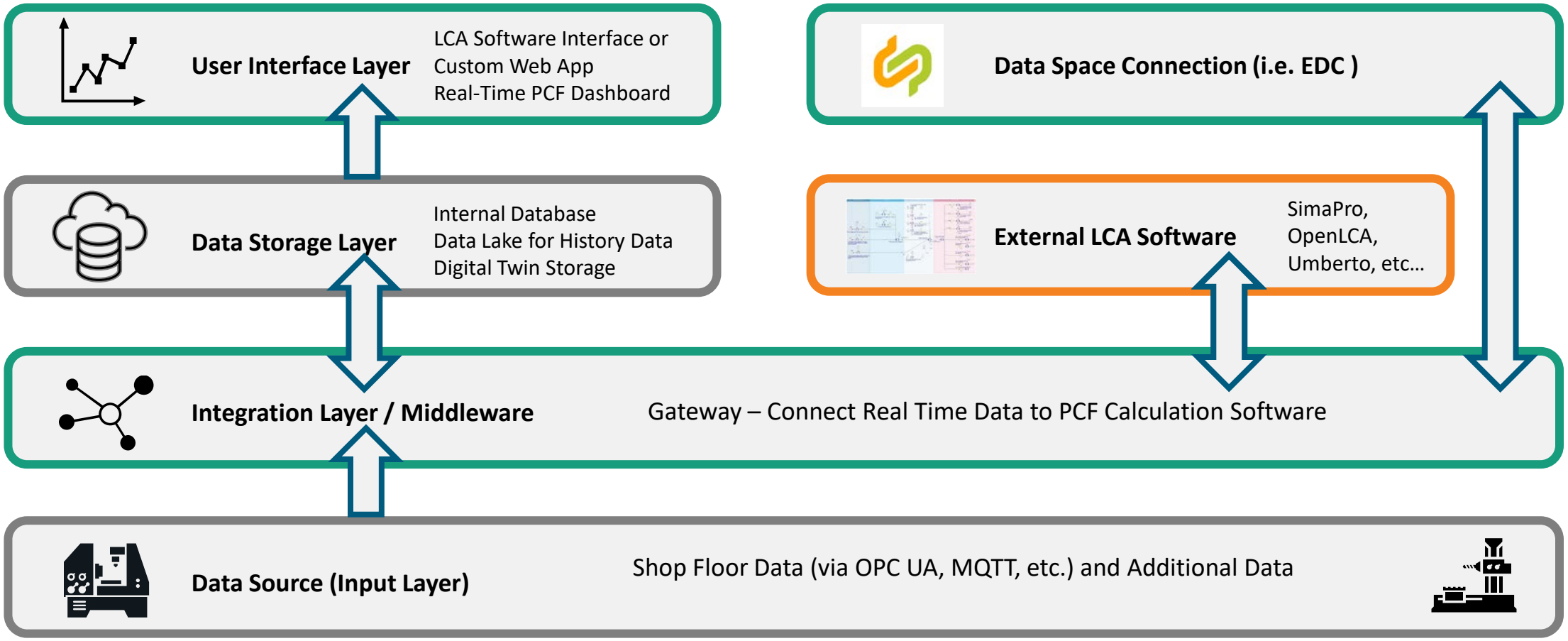
Value-chain PCF exchange through a Data Space



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Reference architecture - System view

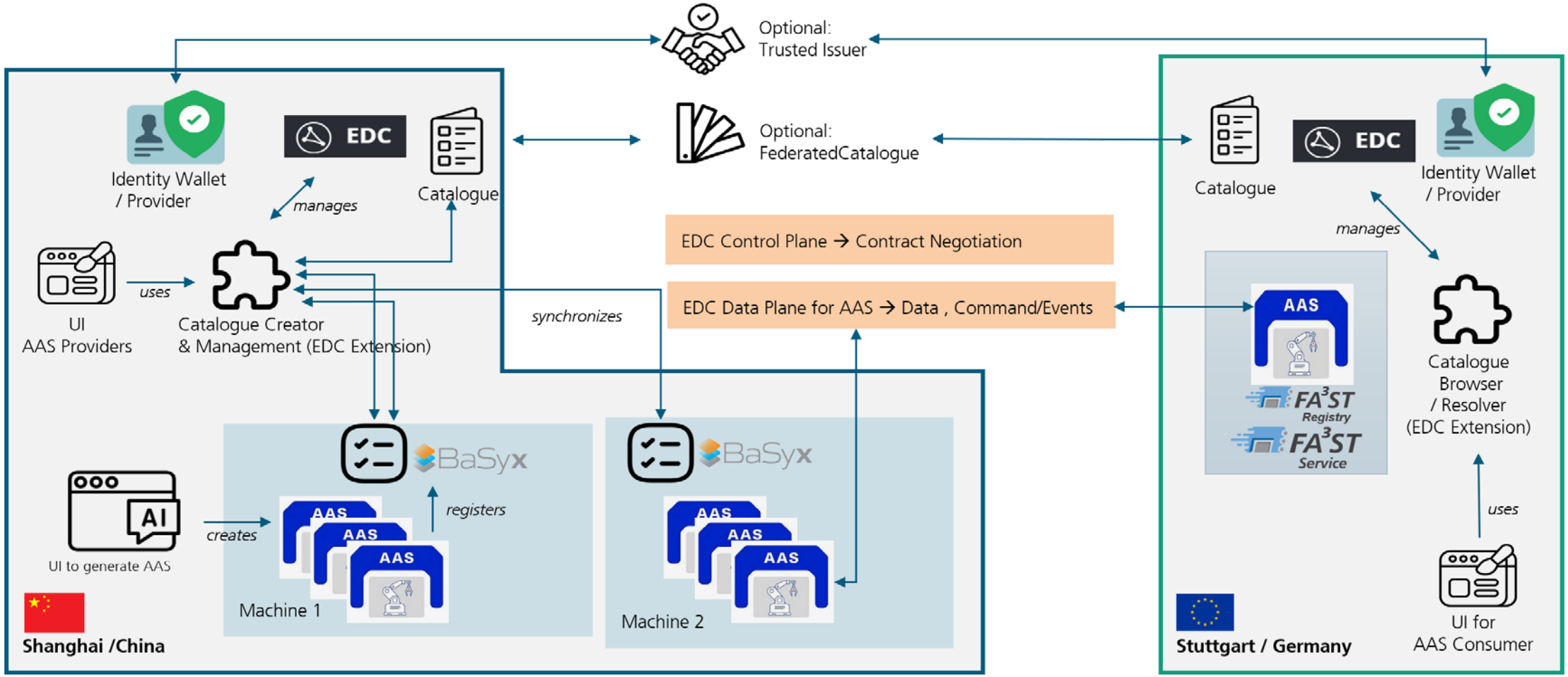
Layered architecture for dynamic PCF



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Implementation

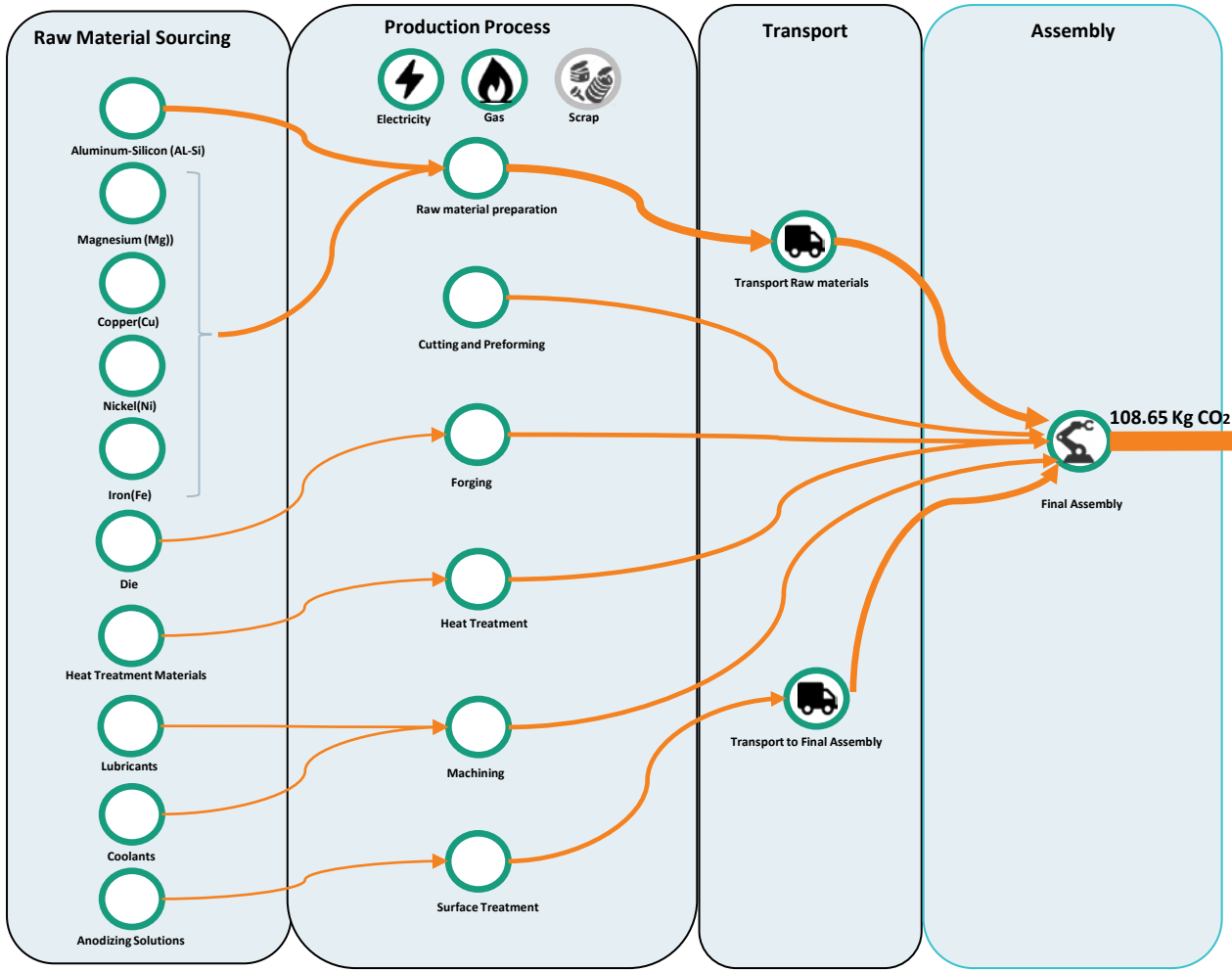
Cross-border AAS DataSpace demonstrator

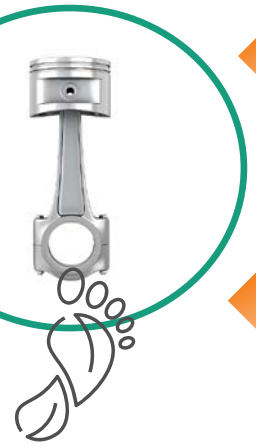


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Implementation - Piston workflow

PCF demonstrator scenario





108.65 Kg CO_2eq

Scope 1 Direct emissions that occur from sources that are controlled and owned by an organization.

Scope 2 Indirect emissions from purchased energy such as electricity and district heat.

Scope 3 Indirect emissions from purchased products and services formed along prganization's value chain

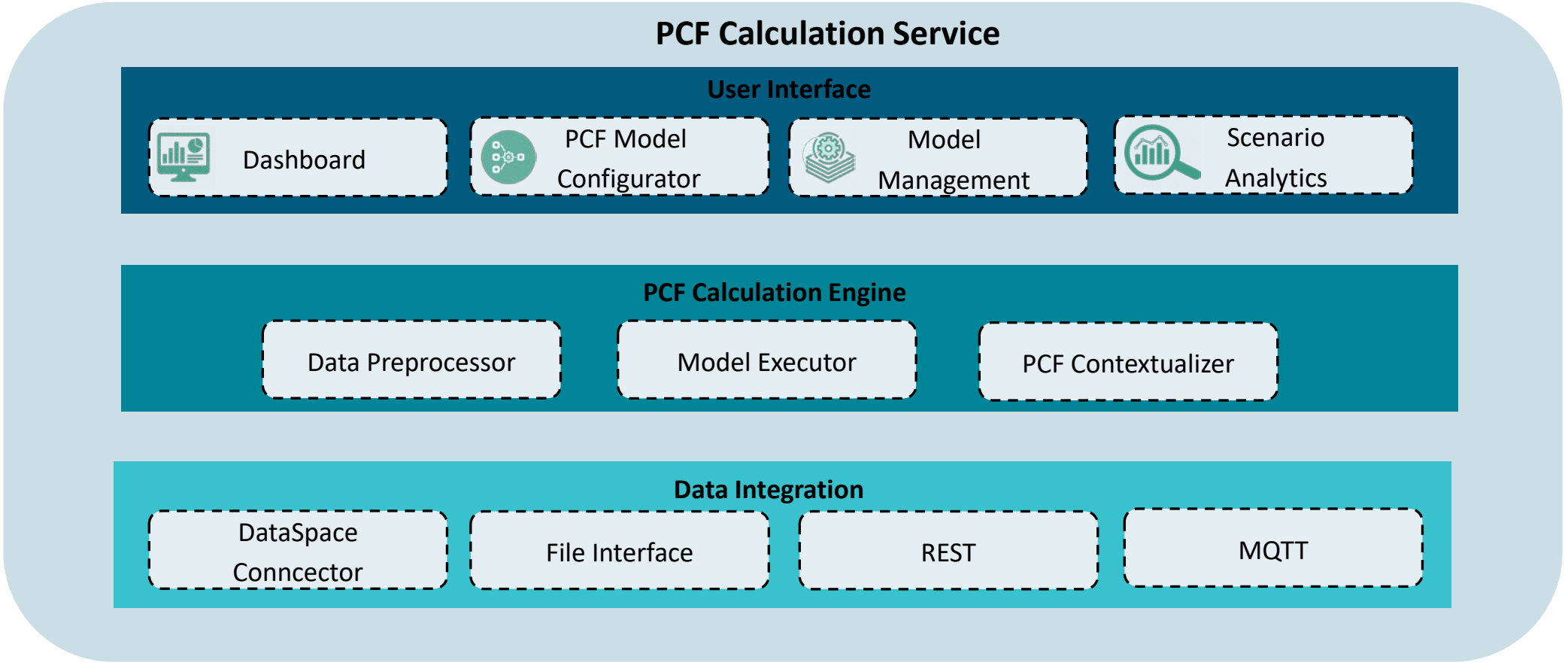
Actual Measurement-based Input*

*Use of catalog values is possible but high fines are due

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Results

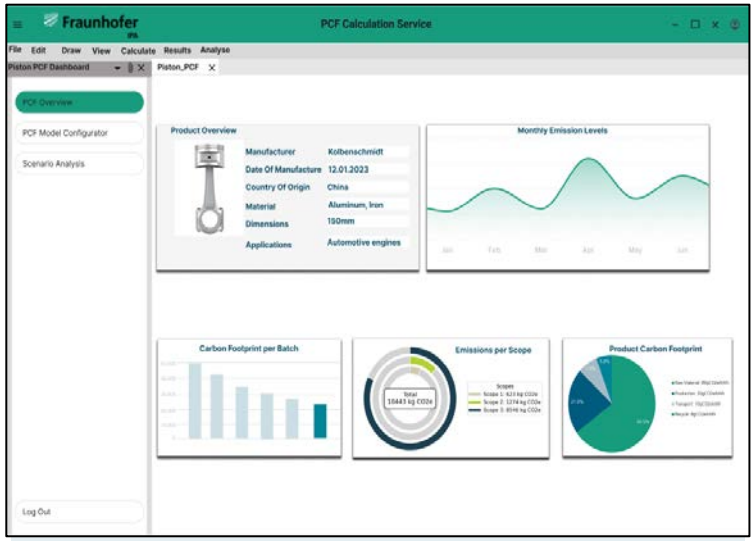
Dynamic PCF workflow



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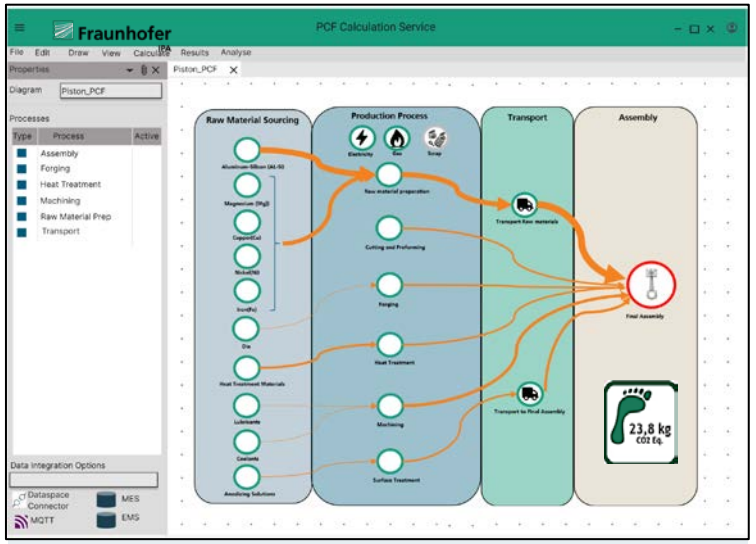
Results

Dynamic PCF workflow



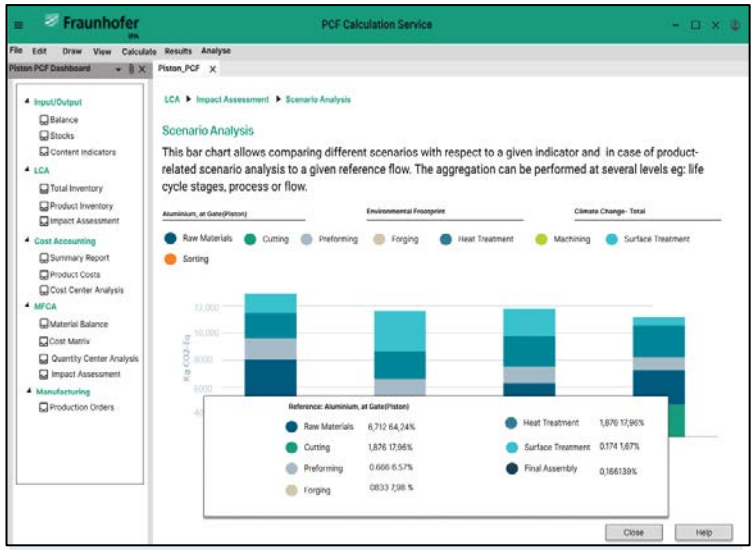
Dashboard

Displays the product's carbon footprint throughout its lifecycle, with key metrics, recent activities, and quick access to features.



PCF Model Configurator

Allows users to create, configure, and manage PCF models with adjustable parameters and real-time previews.



Scenario Analysis

Enables running and comparing different scenarios to analyze potential outcomes and make data-driven decisions.

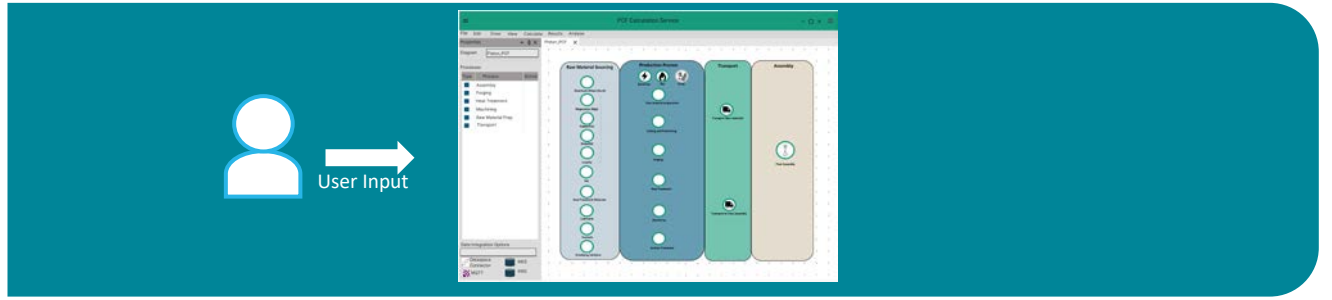
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Results

Dynamic PCF workflow

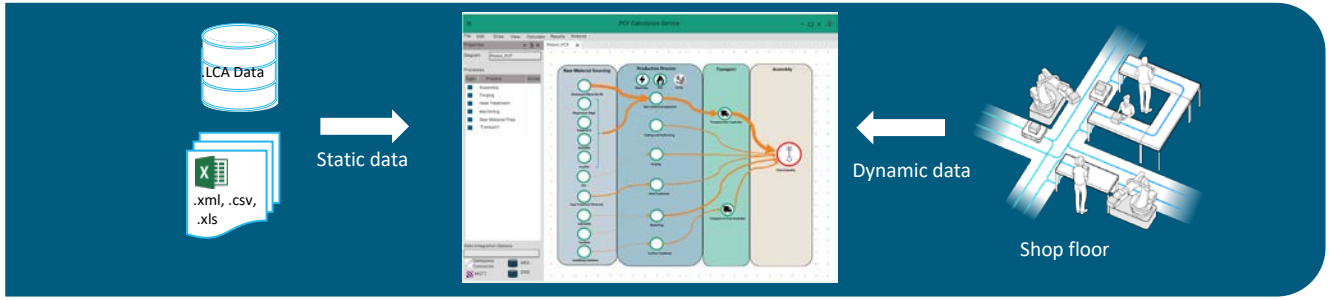
Step 1: Create Model

- Defines the structure and parameters of the PCF model



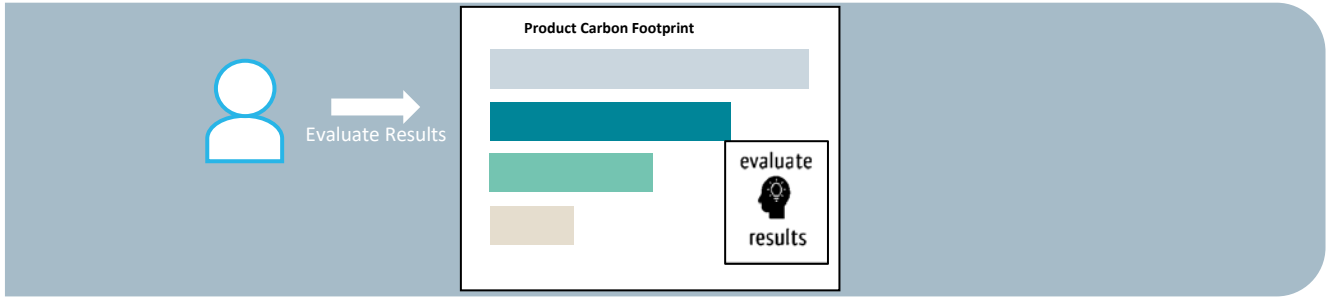
Step 2: Insert Data

- Inputs static data from LCA database
- Collects dynamic data from shopfloor



Step 3: Evaluate Results

- Interpret insights and make data-driven decisions based on outcome

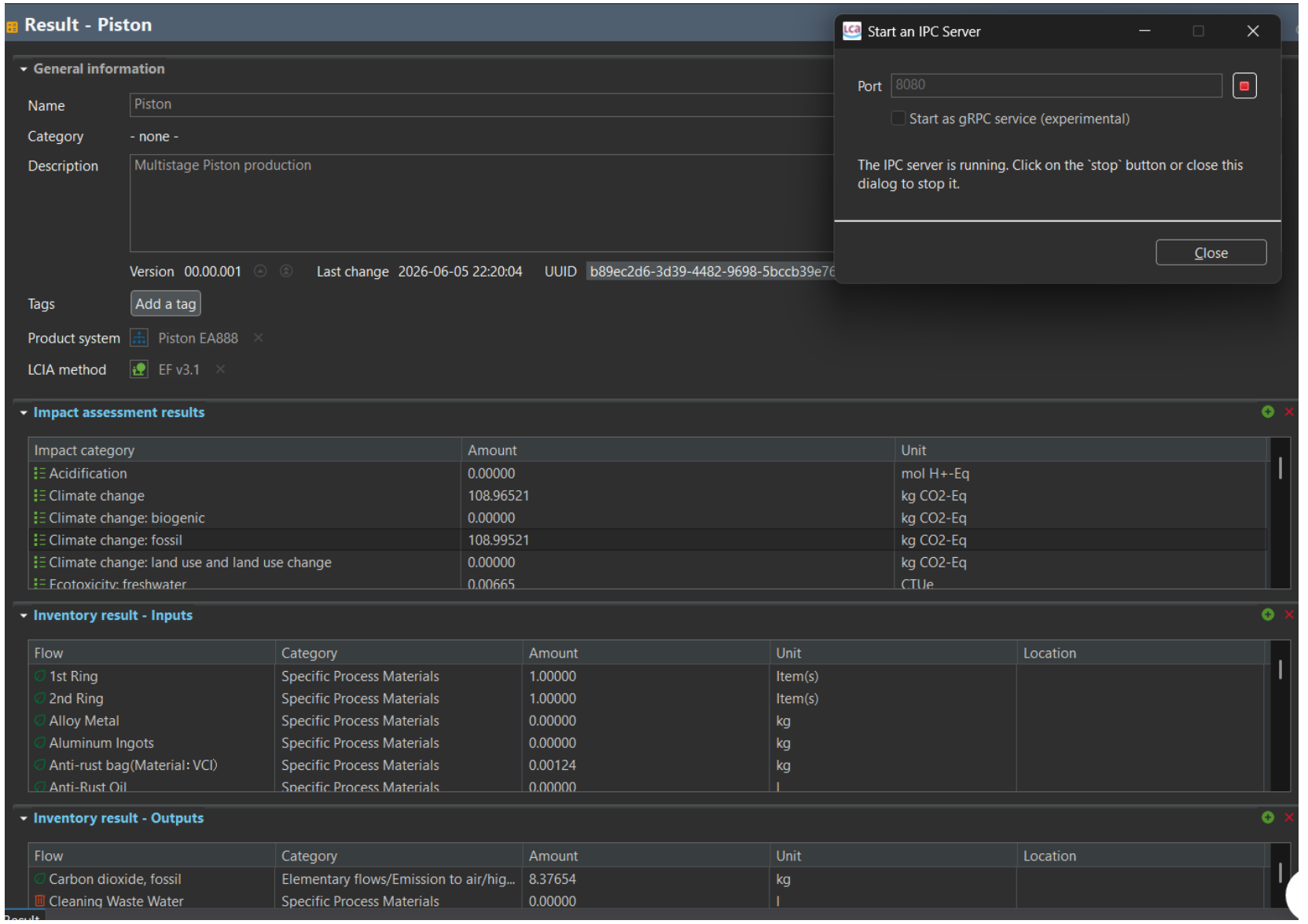


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Results

Dynamic PCF workflow

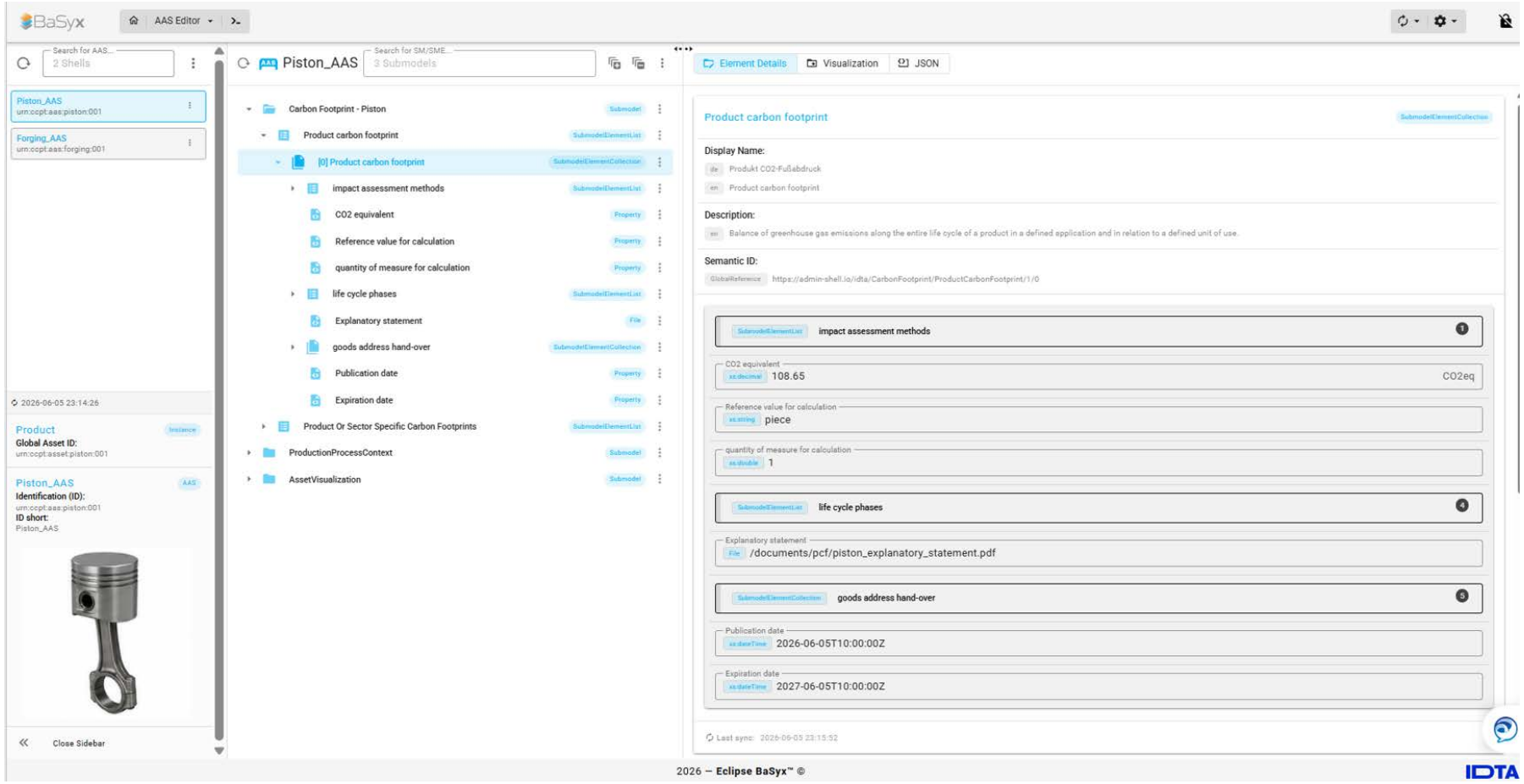
Production-related input data is retrieved by the backend, mapped to the LCA model, and used to trigger openLCA calculation via IPC.



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Results

AAS-based PCF representation



Calculated PCF results are transformed into AAS Carbon Footprint Submodels with contextual metadata such as boundary, timestamp, calculation method and reference quantity.

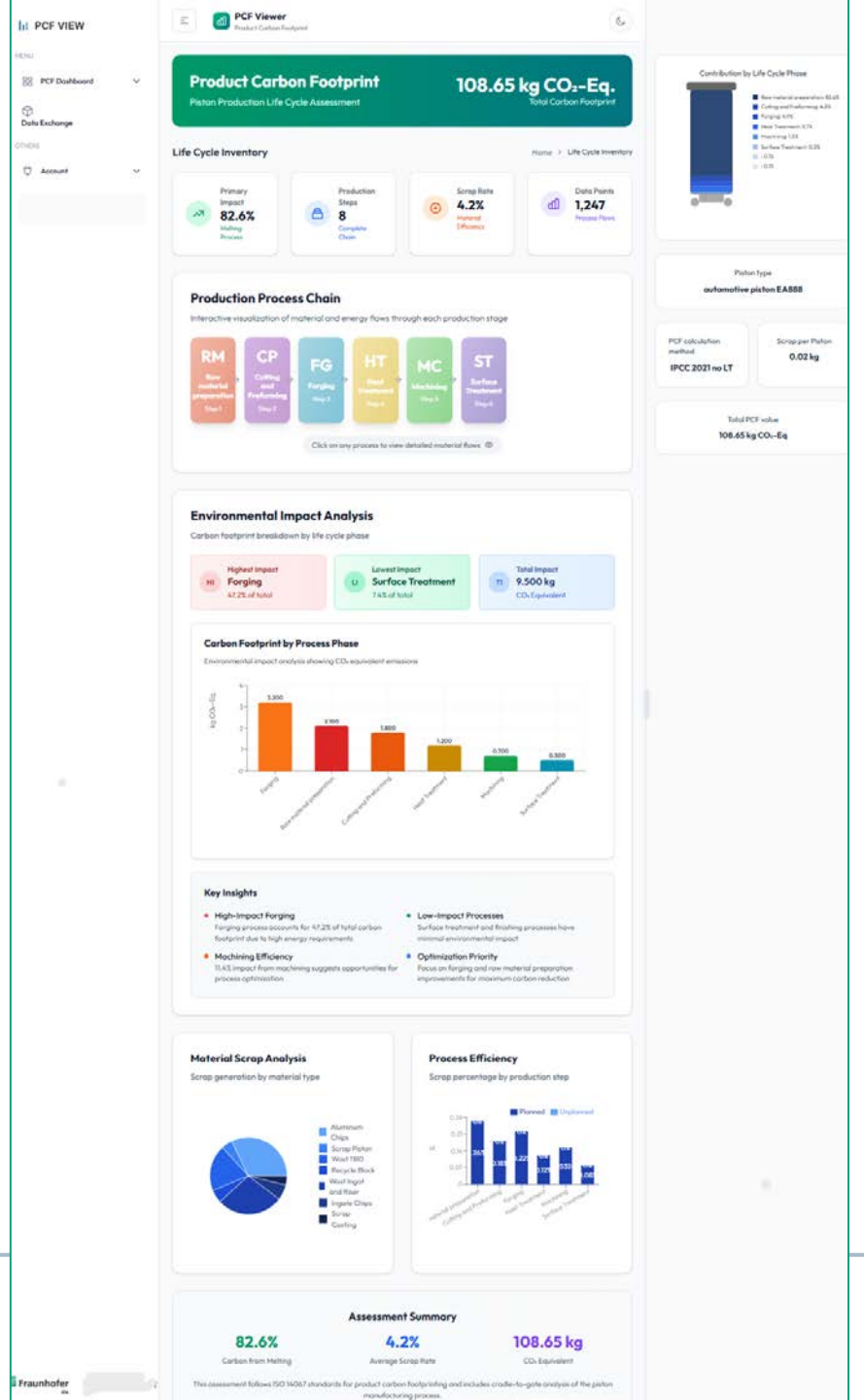
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Result

PCF User Interface

- Displays product-level PCF and process contributions
- Highlights emission hotspots and scrap generation
- Updates automatically after backend recalculation
- Supports production and sustainability decisions

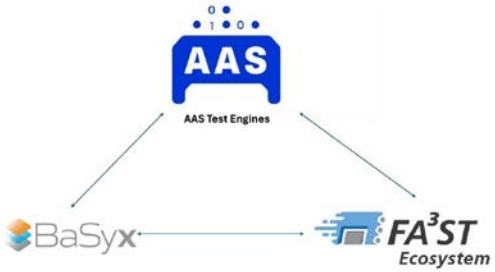
Key result: Dynamic PCF data becomes directly usable through the dashboard.

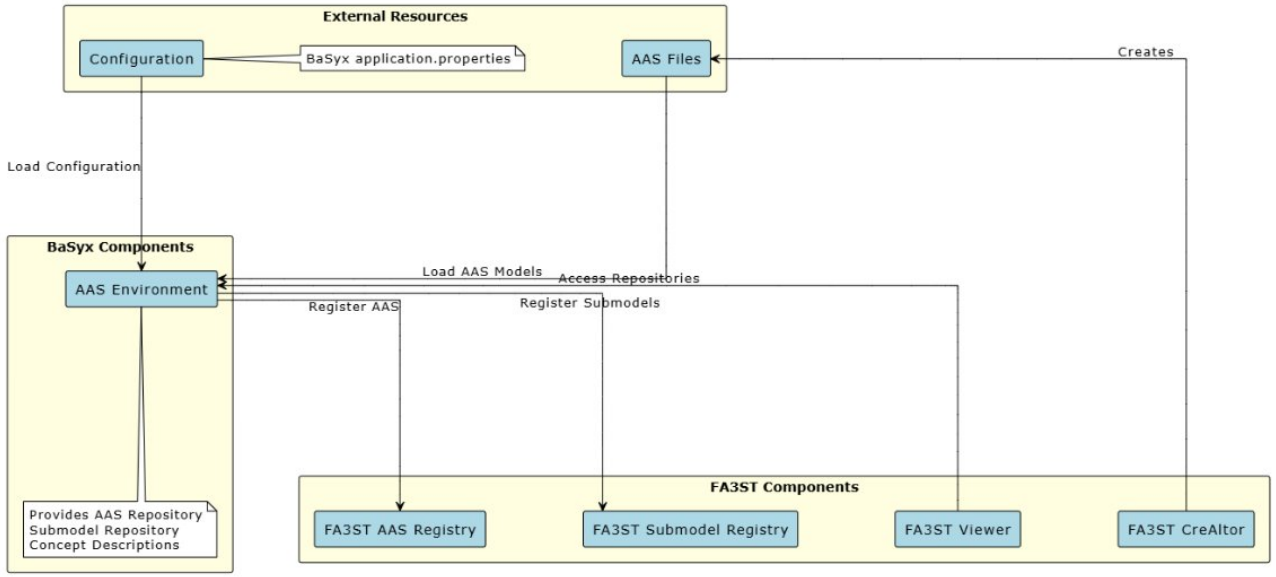


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Results

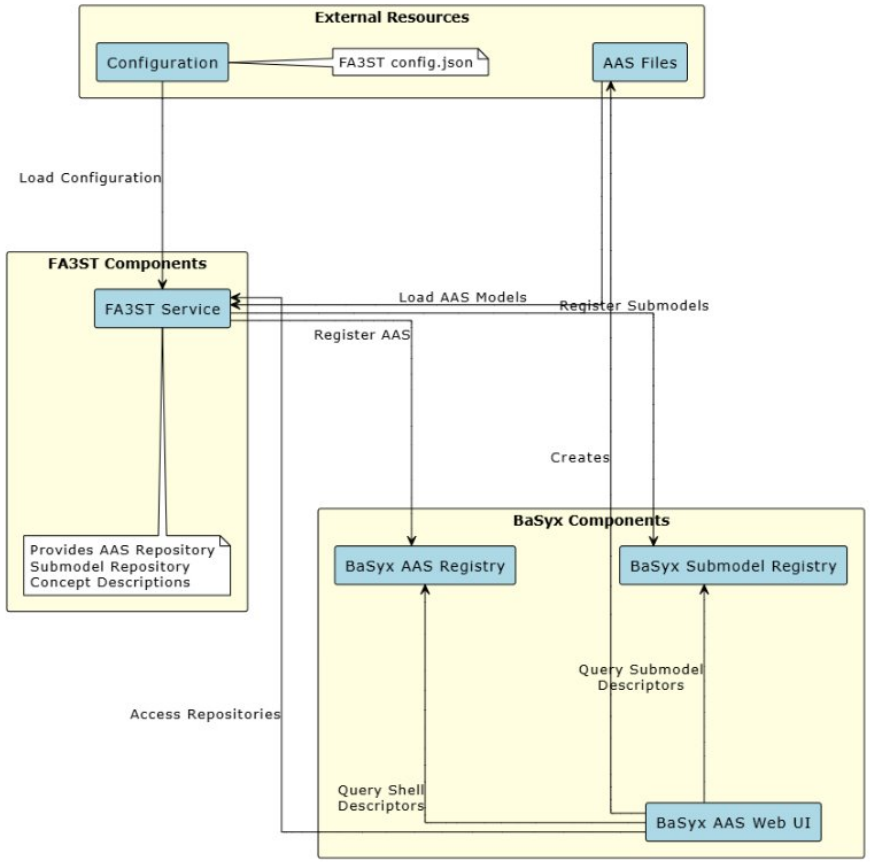
Cross-implementation interoperability





Configuration 1 system architecture:

BaSyx components are used for the *hosting* and *usage* phases, while FA³ST components are used for *creation*, *registration*, and *visualization*.



Configuration 2 system architecture:

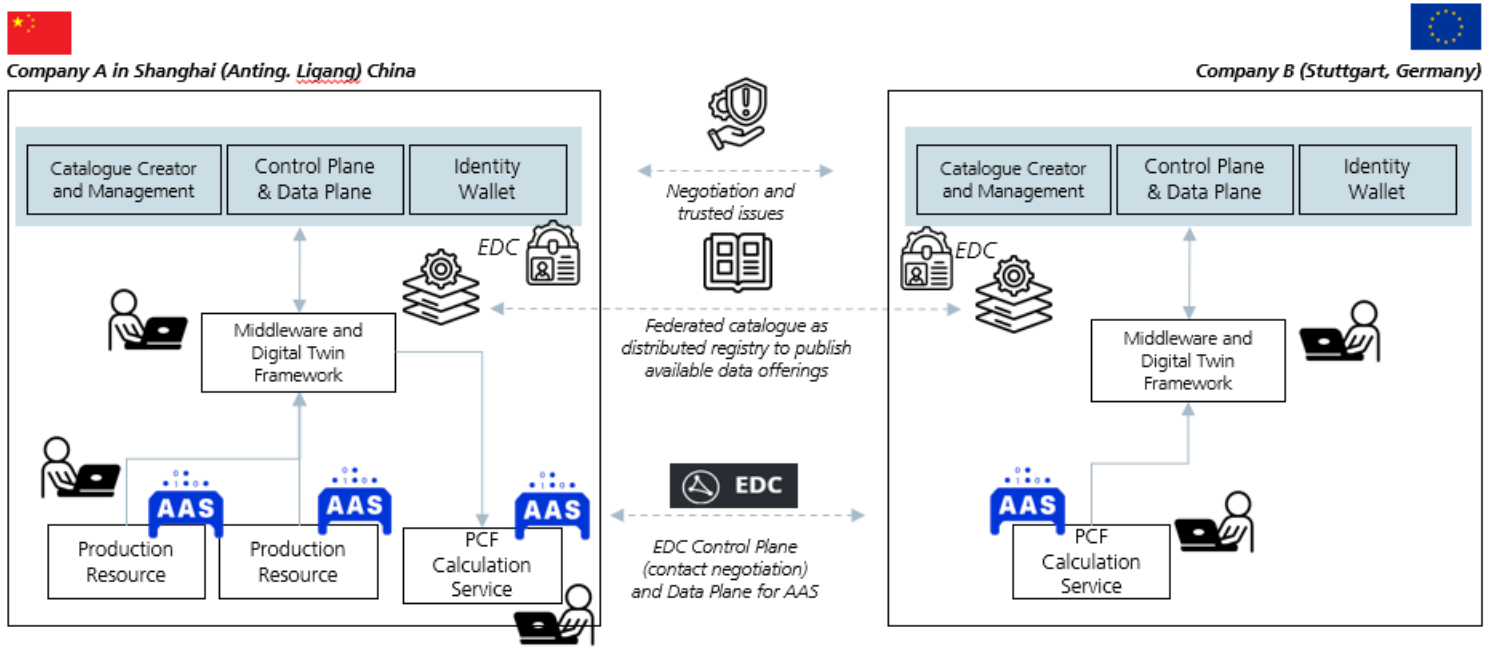
FA³ST components are used for the *hosting* and *usage* phases, while BaSyx components are used for *creation*, *registration*, and *visualization*.

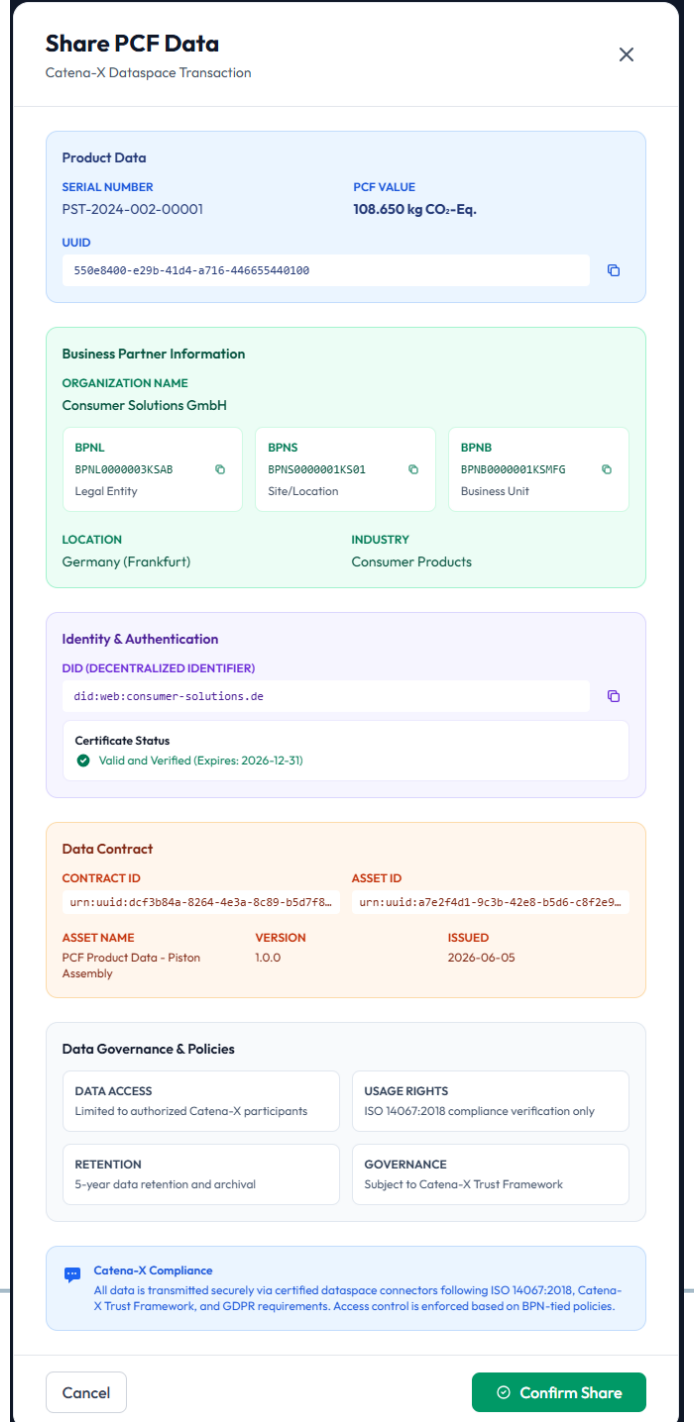
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Results

Sovereign Data Space exchange

PCF information was exposed as an EDC data asset and accessed through catalogue discovery, contract negotiation and controlled data transfer.





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Conclusion and Outlook

Main contribution

A modular architecture for dynamically updated PCF integration using production data, openLCA, AAS-based digital twins and EDC-based Data Spaces.

Scientific relevance

The work shows how sustainability data can move from static LCA reports toward machine-readable, updateable and sovereignly exchangeable industrial data assets.

Practical relevance

The architecture supports supplier-customer PCF exchange without centralizing data ownership or exposing unrelated production data.

Future work

Validate with measured shop-floor data, extend policy templates, scale to multi-tier value networks, and apply the same Data Space architecture to quality data and AI training data.

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Thank You

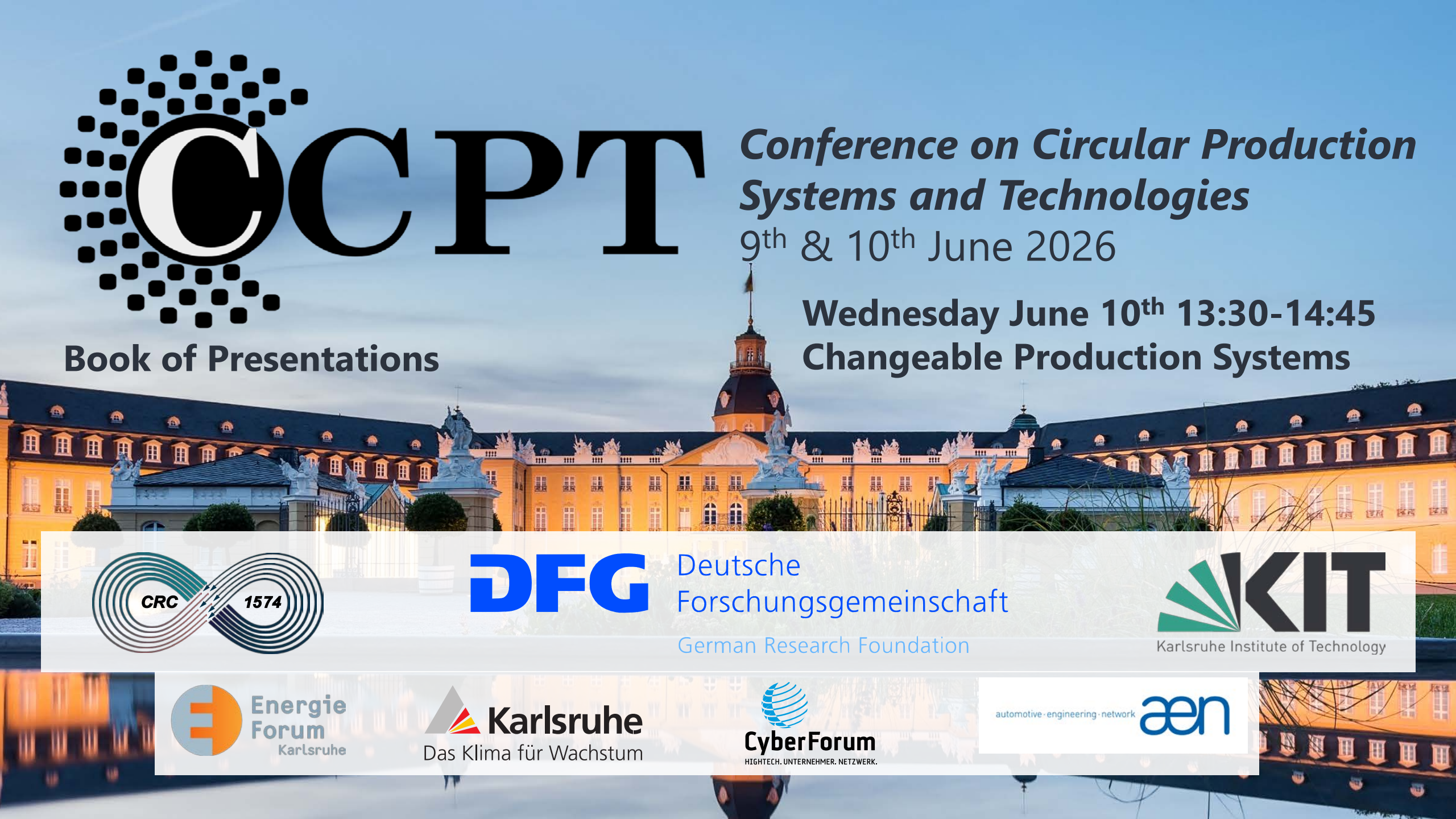
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CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 13:30-14:45
Changeable Production Systems

CRC 1574

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German Research Foundation

KIT Karlsruhe Institute of Technology

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CyberForum HIGHTECH. UNTERNEHMER. NETZWERK.

automotive · engineering · network aen

Bridging Heuristics and Optimality

Integrating Exact Batch Optimization into Auction Mechanisms for Multi-Robot Task Allocation

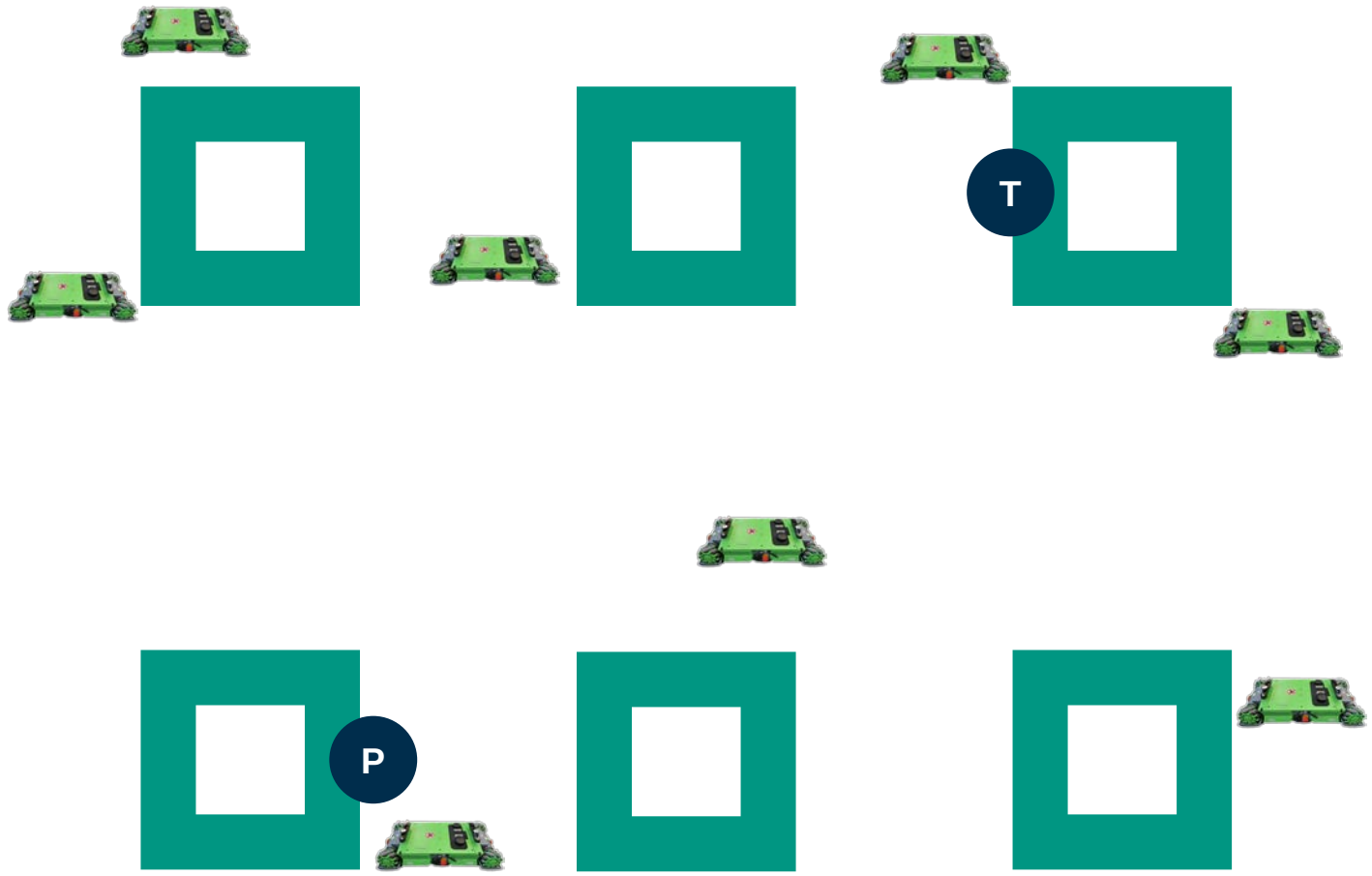


Adrian Vallejo König, Alexander Ernst, Zäzilia Seibold
10.06.2026

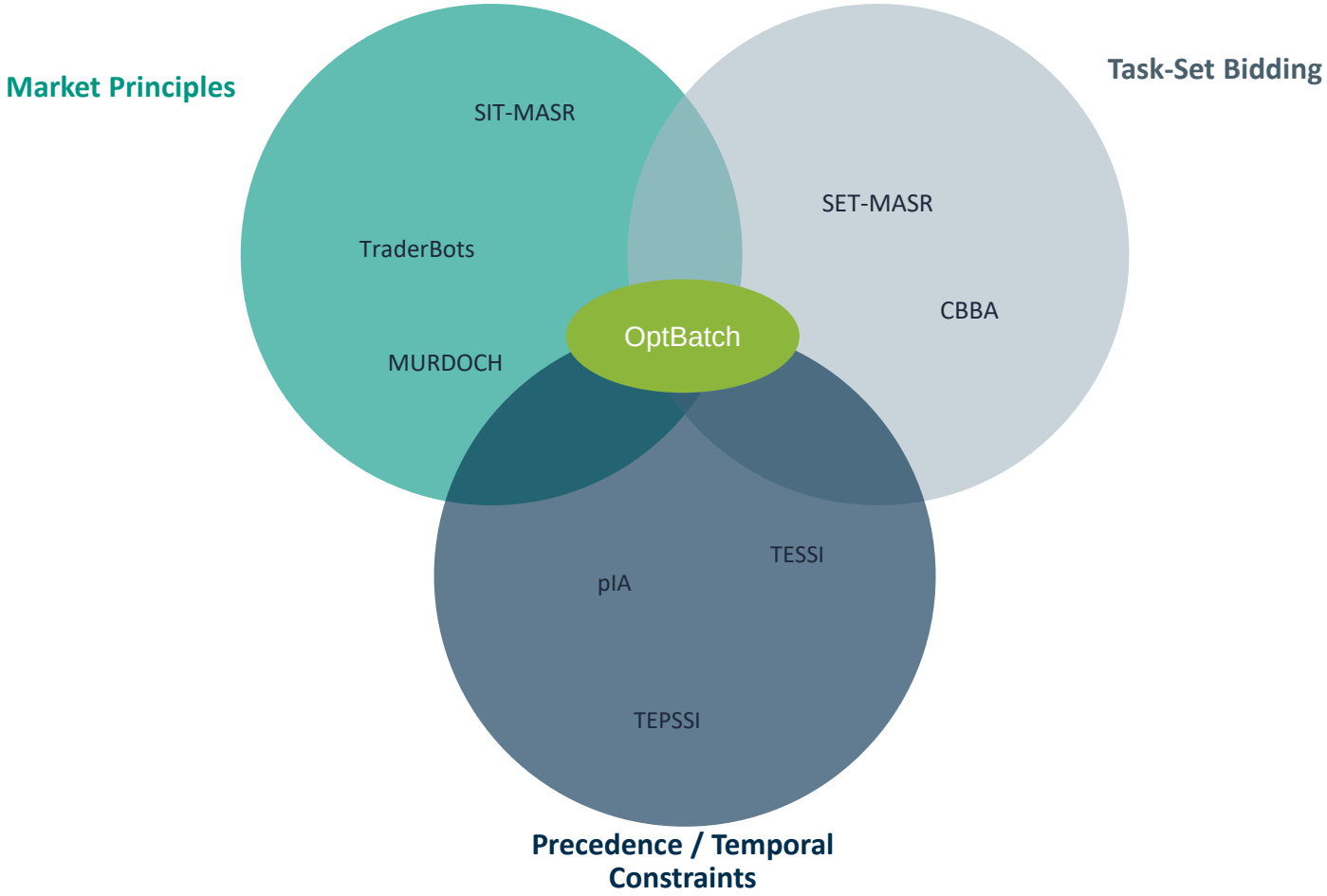
Multi-Robot Task Allocation in Logistics

Which robot performs which task?

- Given is a set of tasks
- Given is a set of robots
- One task must be performed by one robot
- A robot can only perform one task at a time
- A valid solution exists when all tasks are distributed between the different robots and no constraints are broken
- Our target is to minimize the makespan

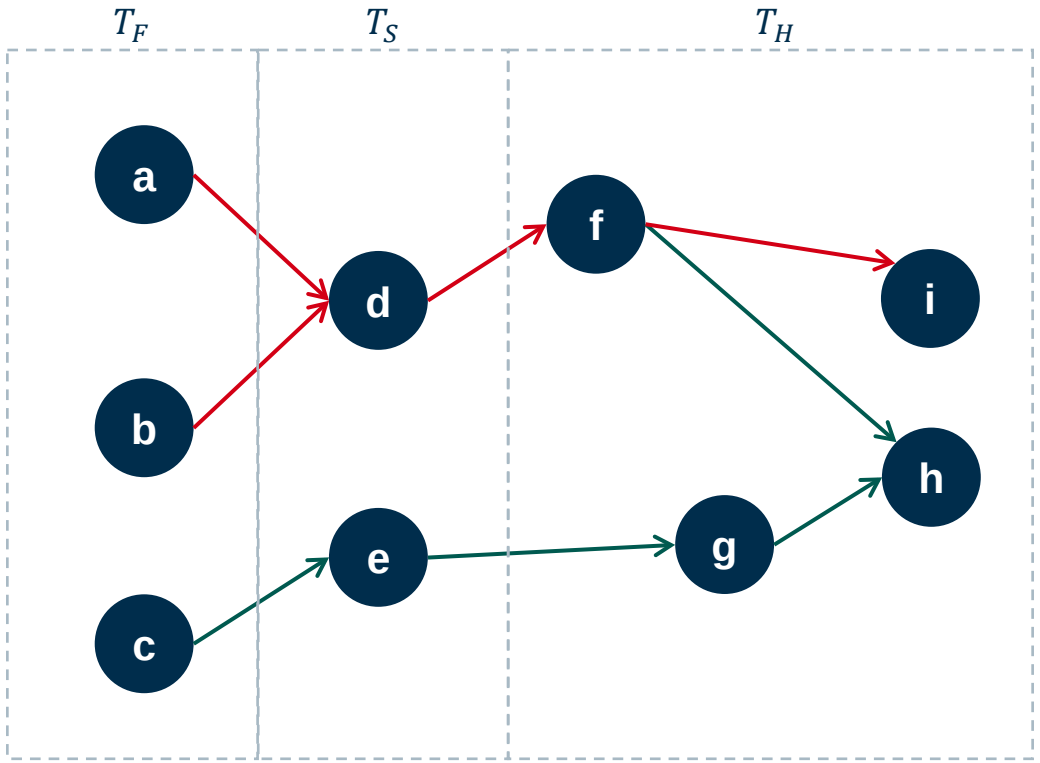


Our Work Combines Market Principles, Task-Set Bidding and Precedence Constraints



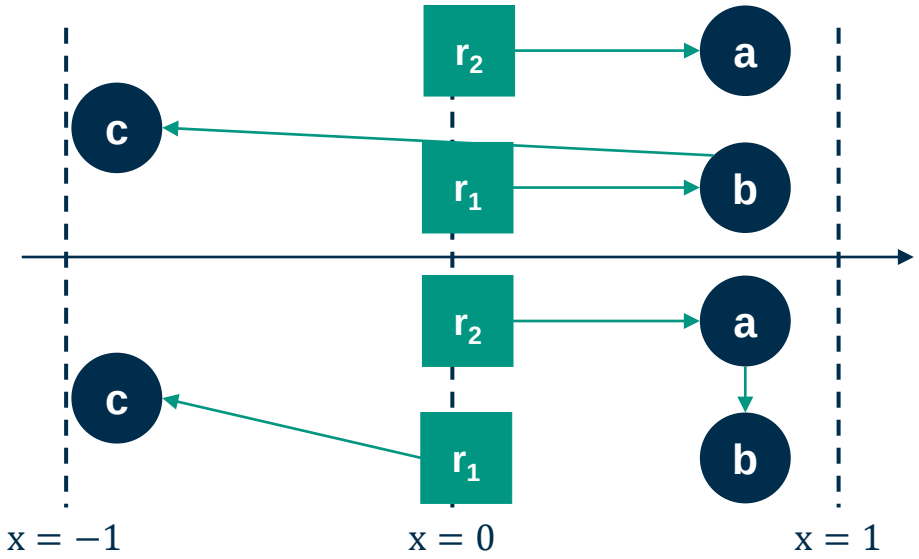
Precedence-aware auctions are usually greedy within each batch, bundle auctions rarely provide exact optimal results during winner determination.

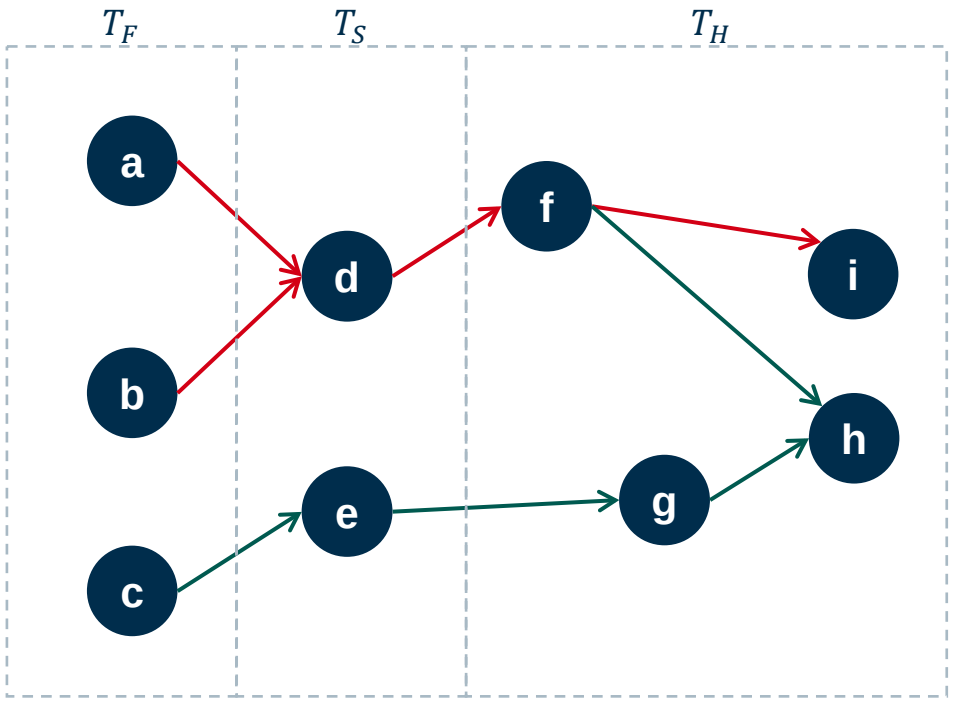
The „Iterated Auction with Prioritization“ (pIA) Creates a Way to Auction Tasks with Precedence Constraints



McIntire et al. (2016)

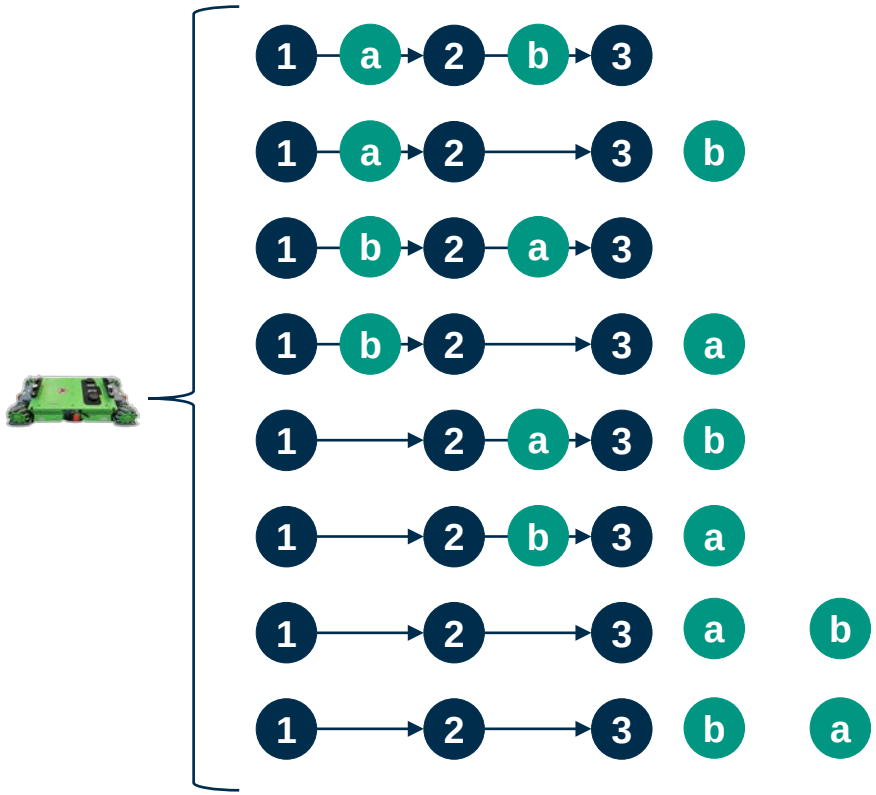
pIA is Agnostic to Synergy and Bundling Effects

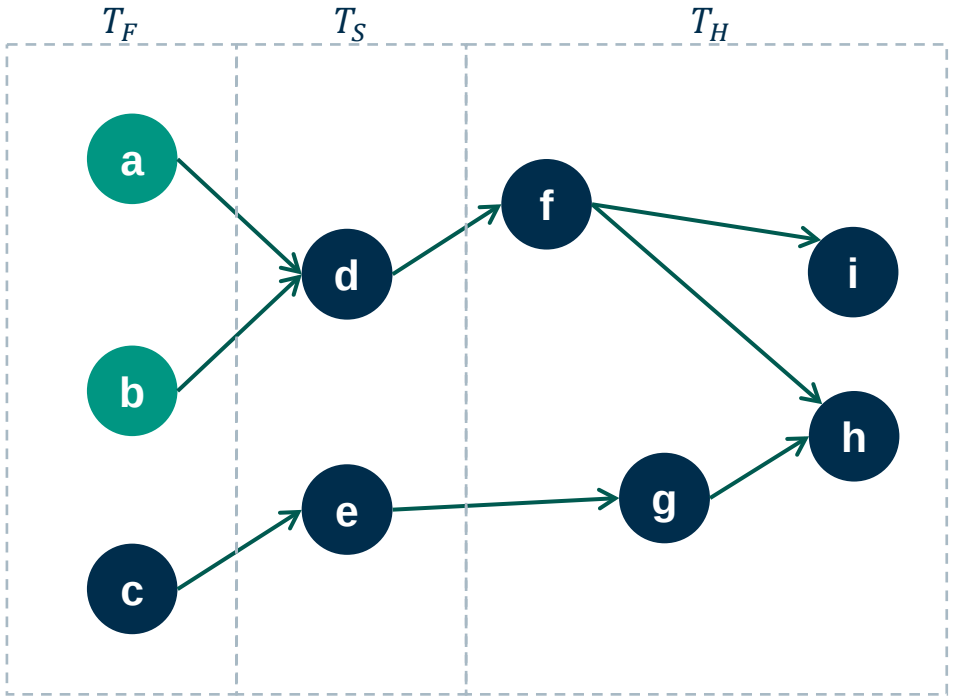




McIntire et al. (2016)

Respecting Synergies Between Tasks Becomes a Challenge in Decentralized Systems with a Rising Number of Tasks

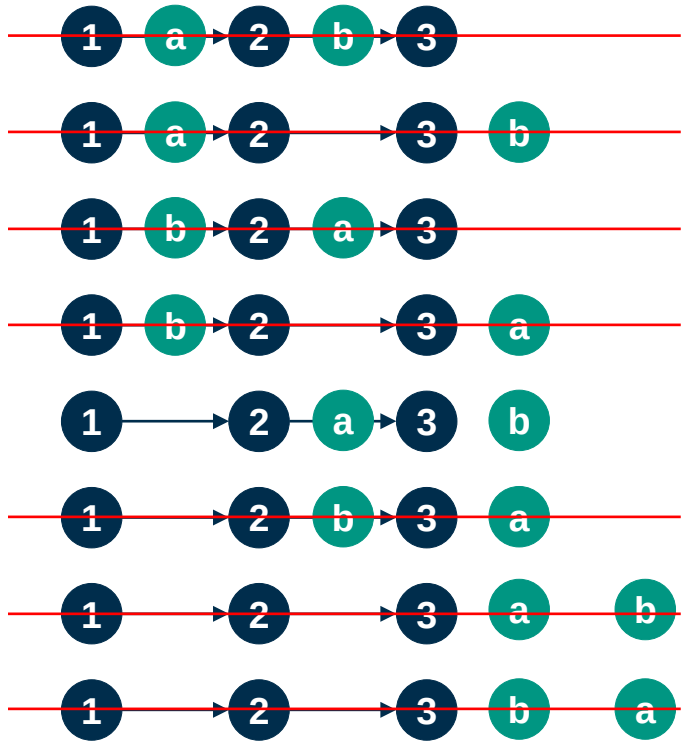




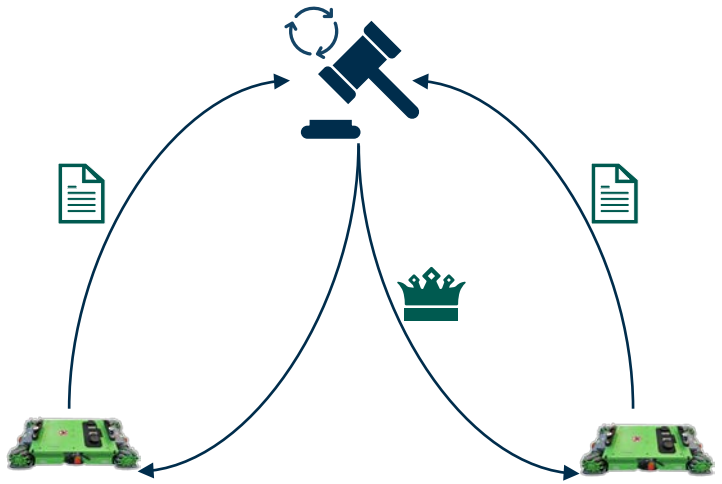
x Previously Scheduled Tasks

OptBatch Consist of a Local and a Global Algorithm

Local Algorithm (1)



Global Algorithm (2)



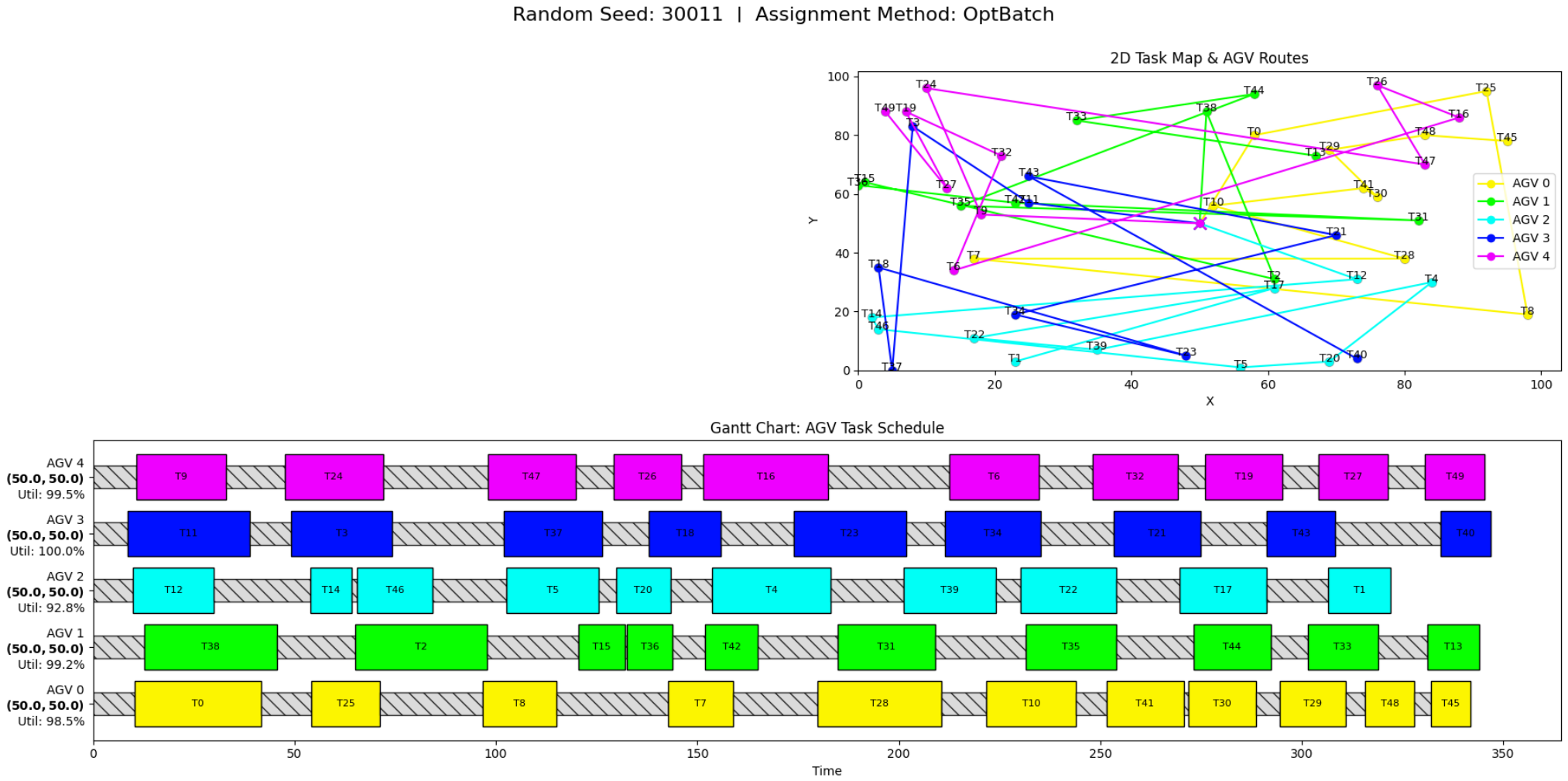
Algorithm 1 AGV.ComputeBids

Require: Batch T_{Auct}, Precedence-Array PC
Ensure: Bid set $B_r = \{(S, m_S, r_i)\}$
$B_r \leftarrow \emptyset$
for all non-empty subsets $S \subseteq T_{Auct}$ **do**
  $(\pi_S, m_S) \leftarrow$ SOLVEINSERTILP(current plan, S, PC)
  $B_r \leftarrow B_r \cup \{(S, m_S, r_i)\}$
end for
return B_r ▷ Communicate all bids to auctioneer

Algorithm 2 Auctioneer: Batch Processing

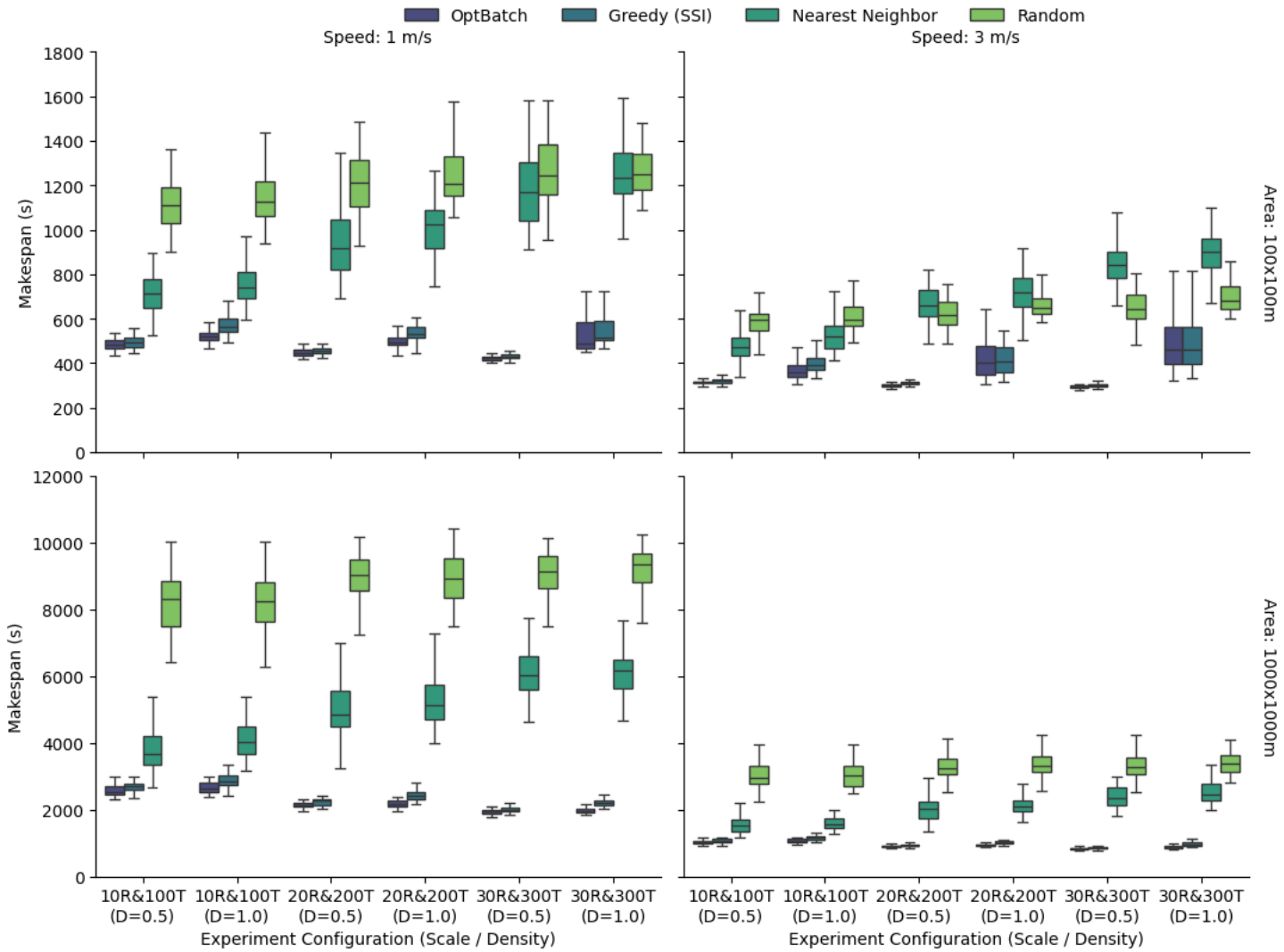
Require: Batch T_{Auct}, Precedence-Array PC, Robot List R
Ensure: Optimal task allocation W
$\mathcal{B} \leftarrow \emptyset$
for all $r \in R$ **do**
  $B_r \leftarrow r$.ComputeBids(T_{Auct}, PC) ▷ Communicate batch content, collect bids
  $\mathcal{B} \leftarrow \mathcal{B} \cup B_r$ ▷ Aggregate into global bid table
end for
Formulate Bundle-MILP using $\mathcal{B}$
Solve MILP → Winner list $\mathcal{W} = \{(r, S_r^*, m_{S_r^*})\}$
for all $(r, S_r^*) \in \mathcal{W}$ **do**
  r.AcceptBundle(S_r^*) ▷ Communicate assignments
end for

Results

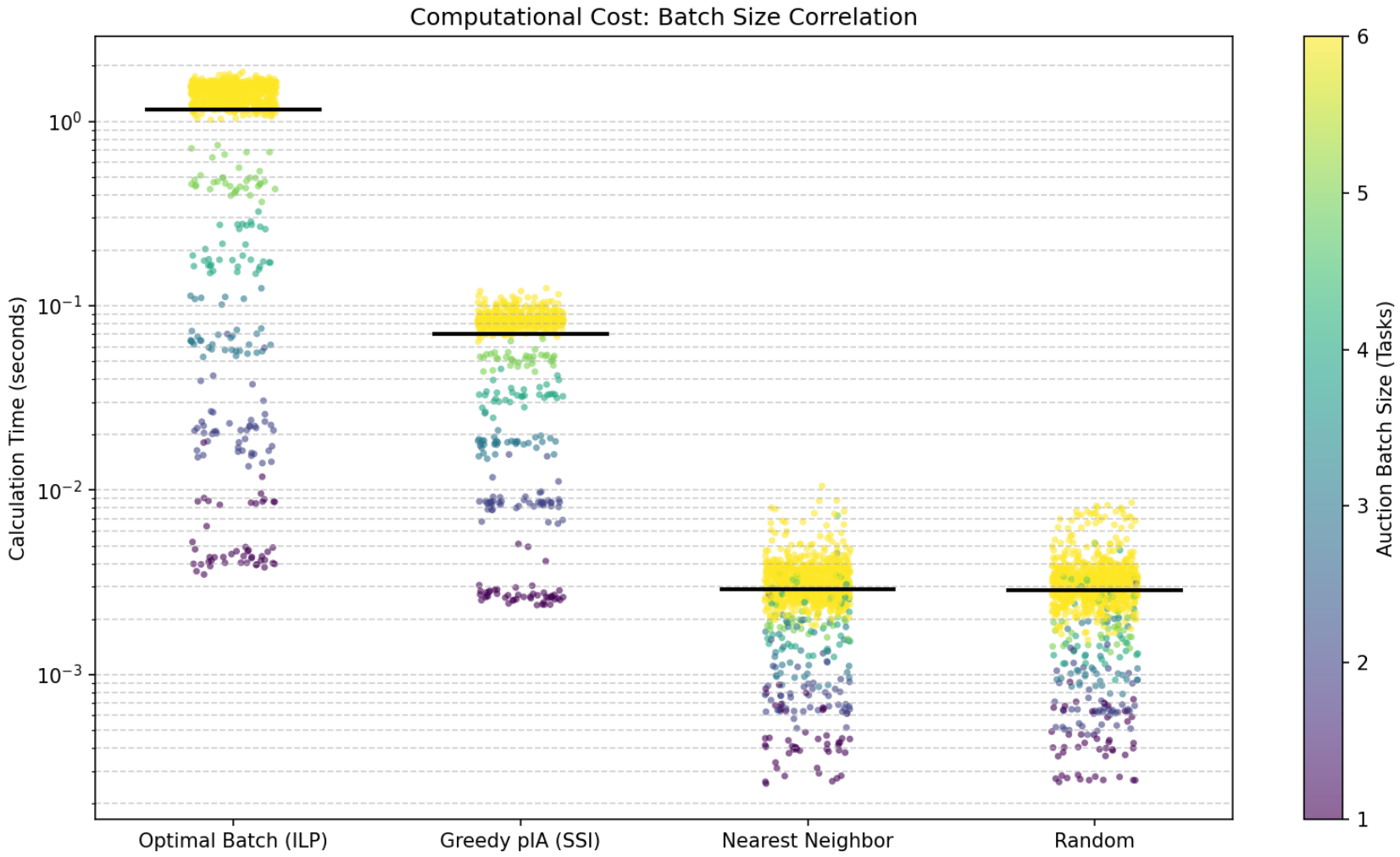


Method=1 (OptBatch, pIA) | Tasks=50 | AvgLen=20 (CV=0.3) | Precedence Graph density: 0.5 (25 max edges) | Robots=5 (v=3) | Seed=30011 | Alpha=0.6

Results Continued



Results Continued





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Institute of Production Science

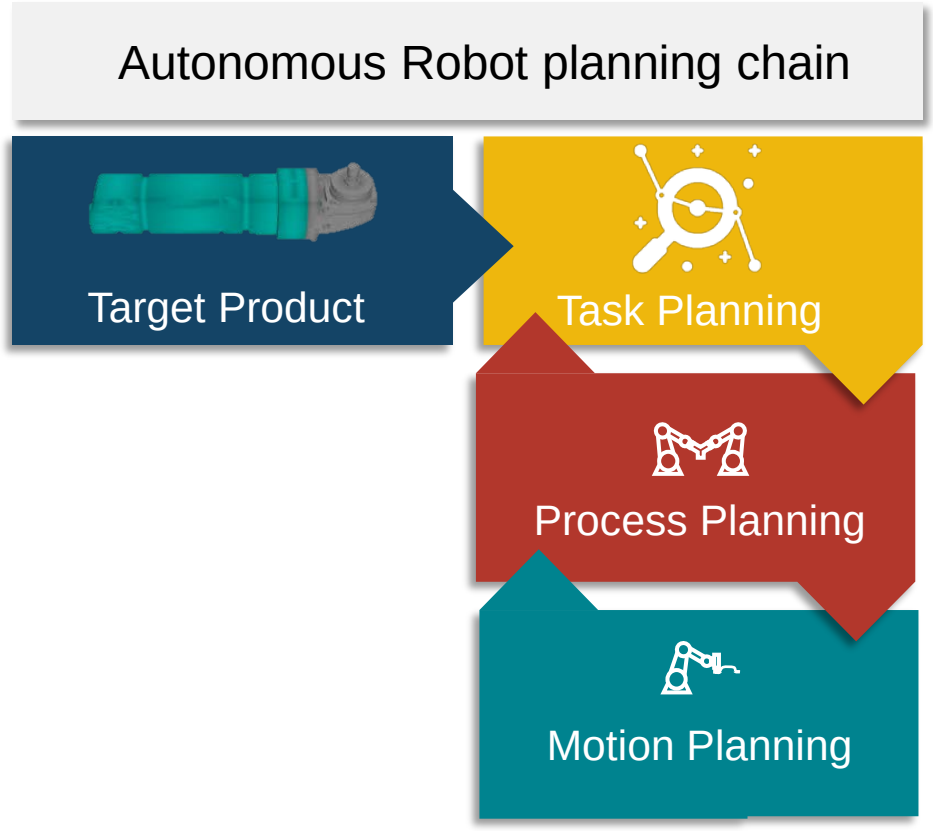
Process Design for Robotic Unscrewing: Sensor-Based Anomaly Handling in Circular Production

M. Goebels, G. Martel, E. Hoffmann, J. Baumgärtner, F. Oexle & J. Fleischer



Anomaly detection for robust circular production



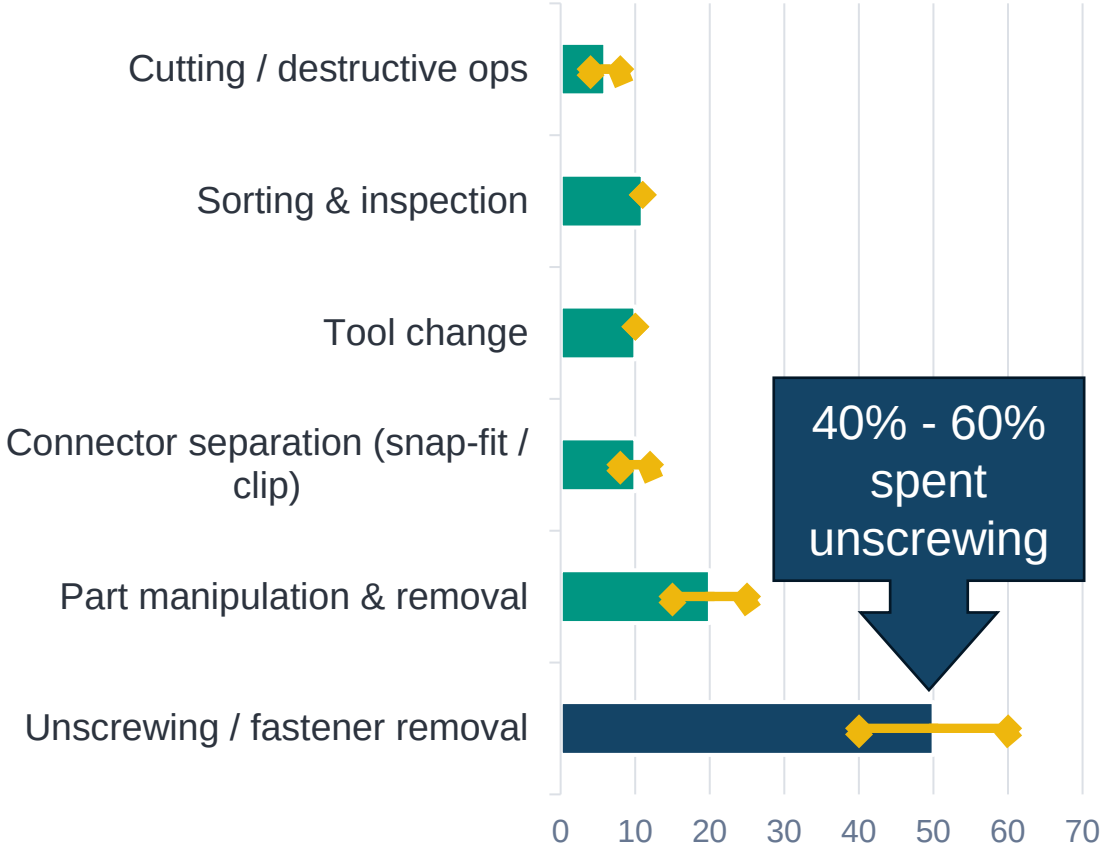


Robotic assembly is mature. End-of-Life **disassembly is unsolved** due to uncertain products.

Baumgärtner – From CAD to POMDP

The Challenge of EOL Disassembly

Disassembly Time in %



Uncertain Condition



Sources: Zhou et al. 2022 (operation count); Ghazilla et al. 2014; Santochi et al. 2002 (CIRP Annals); Peeters et al. 2018 (Resource & Conservation Recycling). Bars show mid-range estimates; error bars show reported ranges.

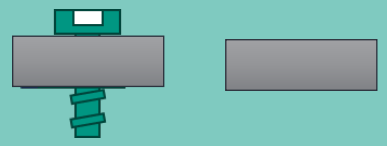
The Eight Failure Modes

Failure Mode Analysis

Consolidated from power-tool fleet data + Würth Masterservice remanufacturing interviews

Proceed normally

Intact Screw | Missing Screw

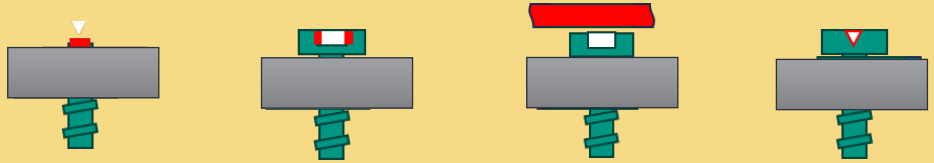


Screw missing



Apply recovery

Missing Head | Rounded Head | Occluded Head | Wrong Type



Missing head



Destructive disassembly

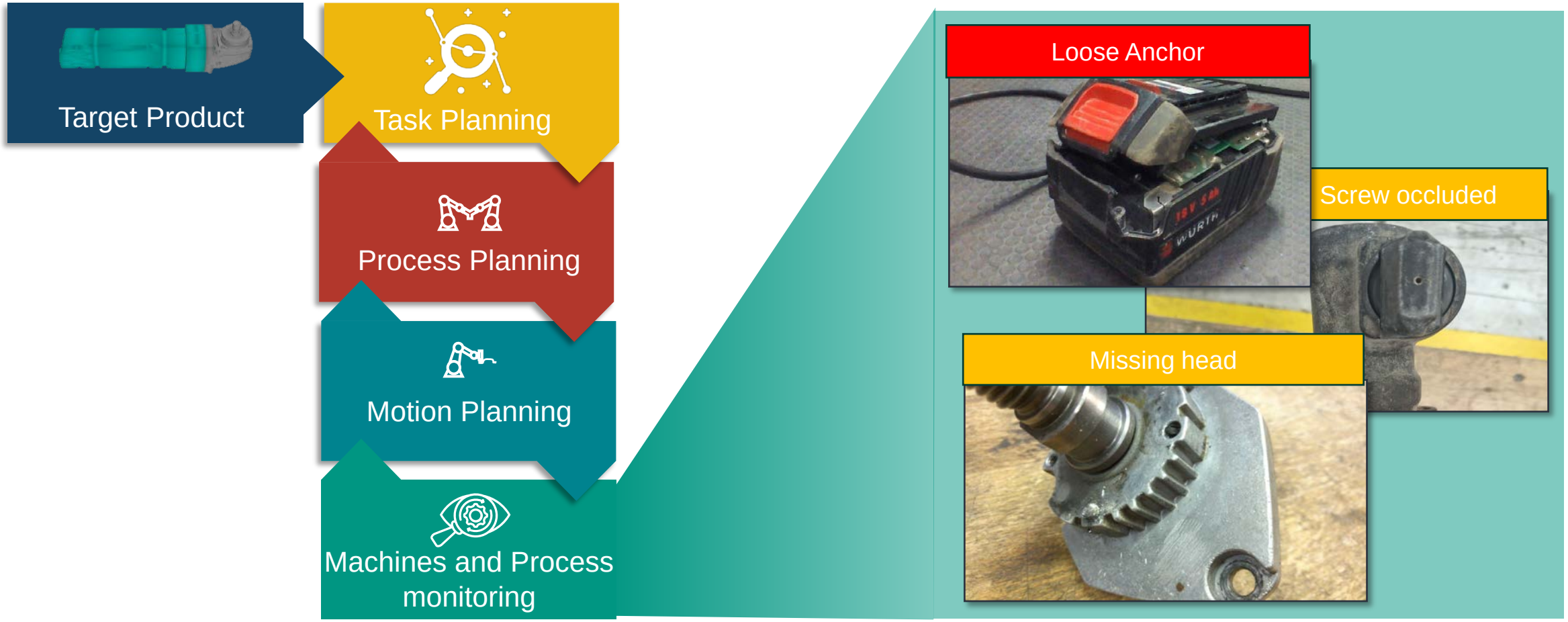
Loose Anchor | Stuck Screw



Loose Anchor



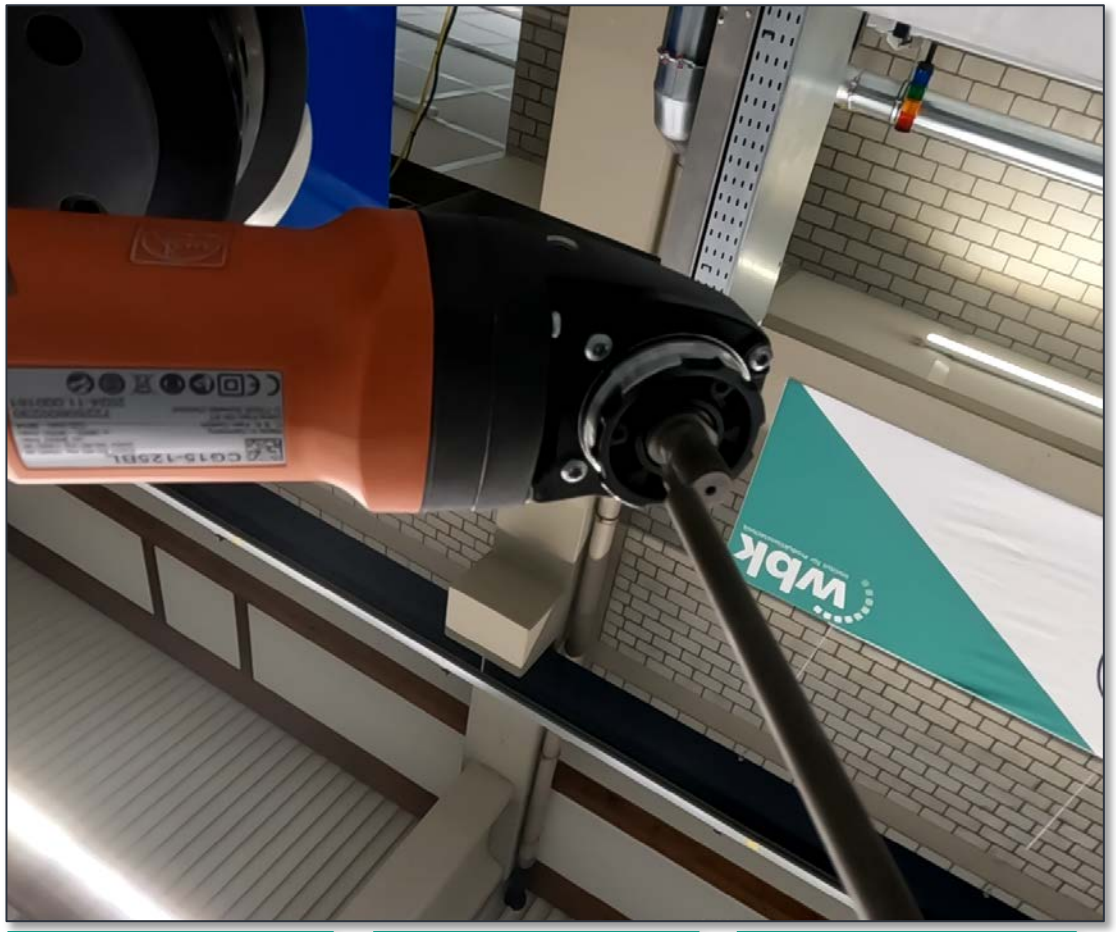
Anomaly detection for robotic unscrewing



Baumgärtner – From CAD to POMDP, Fotos: Jürgen Heim, Würth (2025), https://www.wuerth-ag.ch/de/ch/solutions/service?service=24451&srsltid=AfmBOorgEcDzuQE307LSqUEFA8IraYNyhRSq0Md1PCR1H_ydz-HJTh07

Robotic unscrewing in Industry

What does the process look like?



Approach → Formfit → Disassembly

WEBER SEV-P10 Screwdriver



Max. Torque

Failure Modes and their Signals

Failure Mode	Missing Screw	Intact Screw	Missing Head	Occluded Head	Rounded Head	Wrong Type	Loose Anchor	Stuck Screw
Form-fit torque	X		X		X	X		
Loose torque			X					X
Dynamic torque			X			X		

Relevant Signals – already used

Needs **position**

Needs **axial force**

3 failure modes are **not classifiable** by the current process.

How is the process designed?

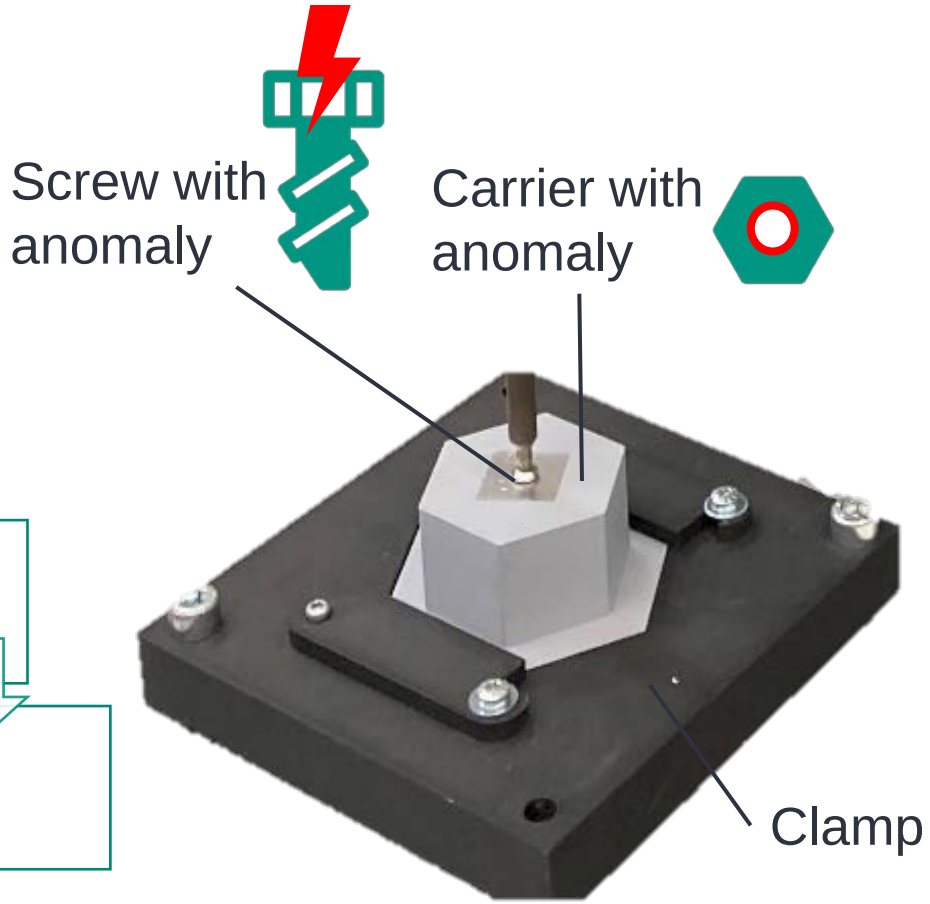
Identified relevant **screw failure modes**

Designed **test pieces** to reproduce failure modes

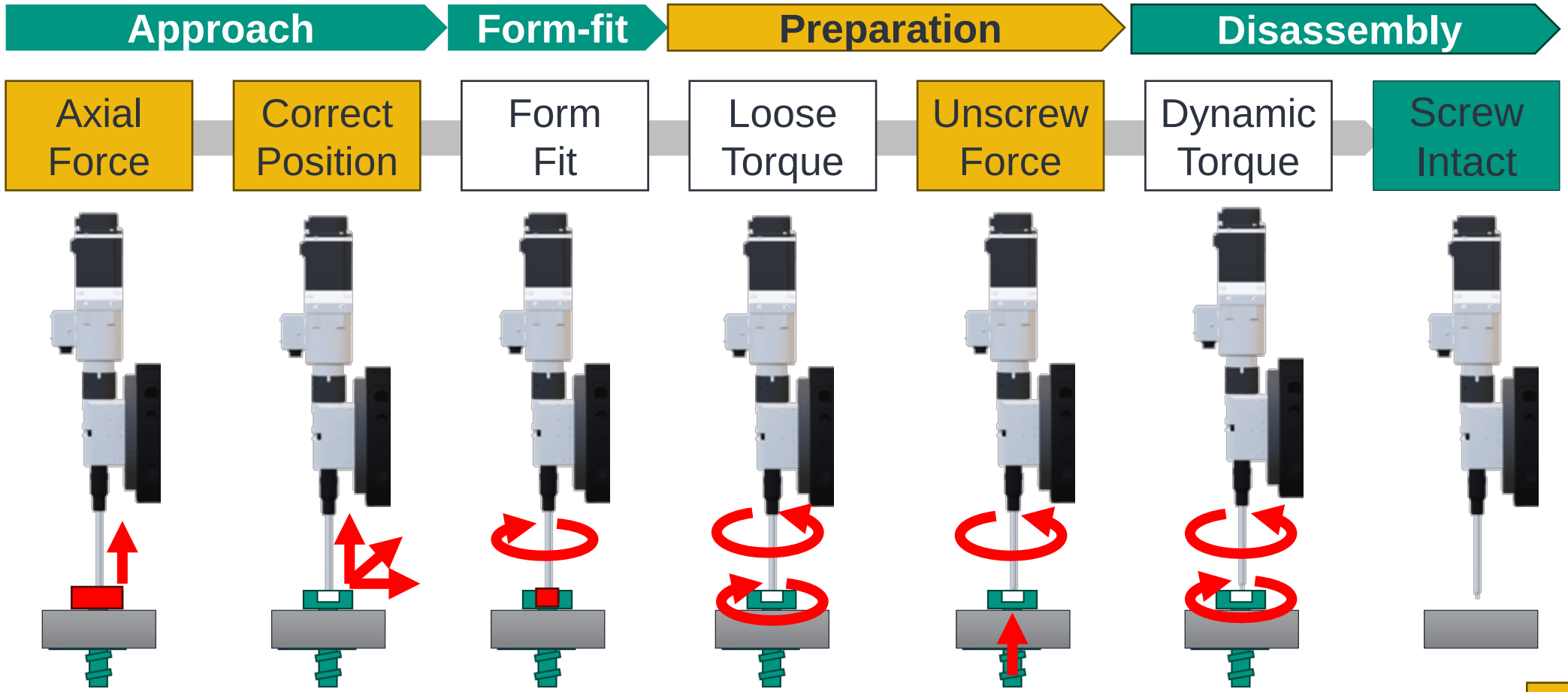
Defined **sensor** requirements and signal set

Developed **unscrewing process** for anomaly detection

Conducted **robustness** experiments on failure cases and tuned parameters



Redesigned Four-Phase Process



Multimodal Sensing & Decision Tree

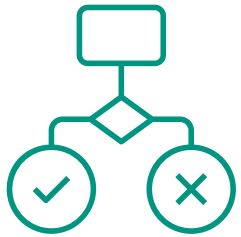
Process



8 Parameters

- axial force (3x min)
- Position (min, max)
- Form-fit torque (min)
- Loose torque (max)
- Dynamic torque (max)

Decision tree



Decision



8 Failure Modes

Validation Approach

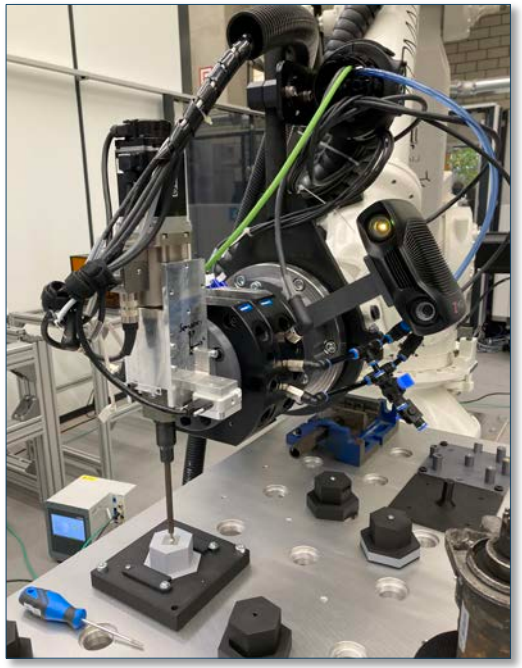
Validation

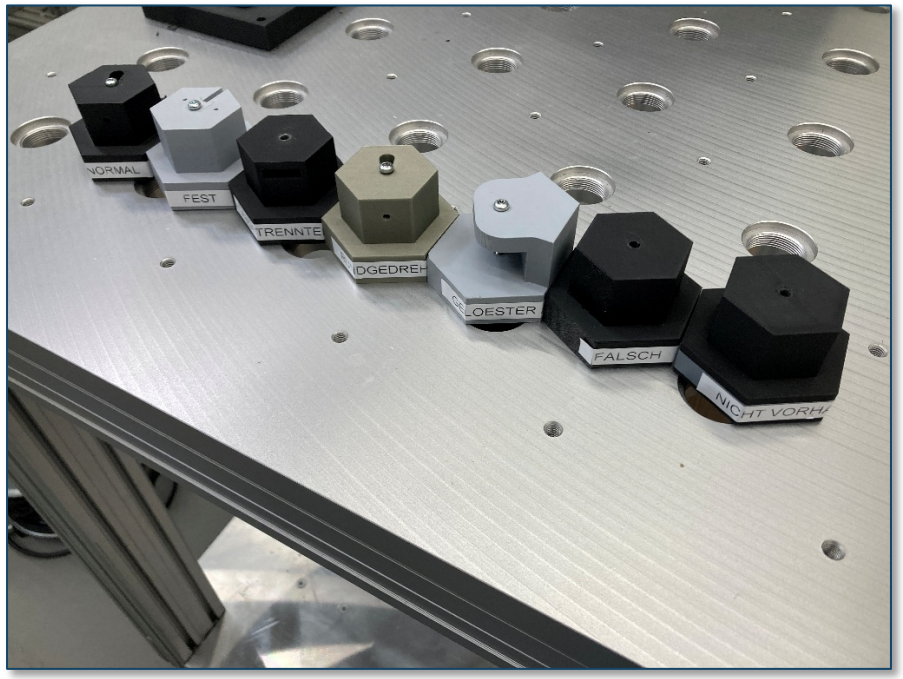
1 · Domain-specific — each failure mode in isolation

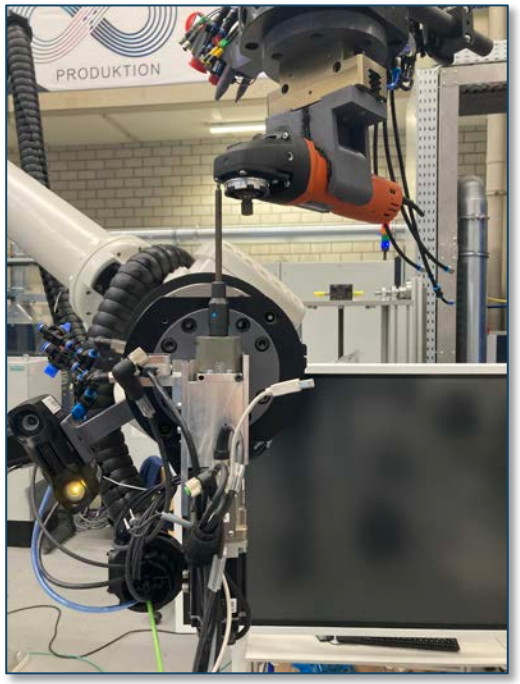
- 3D-printed test specimens with threaded inserts
- Each of the 8 modes tested 35 times

2 · System-level — full pipeline on a real device

- Fein CG15 angle grinder: Torx15 / Torx20, M4 screws
- Outcomes scored via confusion matrix







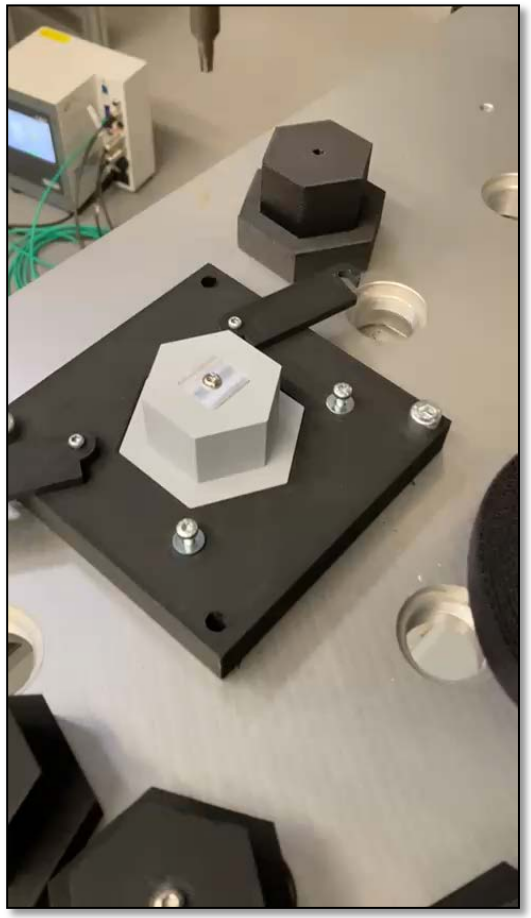
Results

Validation

Anomaly	Detected
Missing Screw	35/35
Screw Intact	35/35
Missing Head	35/35
Head Occluded	35/35
Rounded Head	**100/100**
Wrong Type	35/35
Loose Anchor	**100/100**
Stuck Screw	35/35

See here!

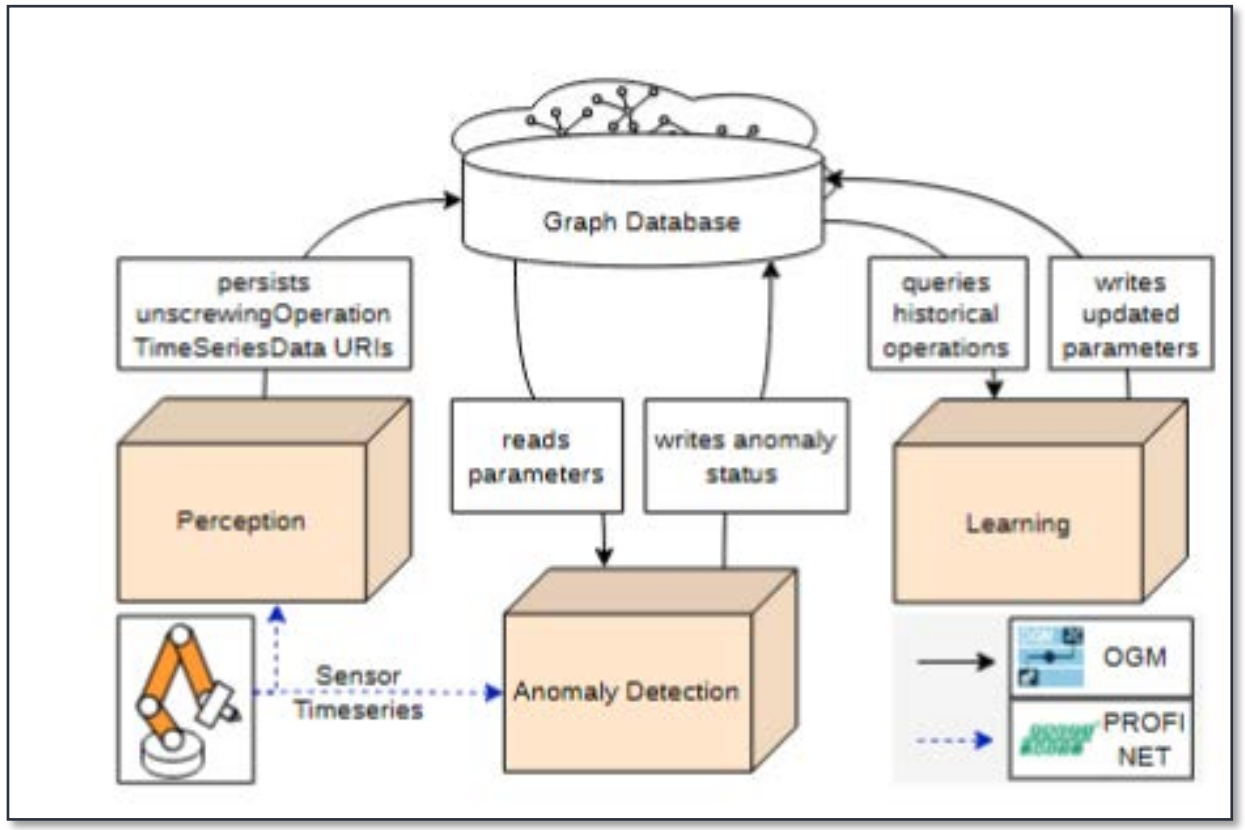
After parameter tuning



Perfect results are achievable, **IF parameters** are tuned correctly.

Integration into the Circular Factory

Knowledge-Graph Integration



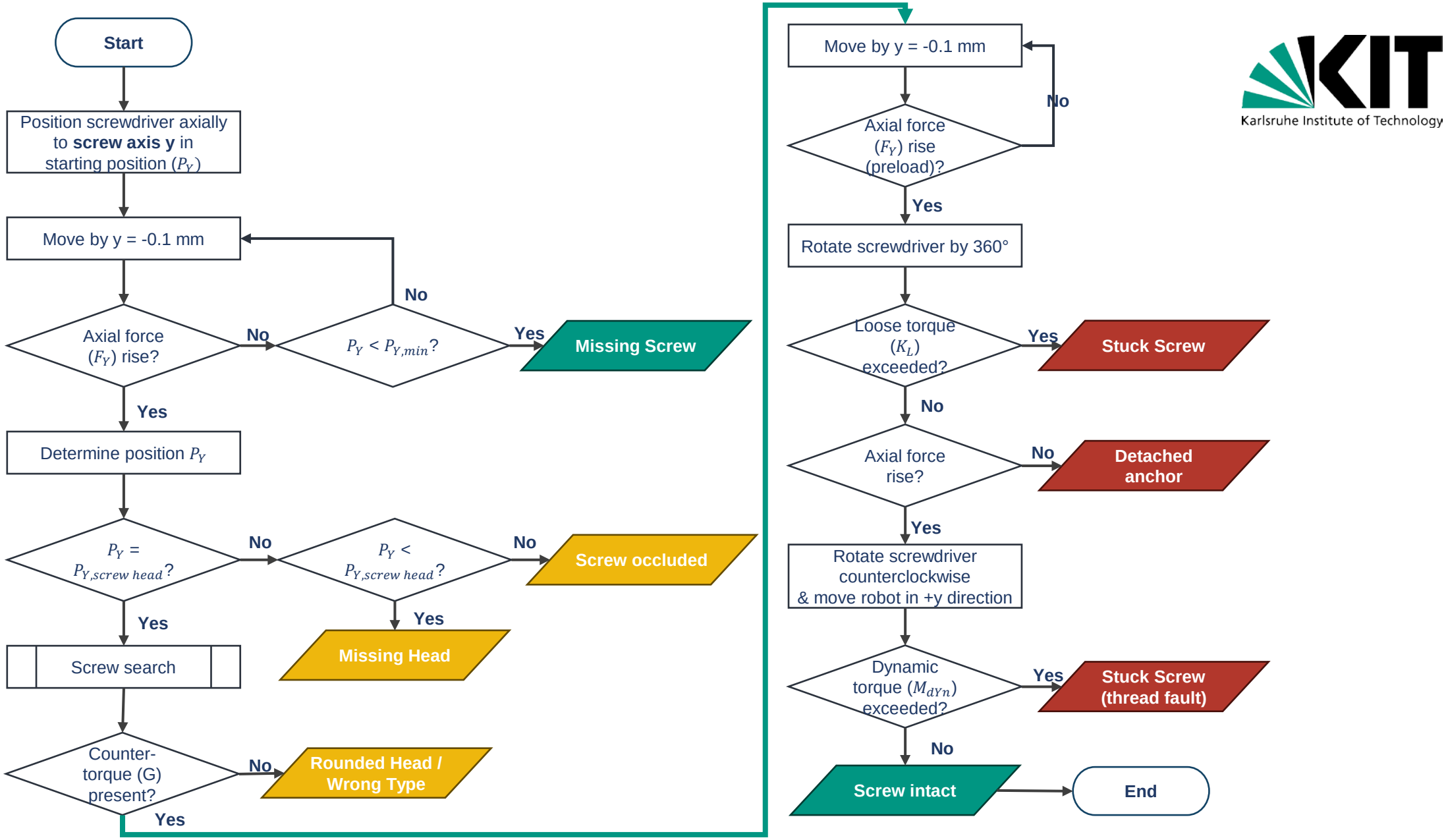
KAPPS: A knowledge-based CPPS Architecture for the Circular Factory

Screw parameters can **be learned and persisted** using knowledge graph architecture.

Thank you!



Questions?


Start
Position screwdriver axially to **screw axis y** in starting position (P_Y)
Move by y = -0.1 mm
Axial force (F_Y) rise?
No
$P_Y < P_{Y,min}$?
No
Yes
Missing Screw
Yes
Determine position P_Y
$P_Y = P_{Y,screw\ head}$?
No
$P_Y < P_{Y,screw\ head}$?
No
Screw occluded
Yes
Missing Head
Yes
Screw search
Counter-torque (G) present?
No
Rounded Head / Wrong Type
Yes
Move by y = -0.1 mm
No
Axial force (F_Y) rise (preload)?
Yes
Rotate screwdriver by 360°
Loose torque (K_L) exceeded?
Yes
Stuck Screw
No
Axial force rise?
No
Detached anchor
Yes
Rotate screwdriver counterclockwise & move robot in +y direction
Dynamic torque (M_{dYn}) exceeded?
Yes
Stuck Screw (thread fault)
No
Screw intact
End

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Capacity Planning for Circular Factories Using Mathematical Modeling

BECKER, HUNDEMER, BAIL , ENGELS, LANZA, GARTNER, STRICKER



CARDIFF UNIVERSITY

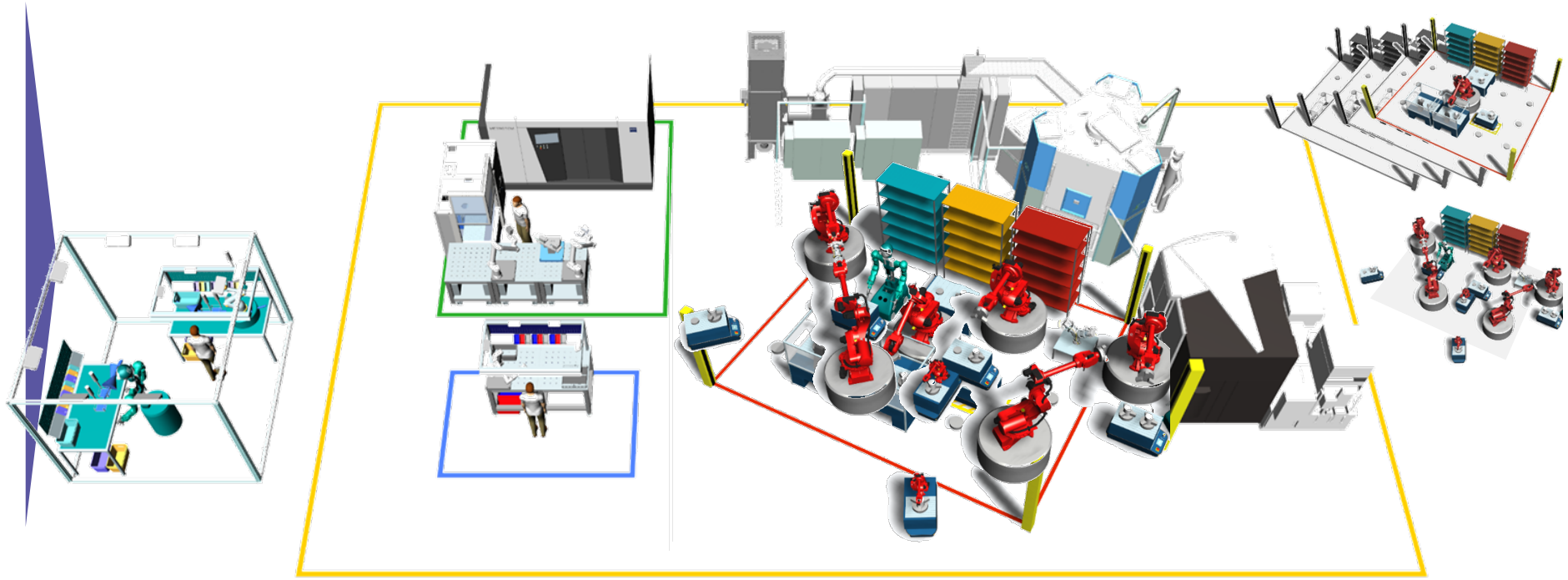
KIT Karlsruhe Institute of Technology

Capacity Planning in Circular Factories

Uncertainty of arrival times, volumes and product variants

Uncertainty of core conditions

Uncertainty of sucess rates of processes

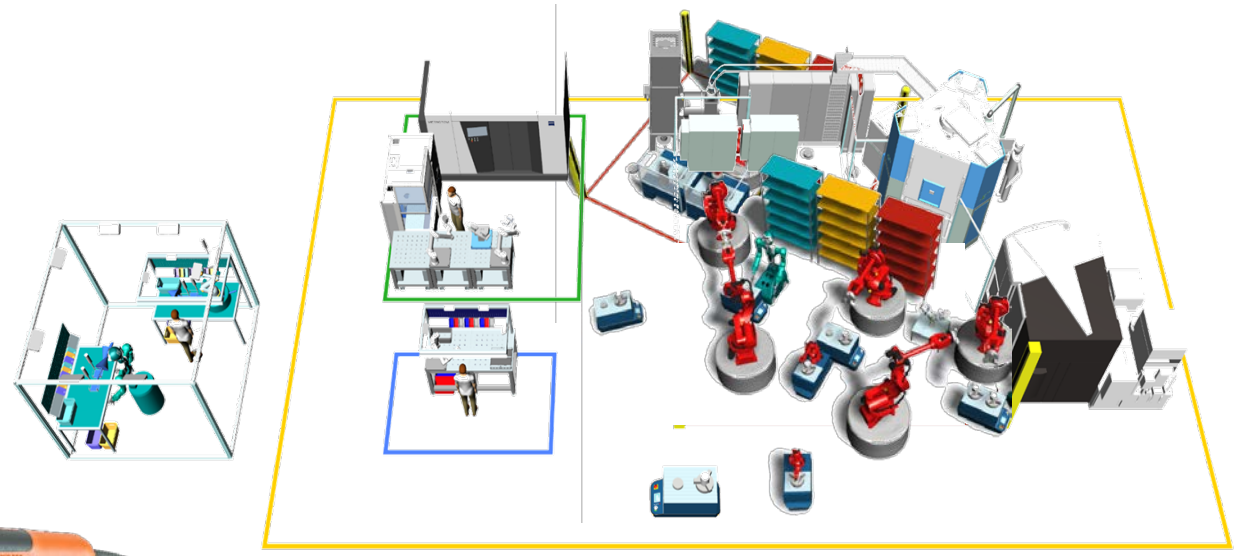


Due to the given uncertainties capacitiy planning for circular factories is a hard problem. Approaches should be able to account for the given uncertainties. We propose the use of a descrete event simulation study.

Case Study

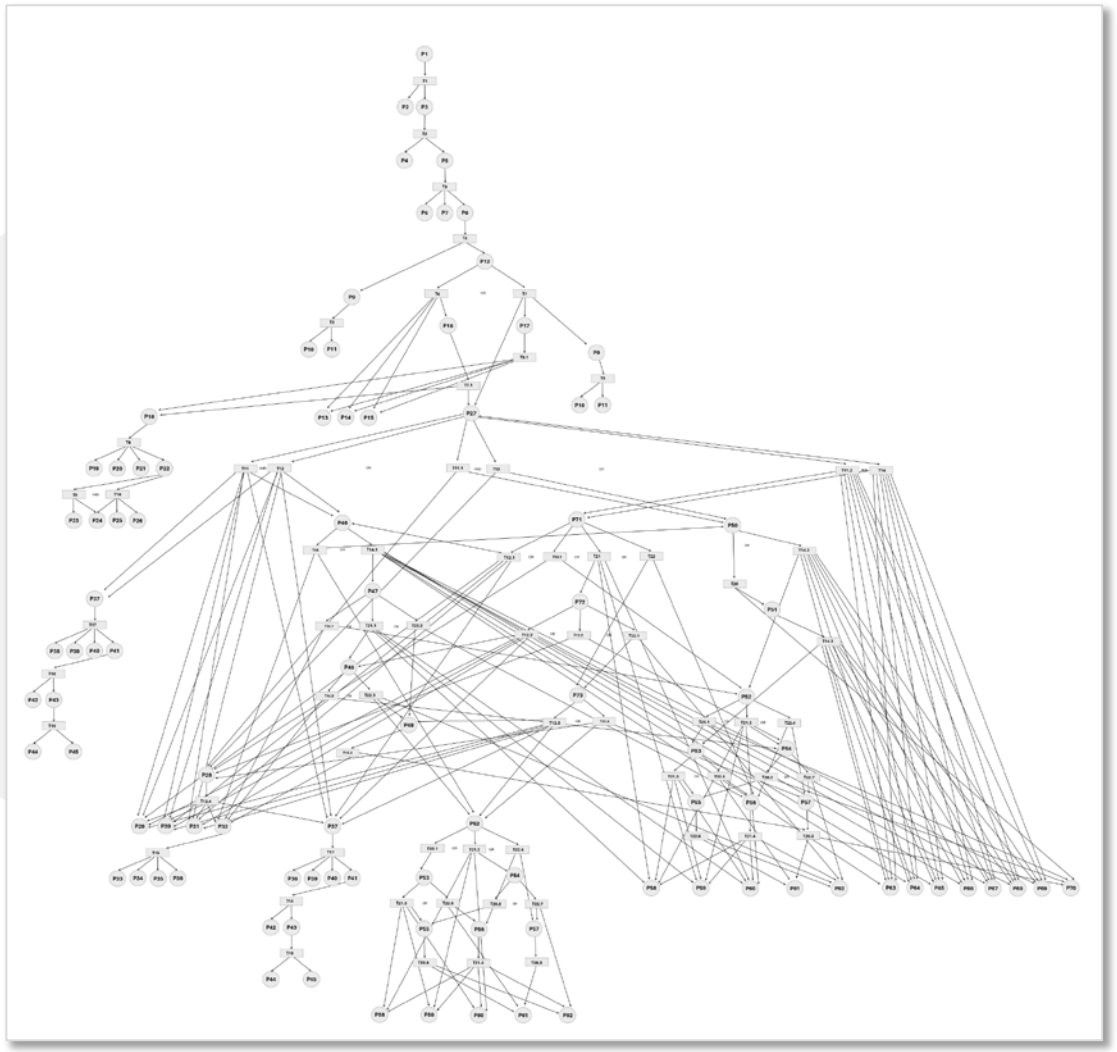
- discrete workstations for inspection, dis-/assembly, reprocessing, and manual operations
- single product type - stochastic variations in product condition are modeled via time-invariant transition probabilities between stations





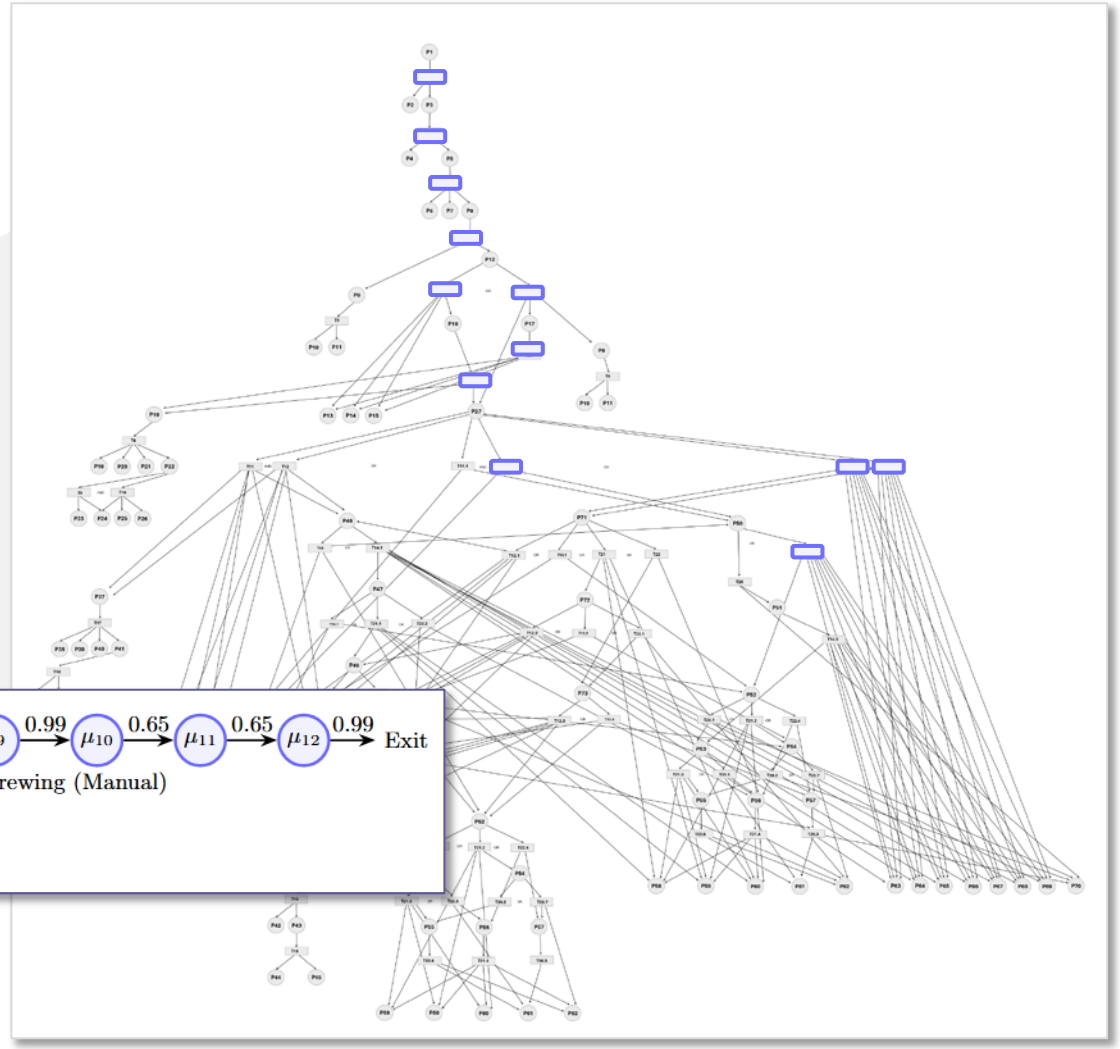
Case Study

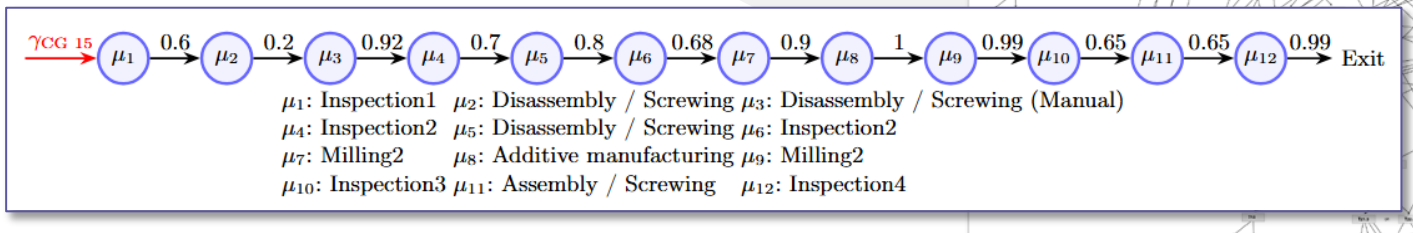




Case Study

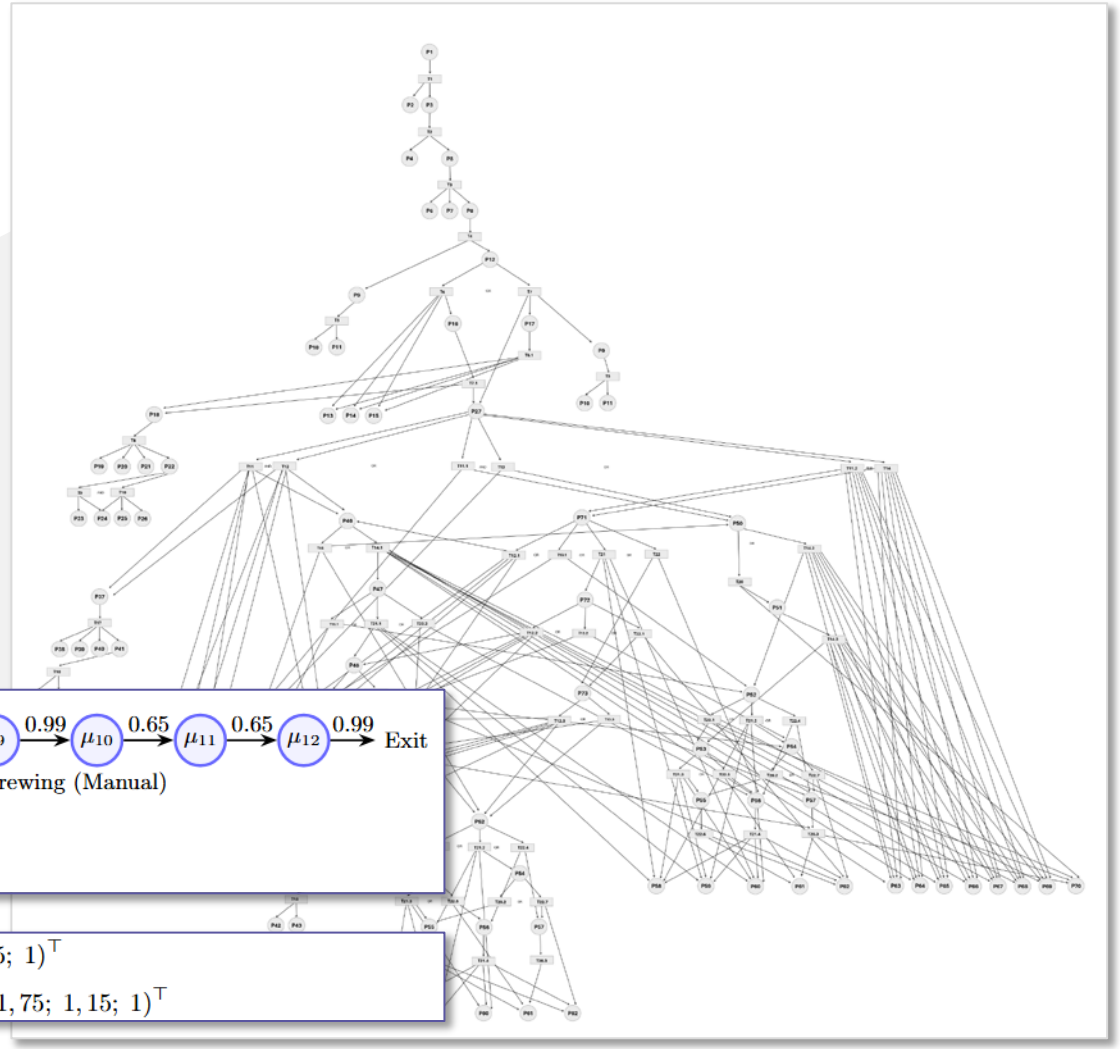

CG 15
BRUSHLESS




γCG 15
μ1
0.6
μ2
0.2
μ3
0.92
μ4
0.7
μ5
0.8
μ6
0.68
μ7
0.9
μ8
1
μ9
0.99
μ10
0.65
μ11
0.65
μ12
0.99
Exit
μ1: Inspection1 μ2: Disassembly / Screwing μ3: Disassembly / Screwing (Manual)
μ4: Inspection2 μ5: Disassembly / Screwing μ6: Inspection2
μ7: Milling2 μ8: Additive manufacturing μ9: Milling2
μ10: Inspection3 μ11: Assembly / Screwing μ12: Inspection4

Case Study





$\gamma_{CG\ 15} \rightarrow \mu_1 \xrightarrow{0.6} \mu_2 \xrightarrow{0.2} \mu_3 \xrightarrow{0.92} \mu_4 \xrightarrow{0.7} \mu_5 \xrightarrow{0.8} \mu_6 \xrightarrow{0.68} \mu_7 \xrightarrow{0.9} \mu_8 \xrightarrow{1} \mu_9 \xrightarrow{0.99} \mu_{10} \xrightarrow{0.65} \mu_{11} \xrightarrow{0.65} \mu_{12} \xrightarrow{0.99} \text{Exit}$

μ_1: Inspection1 μ_2: Disassembly / Screwing μ_3: Disassembly / Screwing (Manual)
μ_4: Inspection2 μ_5: Disassembly / Screwing μ_6: Inspection2
μ_7: Milling2 μ_8: Additive manufacturing μ_9: Milling2
μ_{10}: Inspection3 μ_{11}: Assembly / Screwing μ_{12}: Inspection4

$$\boldsymbol{\mu} = (1;\ 0.5;\ 0,5;\ 1;\ 0,5;\ 1;\ 0,5;\ 0,333;\ 0,5;\ 1;\ 0,5;\ 1)^\top$$

$$\boldsymbol{\lambda} \approx (1,69;\ 1,15;\ 3,24;\ 2,98;\ 2,83;\ 2,91;\ 2,81;\ 2,56;\ 2,23;\ 1,75;\ 1,15;\ 1)^\top$$

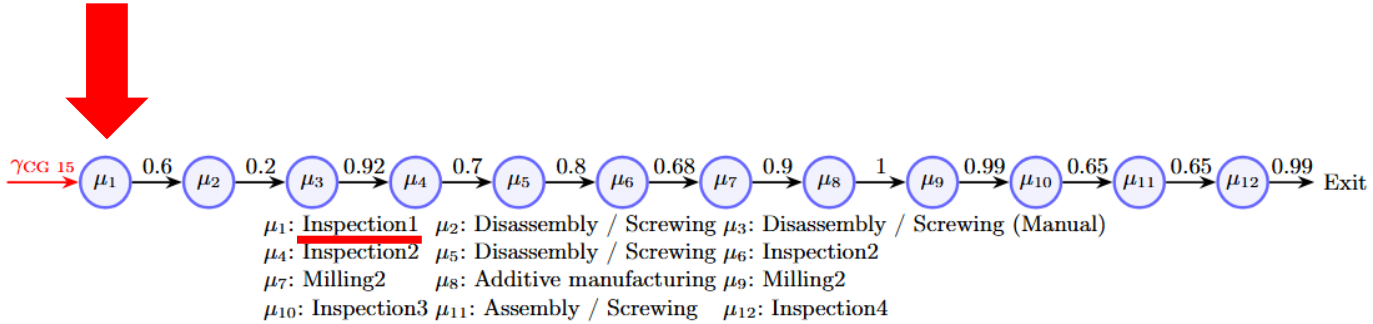
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DFG

Case Study



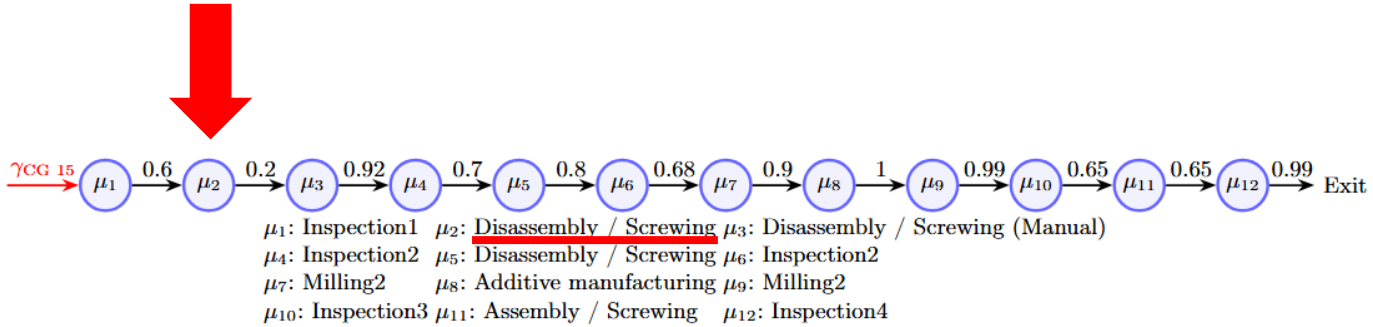

$\gamma_{CG\ 15}$
μ_1 0.6 μ_2 0.2 μ_3 0.92 μ_4 0.7 μ_5 0.8 μ_6 0.68 μ_7 0.9 μ_8 1 μ_9 0.99 μ_{10} 0.65 μ_{11} 0.65 μ_{12} 0.99 Exit
μ_1: Inspection1 μ_2: Disassembly / Screwing μ_3: Disassembly / Screwing (Manual)
μ_4: Inspection2 μ_5: Disassembly / Screwing μ_6: Inspection2
μ_7: Milling2 μ_8: Additive manufacturing μ_9: Milling2
μ_{10}: Inspection3 μ_{11}: Assembly / Screwing μ_{12}: Inspection4

Case Study





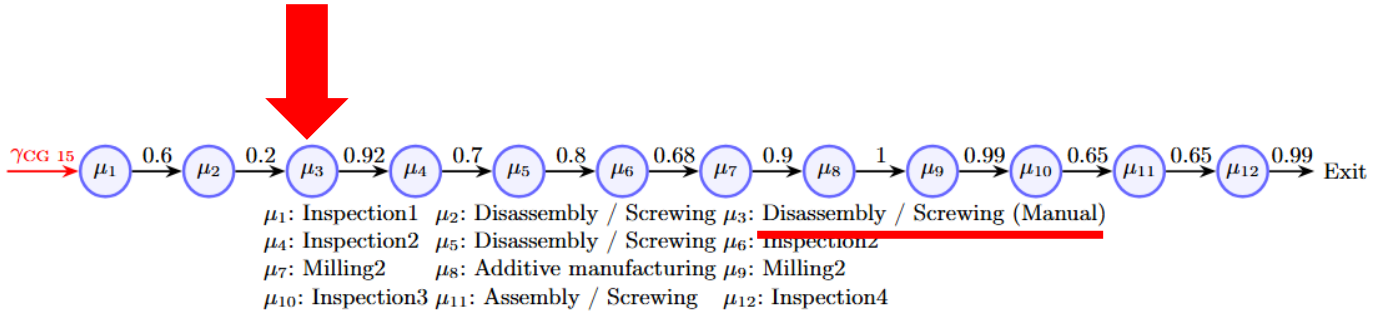
Disassembly / Screwing



Case Study

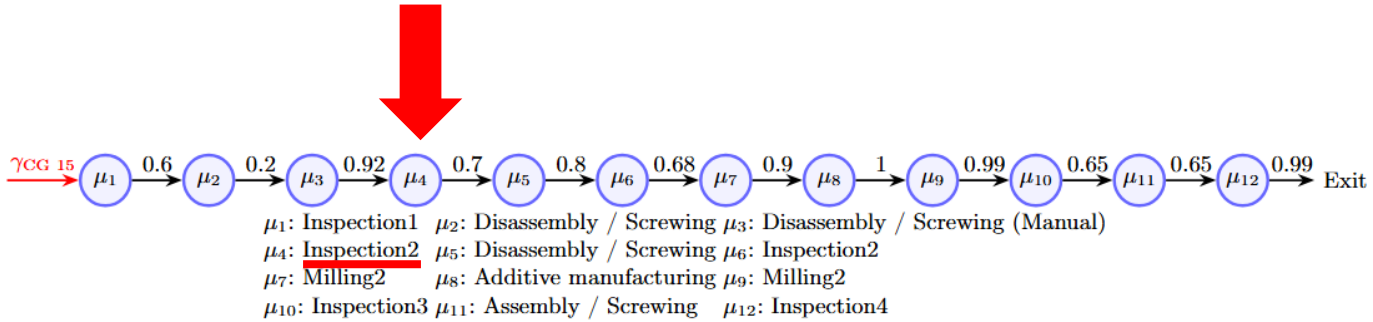


Disassembly / Screwing (Manual)

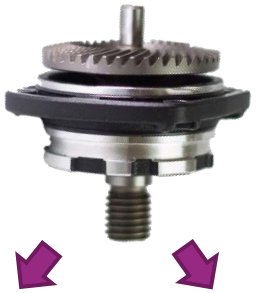


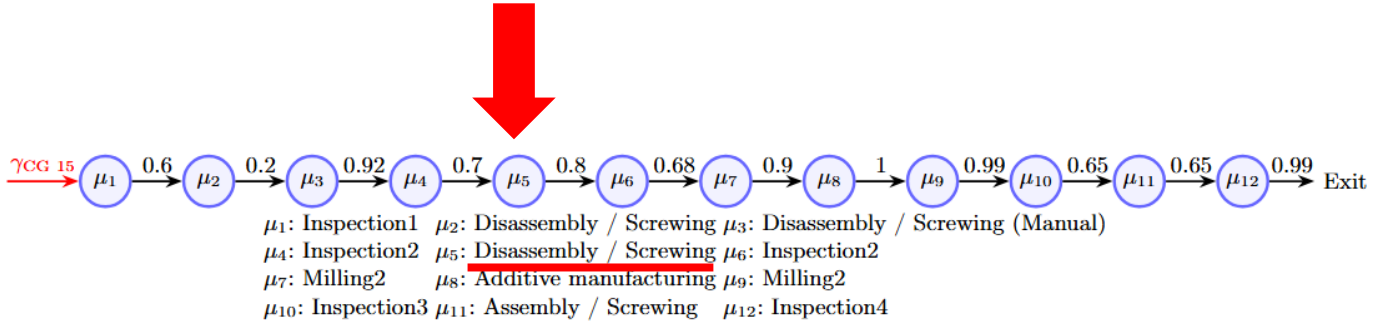
Case Study



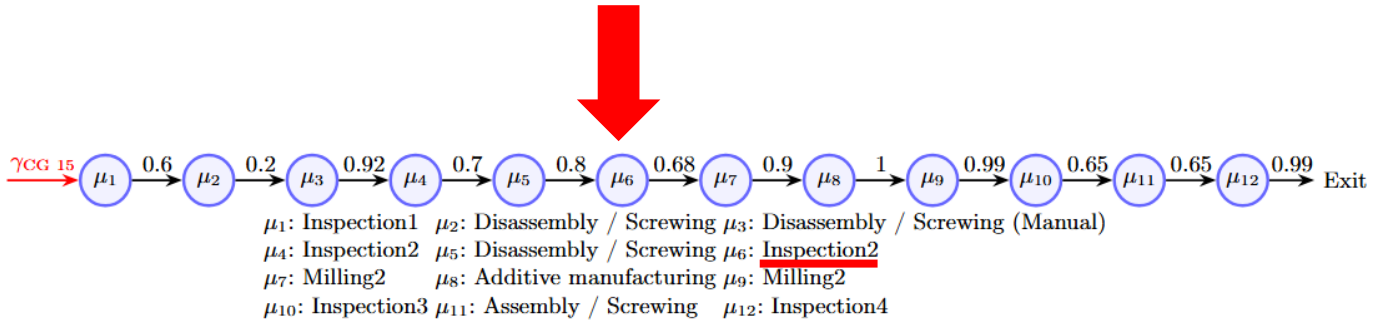

γCG 15
μ1
0.6
μ2
0.2
μ3
0.92
μ4
0.7
μ5
0.8
μ6
0.68
μ7
0.9
μ8
1
μ9
0.99
μ10
0.65
μ11
0.65
μ12
0.99
Exit
μ1: Inspection1 μ2: Disassembly / Screwing μ3: Disassembly / Screwing (Manual)
μ4: Inspection2 μ5: Disassembly / Screwing μ6: Inspection2
μ7: Milling2 μ8: Additive manufacturing μ9: Milling2
μ10: Inspection3 μ11: Assembly / Screwing μ12: Inspection4

Case Study



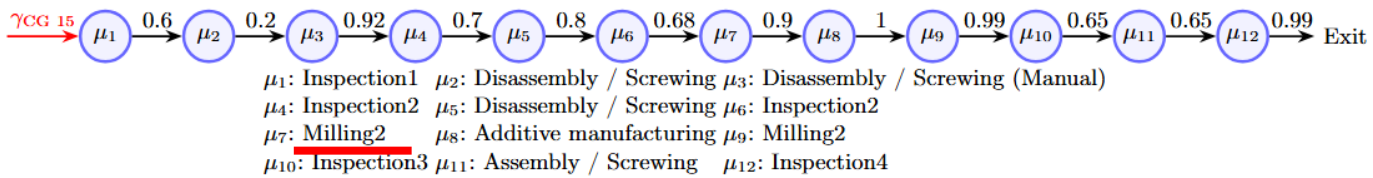

γ_{CG} 15
μ_1
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μ_2
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μ_3
0.92
μ_4
0.7
μ_5
0.8
μ_6
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Case Study


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μ_1
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μ_3
0.92
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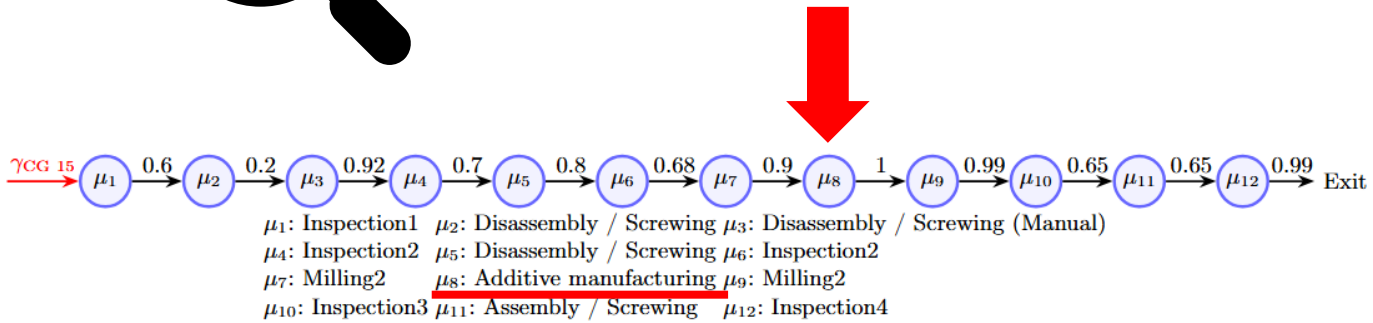
Case Study




γCG 15
μ1
0.6
μ2
0.2
μ3
0.92
μ4
0.7
μ5
0.8
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Case Study

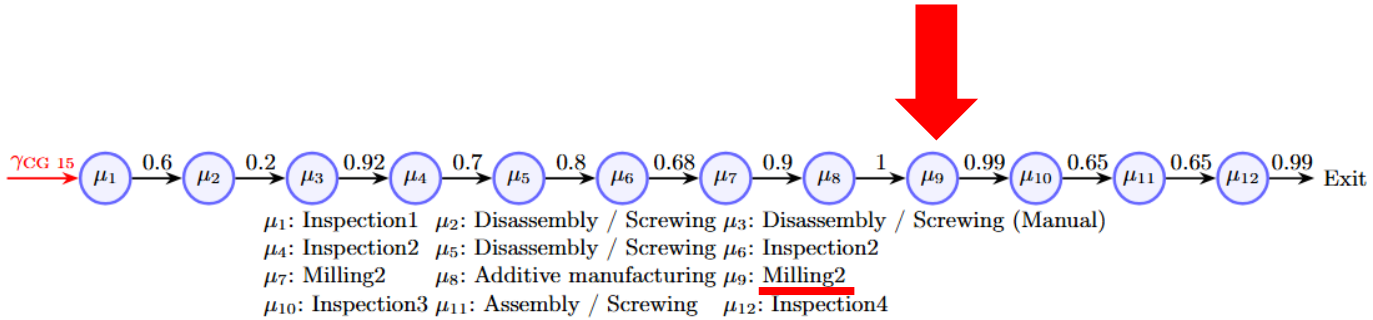



γCG 15
μ1
0.6
μ2
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μ4
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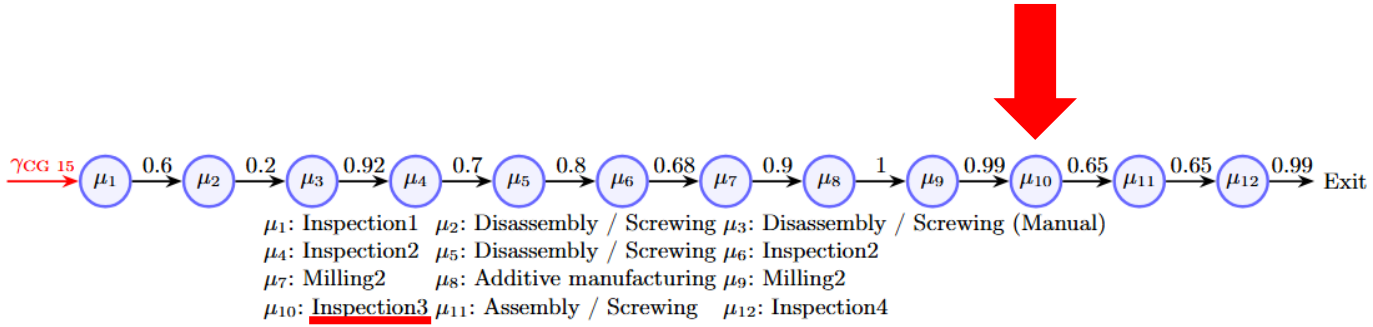
Case Study



Milling for improving geometry of tooth

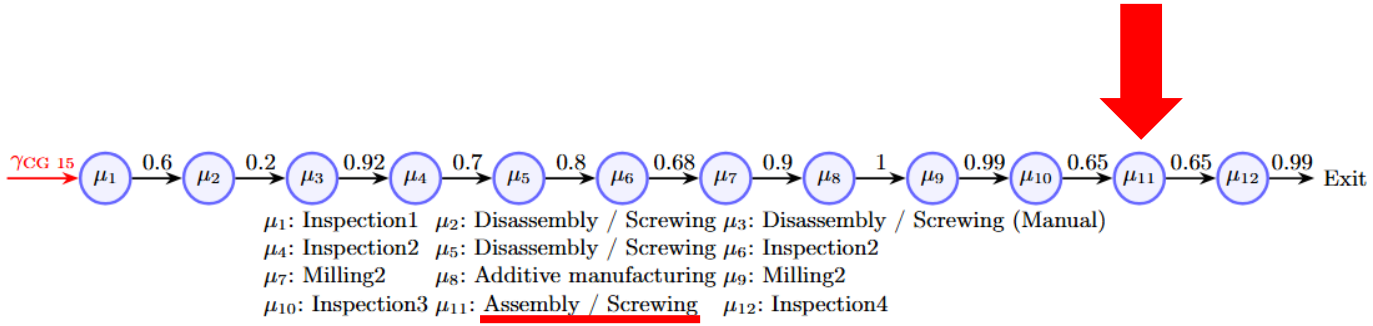


Case Study


γ_{CG} 15
μ_1
0.6
μ_2
0.2
μ_3
0.92
μ_4
0.7
μ_5
0.8
μ_6
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μ_8
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μ_{10}
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μ_{11}
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μ_{12}
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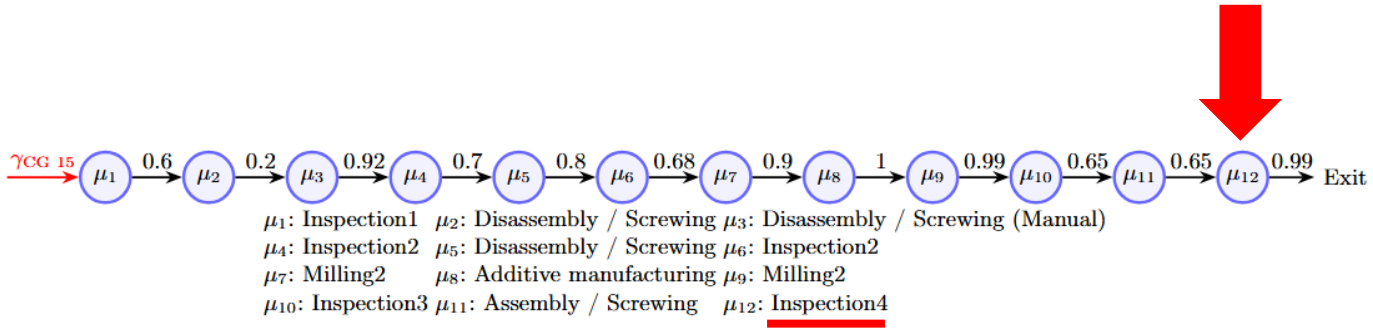
Case Study




γCG 15
μ1
0.6
μ2
0.2
μ3
0.92
μ4
0.7
μ5
0.8
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μ10
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μ12
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Case Study




$\gamma_{CG\ 15}$
μ_1 0.6 μ_2 0.2 μ_3 0.92 μ_4 0.7 μ_5 0.8 μ_6 0.68 μ_7 0.9 μ_8 1 μ_9 0.99 μ_{10} 0.65 μ_{11} 0.65 μ_{12} 0.99 Exit
μ_1: Inspection1 μ_2: Disassembly / Screwing μ_3: Disassembly / Screwing (Manual)
μ_4: Inspection2 μ_5: Disassembly / Screwing μ_6: Inspection2
μ_7: Milling2 μ_8: Additive manufacturing μ_9: Milling2
μ_{10}: Inspection3 μ_{11}: Assembly / Screwing μ_{12}: Inspection4

Modelling in Simul8 - assumptions

- product arrivals are modeled as stationary stochastic process with constant average arrival rate of λ = 1 unit per minute
- individual processing times (incl. set-up etc.) are approximated using exponential distributions
- no planned maintenance and unexpected machine breakdowns
- manual workstations have fully skilled personnel
- inspection stations exhibit ideal defect detection capabilities

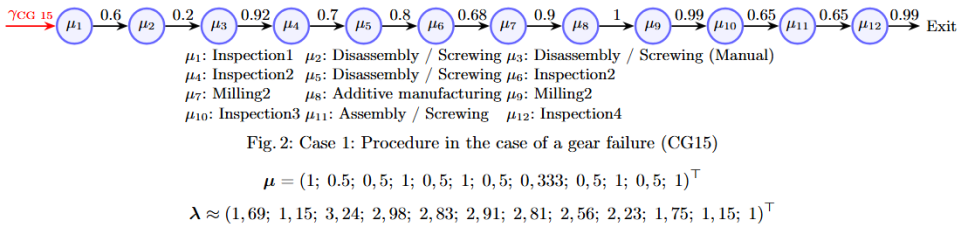
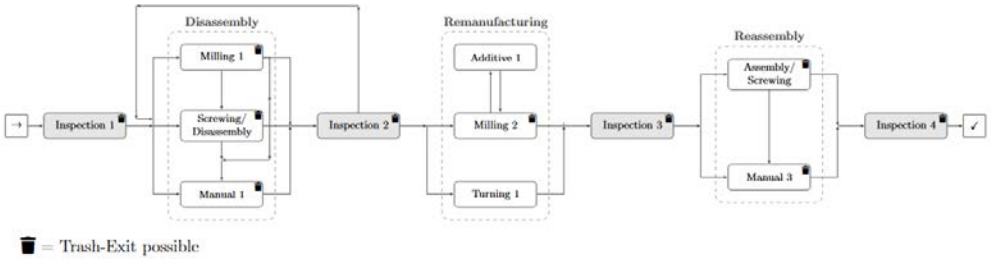


Fig. 2: Case 1: Procedure in the case of a gear failure (CG15)

$$\boldsymbol{\mu} = (1;\ 0.5;\ 0,5;\ 1;\ 0,5;\ 1;\ 0,5;\ 0,333;\ 0,5;\ 1;\ 0,5;\ 1)^\top$$

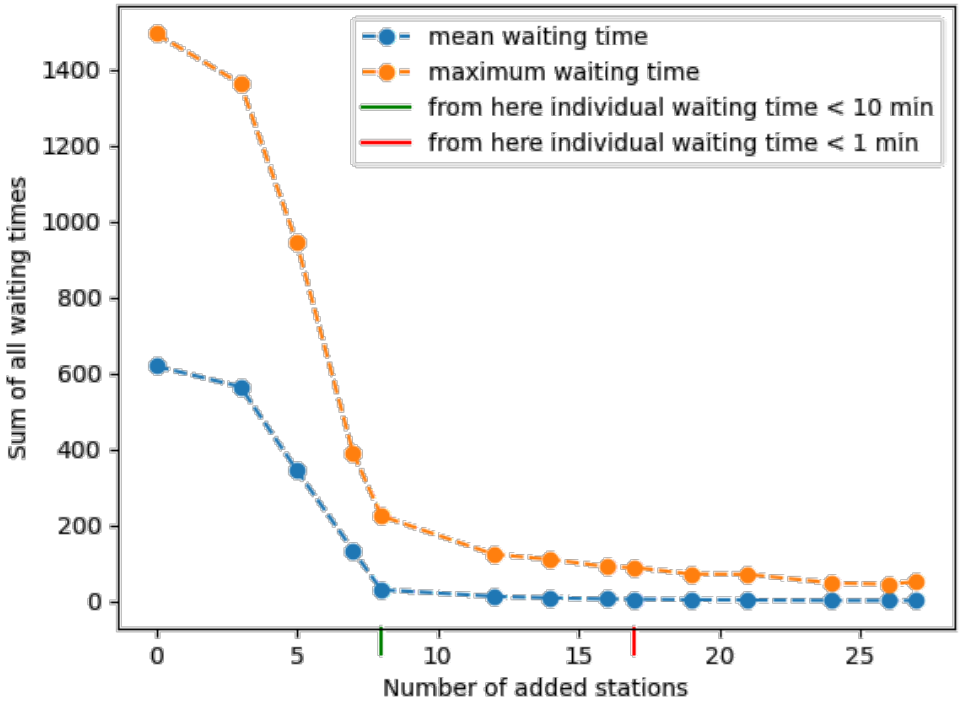
$$\boldsymbol{\lambda} \approx (1,69;\ 1,15;\ 3,24;\ 2,98;\ 2,83;\ 2,91;\ 2,81;\ 2,56;\ 2,23;\ 1,75;\ 1,15;\ 1)^\top$$

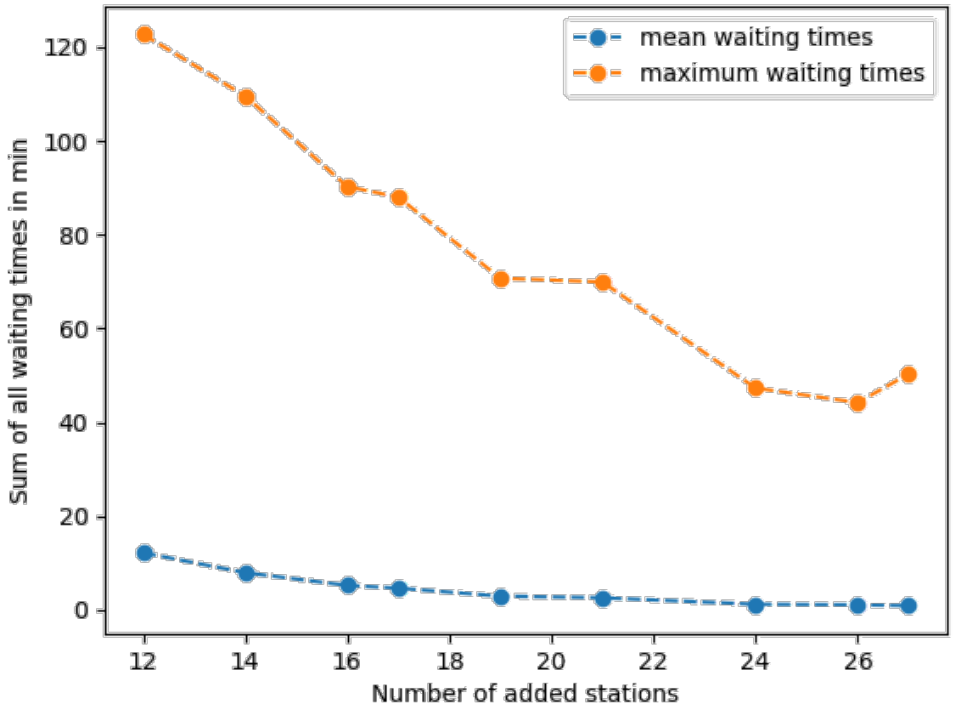


Modelling in Simul8

- simulation span: continuous one-week period, which captures steady-state behavior but may not account for extreme, transient demand spikes.
- For each station the mean and maximum waiting times are captured
- First, each station is considered to exist only once

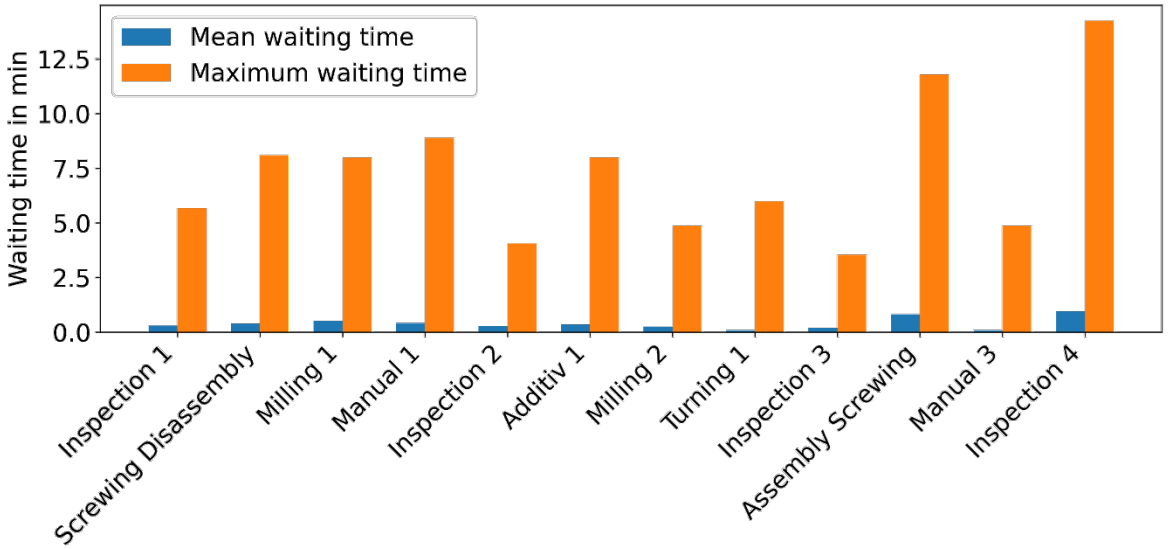
Results

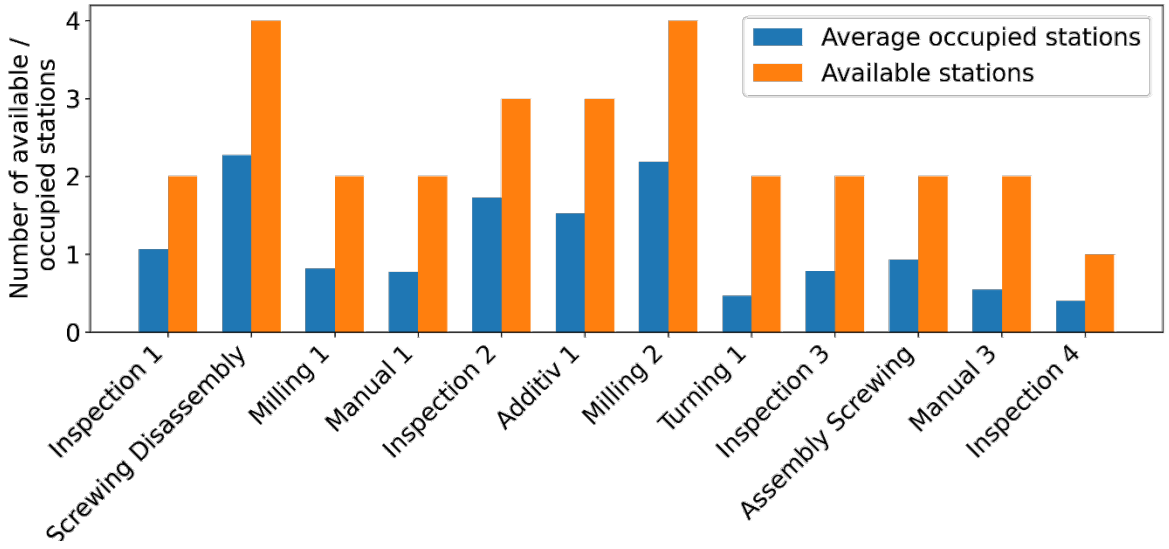




With only one station available for each station type, the resulting waiting times are quite long. Multiplying the number of stations corresponds to a capacity increase.

Results



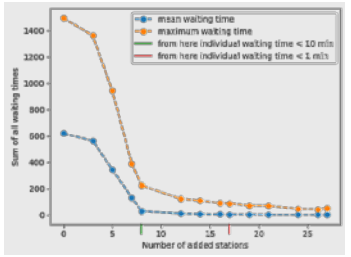


Station	Number	Station	Number	Station	Number
Inspection1	2	Milling2	4	Manual3	2
Screwing Disassembly	4	Turning1	2	Inspection4	1
Milling1	2	Inspection3	2	Assembly Screwing	2
Manual1	2	Inspection2	3	Additive1	3

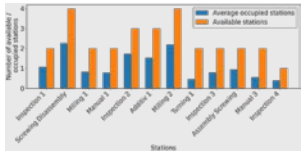
The required amount of stations can easily be found, e.g. for limiting the allowed mean waiting time to 1 min. However, capacity utilization is not ideal. A compromise needs to be found.

Summary

- capacity planning methodology for circular factories due though a discrete-event simulation
- Proposed approach reduces waiting time on the stations thereby increasing the efficiency and robust solution for the capacity allocation
- future research: incorporate interruption mechanisms, integration of revenue management concepts







Prof. Nicole Stricker
Aalen University

nicole.stricker@hs-aalen.de

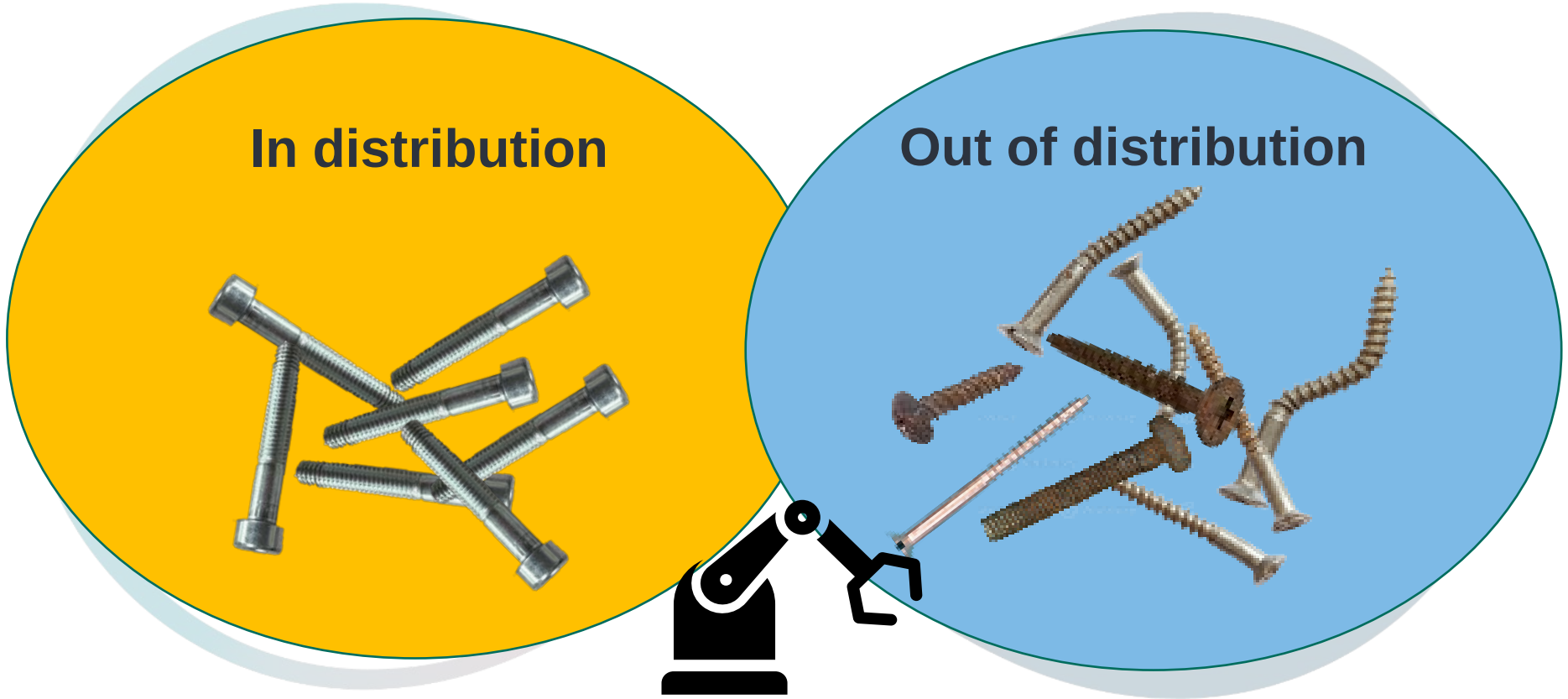


Karlsruhe Institute of Technology

An Autonomous Adaptive Learning System for Robotic Grasping in the Circular Factory

Yitian Shi, Rosa Wolf, Rania Rayyes

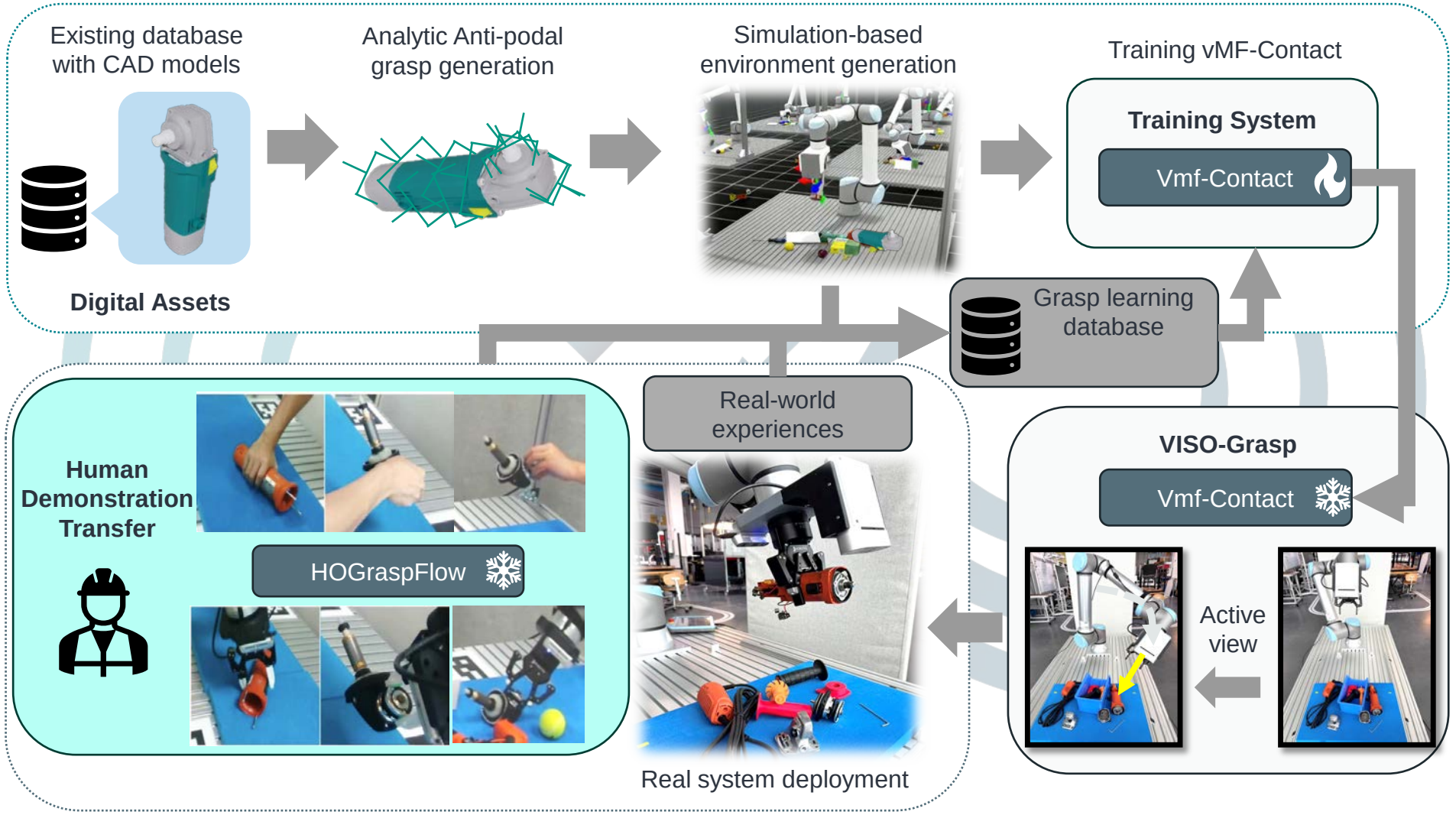
Motivation



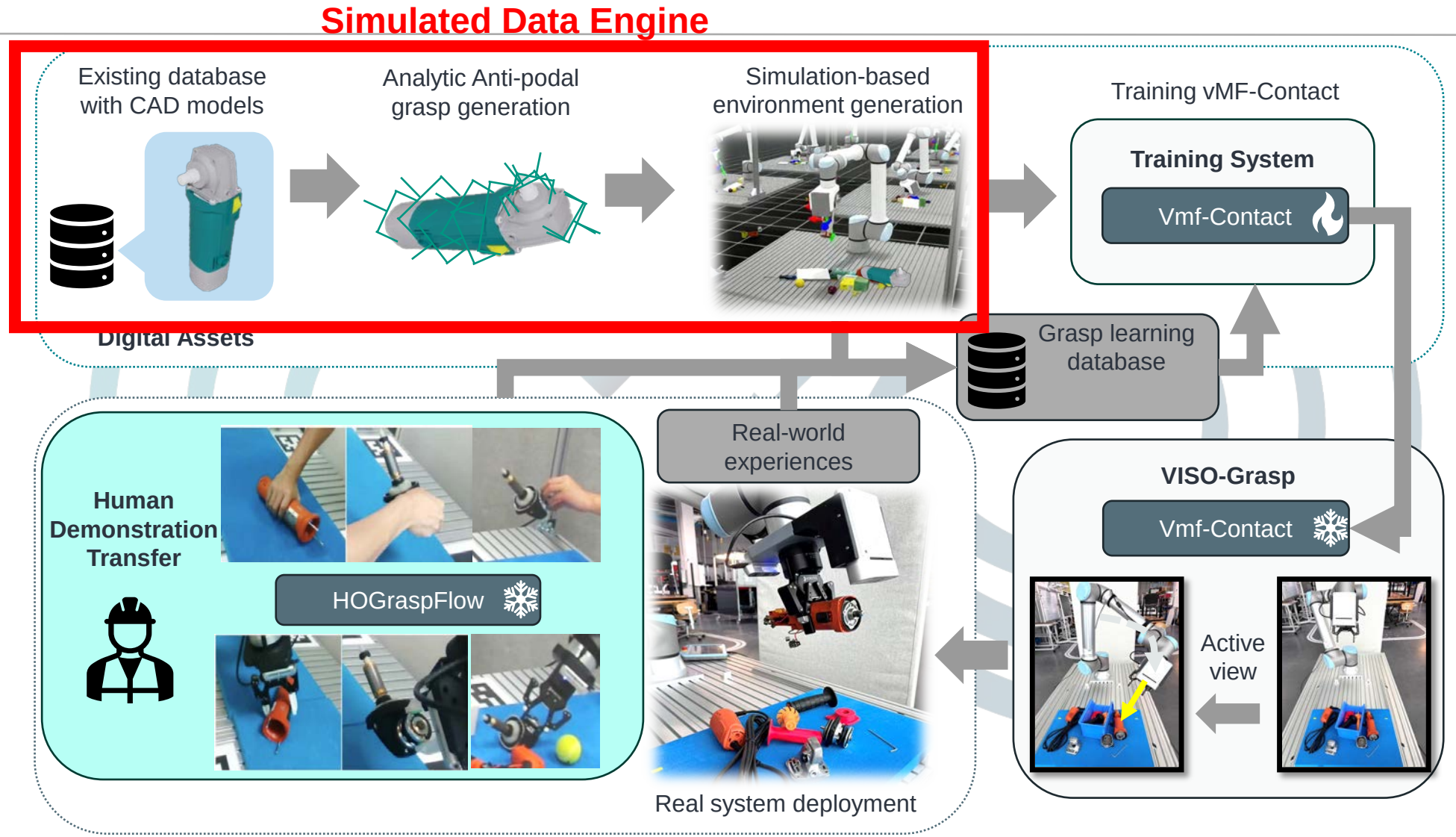
Motivation

- **Circular factories break the assumptions of traditional robotic grasping:** objects may be aged, damaged, deformed, occluded, or mixed across product generations, making fixed models and pre-programmed grasps unreliable.
- **Reliable grasping requires explicit uncertainty reasoning:** robots must distinguish uncertainty from noisy/incomplete sensing from uncertainty caused by novel objects or distribution shifts, and use this information to decide when to grasp, explore, or re-observe.
- **A closed-loop adaptive system is needed:** by combining CAD-based simulation, human demonstration priors, active perception, and real-world execution feedback, the robot can continuously improve grasping robustness in cluttered and variable environments.

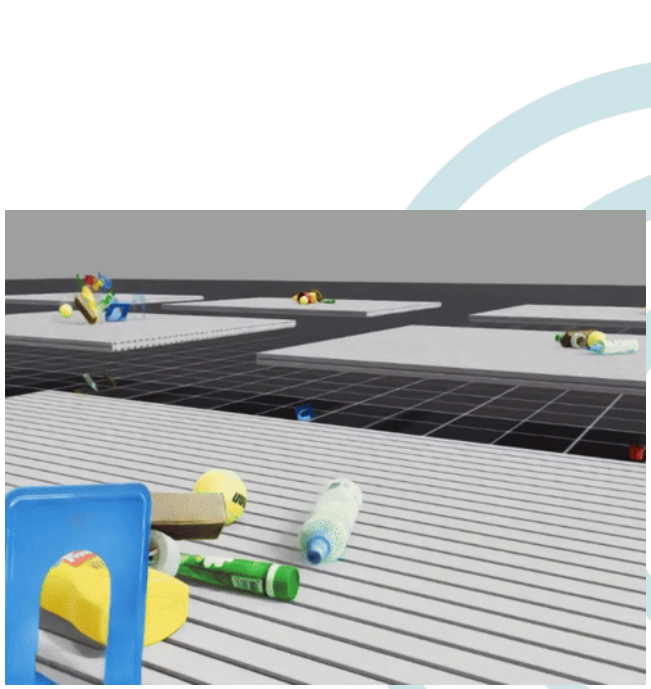
CIRCA-Grasp Overview

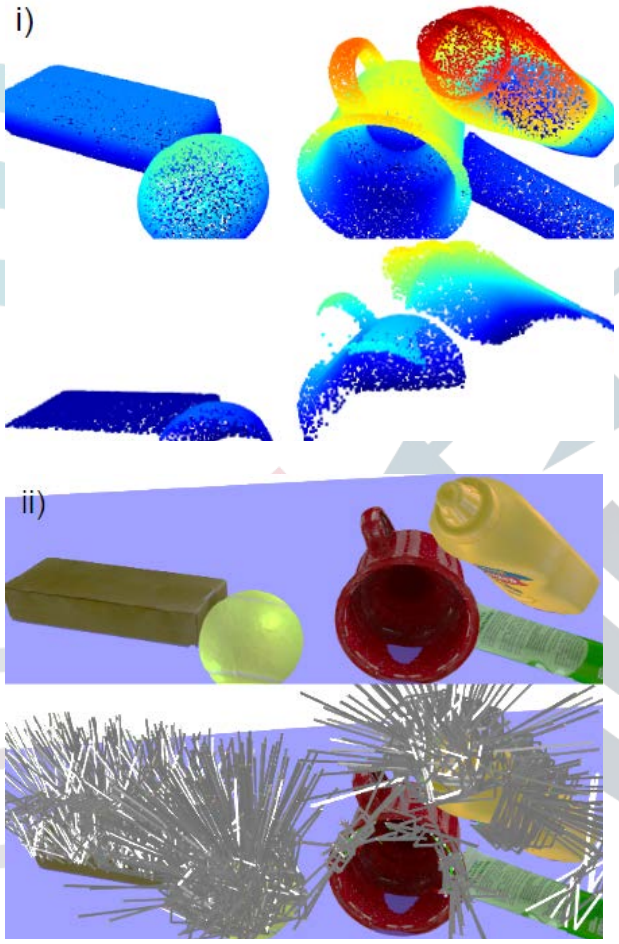


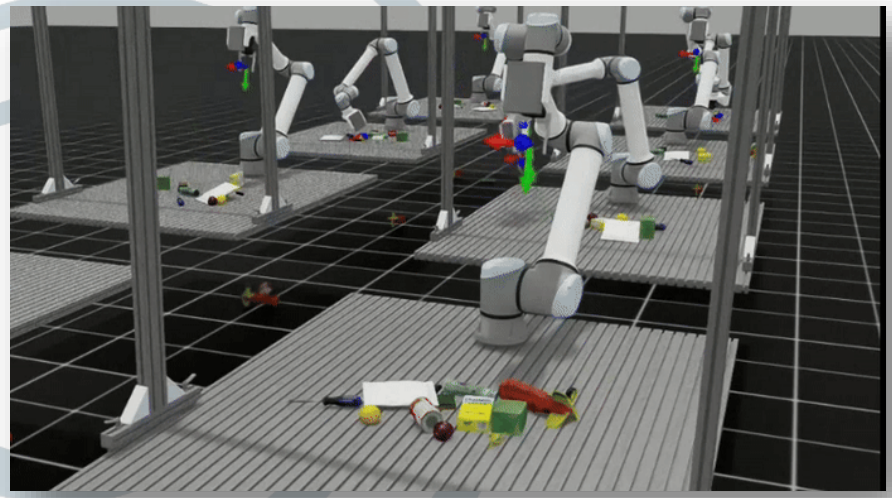
CIRCA-Grasp Overview



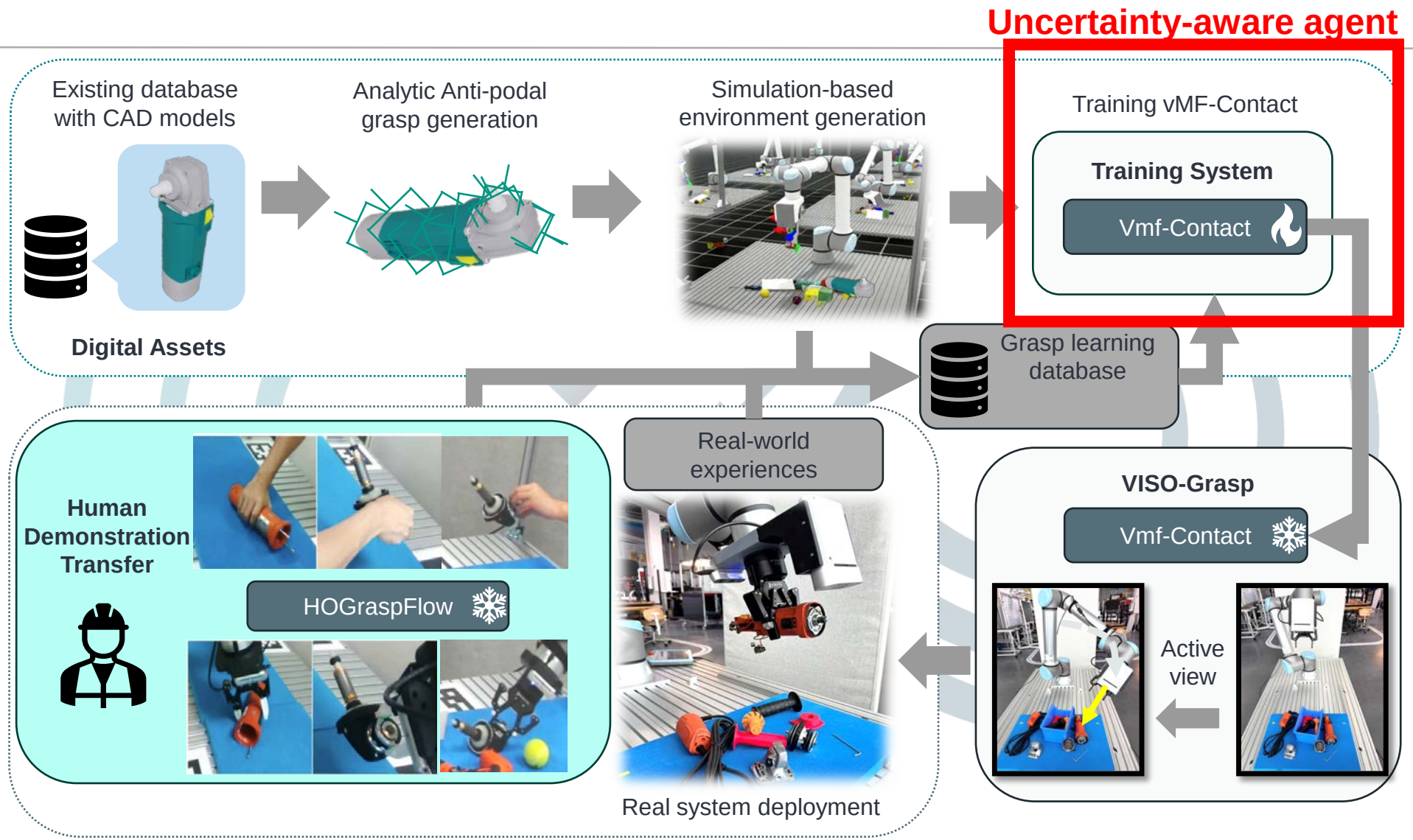
Simulated Data Engine



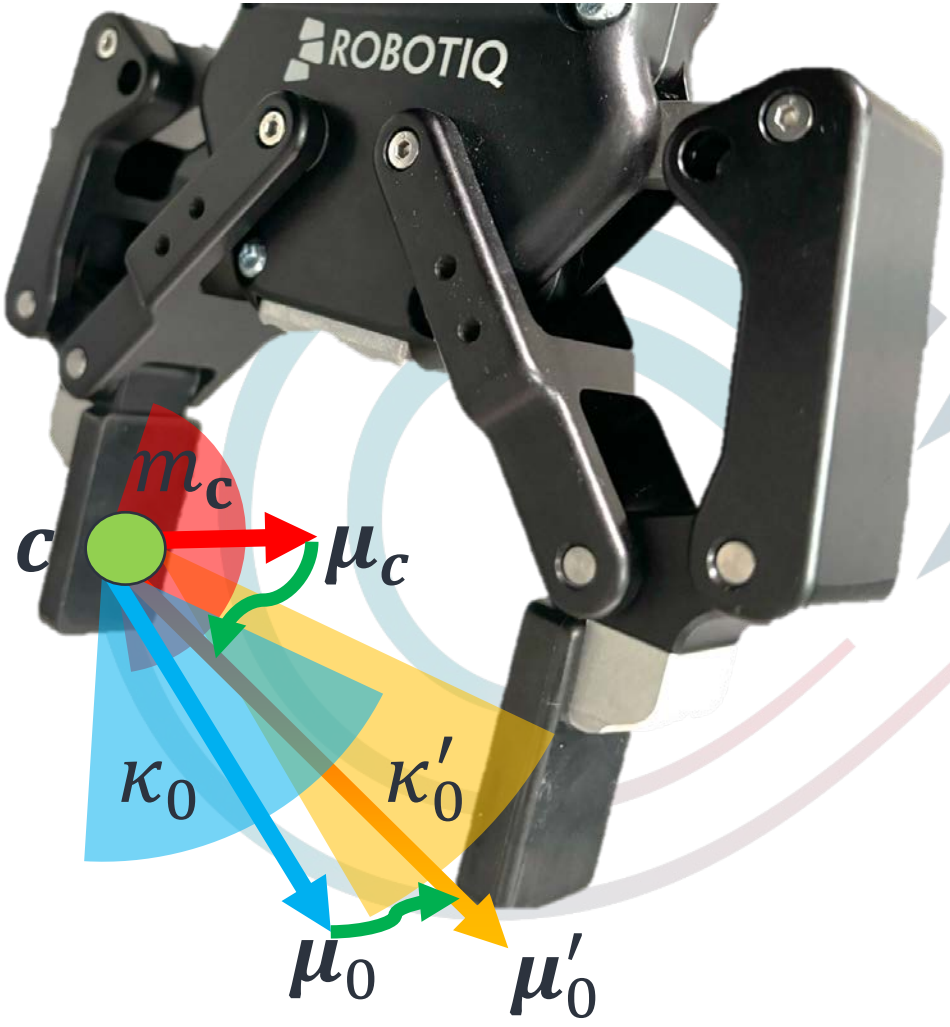




CIRCA-Grasp Overview



Uncertainty-aware Agent



Training System

Vmf-Contact

Likelihood: $\mathbf{b} \sim \mathbf{vMF}(\mathbf{b}|\boldsymbol{\mu_c}, \kappa_c)$

$$(\boldsymbol{\mu_c}, \kappa_c) = \mathrm{MLP}(z_c)$$

Prior: $\boldsymbol{\mu_c} \sim \mathbf{vMF}(\boldsymbol{\mu_0}, \kappa_0)$

Evidence: $m_c = f_\phi(z_c)$

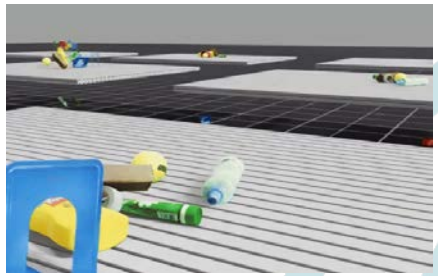
Posterior: $\boldsymbol{\mu_c} \sim \mathbf{vMF}(\boldsymbol{\mu_0'}, \kappa_0')$

$$\mu_0' = \frac{\kappa_0 \mu_0 + m_c \mu_c}{\kappa_0 + m_c}$$

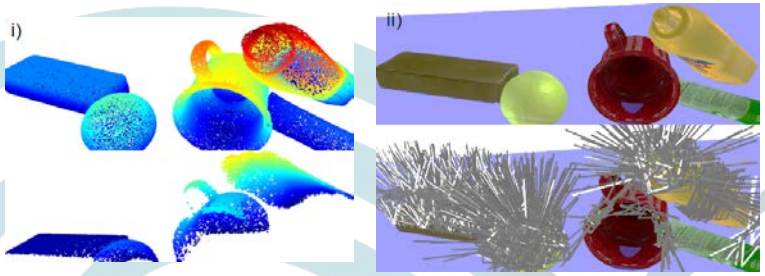
$$\kappa_0' = \kappa_0 + m_c$$

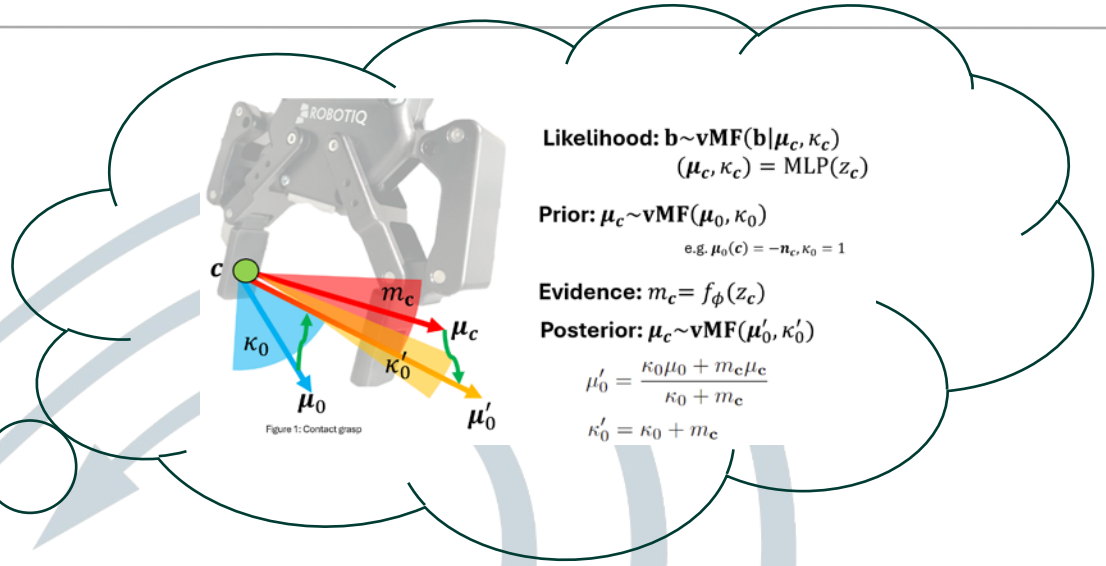
Uncertainty-aware Agent

1) Data generation

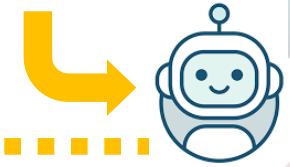


2) Grasp analysis

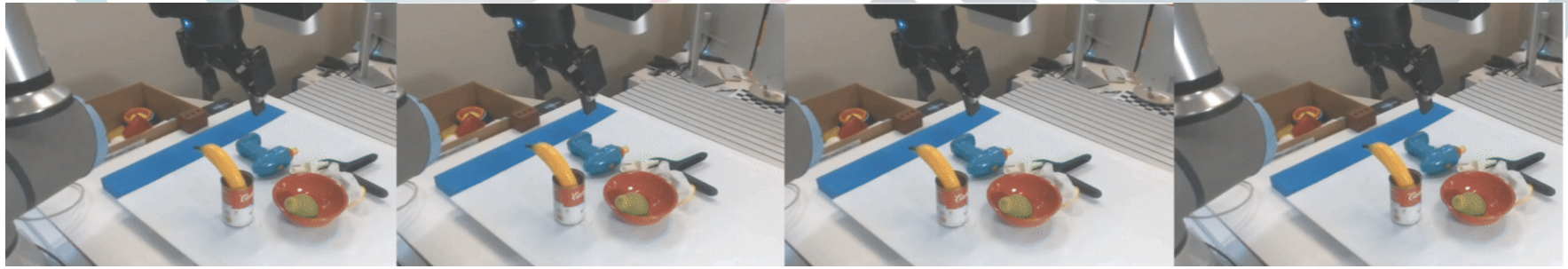




3) Agent training

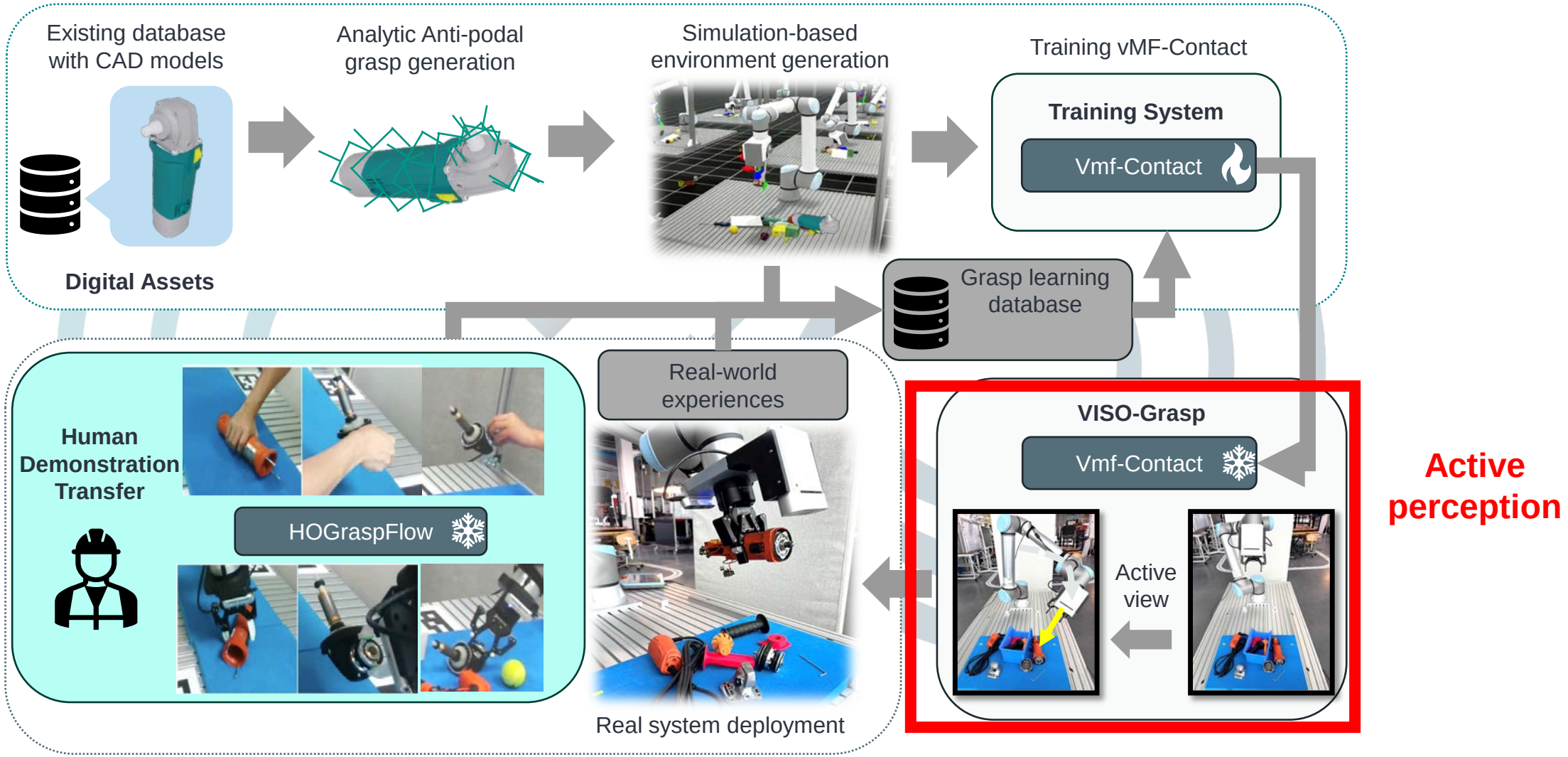


4) Simulation / Real-world Inference

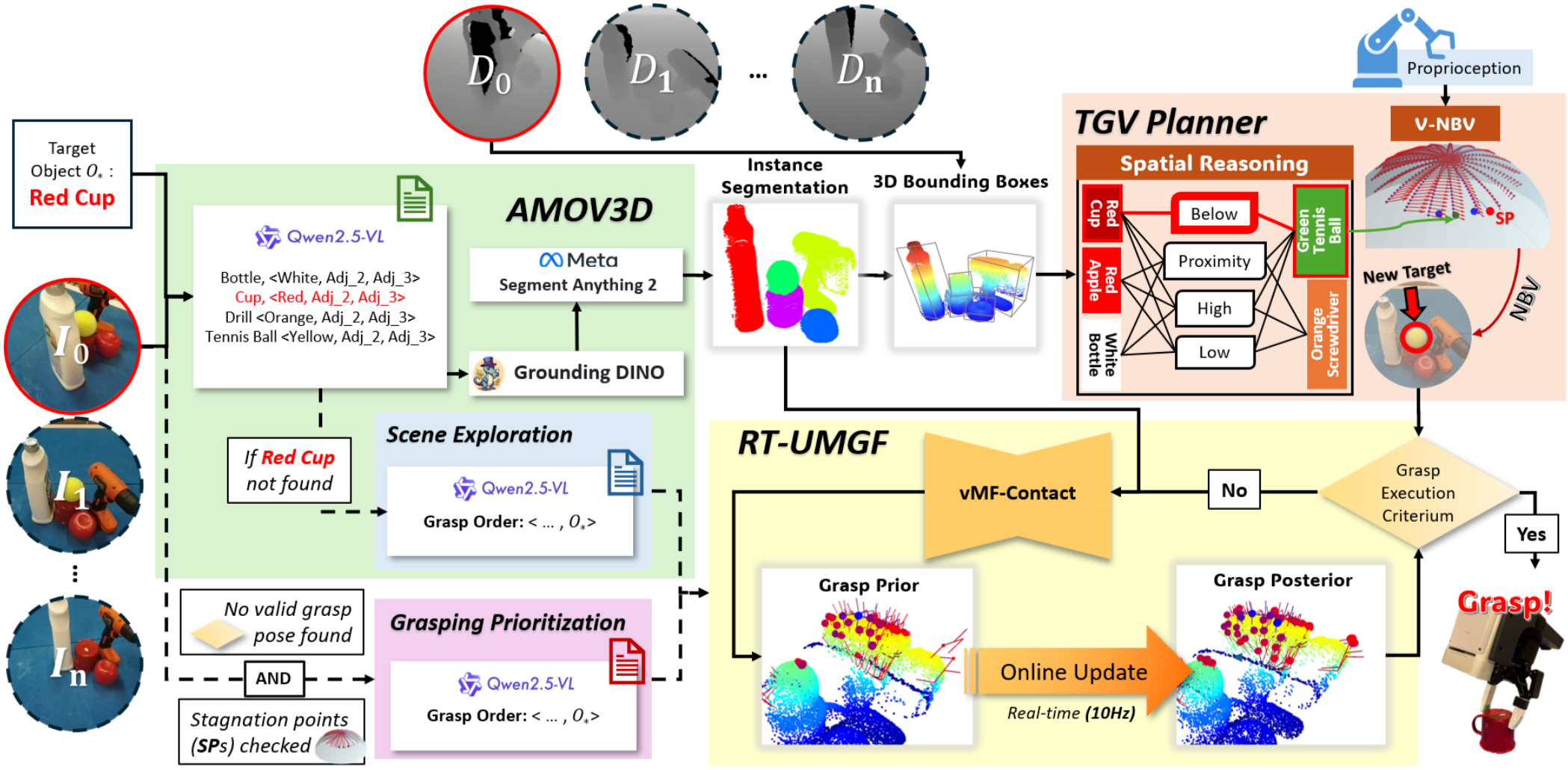


Shi, Yitian, et al. "vMF-Contact: Uncertainty-aware Evidential Learning for Probabilistic Contact-grasp in Noisy Clutter." arXiv preprint arXiv:2411.03591 (2024).

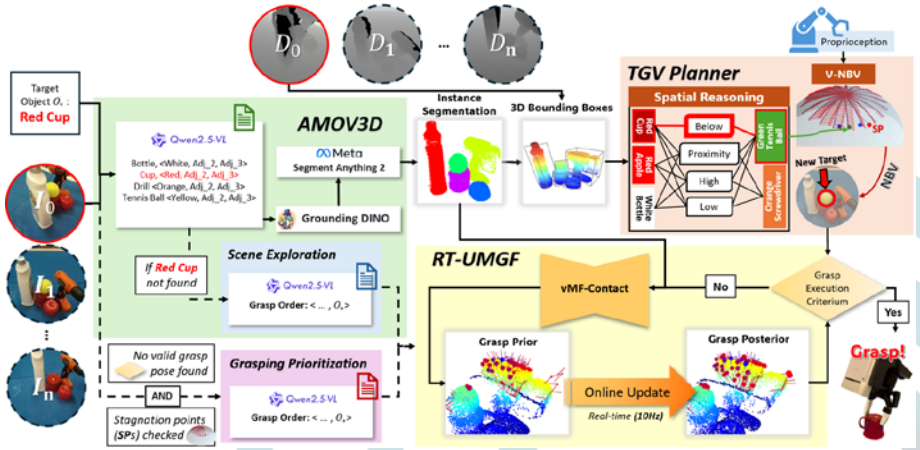
CIRCA-Grasp Overview



Active Perception



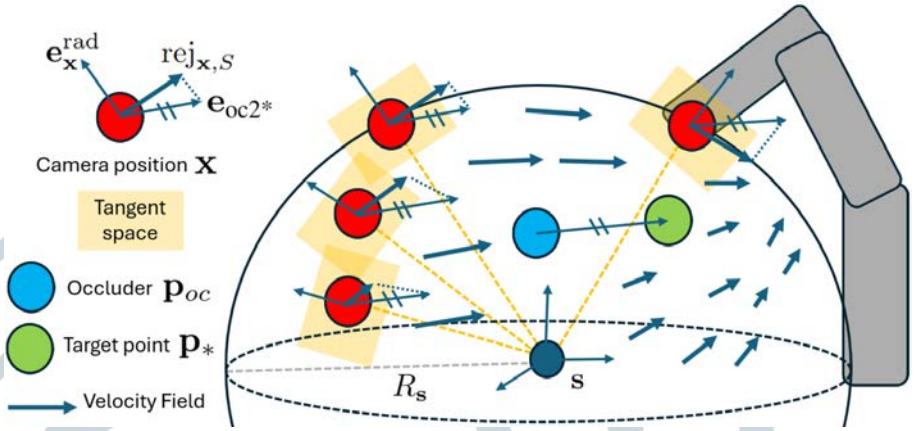
Active Perception



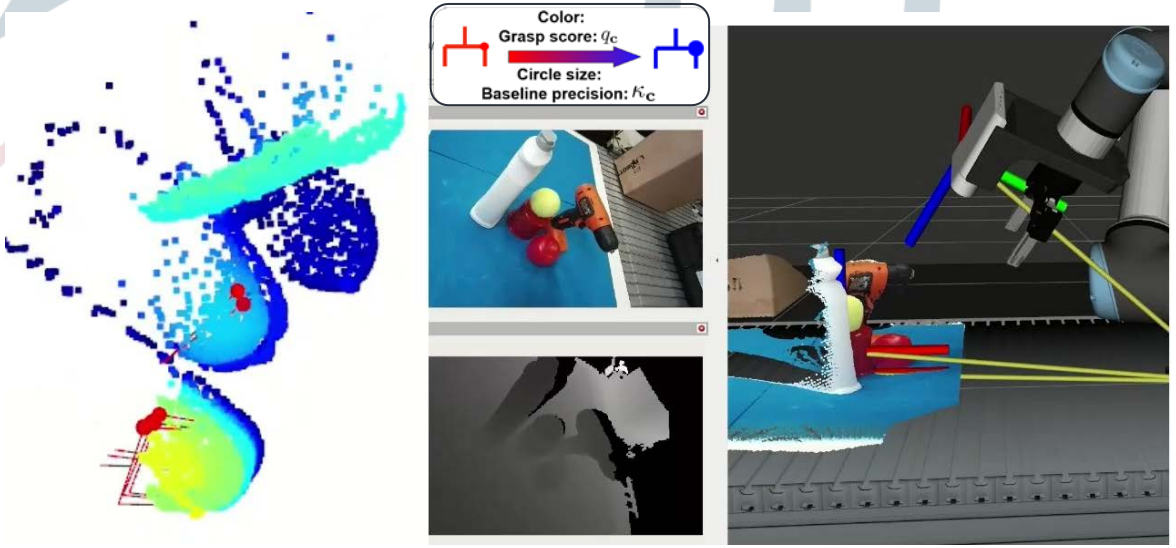
1) Scene understanding



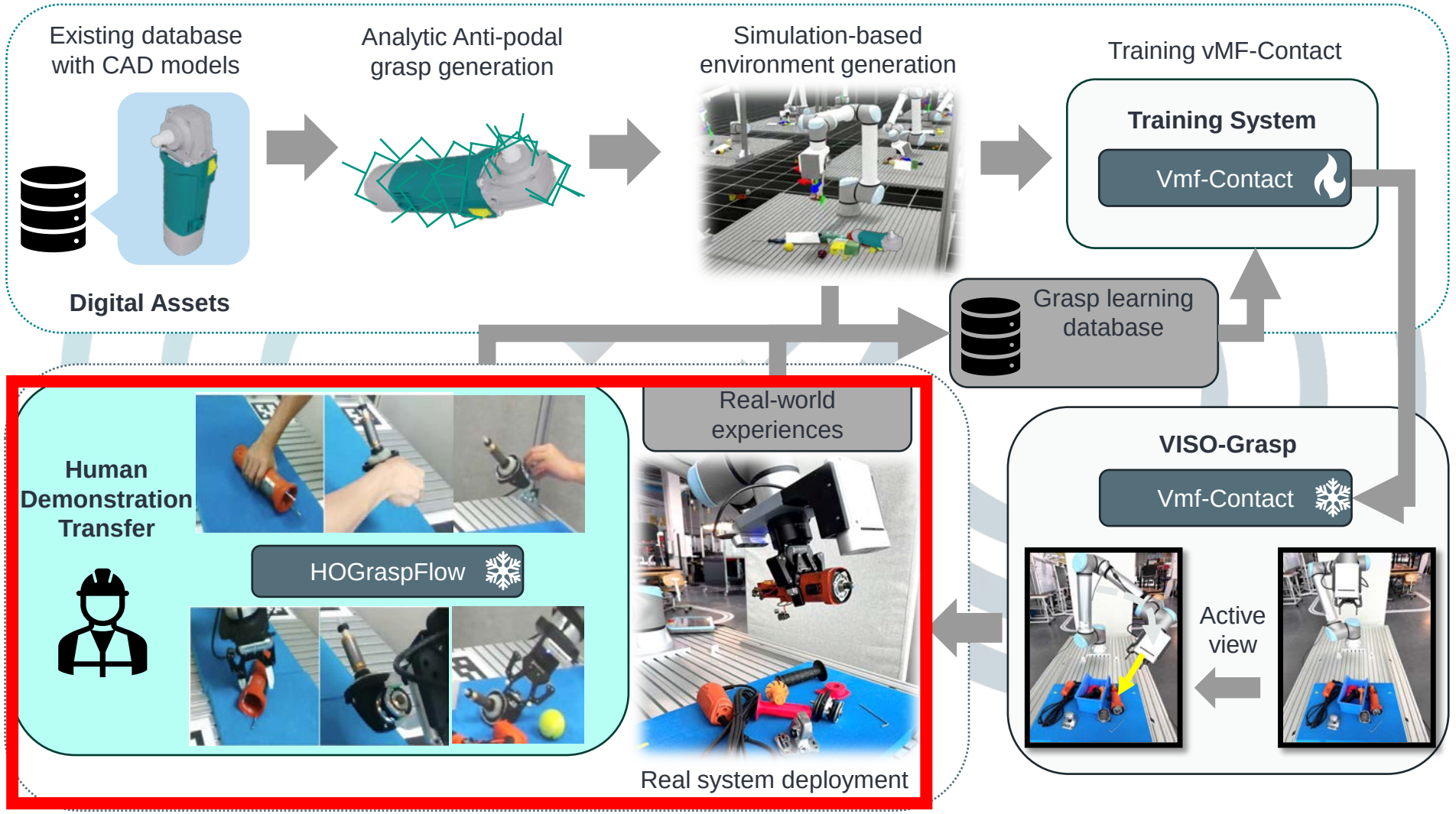
2) View planner



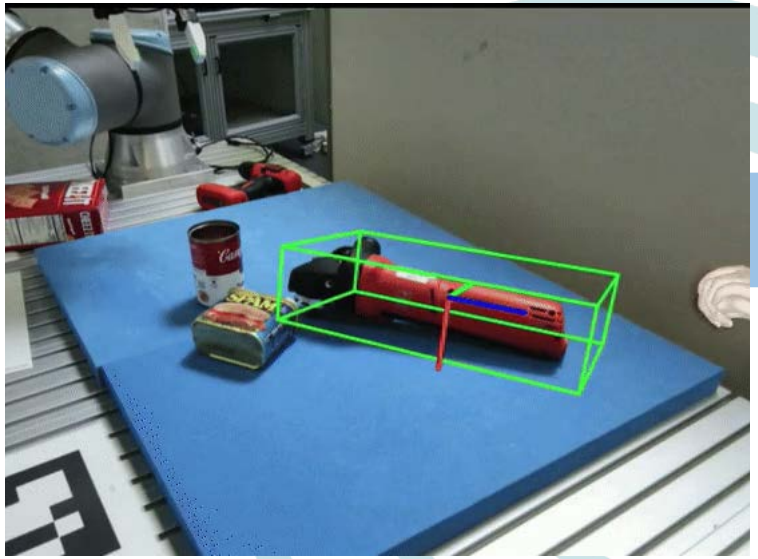
3) Real-time grasp fusion

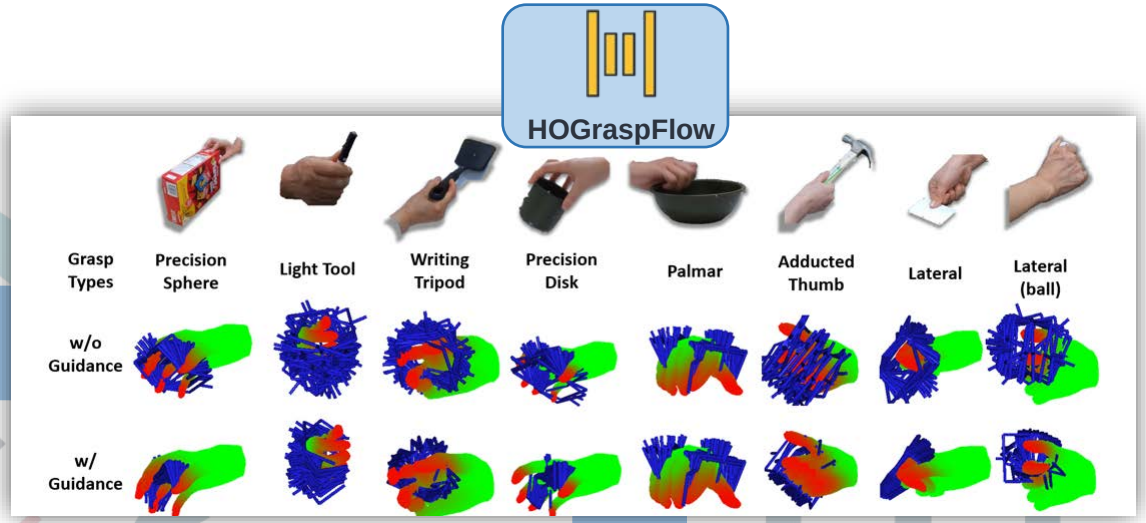


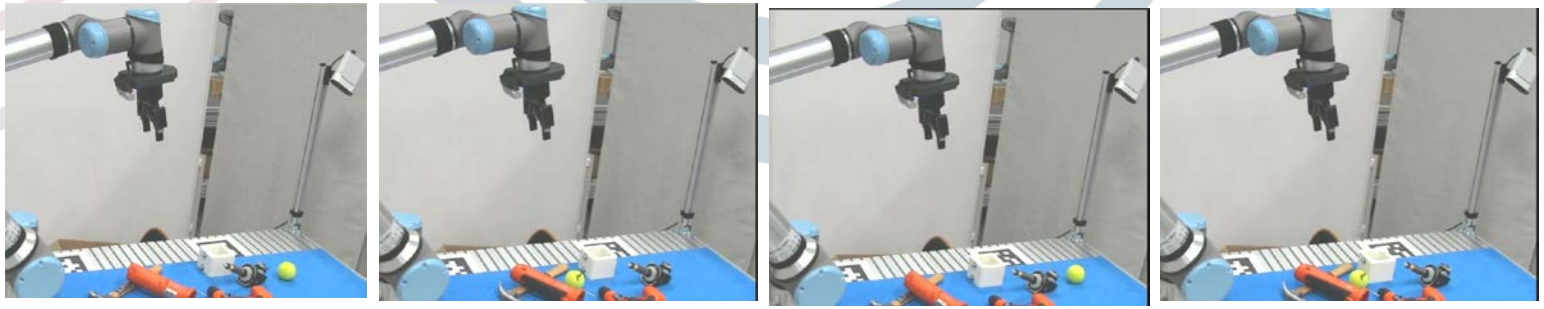
CIRCA-Grasp Overview



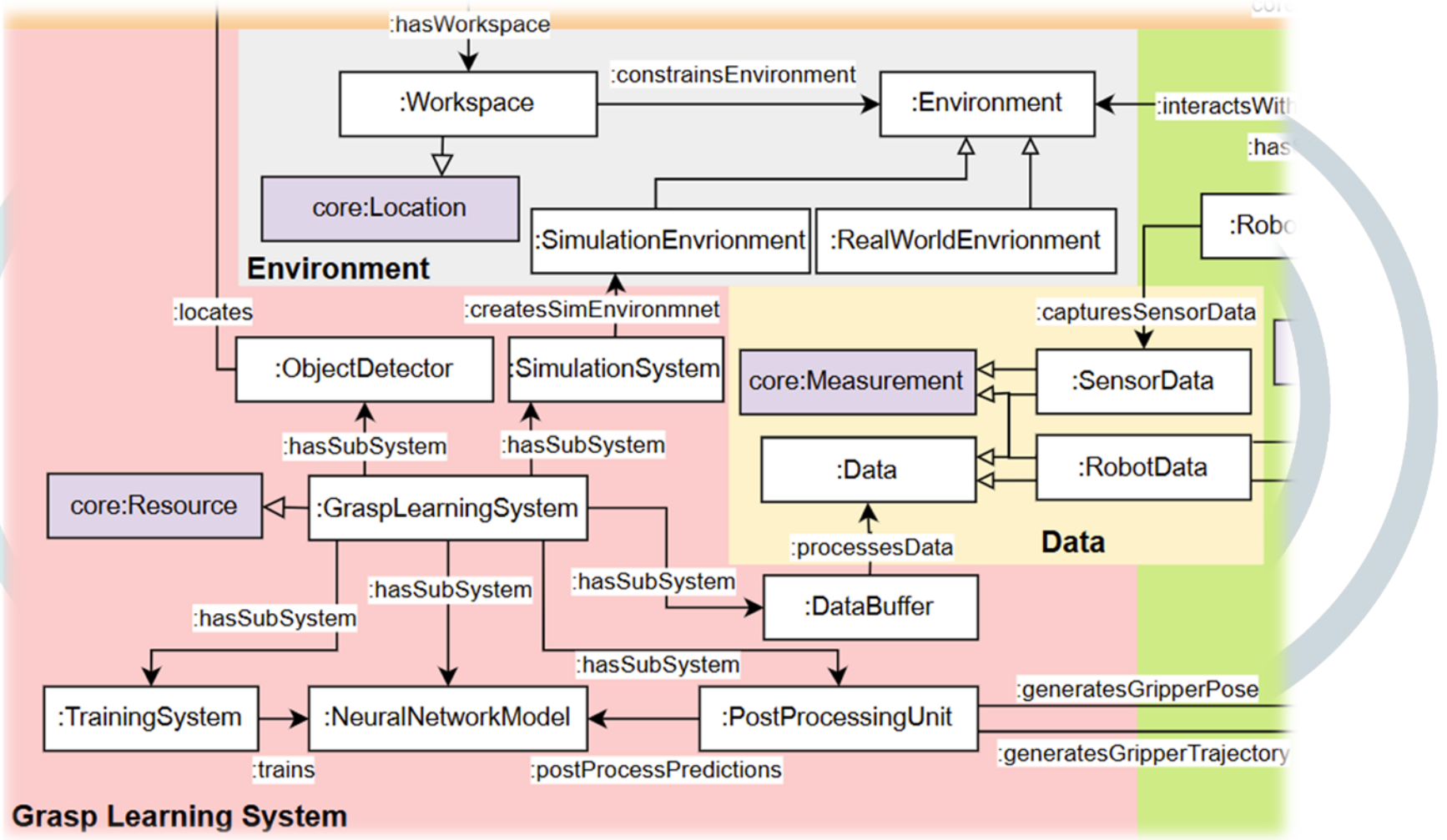
Continual Adaptation



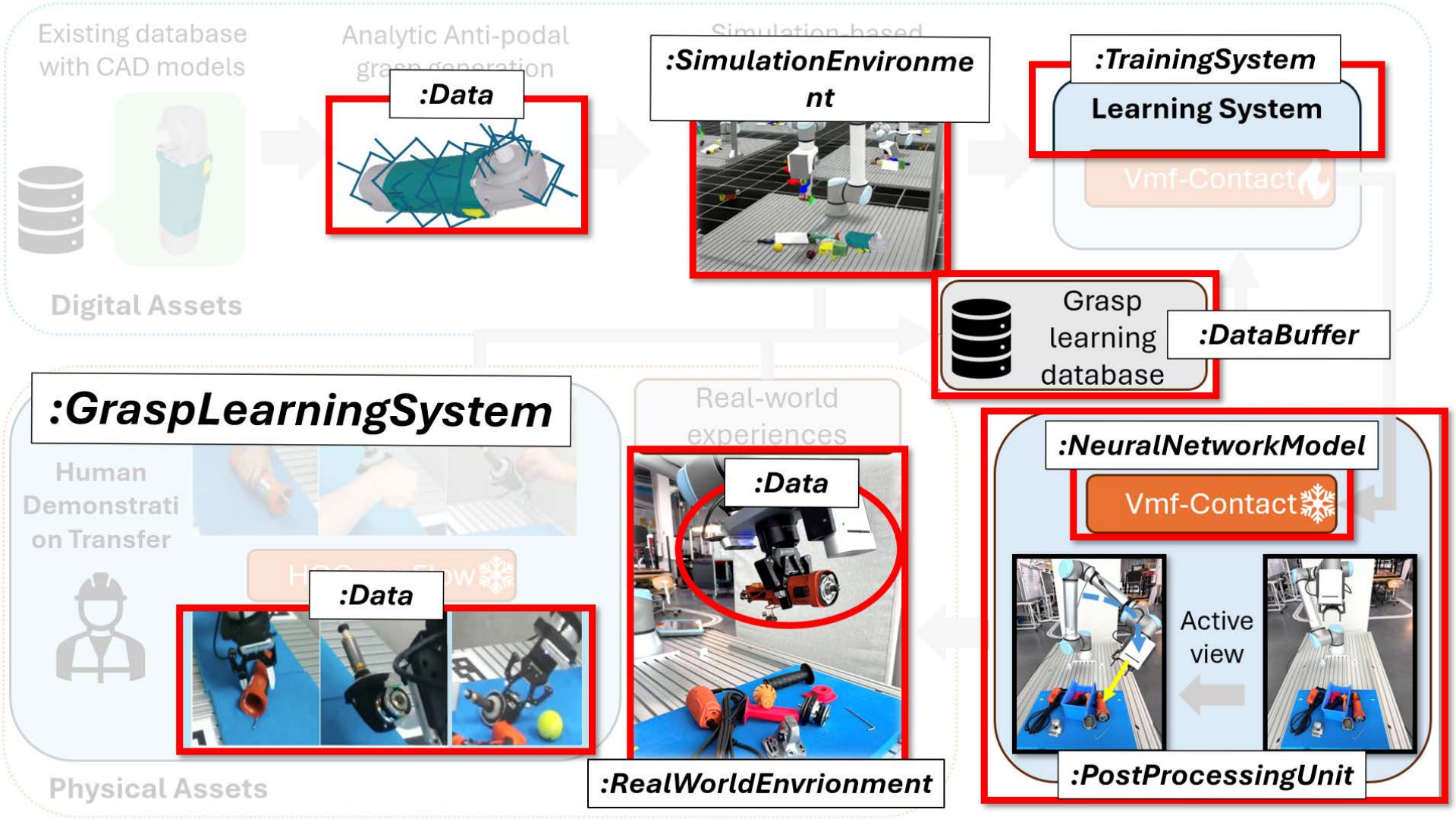




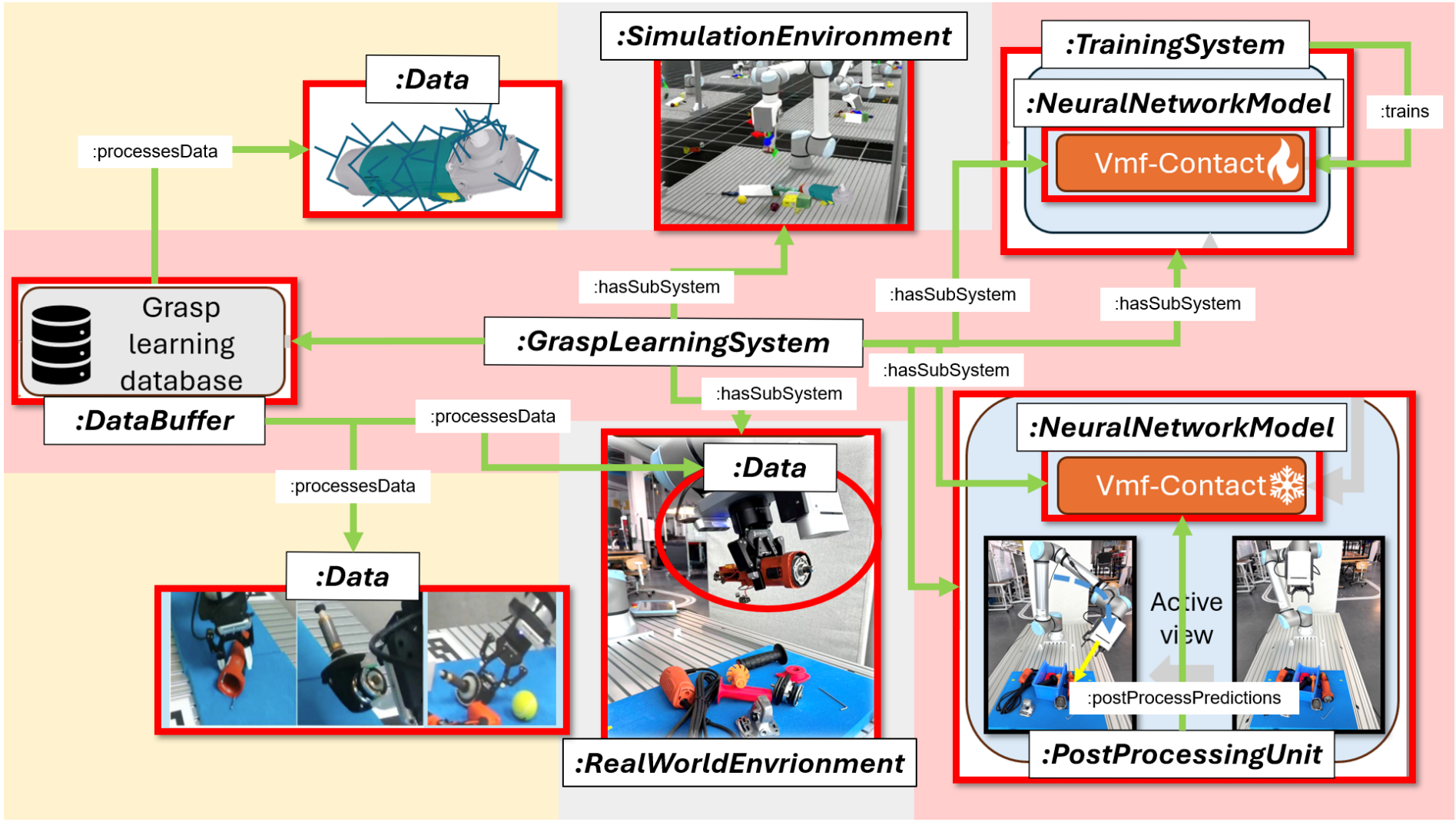
Connection to Knowledge-based Intralogsitics system



Connection to Knowledge-based Intralogsitics system

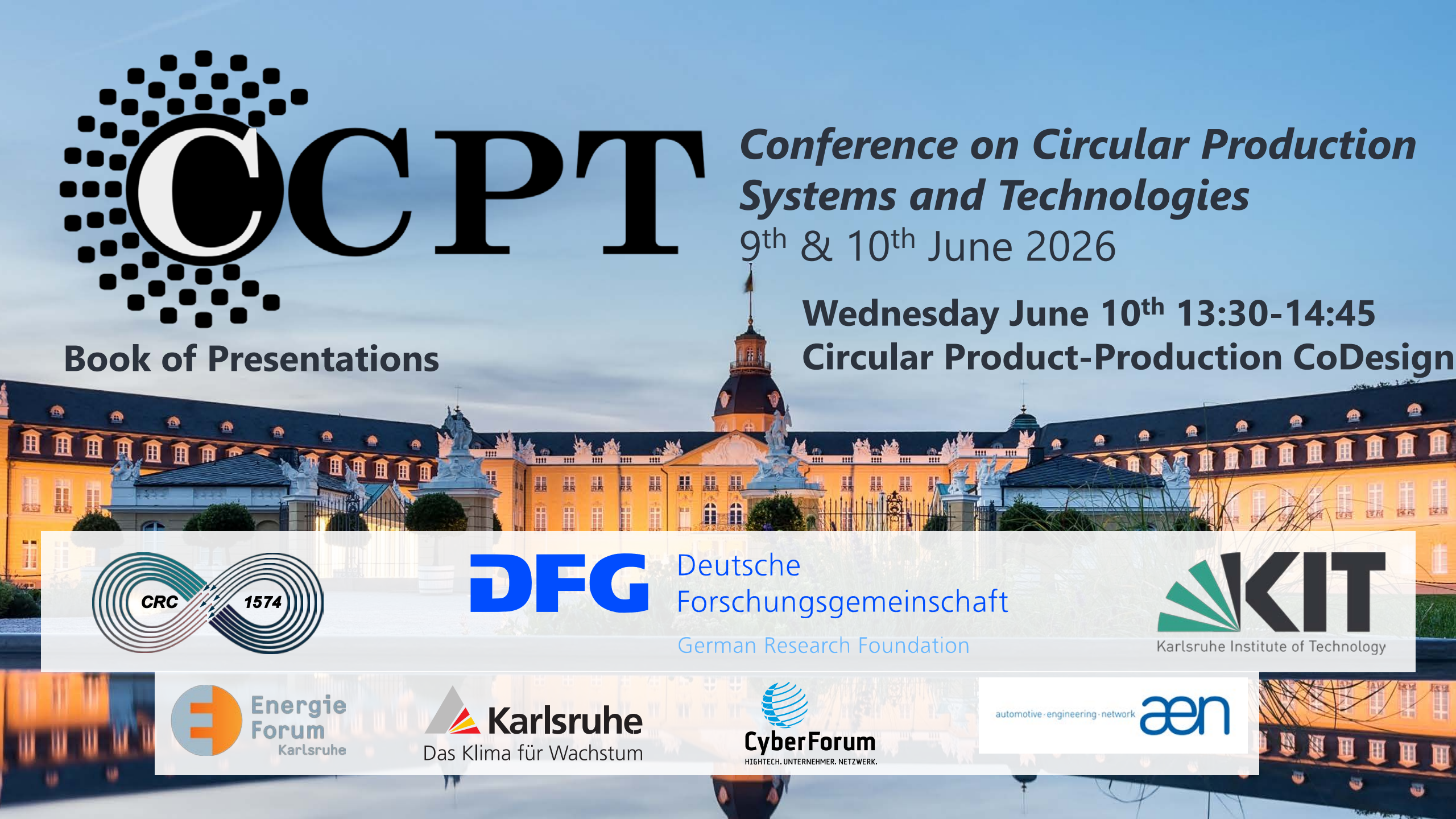


Connection to Knowledge-based Intralogsitics system



Summary

- **We present CIRCA-Grasp:** which provides a unified closed-loop framework for robotic grasping in circular factories by combining synthetic CAD-based data, human demonstration priors, and real-world robot experience.
- **The framework improves robustness under uncertainty:** by integrating uncertainty-aware grasp prediction with active view planning, enabling robots to handle clutter, occlusion, object wear, deformation, and distribution shift.
- **Continuous multi-modal feedback enables long-term adaptation:** execution outcomes are stored in a shared grasp learning database, allowing the system to iteratively refine its policy and generalize to unseen or structurally compromised objects.



CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 13:30-14:45
Circular Product-Production CoDesign

CRC 1574

DFG Deutsche Forschungsgemeinschaft
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CCPT Conference on Circular Production Systems and Technologies
9th & 10th June 2026

Design Thinking for Circular Deconstruction Systems: System Requirement Engineering of an AI-Supported Mobile Artificial Turf Recycling Architecture

by

Nicole Rau, Lorena Lenz,
Doris Aschenbrenner

Presenting author: Maximilian Ummer, Aalen University

Aalen University, E-mail corresponding author: nicole.rau@hs-aalen.de

RewitAI

The Projekt RewitAI - FACTS

- **An interdisciplinary research project, funded by:**
  Ministry of Science, Research and the Arts of Baden-Württemberg (MWK) and European Regional Development Fund (ERDF),
  as part of the “PAN HAW BW programme”.

Baden-Württemberg
MINISTERIUM FÜR WISSENSCHAFT, FORSCHUNG UND KUNST

EFRE
Investition in Ihre Zukunft.

- **Project duration:**
  2023 – 2027 (approx. 4 years).

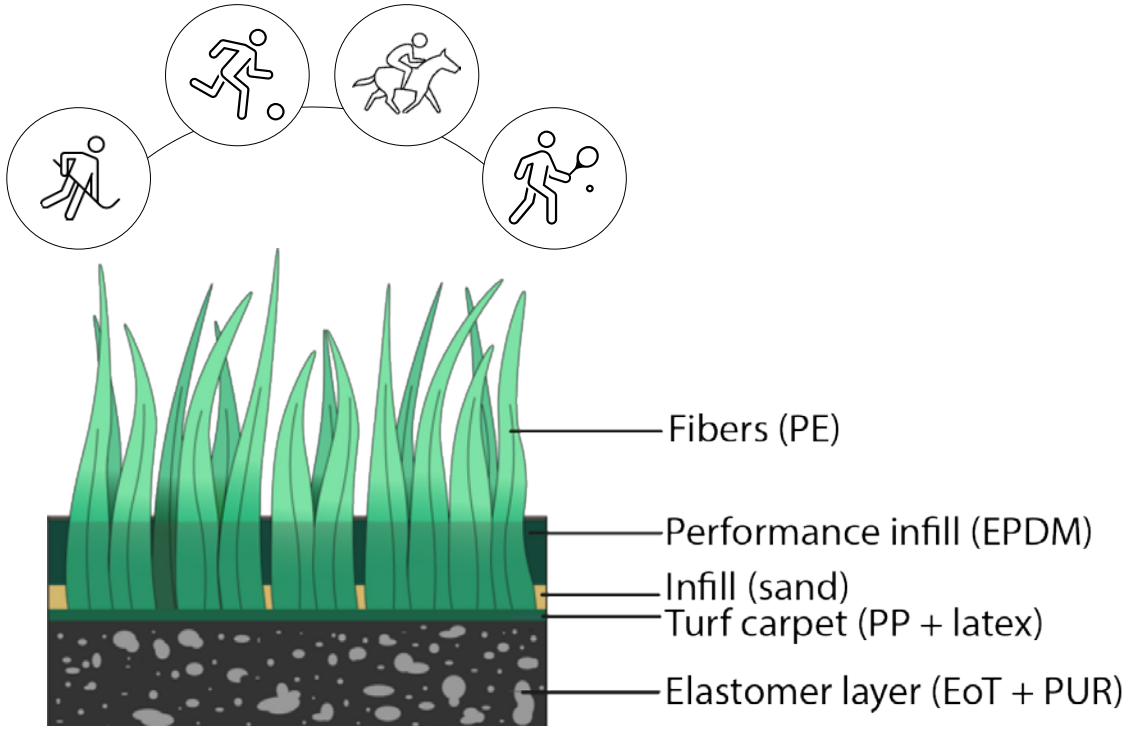
- **Partners:**
  Universities of Aalen (coordination), Furtwangen, Pforzheim, industry and sports partners:

feess · PR RECYCLING Track & Turf · THINKTANK INDUSTRIELLE RESSOURCEN-STRATEGIEN · WeSort.AI · pyrum innovations · TECNARO GESELLSCHAFT ZUR INDUSTRIELLEN ANWENDUNG NACHWACHSENDER ROHSTOFFE mbH · PolymerActive · H2ORG



Motivation

Schematic overview artificial turf:

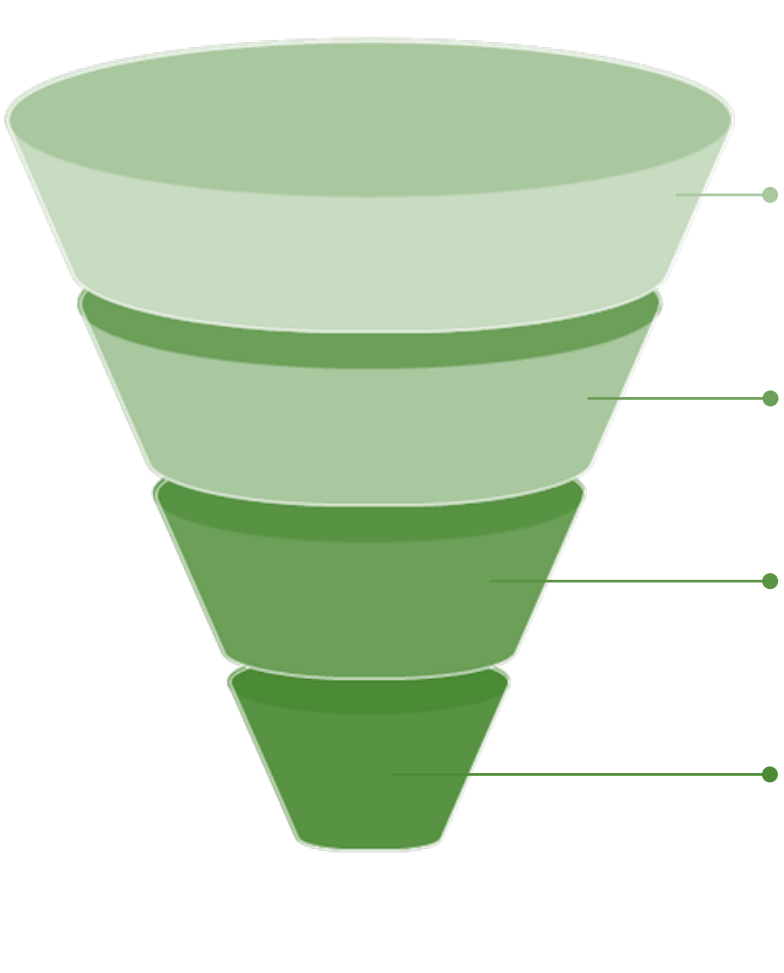


- Cost-effective maintenance
- All-year-round sports facility
- Flexible use in urban areas

- Continuous microplastic release
- Lifespan approx. 15 years
- Complex end-of-life phase, which means:
  - microplastic discharge during deconstruction
  - Limited recyclability
  - Loss of valuable fossil resource

→ Currently no sustainable solutions for the future

Research Gap and Objective



Release of microplastics

Recycling of the materials (end-of-life)

Deconstruction prozess of artificial turf systems (Sota)

Research Gap:
System requirements for future automated turf deconstruction systems



Methodology



1. Context Analysis
   - Market and literature research,
   - Expert interviews,
   - Field Observations
2. Stakeholder Analysis
   - Expert interviews
3. Normative Framework
   - Literature research
4. System Requirements
   - Stakeholder Needs, regulatory and normative requirements.

1.

Context Analysis



1. Cutting in 0,9m wide stripes.



2. Separating the infill-sand mixture from the turf.



3. Rolling up and laying out the turf mats.

1.

Context Analysis

Workforce Challenges
- High personnel requirements (3–4 workers per deconstruction project)
- Staff shortages due to nationwide deployment
- Physically demanding and non-ergonomic work

Environmental Challenges
- Increased microplastic emissions during deconstruction
- No protection against the release of microplastics
- Material is often collected and transported loose on-sit

Technological Challenges
- Existing deconstruction systems are outdated
- Limited potential for automation and autonomous operation
- High transportation costs due to centralized processing



Methodology



1. Context Analysis

Market and literature research,
Expert interviews,
Field Observations

2. Stakeholder Analysis

Expert interviews

3. Normative Framework

Literature research

4. System Requirements

Stakeholder Needs, regulatory and normative requirements.

2.

Stakeholder Analysis

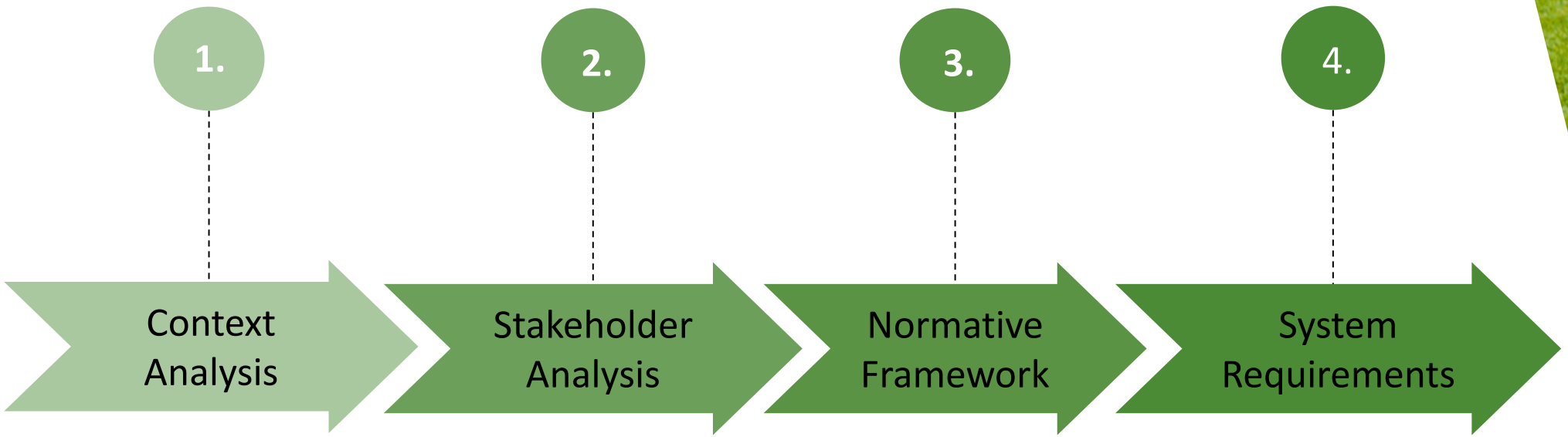
KEEP COMPLETELY INFORMED (High Interest / Low Influence) • LCA Experts • Material Experts • User / Operator	**MANAGE MOST THOROUGHLY** (High Interest / High Influence) • System Experts • Automation Experts • Deconstruction Experts • Recycling Experts • Regulatory Authorities
REGULAR MINIMAL CONTACT (Low Interest / Low Influence) No stakeholders identified	**ANTICIPATE AND MEET NEEDS** (Low Interest / High Influence) • Developers

– INTEREST of STAKEHOLDER +

– INFLUENCE of STAKEHOLDER +



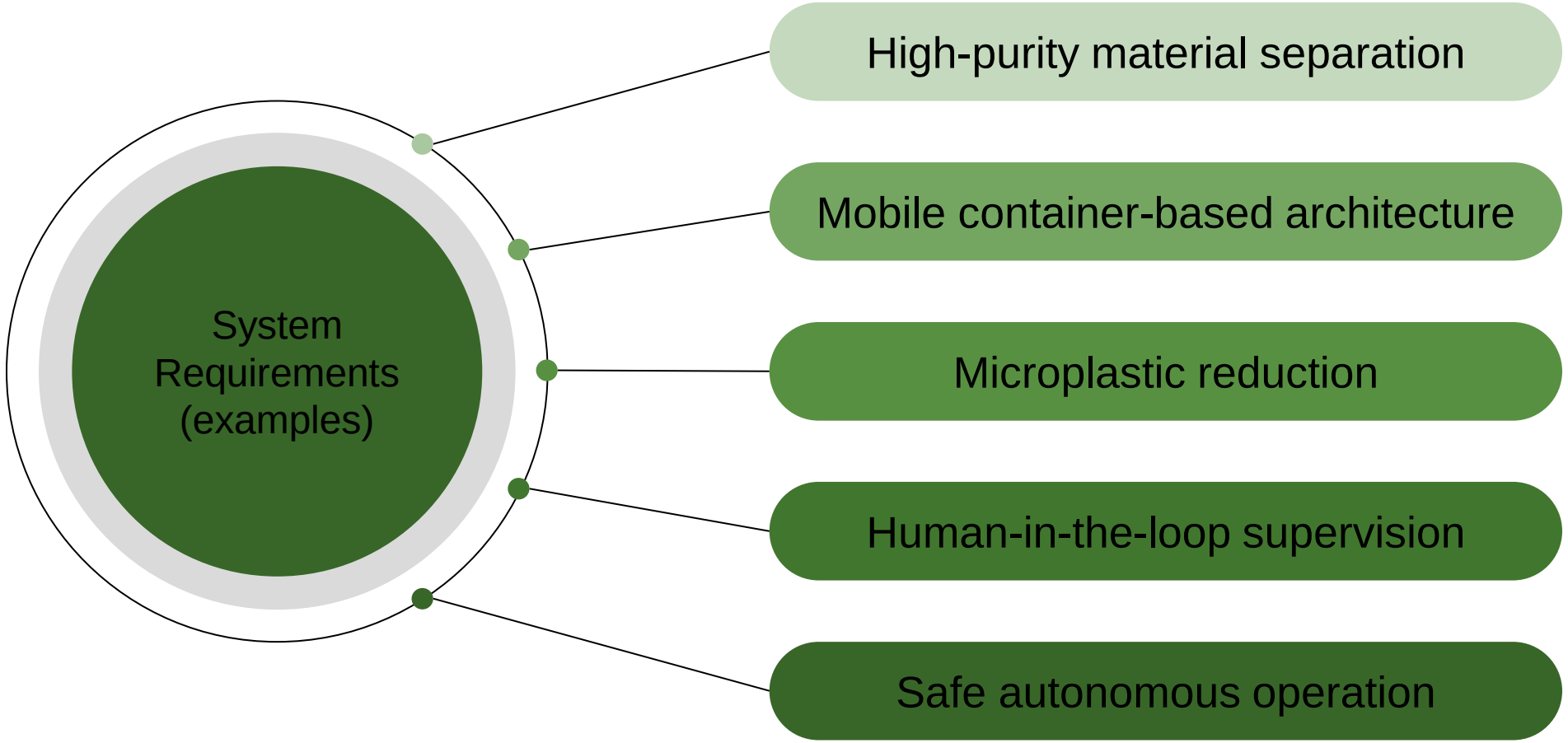
Methodology





4.

Derived System Requirements





Conclusion and Outlook

Conclusion

- Context Analysis,
- Stakeholder Analysis,
- Normative Framework and
- System Requirements.

Next steps

- functional system architecture,
- morphological analyses,
- generate concepts and
- develop prototypes.



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Design Thinking for Circular Deconstruction Systems: System Requirement Engineering of an AI-Supported Mobile Artificial Turf Recycling Architecture

by

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RewitAI

TU Clausthal

IMW
TU Clausthal

Methodology for Integrating MBSE and LCA based on Variation Analysis in Engineering of Product Generations

Conference on Circular Production Systems and Technologies

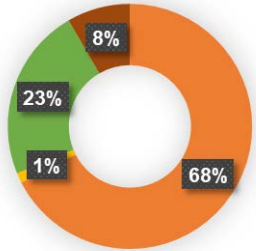
Thomas Schumacher, David Inkermann
TU Clausthal, Institute of Mechanical Engineering

June 10th, 2026

Motivation and Problem Statement



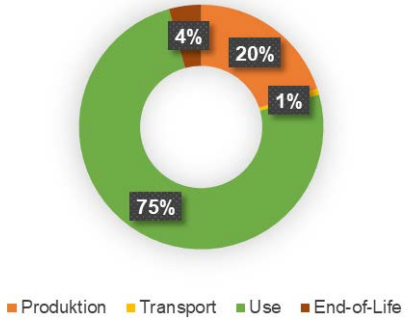
Husqvarna, Automower 220 AC



Eco-Indicator 99



Husqvarna, lawnmower LC48VE



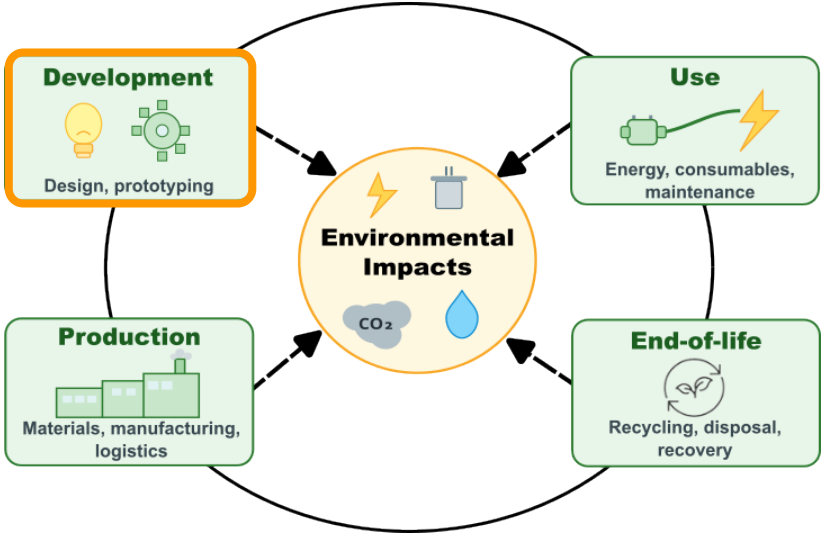
- Quantifying potential environmental impacts of product systems to evaluate EcoDesign strategies in early design stages

Current Challenges

- Large number and diversity of components and technologies
- Strongly differing component lifetimes
- Wide range of potential use cases

Eco-Indicator 99: Damage categories: human health, ecosystem quality, and resource stocks

Motivation and Problem Statement



Environmental impacts resulting from different system life cycle phases

- LCA typically focuses on detailed system design; conceptual design is often neglected
- Component properties such as geometry, weight, and materials are analyzed
- **Limitation:** optimizations at this stage usually impact only future product generations

Early-stage design decisions are essential for reducing environmental impacts

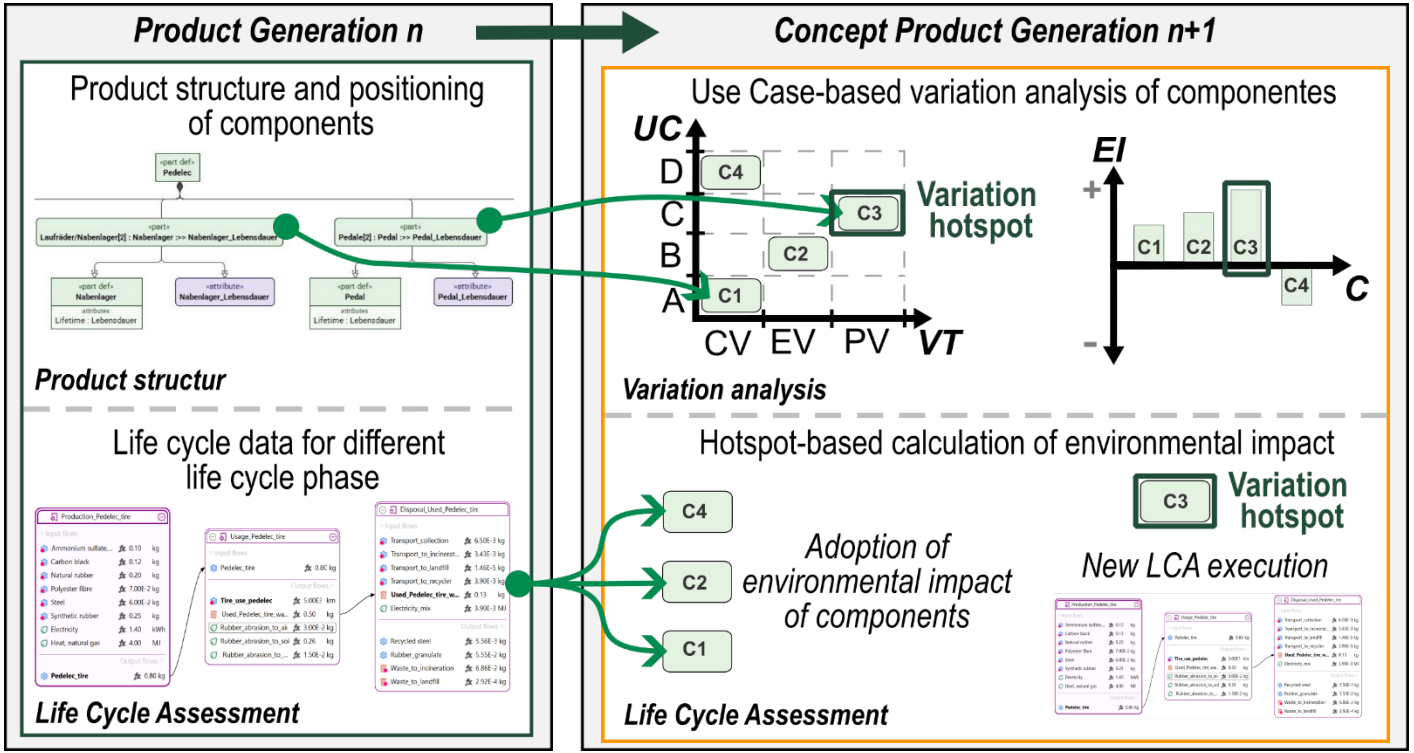
Prospective LCA and Uncertainties

- **Prospective LCA** enables early environmental assessment when design flexibility and improvement potential are highest
- Uncertainties Associated with LCA in Conceptual Design Stage
  - **Model Structure Uncertainties**
    Arise from mismatches between modeled relations and the real system
  - **Study Context Uncertainties**
    stem from choices in goal and scope definition, such as the functional unit or weighting factors
  - **Data Uncertainties**
    result from limited data availability in conceptual design and reliance on transferable data from comparable products

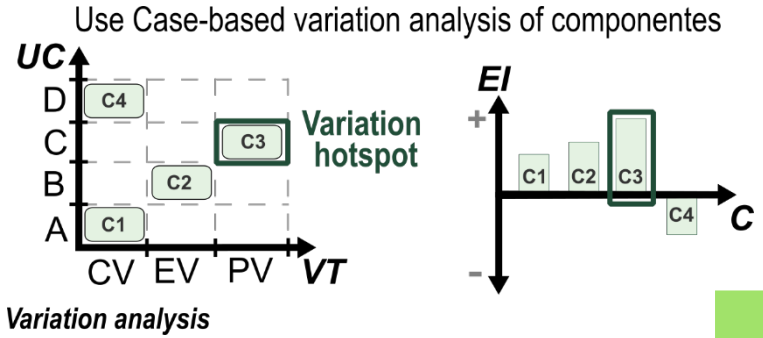
Prospective LCA shows high uncertainty due to data gaps, unknown relationships, and an evolving study context.

The objective of this paper is to address those by developing a similarity-based LCA approach.

Concept Similarity-based LCA



Variation Analysis of Components



Established PGE variation types need to be refined to allocate them more accurately to the life cycle phases and assess their impact

Procedure for determining LCA-oriented subcategories of the PGE variation types and investigating their impact on LCA

1. Decompostion of the PGE variation types
2. Formation of LCA-oriented subcategories of the PGE variation types
3. Deriving LCA impact logic for each subcategory

LCA-oriented Refinement of Variation Types

Product description levels:

1. System/ function level
   (function structure, system architecture)
2. Working principle level
   (mechanical vs. thermal separation)
3. Component/ technology level
   (type of motor, sensor, joining technology)
4. Parameter and usage level
   (dimensions, user behaviour)

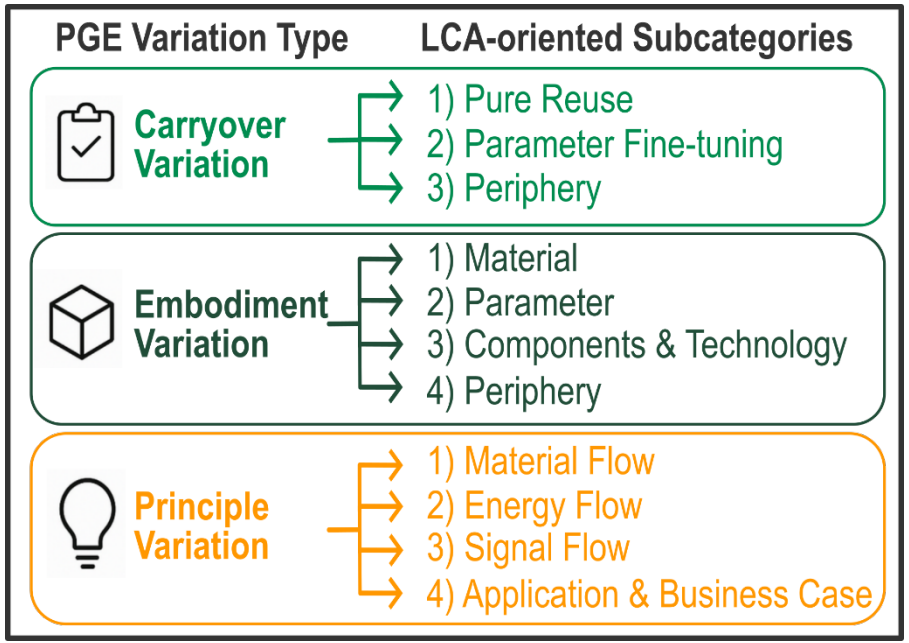
Ecodesign strategies:

- Material substitution
- Life-time extension
- New application models

→ specific patterns of environmental relevance across the life cycle

- **Analyze recurring change mechanisms within each variation type and description level**
- **Combine those with environmental impact pattern from ecodesign strategies to identify affected life cycle phases**

LCA Impact Logic for each Subcategory



Refined PGE variation types into LCA-oriented subcategories

- Specify how and to what extent the *variation type x subcategory* affects the life cycle phases
- Recommendation of appropriate LCA scope
- **Outcome:**
  Decision matrix for defining LCA scope based on the amount of variation

LCA Impact Logic for each Subcategory

Variation Type		Life Cycle Stages R	M	D	U	E	LCA
Carryover Variation	1) Pure Reuse	○	○	○	○	○	Reuse results
	2) Parameter fine-tuning	+	+	○	○	+	Reuse results
	3) Periphery	○	○	+	○	○	Reuse results
Embodiment Variation	1) Material	++	+	○	○	+	Partially, focus R
	2) Parameter	+	++	+	○	+	Partially, focus M
	3) Components & Technology	+	++	○	+	+	Partially, focus M
	4) Periphery	○	○	++	○	○	Partially, focus D
Principle Variation	1) Material Flow	++	++	○	++	++	New, complete
	2) Energy Flow	+	++	○	++	+	New, complete
	3) Signal Flow	+	++	○	++	+	New, complete
	4) Application & Business Case	+	++	+	++	+	New, complete

Legend

R - Raw material acquisition / extraction
M - Manufacturing / production
D - Distribution / transport / logistics
U - Use phase / operation
E - End-of-Life

○ *no or negligible influence*
\+ *relevant, but rather limited/indirect influence*
++ *strong or dominant influence*

Decision matrix for defining LCA scope based on the variation type

Conclusion and Future Work

- Integrating LCA into the **conceptual design** is associated with considerable uncertainty and effort
- Similarity-based LCA approach analyses **product changes** and evaluates their **consequences for the life-cycle stages** relative to the previous product generation
- Contribution is a **systematic allocation** of product changes to their expected influence on the different life-cycle stages
- **PGE variation types are refined** into LCA-oriented subcategories that more accurately align with the life-cycle phases
- **Decision matrix** recommends required **LCA scope** based on the product change

- Verify the proposed allocation between refined variation types and life-cycle stages
- by applying in practical engineering projects and by reviewing it with LCA practitioners
- Technical implementation in MBSE – LCA integration

Thank you for your Attention!





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9th & 10th June 2026

Evaluating the Disassembly Map for Hybrid Human-Robot Remanufacturing: Operative Parameters and Structural Gaps

by

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Nicole Stricker, Doris Aschenbrenner

Hochschule Aalen
UNIVERSITY OF APPLIED SCIENCES

RePAIR labor

Presenting author: Maximilian Ummer, Aalen University

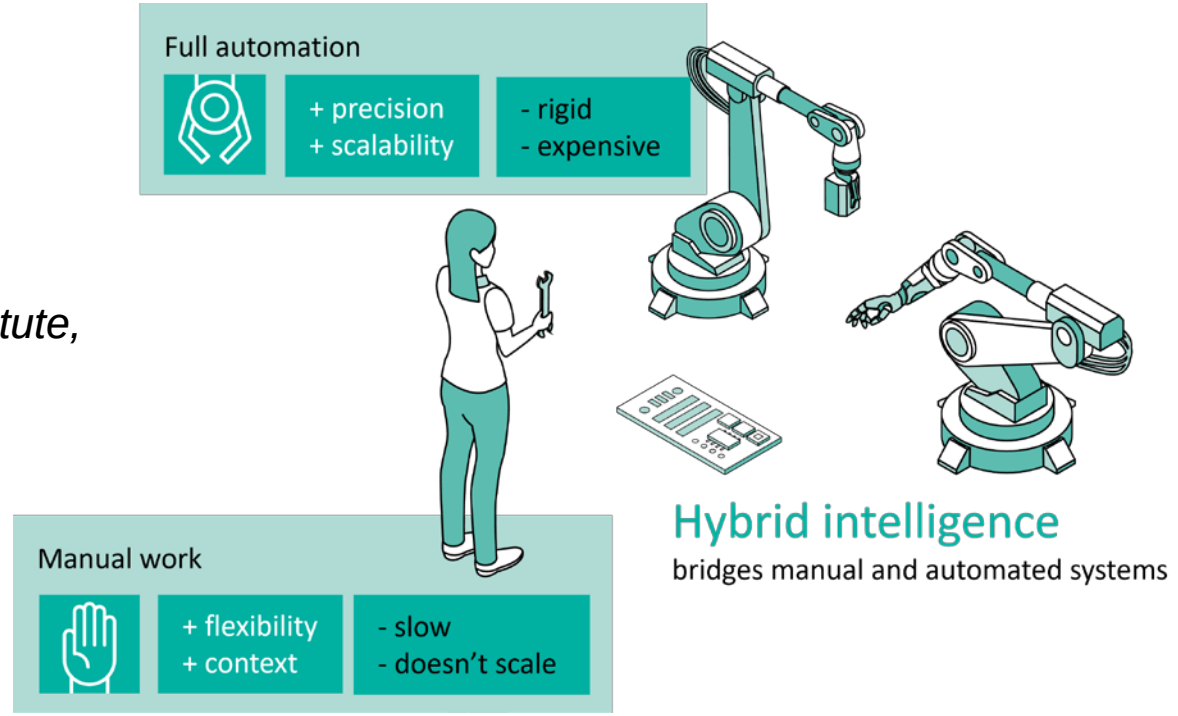
The Project RePAIR

- **Project duration:**

  2026 – 2029 (4 years)
- **Partners *(associated):***

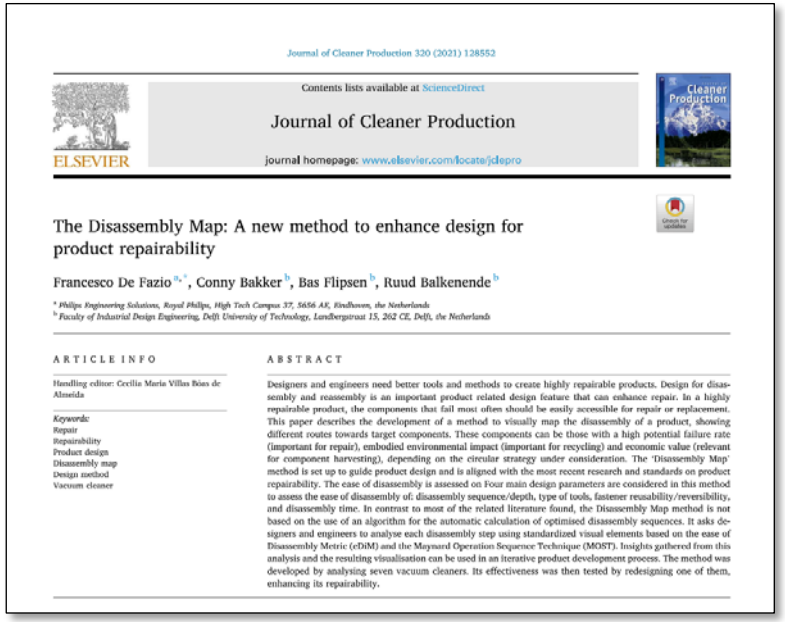
  Aalen University*, Harting, Siemens, Honda Research Institute, Ollo, WeSort.AI, KIT, Hackwerk, Graduate Campus*
- **Project aim:**

  Hybrid intelligence enabling efficient, human-centered remanufacturing at scale
- **Challenge:**
  - Automated HRC task allocation requires structured operative process information [11, 12] – current methods don't provide it [13, 14]



Evaluation of the De Fazio Disassembly Map against requirements

→ Petri nets, AND/OR graphs, and knowledge graphs optimise sequences, but abstract away the operative parameters needed for HRC task allocation. The Disassembly Map captures them directly.



Journal of Cleaner Production 320 (2021) 128552

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

The Disassembly Map: A new method to enhance design for product repairability

Francesco De Fazio [a,*], Conny Bakker [b], Bas Flipsen [b], Ruud Balkenende [b]

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ARTICLE INFO

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ABSTRACT

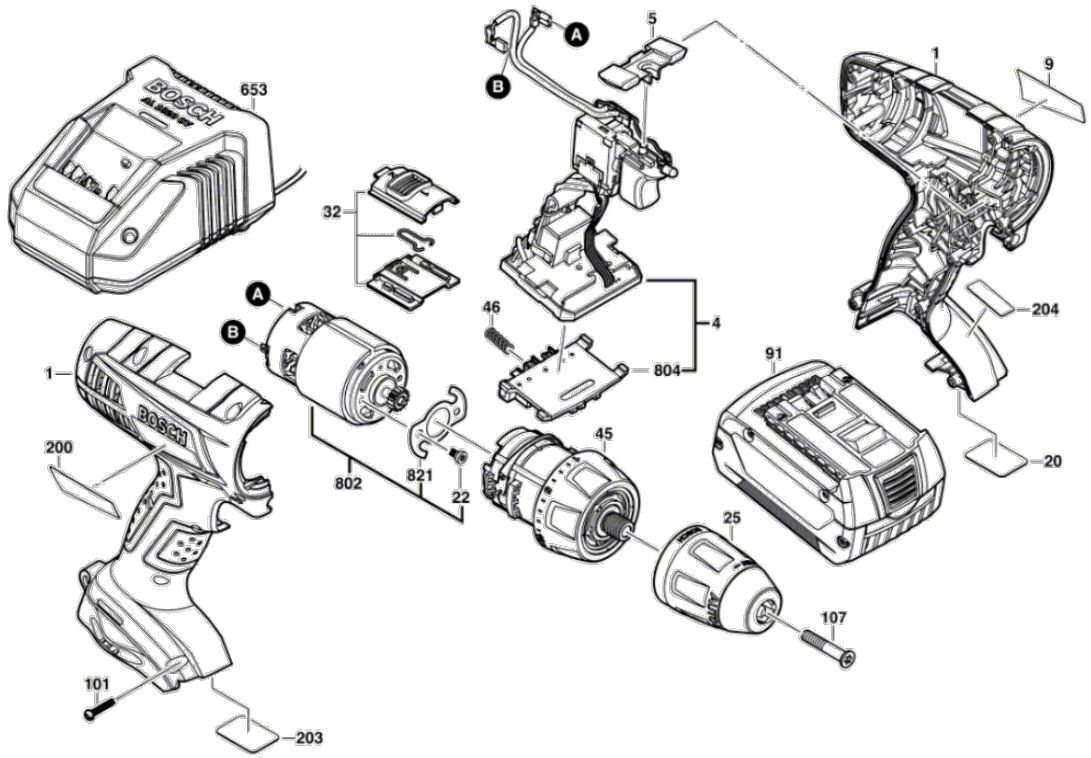
Designers and engineers need better tools and methods to create highly repairable products. Design for disassembly and reassembly is an important product related design feature that can enhance repair. In a highly repairable product, the components that fail most often should be easily accessible for repair or replacement. This paper describes the development of a method to visually map the disassembly of a product, showing different routes towards target components. These components can be those with a high potential failure rate (important for repair), embodied environmental impact (important for recycling) and economic value (relevant for component harvesting), depending on the circular strategy under consideration. The 'Disassembly Map' method is set up to guide product design and is aligned with the most recent research and standards on product repairability. The ease of disassembly is assessed on Four main design parameters are considered in this method to assess the ease of disassembly of: disassembly sequence/depth, type of tools, fastener reusability/reversibility, and disassembly time. In contrast to most of the related literature found, the Disassembly Map method is not based on the use of an algorithm for the automatic calculation of optimised disassembly sequences. It asks designers and engineers to analyse each disassembly step using standardized visual elements based on the ease of Disassembly Metric (eDiM) and the Maynard Operation Sequence Technique (MOST). Insights gathered from this analysis and the resulting visualisation can be used in an iterative product development process. The method was developed by analysing seven vacuum cleaners. Its effectiveness was then tested by redesigning one of them, enhancing its repairability.

De Fazio, F., Bakker, C., Flipsen, B., Balkenende, R.: The disassembly map: A new method to enhance design for product repairability. Journal of Cleaner Production 320, 128552 (2021).

ID	CRITERION
1	Structural process information [11,12]
2	Condition-aware component annotation [23]
3	Bidirectional process coverage [7]
4	Task-type classification [24, 25]

Use case product



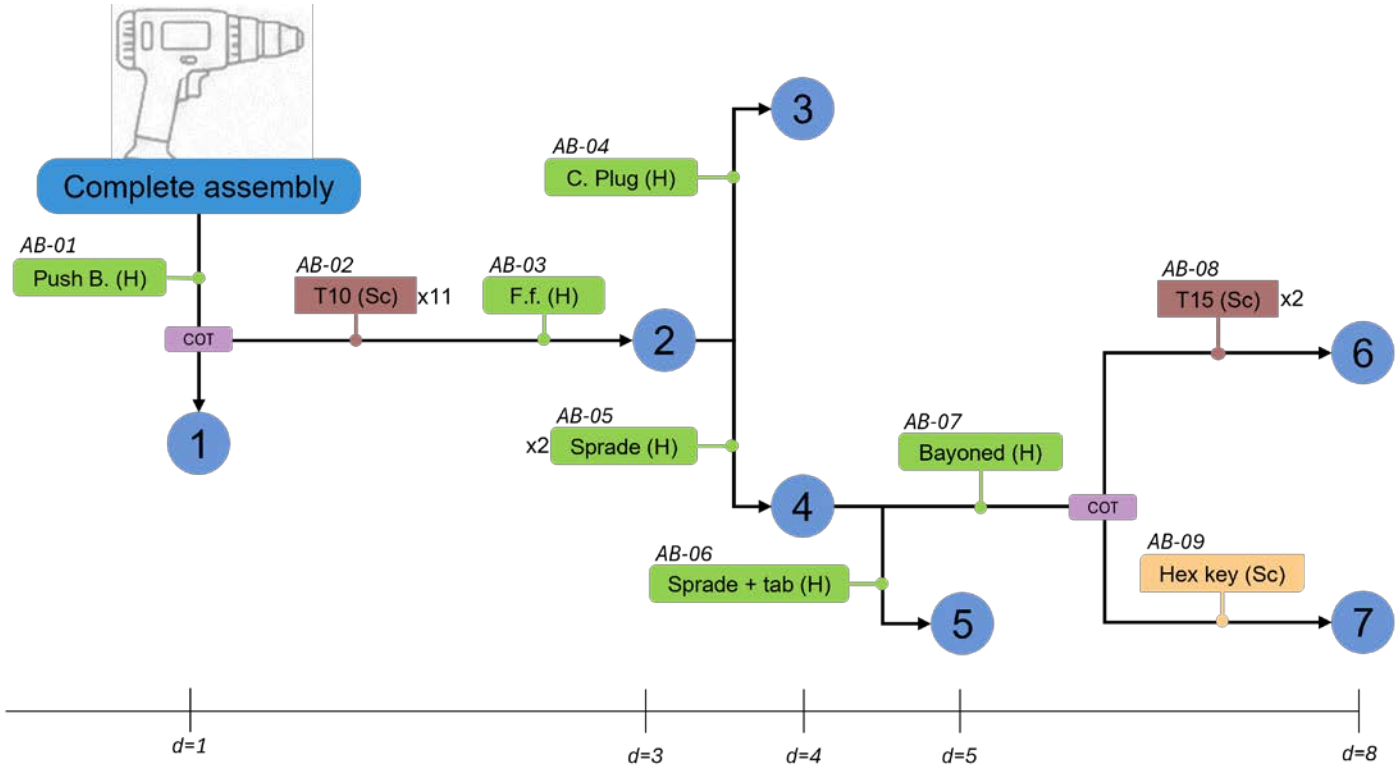


iFixit: Bosch 36618 Drill Driver Teardown (2016). https://de.ifixit.com/Teardown/Bosch+36618+Drill+Driver+Teardown/56493, last accessed 2026/05/11.

Modelled action blocks of the disassembly sequence

ID	OPERATION	ACCESSIBILITY	FASTENING TYPE
AB-01	Remove battery	Direct	Plug
AB-02	Release 11 housing screws	Direct	Torx T10
AB-03	Separate housing halves	After AB-02	Form-fit
AB-04	Remove speed selector	After AB-03	Plug
AB-05	Remove motor-chuck assembly	After AB-03	Spade connector
AB-06	Disconnect electrical connections	After AB-05	Spade connector
AB-07	Separate motor from chuck unit	After AB-05	Bayonet
AB-08	Remove slide plate	After AB-07	Torx T15
AB-09	Remove chuck	After AB-07	Hex screw

Disassembly Map



Legend

Components

1. Power supply
2. Housing Halves
3. Speed Selector
4. Motor-Chuck Assembly
5. Electrical Coon.
6. Slide Plate
7. Chuck

Motion Type

= Hand motion
= Single motion tool
= Multiple motion tool

Penalties

= Penalty
COT = Change of tool

Connectors

Push B. = Push button
C. Plug = Cable plug
F.f. = Form-fit

Type of tool

(H) = Hand
(Sc) = Screwdriver

Evaluation of the Disassembly Map against operative requirements

CRITERION	ASSESSMENT	STATUS
Structural process information	Operation sequences, tool requirements, fastening types, and accessibility hierarchies are reliably extractable from product architecture.	Fulfilled
Condition-aware component annotation	Wear, degradation, and remaining service life are not represented; Core Quality Uncertainty cannot be reflected.	Not representable
Bidirectional process coverage	Reassembly is outside the method's defined scope; reassembly-specific constraints are not representable.	Out of scope
Task-type classification	Operation characteristics are captured but not classified with respect to human or robot execution suitability.	Requires extension

Research directions for extending the Disassembly Map

Foundation:

The Disassembly Map provides reproducible, process-level information on product architecture, but requires targeted extension to enable automated task generation in hybrid human-robot systems.

Condition-aware annotation

Enable degradation-aware operative planning by integrating component condition and Core Quality Uncertainty [23] into the process model.

Bidirectional process modelling

Extend to remanufacturing process chain coverage, capturing reassembly-specific constraints [7].

Task-type clarification

Add a layer mapping operation characteristics to human or robot execution suitability, incorporating force/torque requirements, component weight, precision demands, and ergonomic risk factors [24, 25].

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RePAIR labor

Gefördert durch:

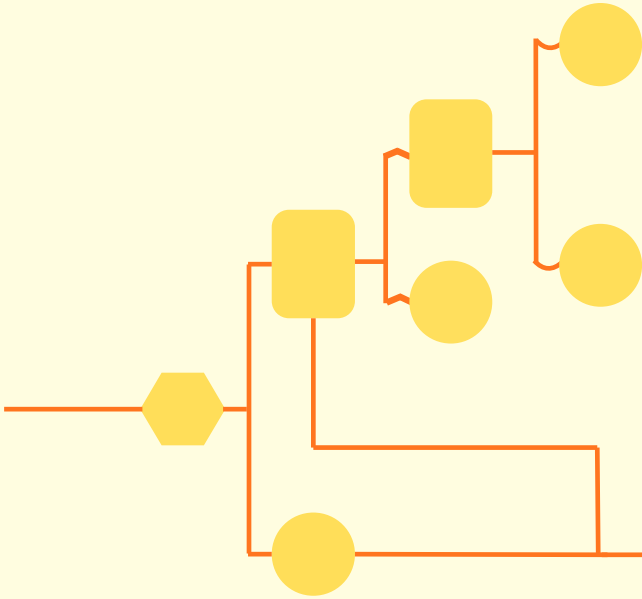
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ADAPTABLE DISASSEMBLY MAP FOR DESIGN FEEDBACK



Mechanical Engineering Department, College of Design and Engineering, National University of Singapore, Singapore

Ng Xin Le
S. K. Ong

NUS National University of Singapore | College of Design and Engineering

DISASSEMBLY

Planning, optimisation and evaluation
of disassembly sequences

DISASSEMBLY

Planning, optimisation and evaluation
of disassembly sequences

↓

Information Communication

DISASSEMBLY

Planning, optimisation and evaluation of disassembly sequences

↓

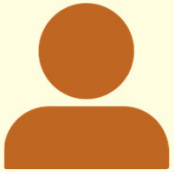
Information Communication

↓

How can we communicate different pieces of information to different stakeholders with varying interests?

DISASSEMBLY

How can we communicate different pieces of information to different stakeholders with varying interests?



Designer

Operations

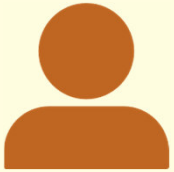


Engineer

DISASSEMBLY

How can we communicate different pieces of information to different stakeholders with varying interests?

Part relations



Designer

Salvage value

Operations

Enviromental Imapct

Disassembly time

Connectors

Safety



Engineer

Tools used

DISASSEMBLY

How can we communicate different pieces of information to different stakeholders with varying interests?

Disassembly Details

Safety

Economic Index

Environmental Index

DISASSEMBLY

How can we communicate <u>different pieces of information</u> to different stakeholders with varying interests?

Disassembly Details

Disassembly Steps

Disassembly Time

Tools Used

Connectors

Part Conditions

Safety

Economic Index

Environmental Index

Maynard Operation Sequence Technique (MOST)

Standard time for a step
= Time measurement unit (TMU) x 0.036

Actions and part manipulation

Part size

Tools used

DISASSEMBLY

How can we communicate <u>different pieces of information</u> to different stakeholders with varying interests?

Disassembly Details

Disassembly Steps

Disassembly Time

Tools Used

Connectors → Adhesives, screws, types of fits, etc

Part Conditions → Rust, glue, lubricants, chips and breaks, etc

Safety

Economic Index

Environmental Index

DISASSEMBLY

How can we communicate <u>different pieces of information</u> to different stakeholders with varying interests?

Disassembly Details

Safety

Economic Index

Environmental Index

Safety Factor
= Likelihood x Serverity

Likelihood

Serverity

Type

S \ L	1	2	3
1	1	2	3
2	2	4	6
3	3	6	9

3 x 3 risk matrix

DISASSEMBLY

How can we communicate <u>different pieces of information</u> to different stakeholders with varying interests?

Disassembly Details

Safety

Economic Index

Environmental Index

Safety Factor
= Likelihood x Serverity

S \ L	1	2	3
1	1	2	3
2	2	4	6
3	3	6	9

3 x 3 risk matrix

Likelihood

Serverity

Type → ISO Workplace Hazards

Hazard	Indicator
General Safety	A
Chemical	B
Physical	C
Ergonomic	D
Biological	E
Psycological	-

DISASSEMBLY

How can we communicate different pieces of information to different stakeholders with varying interests?

Disassembly Details

Safety

Economic Index

Salvage value



Weight (kg) x Selling price of recycled material

Environmental Index

DISASSEMBLY

How can we communicate <u>different pieces of information</u> to different stakeholders with varying interests?

Disassembly Details

Safety

Economic Index

Environmental Index

Recyclability =
Disassembly Rating x Material Recycle Fraction

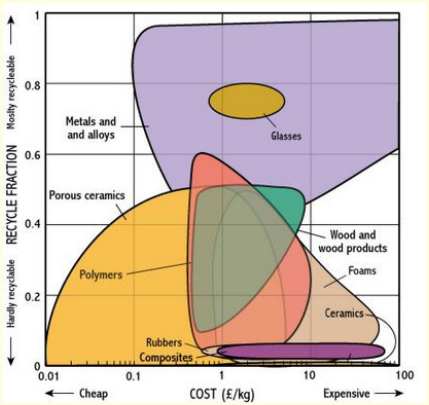
Recyclability

Remanufacturability

Reusability

	Material Connection		Frictional Connection				Positive Connection				
Disassembly rating	Adhesive Bonding	Welding	Magnetic	Velcro	Nut & Bolt	Spring Connection	Snap	Bent Lever	¼ turn	Press turn	Press-Press
	2	1	2	2	2	3	3	3	3	2	2
For the math	0.333	0.333	0.667	0.667	0.667	1	0.333	1	1	1	1

Disassembly rating: Good = 3, Average = 2, Bad = 1



Material Recycle Fraction

DISASSEMBLY

How can we communicate <u>different pieces of information</u> to different stakeholders with varying interests?

Disassembly Details

Safety

Economic Index

Environmental Index

Recyclability

Remanufacturability

Reusability

True/False depending on:

- Material
- Part condition

DISASSEMBLY

How can we communicate different pieces of information to different stakeholders with varying interests?

Disassembly Details

Disassembly Steps

Disassembly Time

Tools Used

Connectors

Part Conditions

Safety

Likelihood

Serverity

Type

Economic Index

Salvage value

Environmental Index

Recyclability

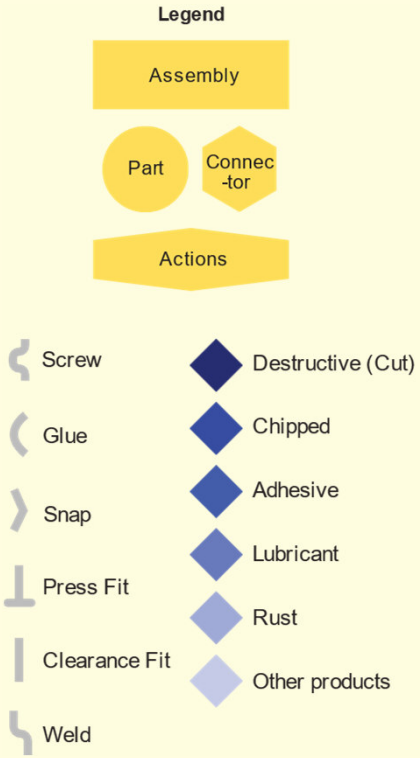
Remanufacturability

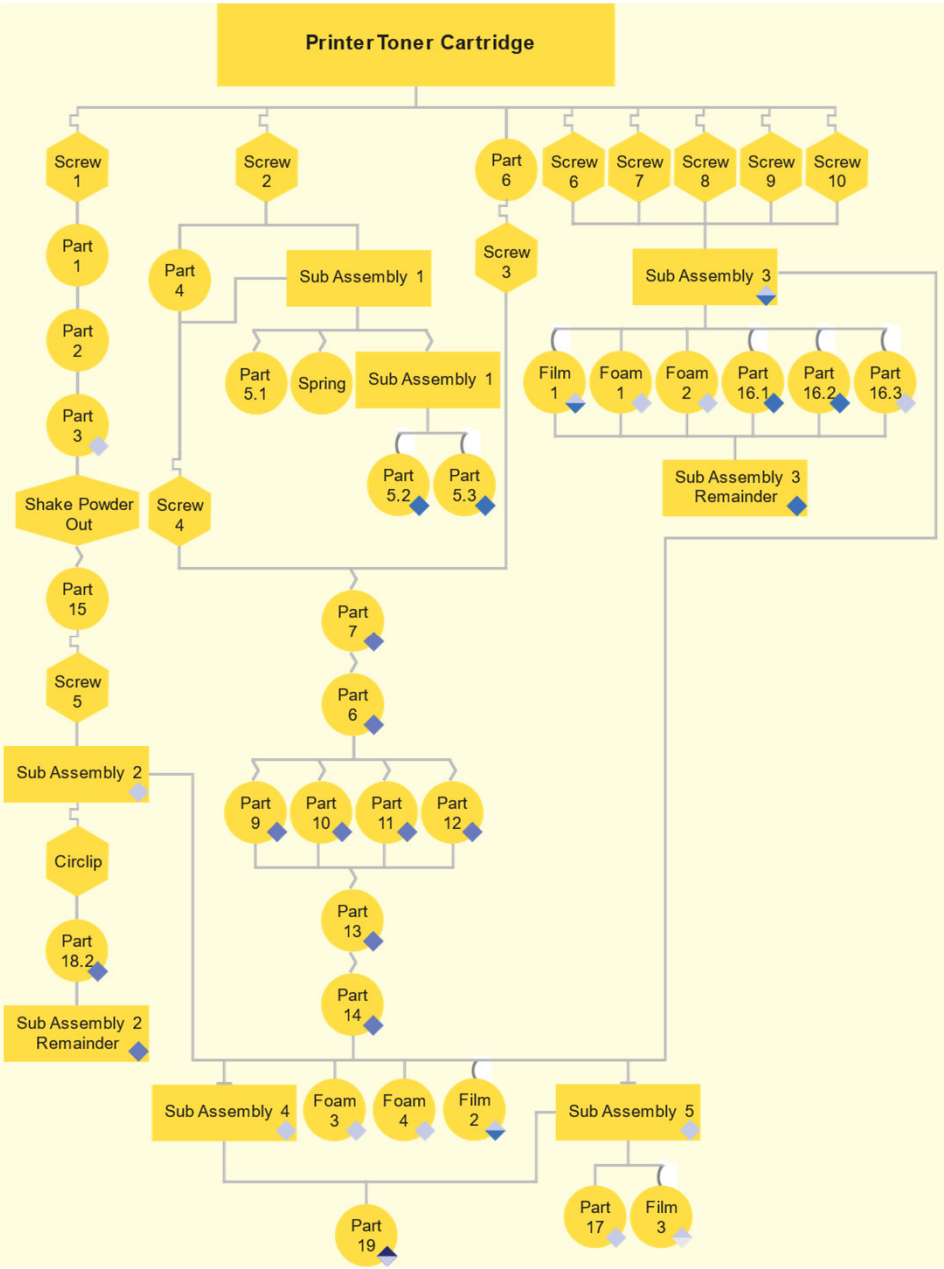
Reusability



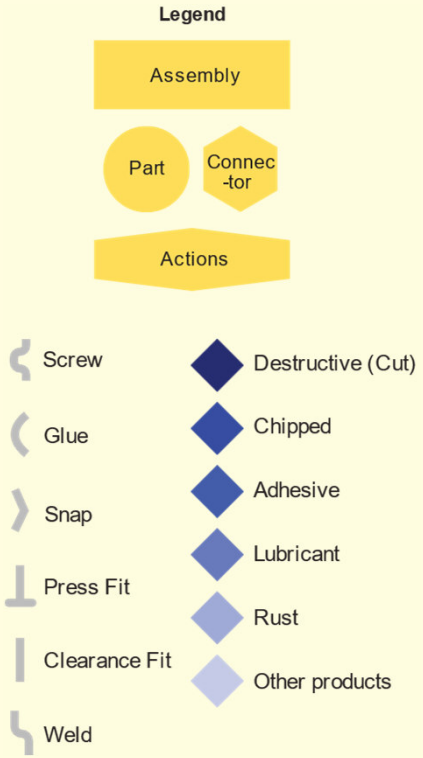
Used printer toner

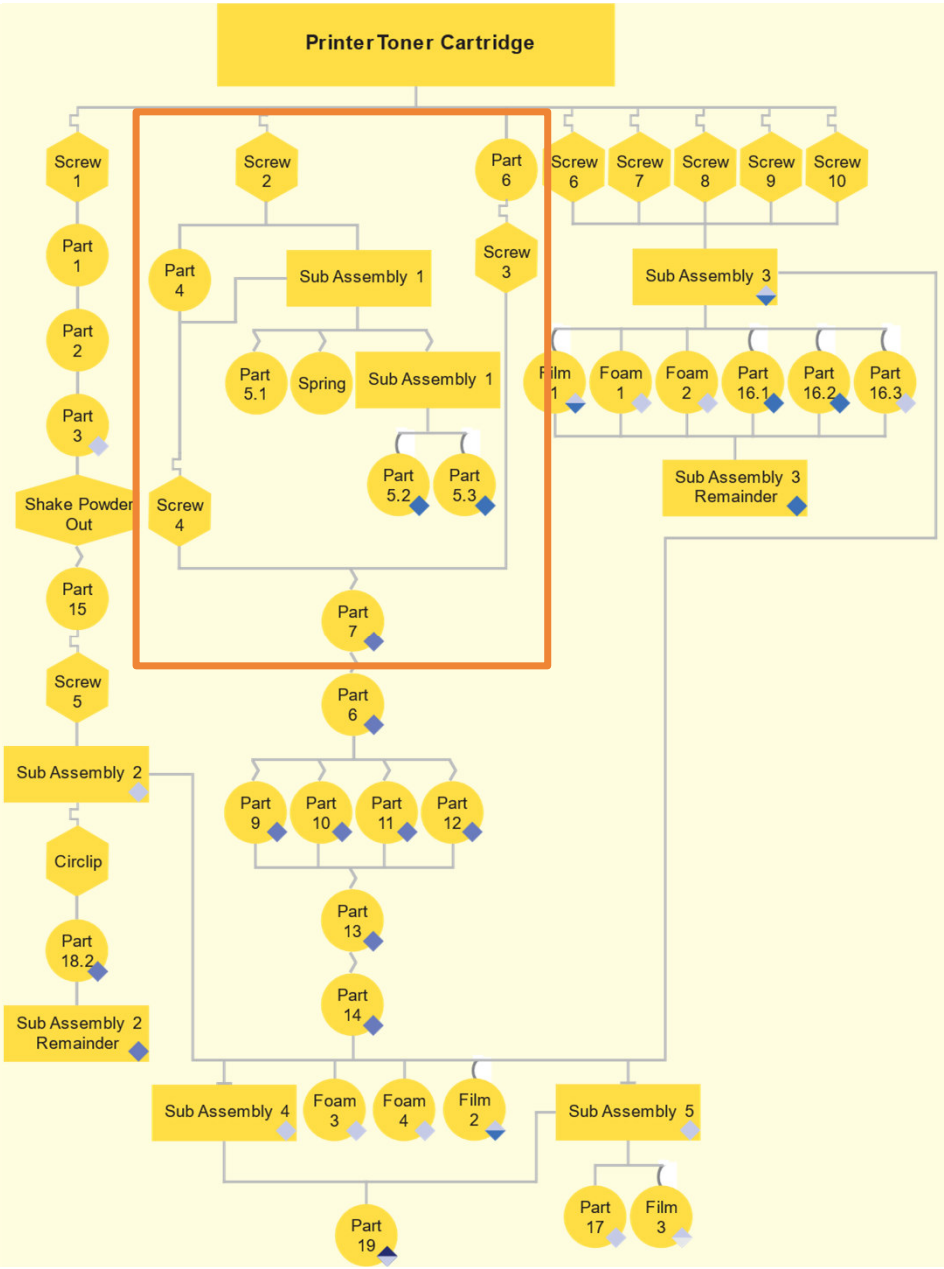
DISASSEMBLY MAP (BASE)





DISASSEMBLY MAP (BASE)





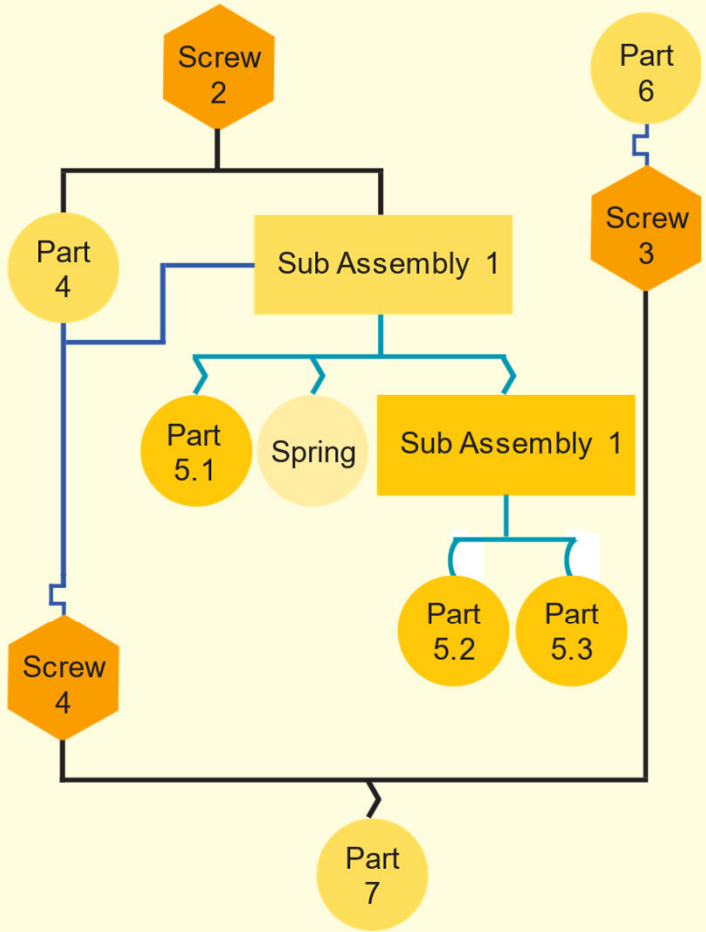
DISASSEMBLY MAP

Tool Used

- Hands
- Philips Screwdriver
- Pliers
- Circlip Plier
- Ultrasonic Cutter
- Flathead Screwdriver

Disassembly Time

- < 3s
- 3 - 5s
- 5 - 10s
- 10 - 20s
- > 20s



DISASSEMBLY MAP

Likelihood

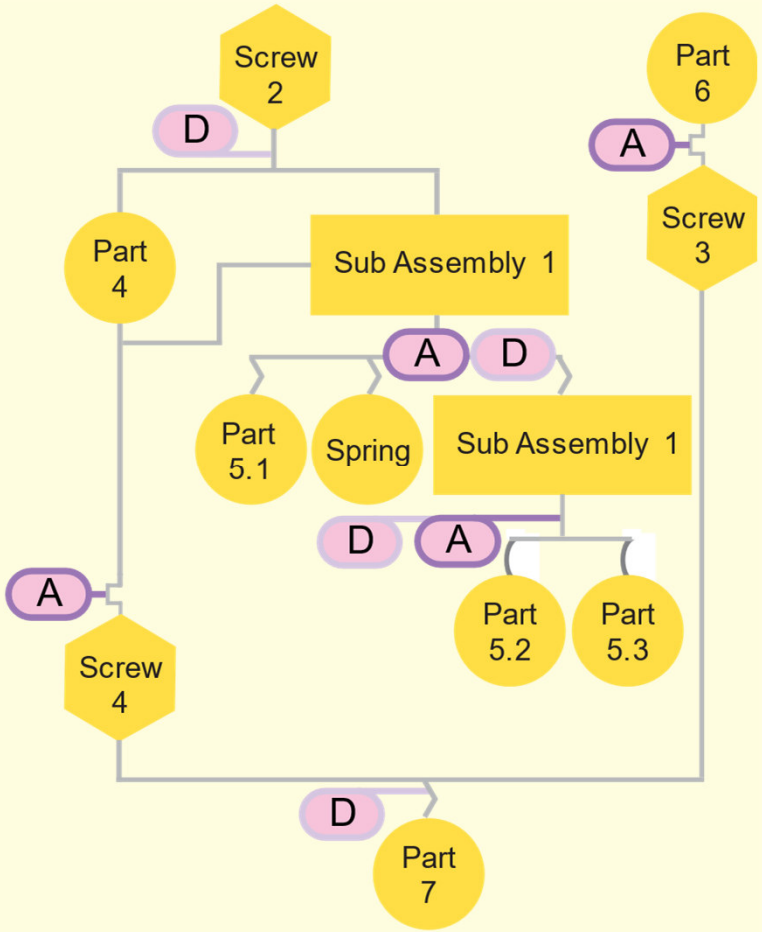
- 1
- 2
- 3

Serverity

- 1
- 2
- 3

Hazard Type

- A Safety
- B Chemical
- C Physical
- D Ergonomic
- E Biological



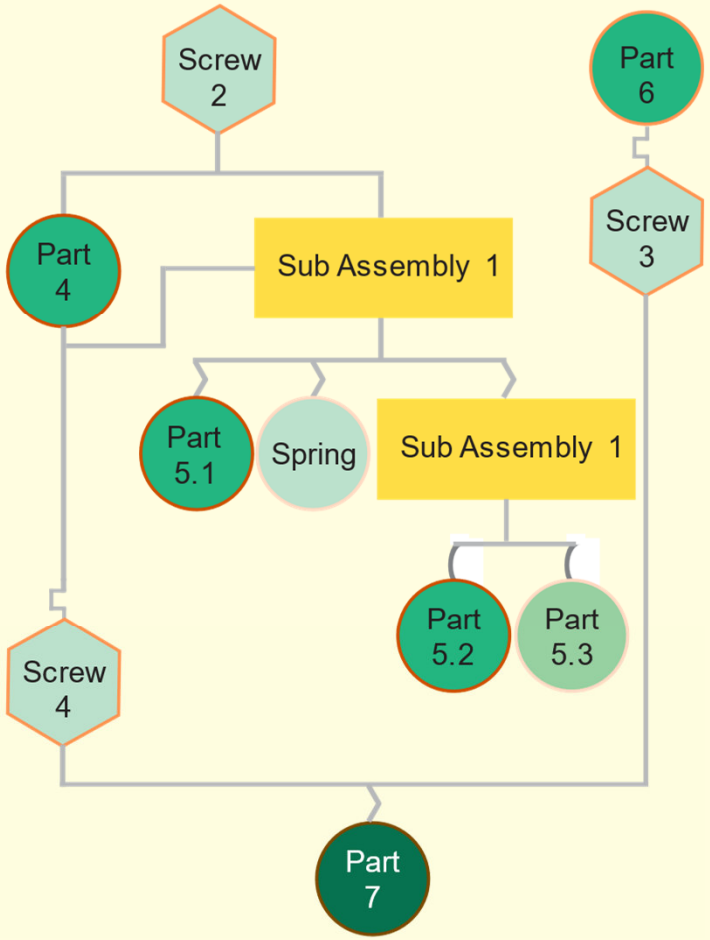
DISASSEMBLY MAP

Value (Euro per 1000 pcs)

- <= 100
- >100, <= 1000
- >1000, <= 5000
- > 5000
- Unable to be sold

Weight (kg)

- <= 0.5
- > 0.5, <= 1
- >1, <= 5
- > 5



DISASSEMBLY MAP

Reuseability/ Remanufacturability

Reuseable

Remanufacturable

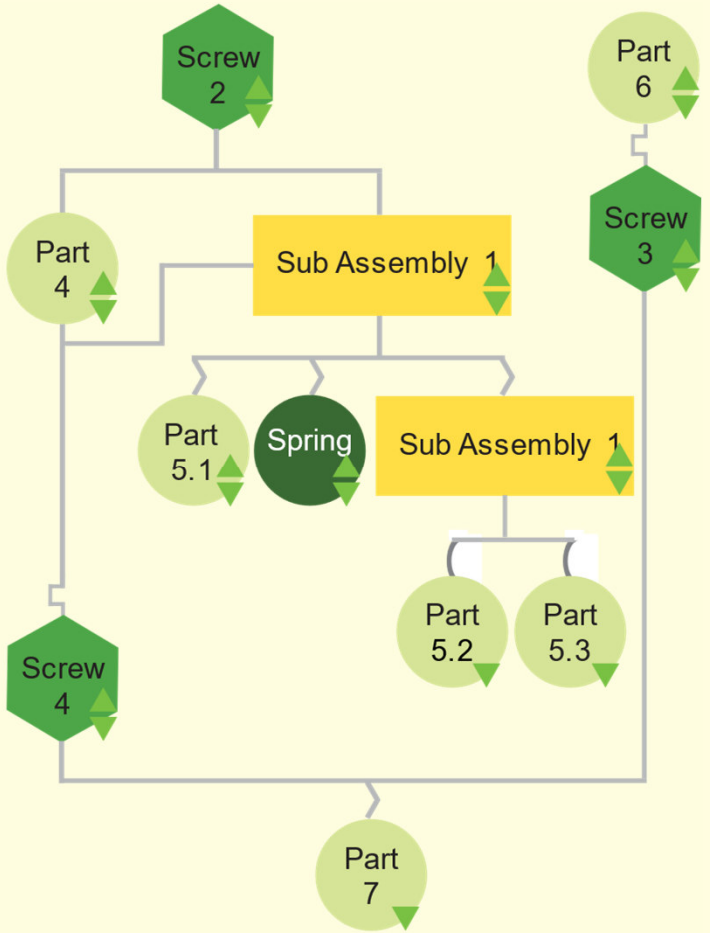
Recyclability Index

<= 0.3

> 0.3, <= 0.6

> 0.6

Unable to recycle

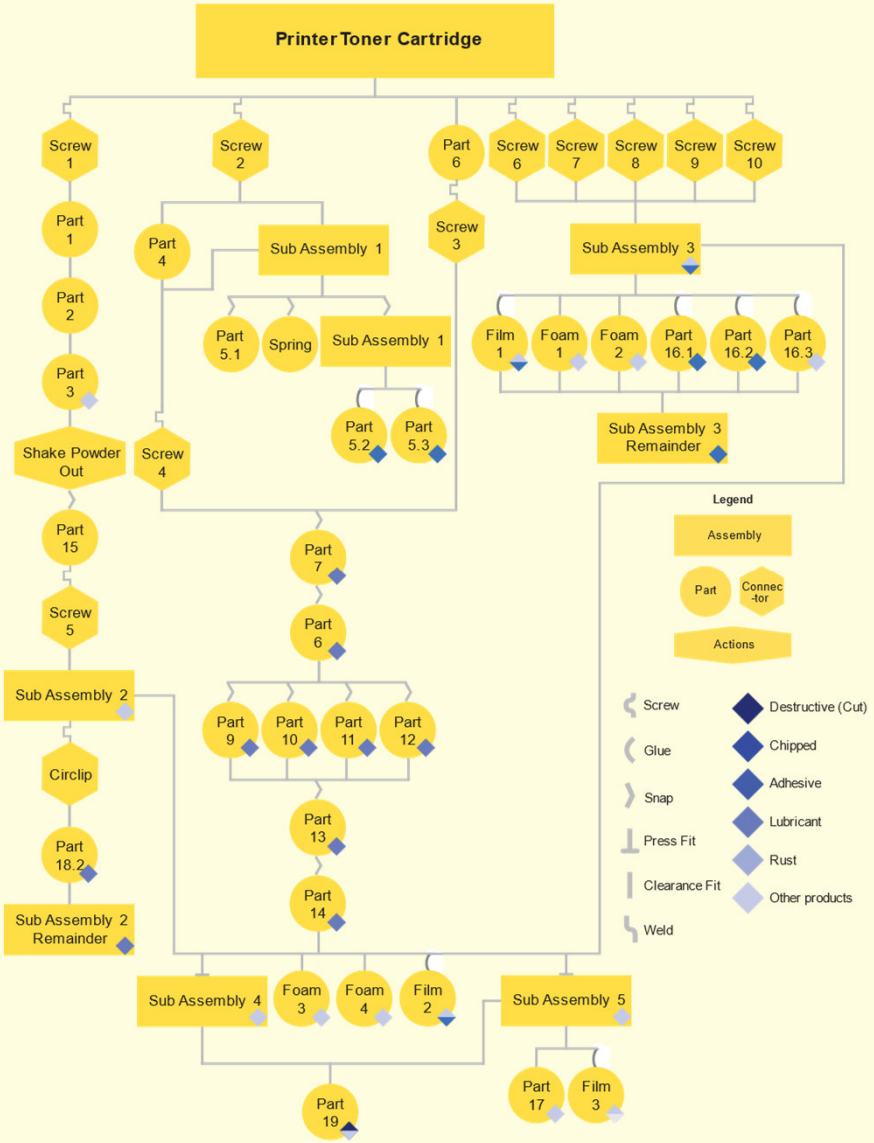


FUTURE WORK

Testing on different products

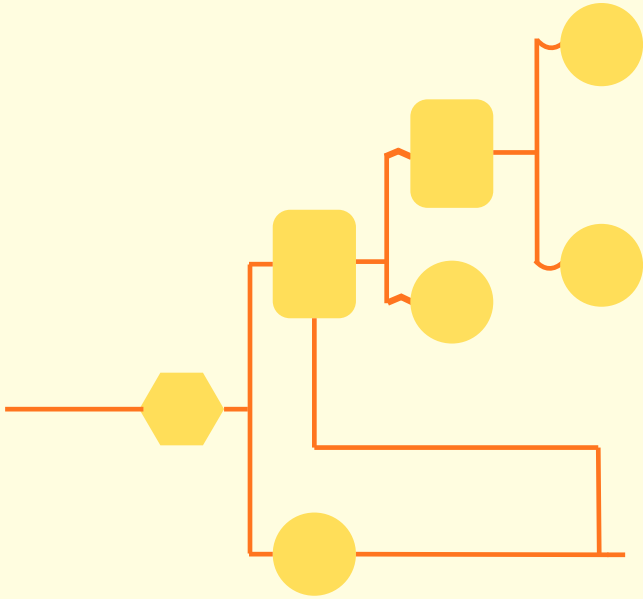
Addition of more factors for evaluation (e.g. force required)

Visualisation using AR



THANK YOU!

Any questions?



NUS National University of Singapore | College of Design and Engineering

INFORMATION PRESENTATION

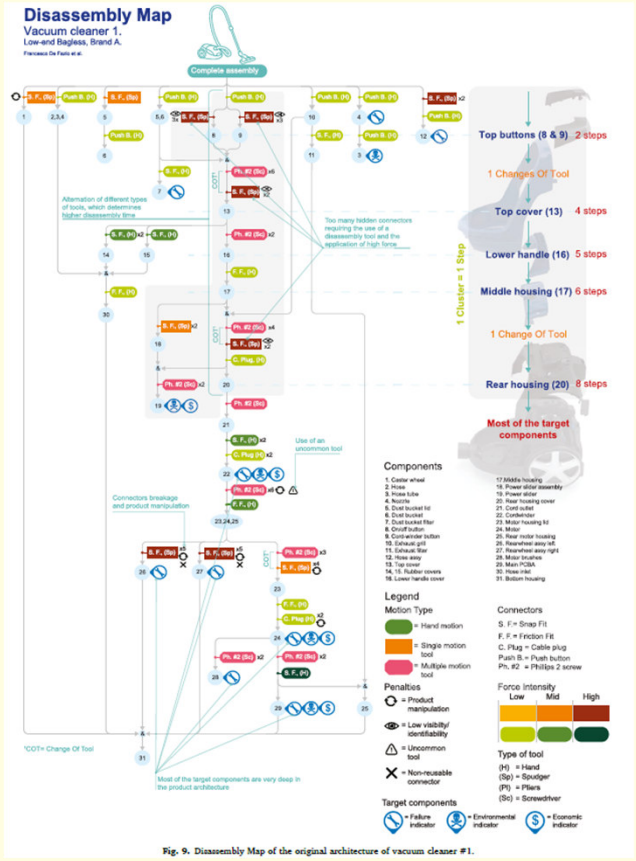


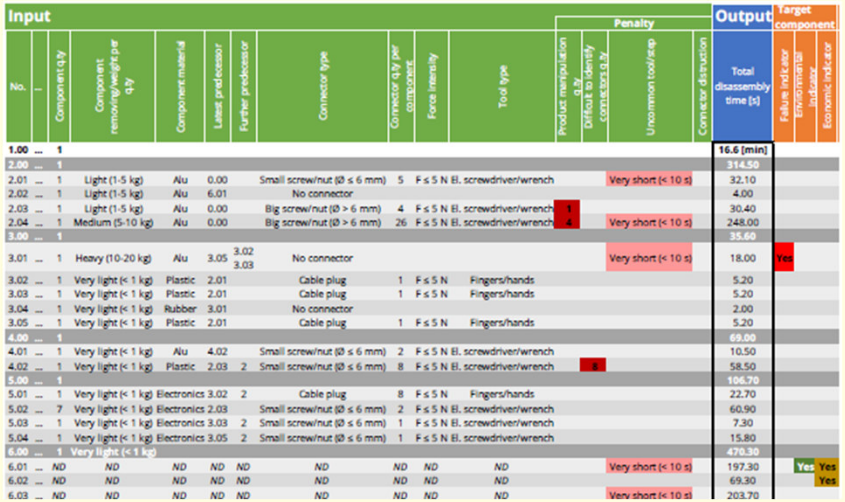
Fig. 9. Disassembly Map of the original architecture of vacuum cleaner #1.

F. De Fazio et al. (2021)

Excel Sheet

Disassembly Map

Math Rules



Input																Output	Target component		
No.	...	Component q.ty	Component removing/weight per q.ty	Component material	Label predecessor	Further predecessor	Connector type	Connector q.ty per component	Force intensity	Tool type	Penalty: Product manipulation q.ty	Penalty: Difficult to identify connectors q.ty	Penalty: Uncommon tool/step	Connector distruction	Total disassembly time [s]	Failure indicator	Environmental indicator	Economic indicator
1.00	...	1													16.6 [min]			
2.00	...	1													314.50			
2.01	...	1	Light (1-5 kg)	Alu	0.00		Small screw/nut (Ø ≤ 6 mm)	5	F ≤ 5 N	El. screwdriver/wrench			Very short (< 10 s)		32.10			
2.02	...	1	Light (1-5 kg)	Alu	6.01		No connector								4.00			
2.03	...	1	Light (1-5 kg)	Alu	0.00		Big screw/nut (Ø > 6 mm)	4	F ≤ 5 N	El. screwdriver/wrench	1				30.40			
2.04	...	1	Medium (5-10 kg)	Alu	0.00		Big screw/nut (Ø > 6 mm)	26	F ≤ 5 N	El. screwdriver/wrench	4		Very short (< 10 s)		248.00			
3.00	...	1													35.60			
3.01	...	1	Heavy (10-20 kg)	Alu	3.05	3.02 3.03	No connector						Very short (< 10 s)		18.00	Yes		
3.02	...	1	Very light (< 1 kg)	Plastic	2.01		Cable plug	1	F ≤ 5 N	Fingers/hands					5.20			
3.03	...	1	Very light (< 1 kg)	Plastic	2.01		Cable plug	1	F ≤ 5 N	Fingers/hands					5.20			
3.04	...	1	Very light (< 1 kg)	Rubber	3.01		No connector								2.00			
3.05	...	1	Very light (< 1 kg)	Plastic	2.01		Cable plug	1	F ≤ 5 N	Fingers/hands					5.20			
4.00	...	1													69.00			
4.01	...	1	Very light (< 1 kg)	Alu	4.02		Small screw/nut (Ø ≤ 6 mm)	2	F ≤ 5 N	El. screwdriver/wrench					10.50			
4.02	...	1	Very light (< 1 kg)	Plastic	2.03	2	Small screw/nut (Ø ≤ 6 mm)	8	F ≤ 5 N	El. screwdriver/wrench		8			58.50			
5.00	...	1													106.70			
5.01	...	1	Very light (< 1 kg)	Electronics	3.02	2	Cable plug	8	F ≤ 5 N	Fingers/hands					22.70			
5.02	...	7	Very light (< 1 kg)	Electronics	2.03		Small screw/nut (Ø ≤ 6 mm)	2	F ≤ 5 N	El. screwdriver/wrench					60.90			
5.03	...	1	Very light (< 1 kg)	Electronics	3.03	2	Small screw/nut (Ø ≤ 6 mm)	1	F ≤ 5 N	El. screwdriver/wrench					7.30			
5.04	...	1	Very light (< 1 kg)	Electronics	3.05	2	Small screw/nut (Ø ≤ 6 mm)	1	F ≤ 5 N	El. screwdriver/wrench					15.80			
6.00	...	1	Very light (< 1 kg)												470.30			
6.01	...	ND	ND	ND	ND	ND	ND	ND	ND	ND			Very short (< 10 s)		197.30	Yes	Yes	
6.02	...	ND	ND	ND	ND	ND	ND	ND	ND	ND					69.30		Yes	
6.03	...	ND	ND	ND	ND	ND	ND	ND	ND	ND			Very short (< 10 s)		203.70			

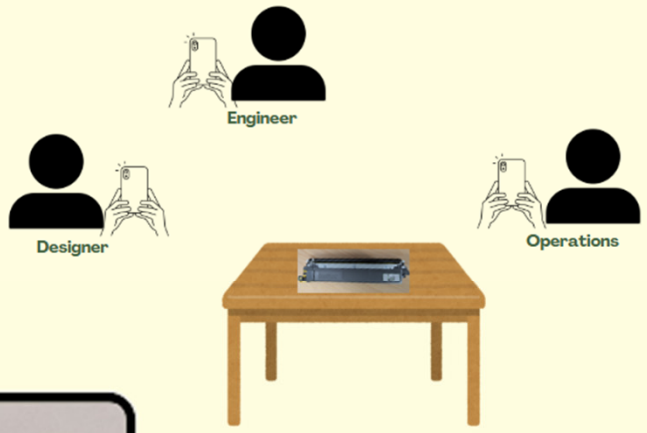
Fabio Marco Monetti , Pablo Zaguirre Martínez and Antonio Maffei (2024)

Parameter	Reference parameter	Mathematical rule	Threshold	Rationale	Eco-design action
D_i	D_{ref}	$\frac{D_i}{D_{ref}}$	$\geq THR$	Cost-benefit analysis validated with the ROC method for the considered mechatronic product family	To reduce the number of steps for the disassembly operation
D_{change}	D_i	$\frac{D_{change}}{D_i}$	>0.5	Since D_i is the sum of two parameters (D_{change} and $D_{removal}$) if this ratio is lower than 0.5 D_{change} is the most critical parameter that downgrade D_i	To uniform the type of fasteners used for the product assembly
$D_{removal}$	D_i	$\frac{D_{removal}}{D_i}$	>0.5	Since D_i is the sum of two parameters (D_{change} and $D_{removal}$) if this ratio is lower than 0.5 $D_{removal}$ is the most critical parameter that downgrade D_i	To reduce the number of components that need to be removed to reach the target
Fasteners	Removable and reusable connector	$S_{2,i}$	<1	Whenever different fasteners than "removable and reusable connector" is used this value is strongly influenced	To change the type of fasteners or connectors (avoiding non-reusable or permanent joints)
Tools	Common tool	$S_{3,i}$	<1	Whenever different tools than "common tool" used this value is strongly influenced	To change the type of tools needed (avoiding specific or proprietary tools)
T_i	T_{ref}	$\frac{T_i}{T_{ref}}$	$\geq THR$	Cost-benefit analysis validated with the ROC method for the considered mechatronic product family	To simplify the operations to reduce the disassembly time
T_{change}	T_i	$\frac{T_{change}}{T_i}$	>0.20	Since T_i is the sum of five parameters if this ratio is lower than 0.2, T_{change} is the most critical parameter	To uniform the type of fasteners used for the product assembly
T_{manip}	T_i	$\frac{T_{manip}}{T_i}$	>0.20	Since T_i is the sum of five parameters if this ratio is lower than 0.2, T_{manip} is the most critical parameter	To allow easy access to the target component (avoiding the need to rotate the product)
$T_{position}$	T_i	$\frac{T_{position}}{T_i}$	>0.20	Since T_i is the sum of five parameters if this ratio is lower than 0.2, $T_{position}$ is the most critical parameter	To simplify the type of connectors or to reduce their number (avoiding the need for heavy pressure or excessive precision)
T_{discon}	T_i	$\frac{T_{discon}}{T_i}$	>0.20	Since T_i is the sum of five parameters if this ratio is lower than 0.2, T_{discon} is the most critical parameter	To reduce the number of connectors or to simplify them (e.g., avoiding the use of excessively long screws)
$T_{removal}$	T_i	$\frac{T_{removal}}{T_i}$	>0.20	Since T_i is the sum of five parameters if this ratio is lower than 0.2, $T_{removal}$ is the most critical parameter	To reduce the number of components that need to be removed to reach the target

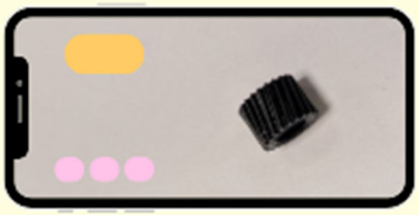
Nuŕia Boix Rodrıgúez, Claudio Favi (2024)

FUTURE WORK

Goal: Design feedback for collaboration

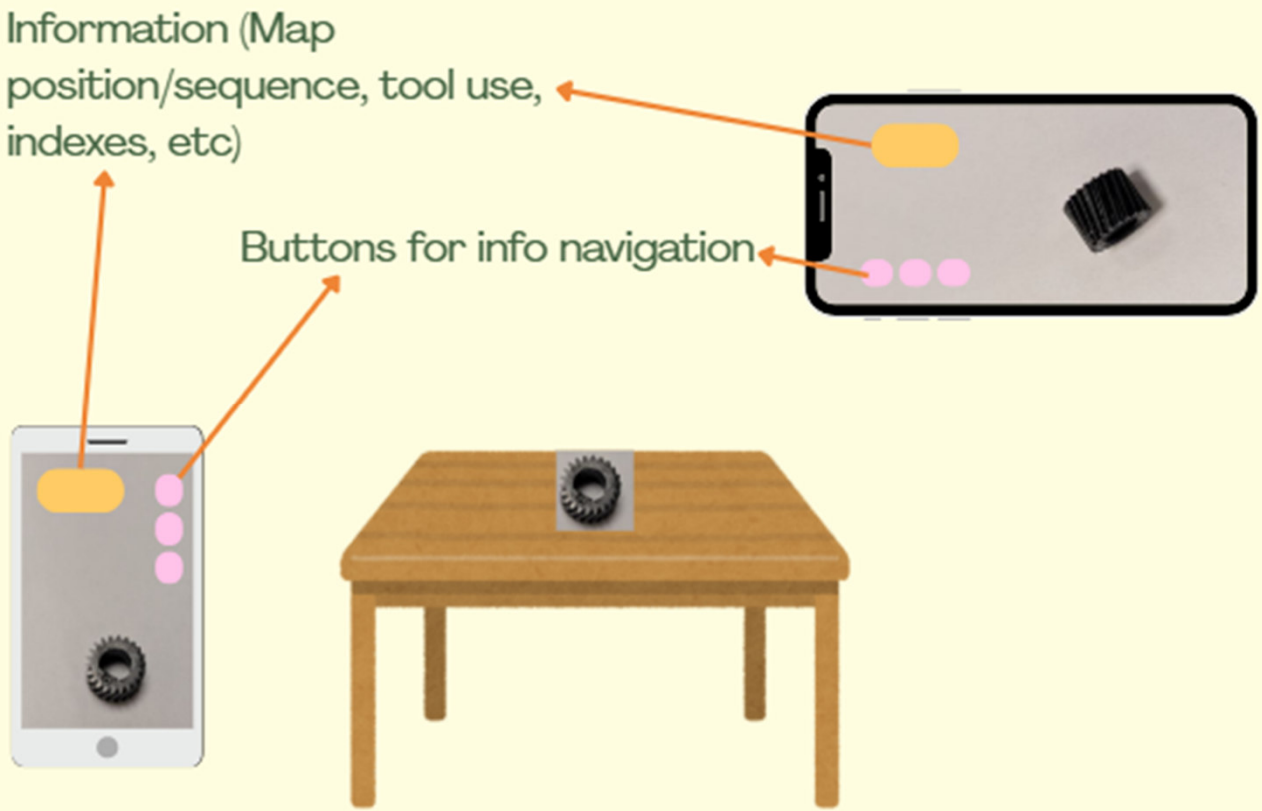


Auto-detect which part it is and where on the disassembly map





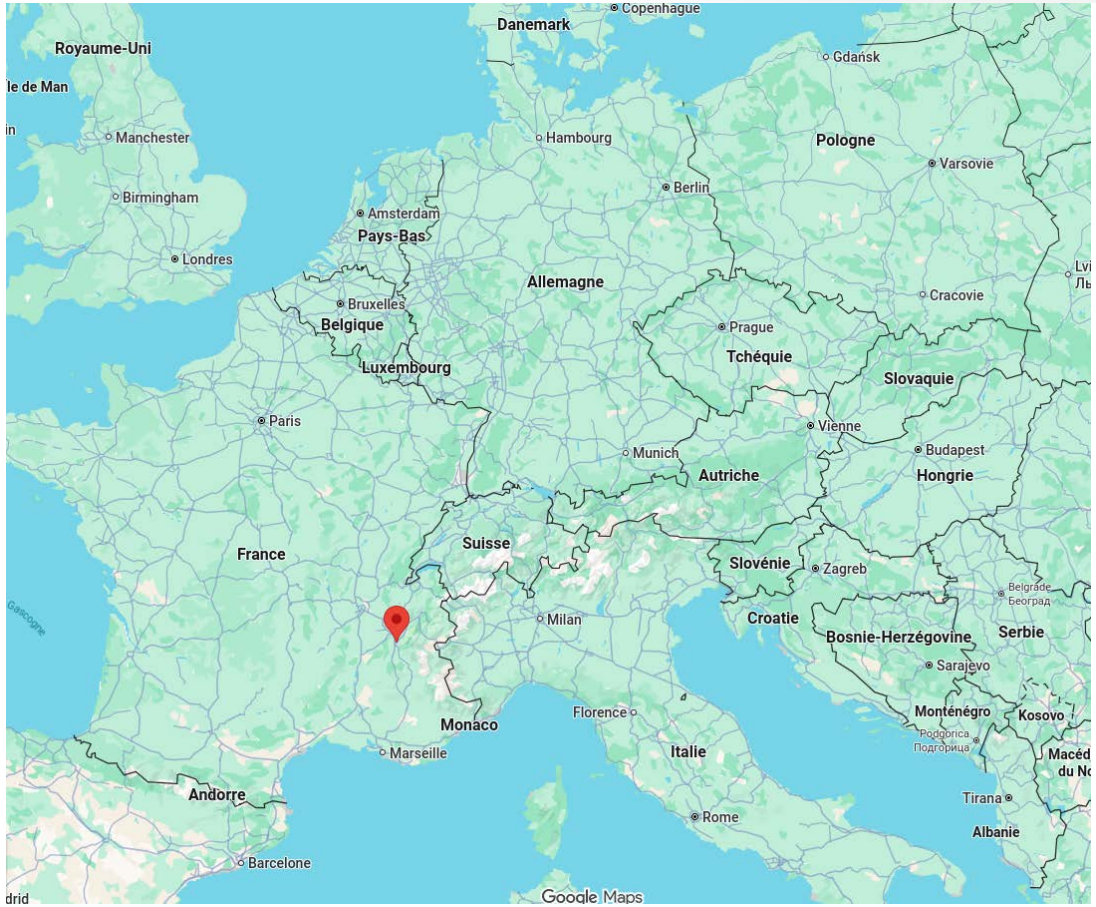
FUTURE WORK


Information (Map position/sequence, tool use, indexes, etc)
Buttons for info navigation

Development of a decision-making tool for the industrialisation of regeneration scenarios: application to an Industry 5.0 platform in support of training and research

Yannis ROSSET [*1]
Helmi BEN REJEB [1]
Peggy ZWOLINSKI [1]
[1] Univ. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, 38000 Grenoble, France
[*] Corresponding author : yannis.rosset@grenoble-inp.fr

10/06/2026





G-SCOP laboratory, Grenoble, France

Source : google Maps

« Operating Management » Plateform

Teaching factory / Modular workshop

G-SCOP Laboratory

Context

- Request of plateform users for a tool to calculate the environmental impact of their usage
- Lack of tools centered in ecodesign of assembly / disassembly lines [1]
  - Most of them are product centered
  - Lack of data, especially for new technologies
- Existing tools often complicated and time-consuming [2]

Research questions

1. How to develop a decision-making tool to calculate and compare the environmental and economic impacts of regeneration lines ?
2. Are the results sufficiently actionable and accurate to aid in decision-making?

[1] Sherif, Z., Salonitis, K., A systematic review of decision tools for process selection and performance improvement in manufacturing (2025)

[2] Schäfer & al, Ecodesign—A Review of Reviews (2021)

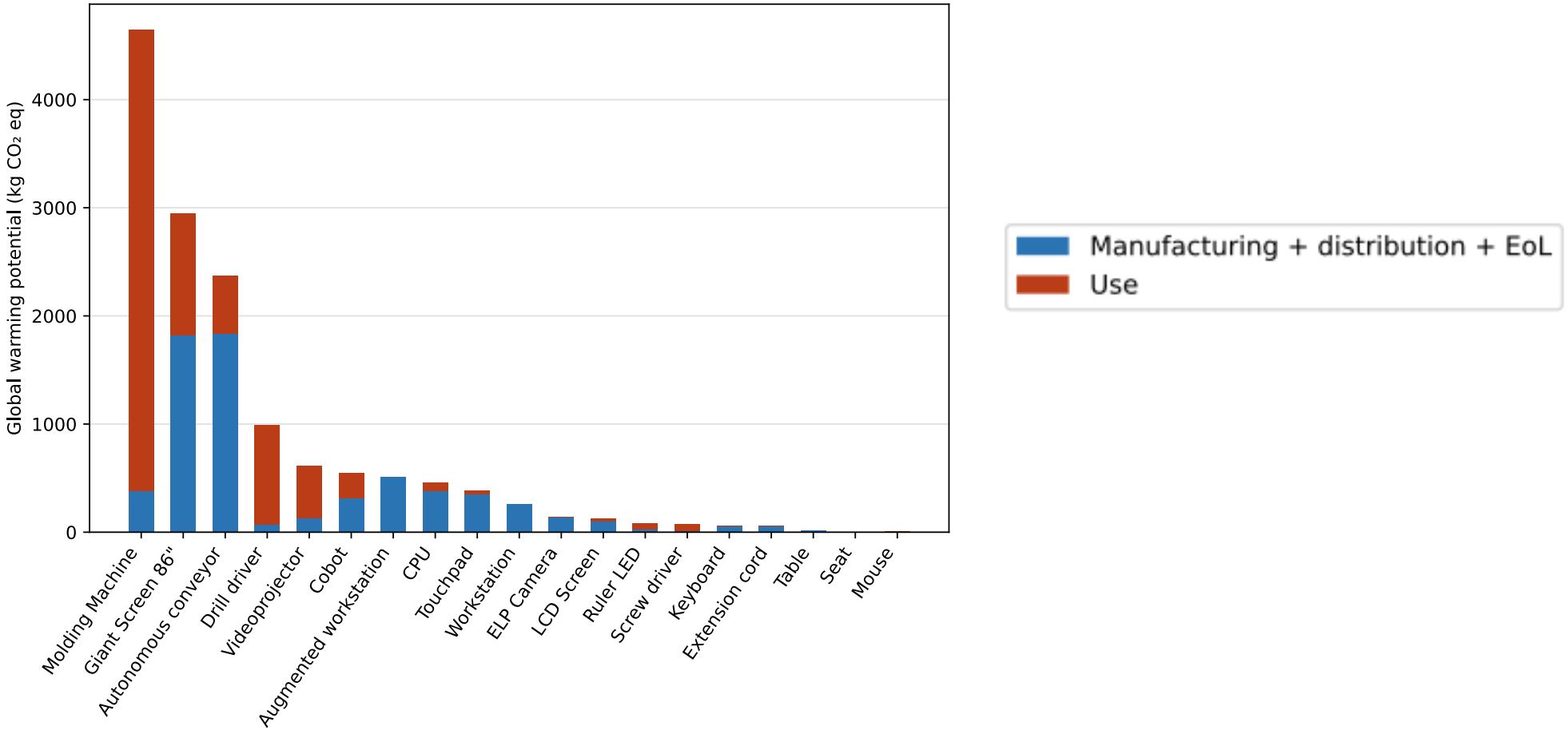
Development : Methodology used

1. How to develop a decision-making tool to calculate and compare the environmental and economic impacts of regeneration lines ?

	Environmental analysis	Economical analysis
Method used	Life cycle assessment (LCA)	Life cycle cost (simplified)
Tools used	LCA software : Brightway LCA database : EcoInvent Libreoffice Calc	Libreoffice Calc
Main Data needed	Bill of materials, production location, consumptions, type of End of Life	Purchase cost Maintenance cost Use cost
Data Collection method	From manufacturers From disassembly From estimations	Bills Technical datasheet with electricity cost

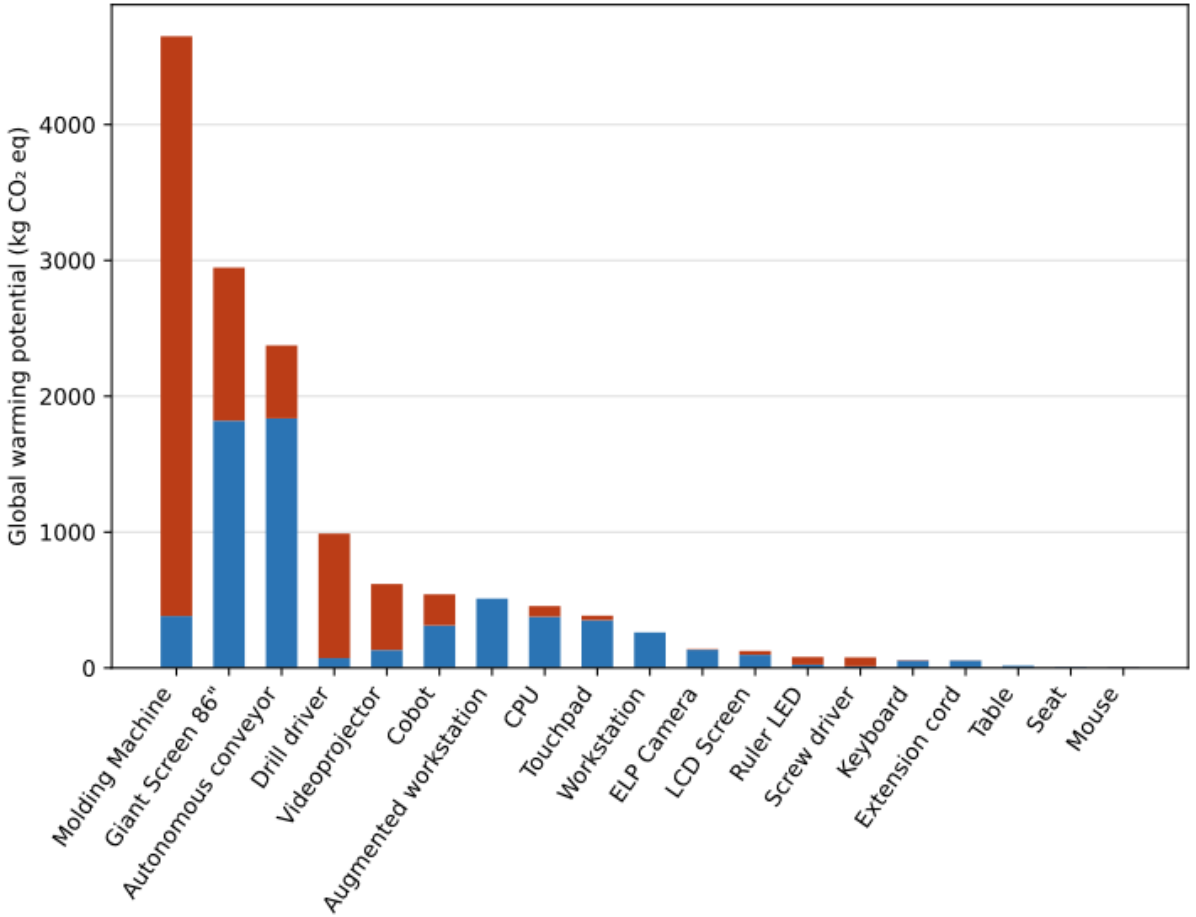
Decision-Making tool developed on OM Plateform, with Data collected on site

Development : Methodology intermediary results

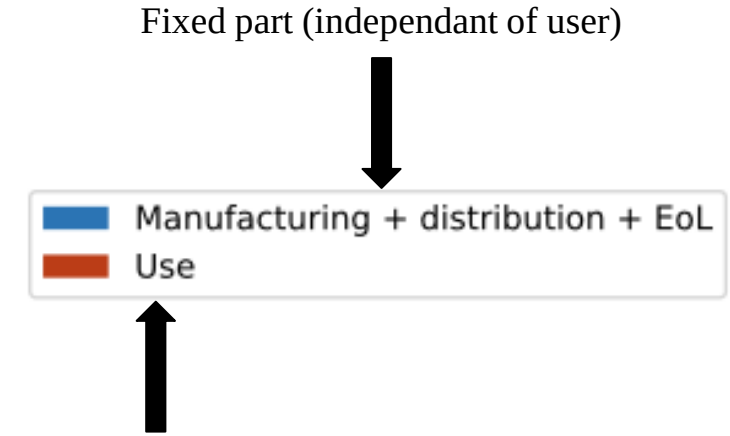


Climate change impact - Absolute value for 19 machines

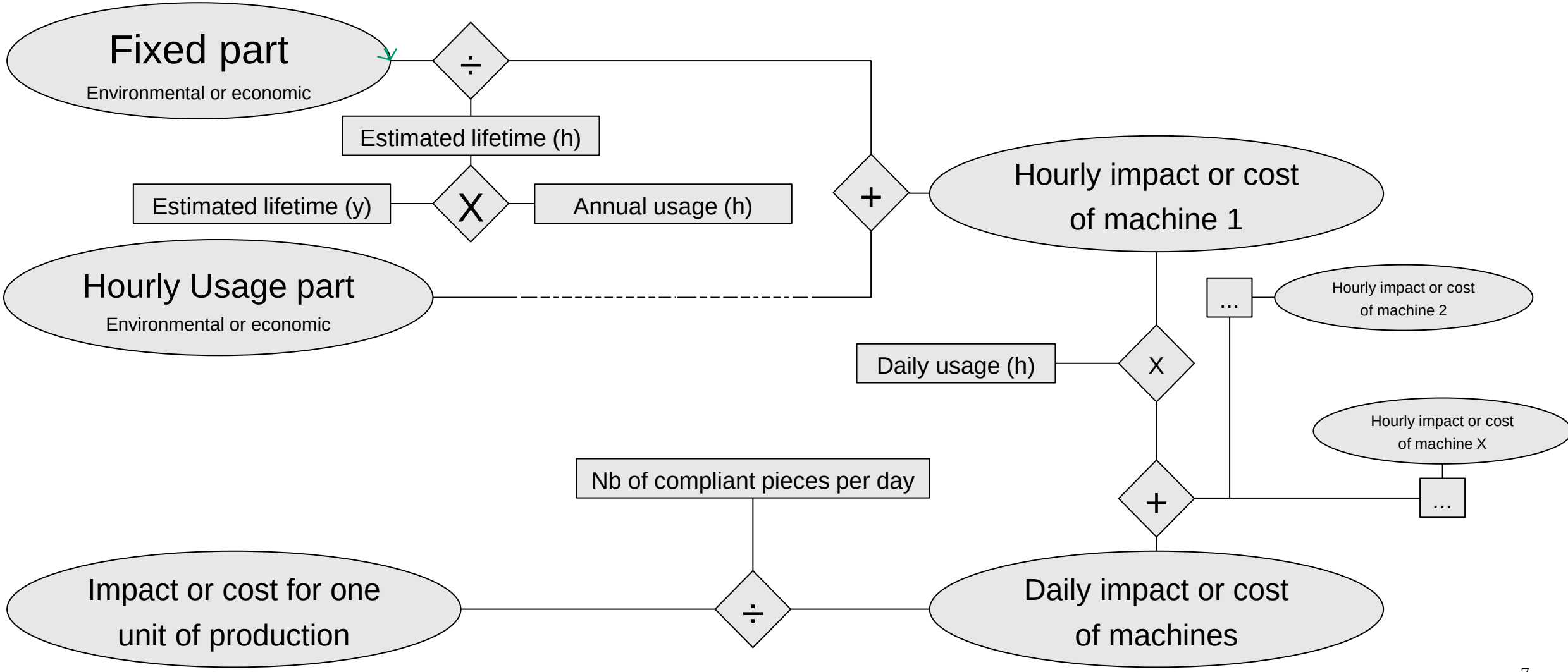
Development : Methodology results



Climate change impact - Absolute value for 19 machines



Development : Combining and using impact factors



Development : Decision making tool prototype

PROCESS : Input Data

Production		
	Product name	Number of compliant pieces per day (annual mean)
Product A	Tidal turbine – manual line 21,5 unit/day	21,5
Product B	Tidal turbine – Industry 5.0 line 30 unit/day	30

Production Organization		
Nb worked days/week	nb worked weeks/year	day worked / year
5	50	250

Employees costs	
	Annual cost / employee
Employee – unskilled	27 347,00 €
Employee – skilled	43 500,00 €
Employee – expert	95 000,00 €

Equipment or employee used for one day of production	Quantity	Operating time per unit (h/d)
Employee – unskilled	11	8
Screw driver	5	4
Seat	10	8
Workstation	9	8
Table	1	8
CPU	1	8
LCD Screen	1	8
Keyboard	1	8
Mouse	1	8

PROCESS : Output Data

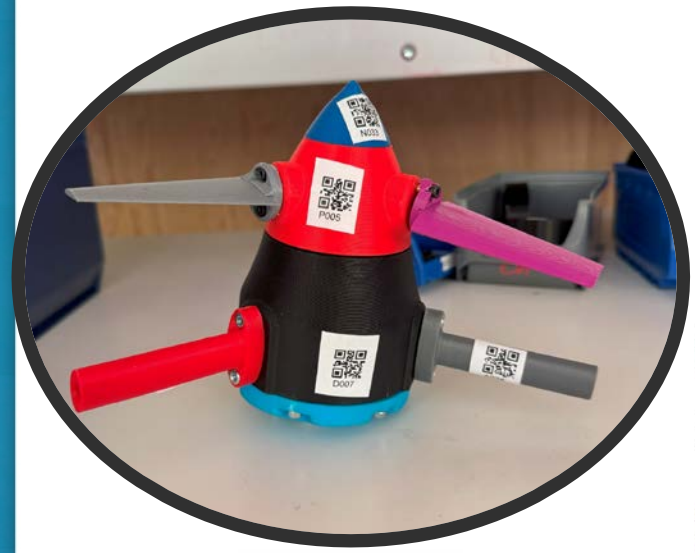
Indicator \ Equipment	climate change Global warming potential (GWP100)			
	Tidal turbine – manual line 21,5 unit/day		Tidal turbine – Industry 5.0 line 30 unit/day	
	kgCO2eq	%	kgCO2eq	%
Employee – unskilled				
Screw driver	6,15E-03	39,25%	4,41E-03	28,13%
Seat	8,20E-05	0,52%	5,88E-05	0,38%
Workstation	2,43E-03	15,51%	1,74E-03	11,12%
Table	3,07E-04	1,96%	2,20E-04	1,40%
CPU	3,80E-03	24,26%	2,72E-03	17,39%
LCD Screen	2,02E-03	12,89%	1,45E-03	9,24%
Keyboard	8,04E-04	5,13%	5,76E-04	3,68%
Mouse	7,37E-05	0,47%	5,28E-05	0,34%
Autonomous conveyor			3,88E-02	247,80%
Cobot			7,16E-03	45,67%
Videoprojector			9,87E-03	63,02%
Touchpad			1,12E-03	7,12%
Giant Screen 86"			5,38E-03	34,31%
Sum	**1,57E-02**	**100,00 %**	**7,36E-02**	**469,58 %**

Test : Case study description & input data

1. Are the results sufficiently actionable and accurate to aid in decision-making?

Tidal turbine

- Designed for the teaching factory
- Can be (dis)assembled by a beginner





Remanufacturing lines comparison

S1 : Manual line

Input data

21.5 unit/day

11 Employees 8h/d
9 Workstations 8h/d
5 Screw drivers 4h/d
1 Computer 8h/d

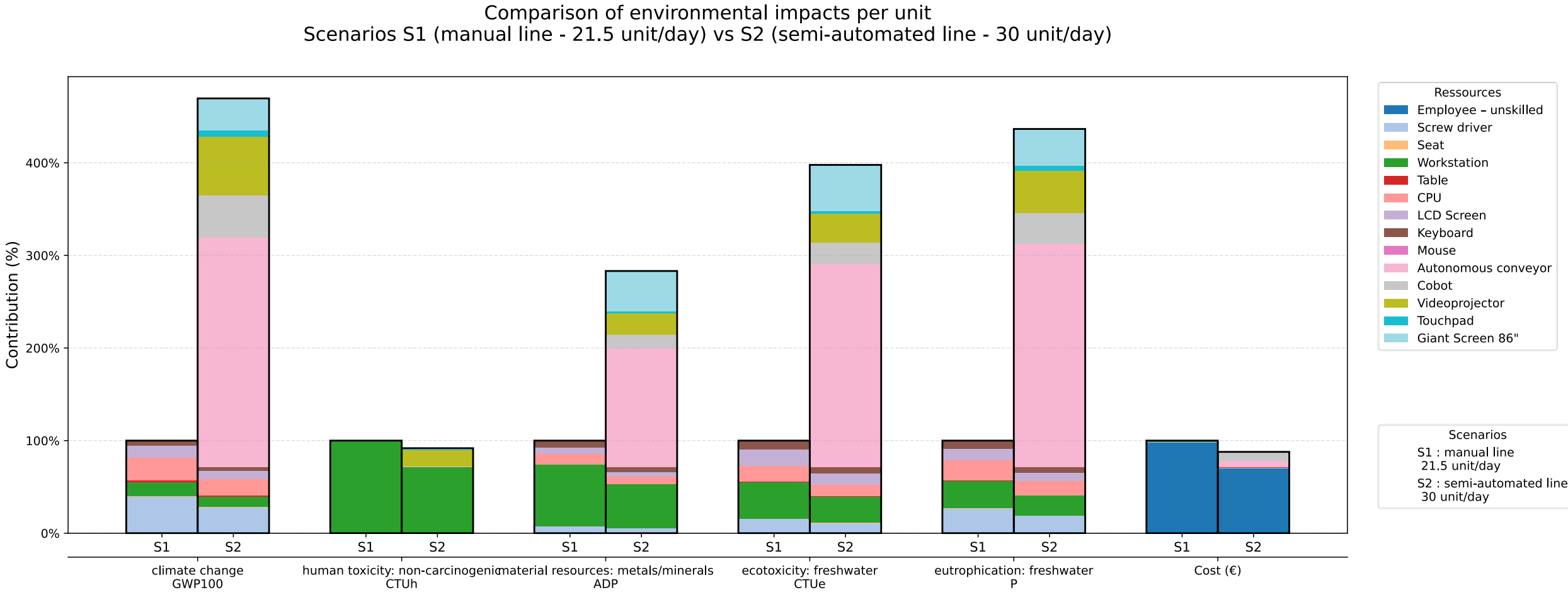
S2 : Semi-automated line

Input data

30 unit /day

11 Employees 8h/d
8 Workstations 8h/d
5 Screw drivers 4h/d
1 Computer 8h/d
8 Touchpads 8h/d
1 Giant screen 8h/d
2 Cobots 8h/d
2 Autonomous conveyors 8h/d

Test : Decision-making tool output data



- S2 much greater impact for 4 indicators (+290% to +450%)
- S2 smaller impact for 2 indicators, including **cost** (-9% to -12%)

- Some ressources concentrate most of the impacts (*autonomous conveyor*, *worksations*, *employees* for the cost)

Conclusion and perspective

1. How to develop a decision-making tool to calculate and compare the environmental and economic impacts of regeneration lines ?

- Large data collection to realize LCAs and LCC and assemble results in an excel file
- The tool use requires only data commonly used by designers (type, number and using time of machine) : easy to use

2. Are the results sufficiently actionable and accurate to aid in decision-making?

- Outputs really different in our case study depending on the indicator
- Results are accurate due to the on-site data collection. Tool specific to our « OM » Plateform

Perspectives

- Expand the scope of the tool to account for material impacts, particularly in cases where repairs are made using new parts
- Portability to other workshops

Thank you for your attention

Coffee Break



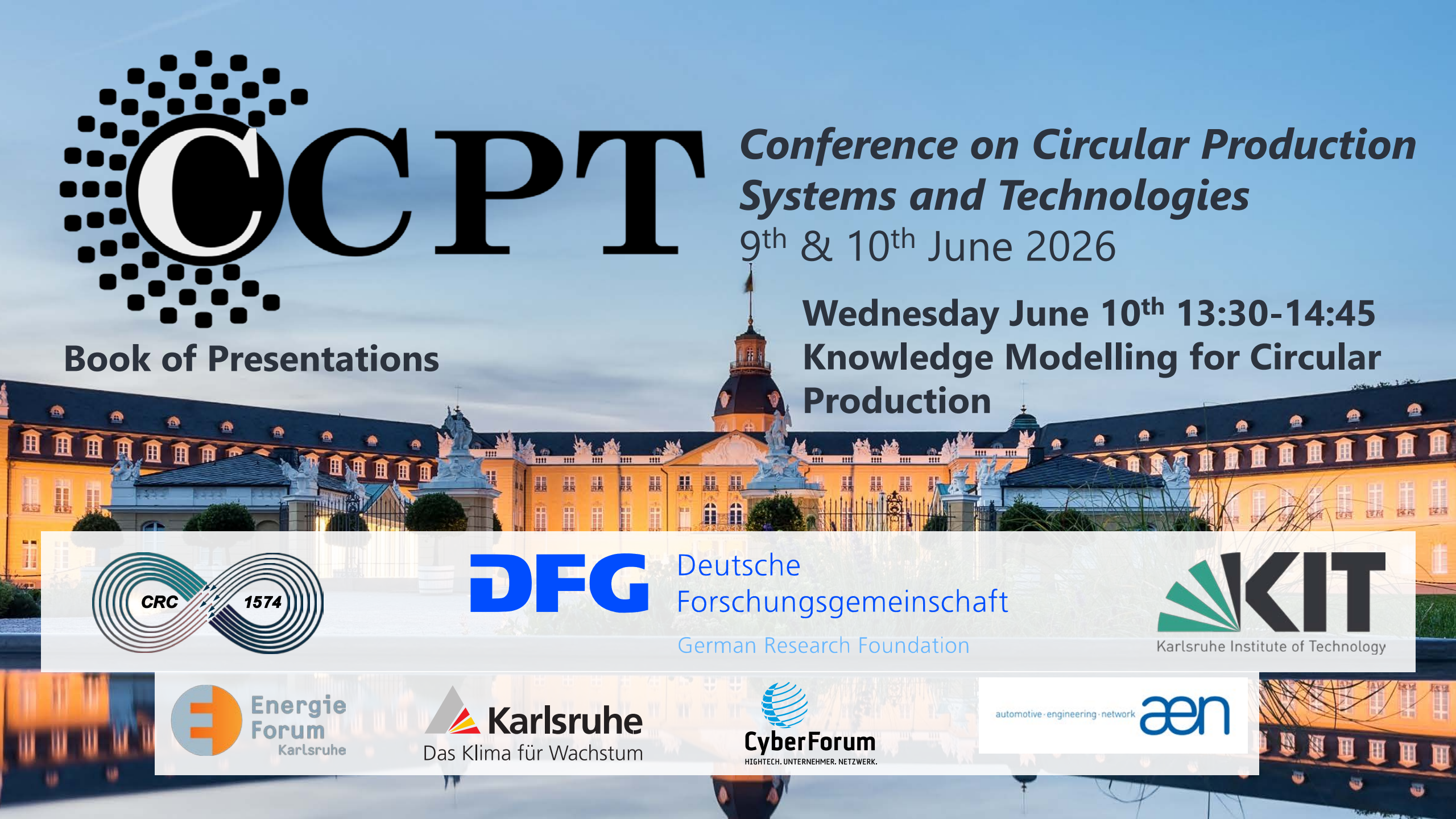
Paper Sessions start at 15:15

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DFG Deutsche Forschungsgemeinschaft
German Research Foundation

KIT Karlsruhe Institute of Technology



CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 13:30-14:45
Knowledge Modelling for Circular Production

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Conference on Circular Production Systems and Technology
9th & 10th June 2026

A Framework for the integrative design of circular Lean Production Systems (LPS)

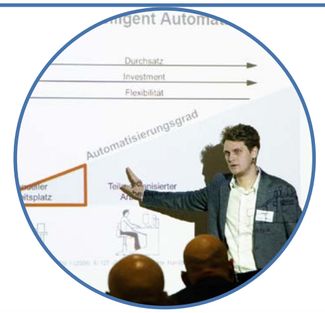
Christoph Müller, Prof. Dr. Markus Schneider

Landshut University of Applied Sciences (HAW Landshut) –Technology Center for Production and Logistics Systems (TZ PULS),

About ...

... the author

Christoph Müller (M. Eng.)
Born in 1996 In Bavaria
Acadamic Assoicate @ TZ PULS:
Logistics, Lean Production, Sustainability



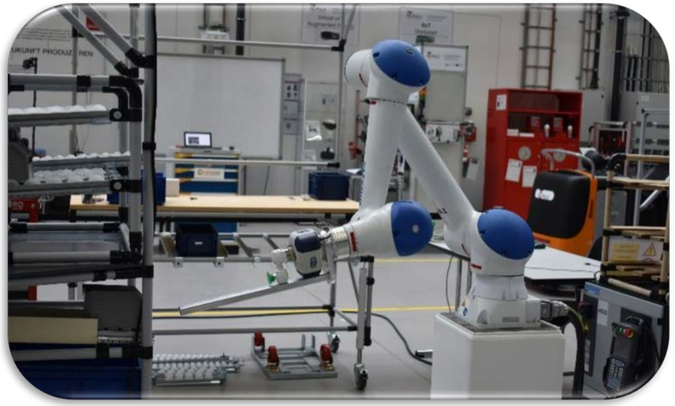
... TZ PULS

Techonlogy Center for Production an Logistics
Part of Landshut University of Applied Sciences
Research, Teaching, Network
900 m² Learning and Innovation (Model) Factory





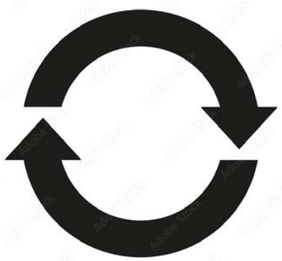




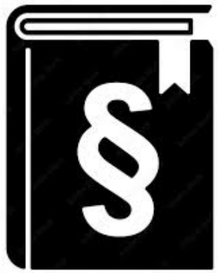
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Motivation

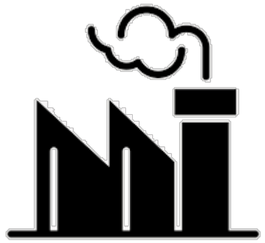
The linear model is reaching its limits
Primary material consumption must drop by one third within 15 years — circular economy as a necessary alternative



Regulatory pressure is mounting
EPR schemes & national regulations such as KrWG oblige manufacturers to recover, disassemble, and reintegrate used products



Reverse logistics- although in need to be scaled - remains peripheral
Required for closing the loop — yet rarely integrated into the core design of production systems

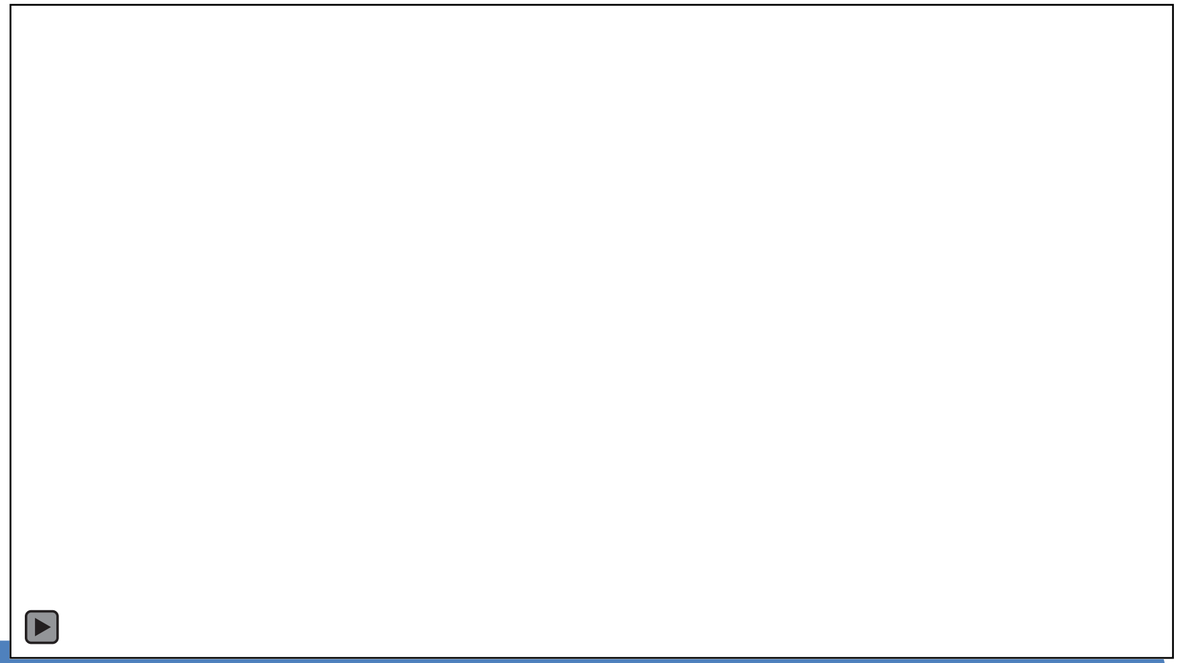


State of the art

CE as target state widely recognized

Remanufacturing: most value-retentive R-strategy

Yet: complexity remains major barrier to industrial diffusion



Existing approaches lack **a systematic** perspective

Reverse logistics treated as downstream or outsourced — not **integratively** embedded

VDI 2870 does not account for reverse logistics → "worth revising and supplementing"

[Video from DMG MORI - Maschinenüberholung Ihrer Maschine mit DMG MORI Used Machines]

Central research objective



Develop an extended production system framework — building on VDI guideline 2870 — that enables the integrative and systematic design of circular LPS, with a specific focus on remanufacturing

Methodology

following Aleo et al., 2026; Errington & Childe, 2013; Hevner et al., 2004 among others

01

Literature Review & Best-Practice Analysis

Structured review to substantiate the research gap and derive initial design requirements for reverse logistics integration.

02

Two Industrial Case Studies

On-site visits & gemba walks at two mechanical engineering SMEs in southern Germany currently scaling reverse logistics. (following case study design acc. to (Errington & Childe, 2013)

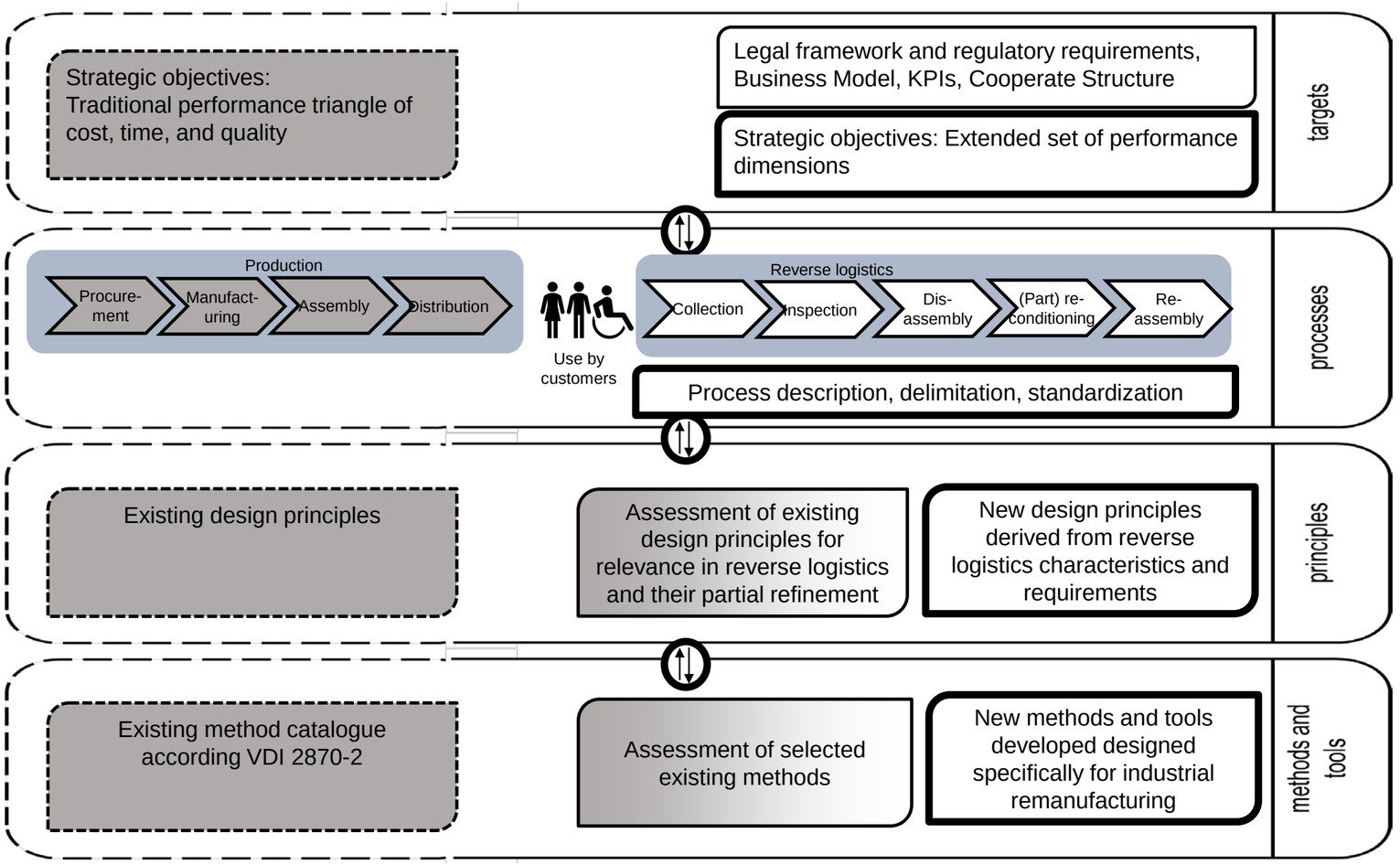
03

Framework Development

Conceptual synthesis grounded in VDI 2870 structure — targets · processes · principles · methods — validated on basic structure level.
→ Further elaboration and empirical evaluation ongoing

by Christoph Müller, Prof. Dr. Markus Schneider, HAW Landshut

Framework for Circular LPS —Basic Structure and Key Elements

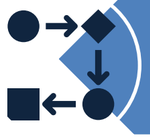


by Christoph Müller, Prof. Dr. Markus Schneider, HAW Landshut

Conclusion



'Race for the LPS of the future' (Bauernhansl, 2017) has begun, Framework bridges the gap between CE strategy and LPS design



Grounded in literature review + two industrial case studies in southern German mechanical engineering



Potential to evolve industrial standards — enabling circular economy at production system level



Introduces novel strategic approaches, defines new processes and establishes innovatice design principles and methods

As a next step: Full elaboration of framework elements · Evaluation at BBW GmbH model factory (TZ PULS) · Quantitative validation of economic viability

by Christoph Müller, Prof. Dr. Markus Schneider, HAW Landshut

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- If you have any questions or are interested in an exchange, please do not hesitate to contact me.

- Thank you and have a pleasant stay here in the heart of Baden!

- Questions / Discussion -

References

among others

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Developing a Conceptual Data Model for Residual Value Assessment in the Circular Economy

Structuring product lifecycle data for data-driven selection of economically viable post-use options

CCPT 2026

Brennert, Julia | Karlsruhe | 06/10/2026

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The value-retaining circular economy still stays on paper

Motivation



Disposal still wins
Recycling and disposal continue to dominate end-of-use over value-retaining post-use options

Economic value leaks
Residual value embodied in products and components is lost when they are discarded

Value-retaining R-strategies are idle
Reuse, remanufacturing, repurposing and refurbishment remain underused in industrial practice

Knowledge of the **residual value** of products and components **enables** a **transparent assessment** of **the economic viability of remanufacturing** and can thus **reduce value losses**.

1) Eurostat statistics (2024): Waste electrical and electronic equipment (WEEE) by waste management operations; 2) Li et al. (2018): The Impact of Information Asymmetry on Consumer Purchase Intentions in the Context of Remanufactured Products

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The barrier: residual value is invisible for producers and consumers

Motivation



Residual value

The economically realizable market value of a product or component at the end of its use phase, which is influenced by technical and market-related data.

It is the central indicator for comparing post-use options and selecting the most economically viable one.

Without transparency on residual value:



Companies decide against value-retaining post-use options

even when reuse or remanufacturing would be profitable



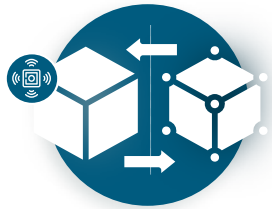
Consumers distrust the quality of refurbished goods

information asymmetry lowers their willingness to pay

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The digital shadow could make it visible and measurable, but how?

Motivation



The digital shadow

A data-driven digital representation of a physical product, where data automatically flows unidirectional from the object to the model.

It captures **product lifecycle data (PLD)** across every lifecycle phase of a product:
Beginning of Life (BoL) · Middle of Life (MoL) · End of Use (EoU) · End of Life (EoL) · Second Life (SL)

BUT



The research gap

No standardized data model structures this PLD for residual value assessment. No technical interface given to collect and provide relevant data for the calculation.

Existing approaches fail to link relevant data at product, component and material levels with the lifecycle phases for value assessment.

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Research question



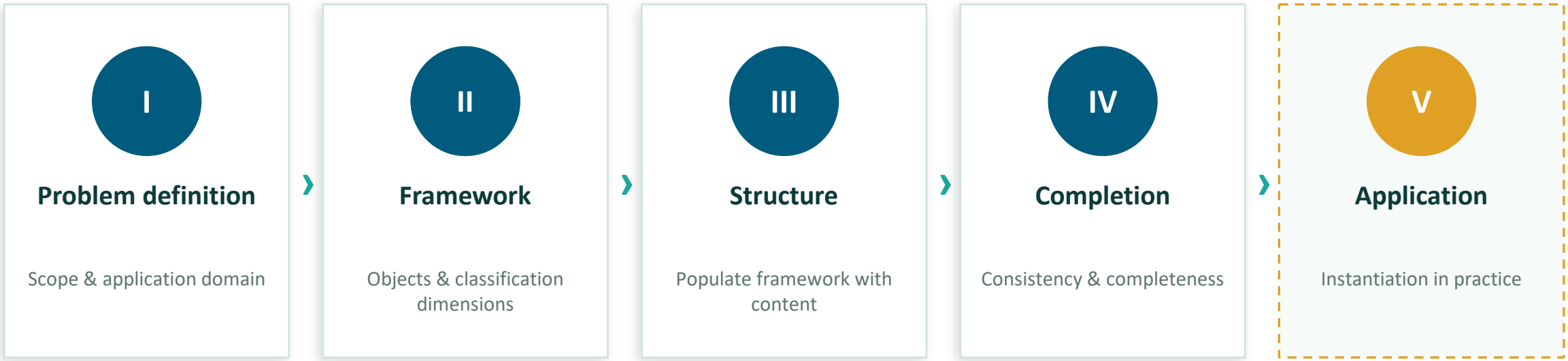
How must a conceptual data model structure residual-value-relevant product lifecycle data within the digital shadow?

Positioning: the 2nd of four interdependent submodels of a broader residual-value methodology (Schuh & Brennert 2025) which provides the **data-side prerequisite** linking parameter identification to computation-ready evaluation.

Reference modeling for building the conceptual data model

Methodology and research approach

Reference modeling by Schütte (1999) allows that model content and structure are defined once at a generic level, then instantiated across different manufacturing contexts without rebuilding.



Existing models are analyzed, and usable parts are revised and adopted

Phase V (application) is out of scope here and future work.

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Building the model: using structural analogies of established standards

Phase III: Structuring and populating the conceptual data model

Identification of existing models

Scopus · Web of Science · Google Scholar: focus on data & information models across the lifecycle

Selection of source models

3-stage filter: real data model → normatively established → contribution to requirements for the conceptual data model for residual value assessment (R1-R3)*

Consolidation into parameter categories

Merge structurally equivalent concepts into reusable parameter categories.

→ ***11 consolidated parameter categories***

* ***R1:*** *the model must structure residual-value-relevant technical data, both raw and derived, along the product lifecycle phases.*

R2: *the model must integrate market-related data within its structure*

R3: *the model must represent residual-value-relevant data per post-use option.*

6 source models

DPP Digital Product Passport

MP Materials Passport

AAS Asset Administration Shell

PLCS Product Life Cycle Support

OPC UA OPC Unified Architecture

ECLASS Classification standard

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The developed conceptual data model

Results I/II

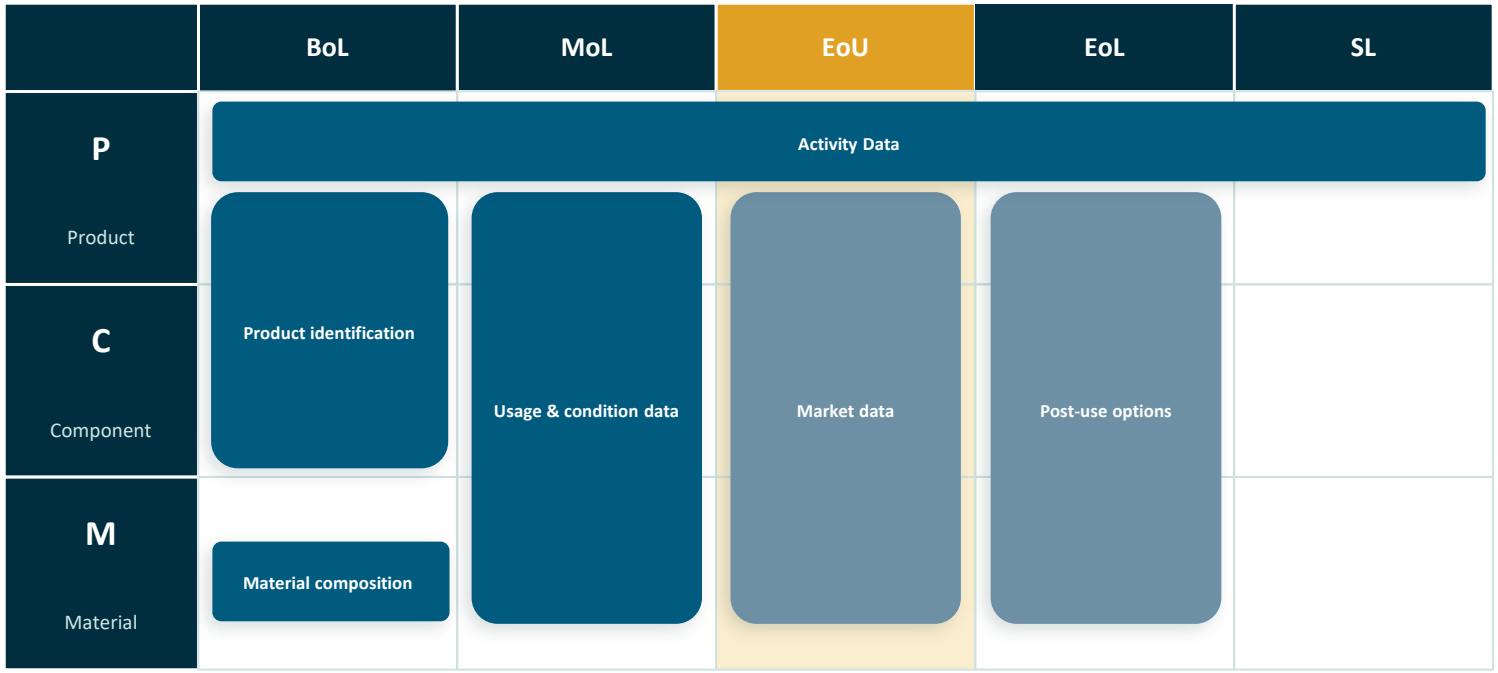
Parameter categories

Product identification	Granularity & semantics
Product classification	Data quality & governance
Product structure	Activity data
Material composition	Usage & condition data
Technical baseline	Derived condition data
Substances of concern	Market data
Circularity information	Post-use option & residual value data

11 derivated from existing models **+**

3 deductive from R1-R3

The conceptual data model an its assigned parameter categories



*Residual value is assessed at **End of Use (EoU)** from data accumulated across all phases*

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Three levels of granularity within the developed conceptual data model

Results II/II

1 Parameter category

A thematically coherent group of residual-value-relevant data.

e.g. **Usage data**

2 Data class

An object bundling related data elements.

e.g. **Operating profile**

3 Attribute

The smallest element — value, datatype, value range.

e.g. **Operating hours · integer · [0, max]**

Each cell of the framework is **detailed top-down** from **category to the smallest data element**.

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Contribution and outlook

Closes the gap

The first model linking all product levels with all lifecycle phases for residual value assessment.

The data-side prerequisite

2nd of 4 submodels which bridges parameter identification to computation-ready evaluation.

A transferable foundation

Generic across manufacturing industries and thus a building block for circular production systems.

Next: complete the remaining submodels and validate the model through expert interviews.



THANK YOU FOR YOUR ATTENTION!

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BRENNERT, JULIA | KARLSRUHE | 06/10/2026

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Toward Scalable Circular Repair Support:

A Circular Data-Inspired Architecture and the RITA Proof-of-Concept

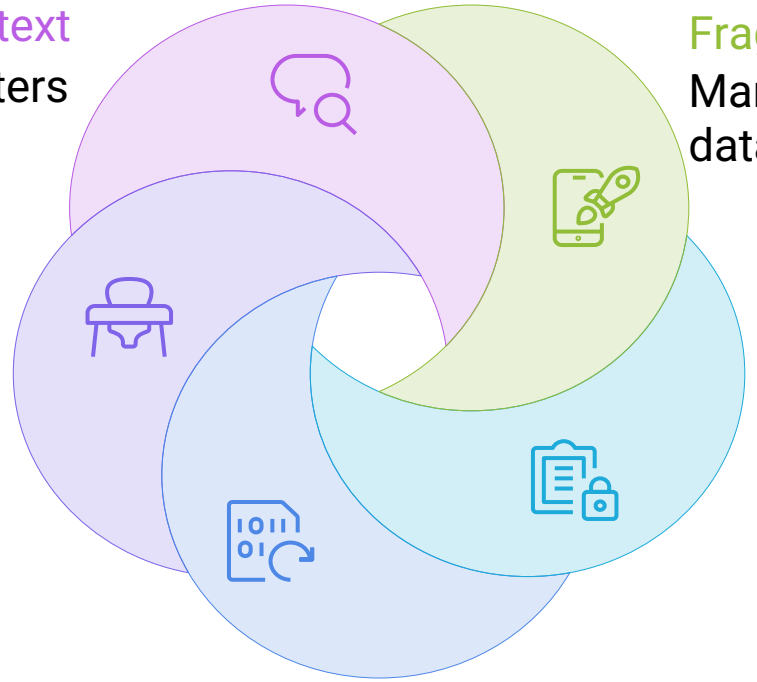
Sharon Vásquez-Díaz

Nadine Yilmaz, Jakob Gros, Lorena Lenz,
Nicole Stricker and Doris Aschenbrenner

The problem: repair needs the right product knowledge

Workbench Context
Actual product matters

Fragmented Repair Knowledge
Manuals, records, labels, databases



Safety Constraints
Device-specific risks

Product Variability
Models, components, layouts

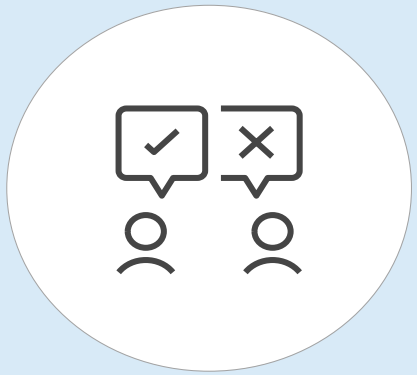
Inconsistent Procedures
Correct actions vary between products

The challenge is activating the right knowledge for the right device.

Why LLMs alone are not enough for physical repair?

LLMs can support repair by:

- Retrieving information
- Summarizing manuals
- Translating instructions
- Restructuring repair knowledge



Plausible ≠ grounded

Without physical grounding:

- Wrong device context
- Contextual errors
- Inefficient repairs
- Component damage
- Safety risks

A plausible answer can still be wrong if it is generated for the wrong device.

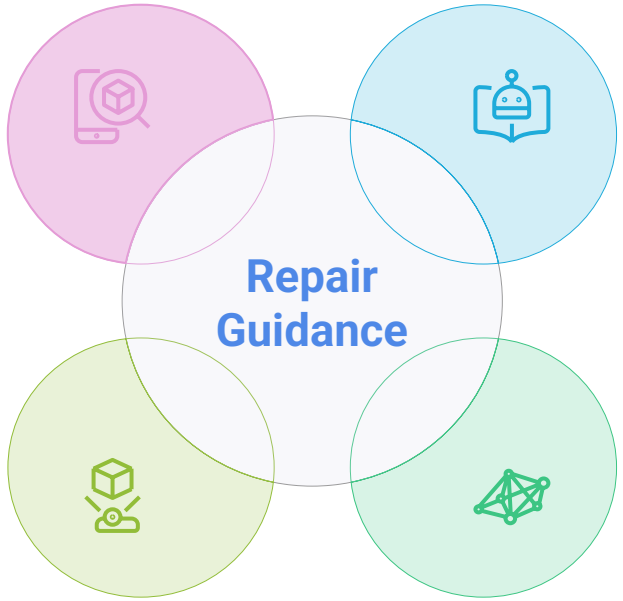
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RePAIR labor

Research gap and objective

Existing approaches solve parts of the problem:

Digital Product Passports
Provides access to product information and history.



RAG
Retrieval Augmented Generation enhances factuality through external knowledge.

Computer Vision
Identifies products and defects using visual analysis.

Knowledge Graphs
Structures domain knowledge for better understanding.

Gap: No reliable integration of physical perception, knowledge activation and LLM-based repair guidance.

Objective: How can generative AI repair assistance be grounded in physical circular repair environments?

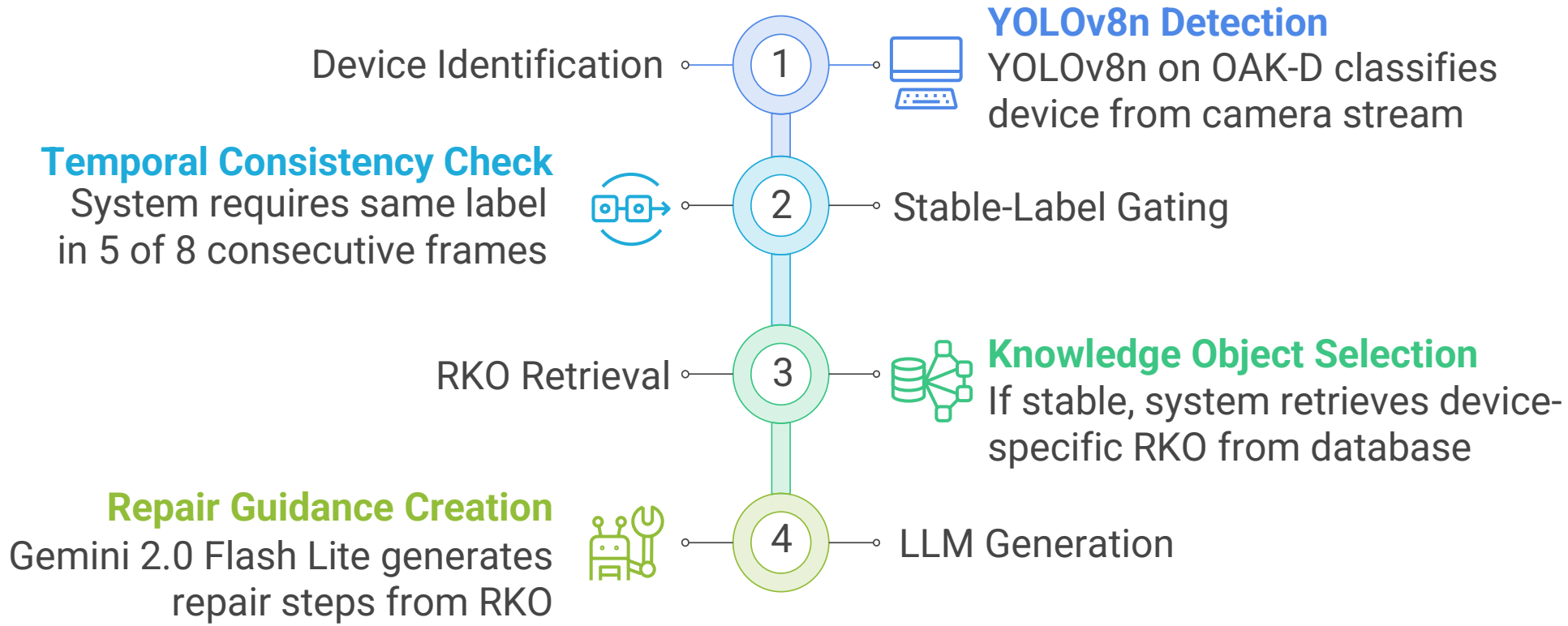
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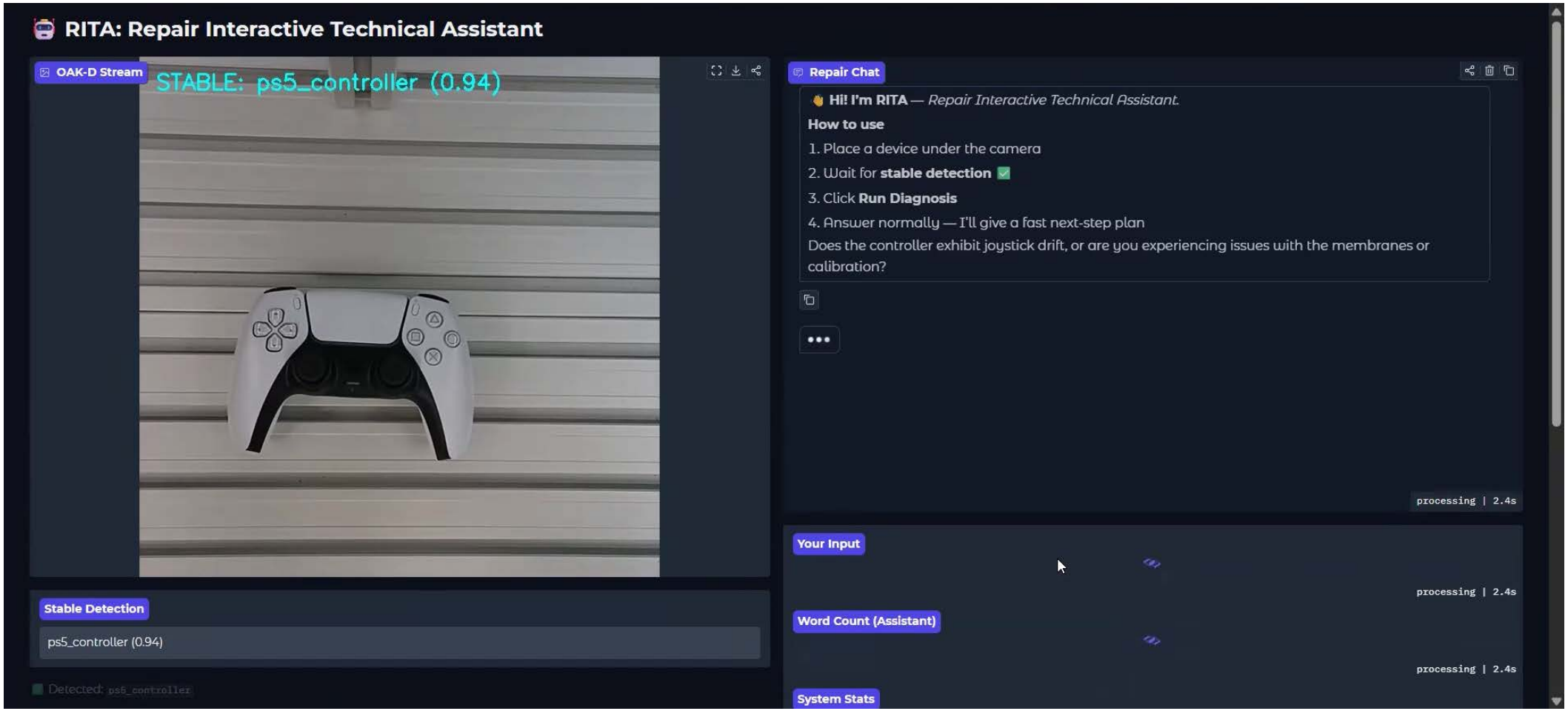
From Circular Data to Grounded Repair Assistance

Core contribution:
A Circular Data-inspired architecture that grounds LLM-based repair guidance in verified product context.

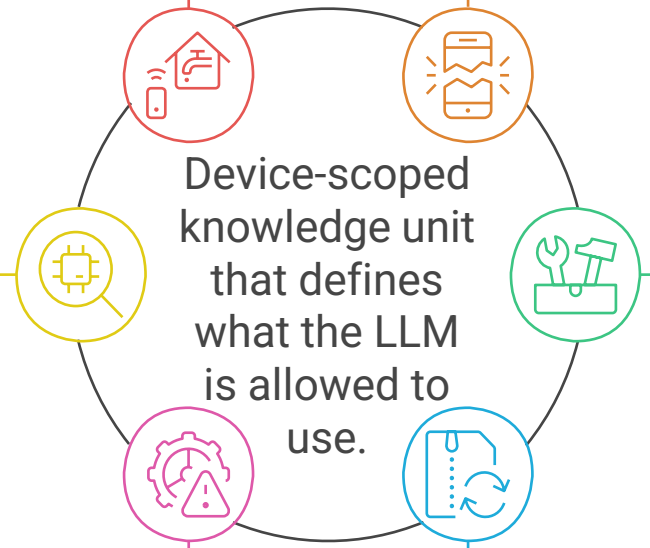
RITA as first MVP: See → Verify → Retrieve → Guide



RITA MVP interface



Repair Knowledge Objects: Scoping the LLM



Fault Modes

Common failures and likely causes

Observable Symptoms

Visible or reported signs of failure

Diagnostic Indicators

Clues for troubleshooting

Tool Requirements

Tools needed for the repair task

Safety Constraints

Precautions and risk-relevant information

Repair Steps

Task-specific repair actions

RKOs reduce wrong-device guidance and keep repair knowledge auditable.

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Exploratory functional validation

Exploratory feasibility assessment - not final performance evaluation.

Identification	Gating	RKO-constrained response
• Can vision trigger device-specific RKO retrieval? • **Observed:** activated for all four device classes	• Can temporal consistency reduce wrong-context activation? • **Observed:** reduced transient misclassifications and abstained when uncertain	• Does guidance remain within the retrieved RKO? • **Observed:** most responses remained RKO-consistent

Initial feasibility indication under controlled MVP conditions.

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RePAIR labor

Conclusion

Grounded repair assistance is not just an LLM task.

It requires the combination of:

- Verified product context
- Task-scoped repair knowledge
- Human-centered interaction

RITA demonstrates this principle as a first MVP.

Takeaways and future work

RITA MVP
First demonstrator of grounded LLM-based repair assistance

Richer Perception
Move beyond device labels toward repair-state recognition

Alternative Knowledge Architectures
RKOs, RAG, knowledge graphs and MoE



Larger Product Datasets
Scale to more devices, variants and repair domains

DPP/QR/Barcode Integration
Link physical products to trusted circular data sources

User-Centered Technician Studies
Evaluate trust, usability, cognitive load and repair quality

Verified product context before AI-generated repair guidance.

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labor

Further questions or interest in collaboration, please feel free to contact prof. Dr. Doris Aschenbrenner

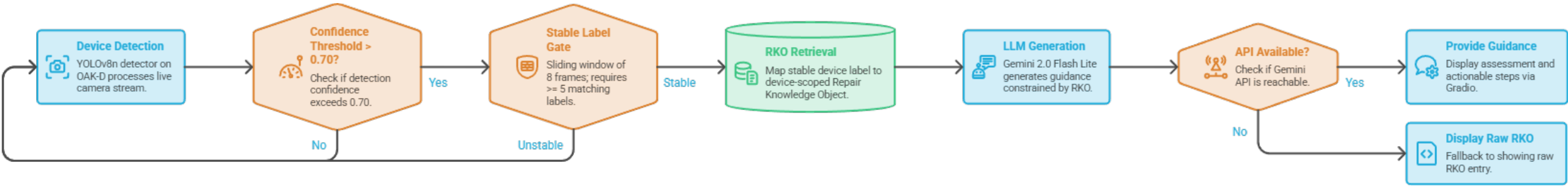
Doris.Aschenbrenner@hs-aalen.de

Sharon Vásquez-Díaz

RITA architecture

Table 1. Overview of the RITA prototype architecture and implementation

Component	Implementation in RITA
Device classes	Keyboard, PS5 controller, TV remote, wired mouse
Vision and deployment	YOLOv8n on Luxonis OAK-D, deployed as OpenVINO blob
Dataset	Roboflow augmented dataset with 1,371 images; 70/20/10 split
Detection logic	0.70 confidence threshold; 8-frame sliding window with ≥ 5 matching labels
RKO corpus	iFixit-derived repair snippets, manually curated
Language model	Gemini 2.0 Flash Lite via API
Prompt constraint	Answer only from the retrieved RKO
Interface	Gradio dashboard with live OAK-D stream and diagnostic chat
Audit trail	JSON session export with label, RKO, user input, and response



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RePAIR labor

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Digital Twins as Enablers for Tasks in the Circular Economy

Easily Accessible and Editable Digital Twins of Industrial Products, Powered by Game Engines, for Automation Across Tasks and Lifecycle Phases in the Circular Economy

Cedric Kiener and Prof. Dr. Steffen Schwarzer | University of Applied Sciences Aalen

Agenda
Overview of topics covered in this presentation

- **1. Motivation & Research Question**
- Why circular products need better digital twins
- **2. Lifecycle Phases of Circular Products**
- From design to recycling and back
- **3. Requirements for Digital Twins**
- Interoperability, web access, long-term availability, automation
- **4. Game Engines as Enablers**
- Unity, Unreal, Godot – comparison and advantages
- **5. Technical Approach & Web Deployment + Examples**
- CAD → glTF → Game Engine → Browser
- **6. Conclusion & Outlook**

Motivation & Research Question

- **The Challenge**
  - Circular products undergo repeated use, refurbishment, and reuse phases
  - Heterogeneous actor networks: manufacturers, recyclers, repair shops, remanufacturers
  - PLM systems lack open, long-term, multi-actor-capable digital twin support
- **Research Question**
  - How can digital twins meet the specific requirements of circular products – especially long-term availability, multi-actor accessibility, automatability, and interoperability – across extended life cycles?
- **Key Gaps in Existing PLM Systems**
  - (a) Multi-actor accessibility – licensing barriers for recyclers and repair shops
  - (b) Long-term availability over decades, even with vendor transitions
  - (c) Interoperability through automatable open interfaces

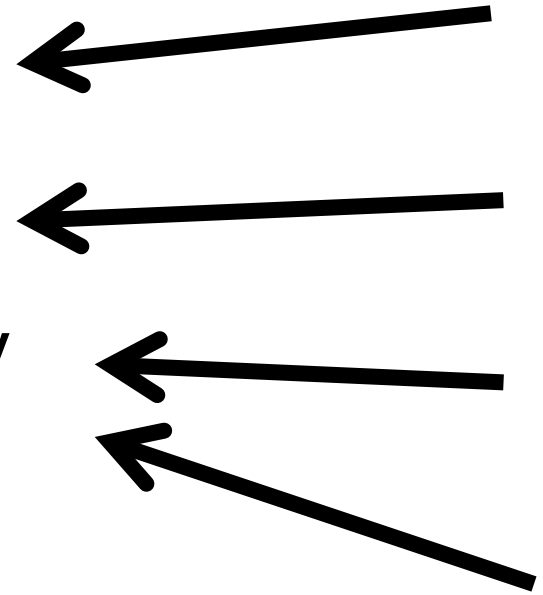
Lifecycle Phases of Circular Products

- **1. Design & Material Selection**
  - Modular design for easy component replaceability; CAD data feeds directly into digital twin creation
- **2. Production & Distribution**
  - Assembly visualization; 3D web representations for retail; Digital Product Passport assignment
- **3. Use Phase**
  - Interactive operating instructions, maintenance guidance, spare part info; product return facilitation
- **4. End-of-Life: Repair / Remanufacturing / Recycling**
  - Re-inventorying via unique product ID; component-level assessment; guided disassembly via AR
  - Innovation flow: component upgrades create new variants → requires automated DT generation

Requirements for Digital Twins of Circular Products

Key Requirements

- **Interoperability**
- **Web Accessibility**
- **Long-Term Availability**



Stakeholder Benefits

Manufacturer
Quality control, Digital Product Passport compliance, Product Insights

Distributor / Collector
3D product representations, customer transparency

Remanufacturing
Rapid re-inventorying, component-level assessment

Recycling & Repair
Disassembly guidance, bill of materials, spare parts access

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Game Engines as Enablers for Digital Twins

- **Core Advantages of Game Engines**
  - Prebuild simulation, visualization, and interaction function
  - Cross-platform deployment from a single codebase (desktop, mobile, web)
  - Source code access (with godot even commercial use of editor and engine code)
  - Built-in physics, AI, networking, and real-time rendering capabilities
  - glTF import/export ensures interoperability with existing CAD and PLM systems

Comparison Game Engines: Unreal, Unity, Godot

Criteria	**Unreal**	**Unity**	**Godot**
Resource Requirements	higher	Advantage	mostly low
Energy Efficiency	partially higher consumption	Advantage	limited research
Industrial DT Publications	very many	very many	few
C#/Enterprise Integration	weaker	strong	limited
Learning Curve	high	moderate	low
Open Source	no	no	Advantage
High-End Visualization	Advantage	good	weaker

Source: Ezhil 2025; Kiener et al. 2025

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Technical Approach: CAD → glTF → Game Engine

- **Pipeline Steps**
  - **CAD** → Engineering design data (parametric, with tolerances)
  - **STEP** → Universal CAD exchange format
  - **glTF** → Web-optimized 3D format; naturally protects IP (no tolerances/parametrization)
  - **Game Engine** → Interactive, physics-based, real-time digital twin
- **Key Advantages of glTF as Universal Format**
  - Supported by all three major game engines (Unity, Unreal, Godot)
  - High interoperability with existing software landscapes
  - Automated runtime import already successfully implemented and published with UE [1]
  - ISO/IEC 12113:2022 standard – broad industry adoption

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[1] Kiener 2025, https://ieeexplore.ieee.org/document/10896683

Web-Based Deployment & Multi-Actor Accessibility

Enabling device-independent access for all actors in CE

- **Deployment Options by Engine**
  - **Godot:** Direct WebAssembly/WebGL export – runs entirely in browser (free, MIT)
  - **Unity:** WebGL build target – WebAssembly in browser (strong mobile/industrial base)
  - **Unreal:** Pixel Streaming – server-side rendering, highest visual quality, higher costs
- **Engine-Agnostic Architecture (Key Innovation)**
  - Godot's MIT license enables a fully open update pathway: CAD → glTF → Web
  - Component manufacturer (Godot) → Producer (Unity) → Distributor (Unreal)
  - Even if a critical actor becomes unavailable – digital twin can be migrated or mirrored
- **Regulatory Context**
  - EU Digital Product Passport (Regulation 2024/1781) – mandatory across EU in coming years
  - EU Right to Repair (Directive 2024/1799) – 3D digital representations as meaningful complement

Game Engine Visual Example

Unreal Engine



Unity



Godot



Quellen:

[1] https://www.unrealengine.com/marketplace/en-US/product/automotive-configurator-01

[2] https://jamesarndt.itch.io/car-configurator-extended

[3] https://www.youtube.com/watch?v=Fx5lH6f0uxE

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Conclusion & Outlook

Game-engine-based digital twins for circular products

- **Key Findings**
  - Game engines address the requirements: interoperability, web access, long-term, availability
  - The CAD → STEP → glTF → Game Engine pipeline was automated
  - Combining game engines enables an engine-agnostic system – vendor lock-in eliminated
  - Godot’s MIT license provides the free update pathway accessible to all actors, including resource-limited ones
  - Supports compliance with EU Digital Product Passport and Right to Repair legislation
- **Outlook**
  - Universal semantics for digital twins is needed to overcome the “silo problem” across circular value networks
  - MIT-licensed toolchains as catalyst for automated, scalable circular factory concepts

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Thank you for your Attention



Karlsruher Institut für Technologie

GANResilRob: LLM-Based Autonomous Robotic Disassembly in E-Waste Recycling

David Timmermann[12], Elias Hofele[2], Robert Wilbrandt[12],
Vincenzo Di Pentima[12], Georg Heppner[2], Tristan Schnell[2] and Arne Roennau[12]

[1]Karlsruhe Institute of Technology, [2]FZI Forschungszentrum Informatik

MAIRo

FZI

Outline

- Motivation
- Problem Statement
- Disassembly Sequences
- Behavior Tree Generation
- Field Test Evaluation
- Conclusion & Outlook



Motivation AI-Powered Robotic Battery Recycling

Current State of the Art in Recycling E-Waste

- More and **more daily products** contain batteries
  - Heat meters, smoke detectors, smartphones, toothbrush
- **Extraction of the battery** is critical and necessary
  - Reducing fire hazards / **recover valuable resources**
- Extraction normally done by a human
  - Products vary and reach their EOL in different conditions





Vision: Combine AI and robotics to enable the disassembly of battery-containing electronics

Research Challenge

Challenges

- Recycling facilities process a wide variety of products, requiring **online re-planning**
- Product designs, battery locations, and damage conditions **vary significantly**
- **Hardcoded** disassembly procedures do not scale to real-world recycling applications

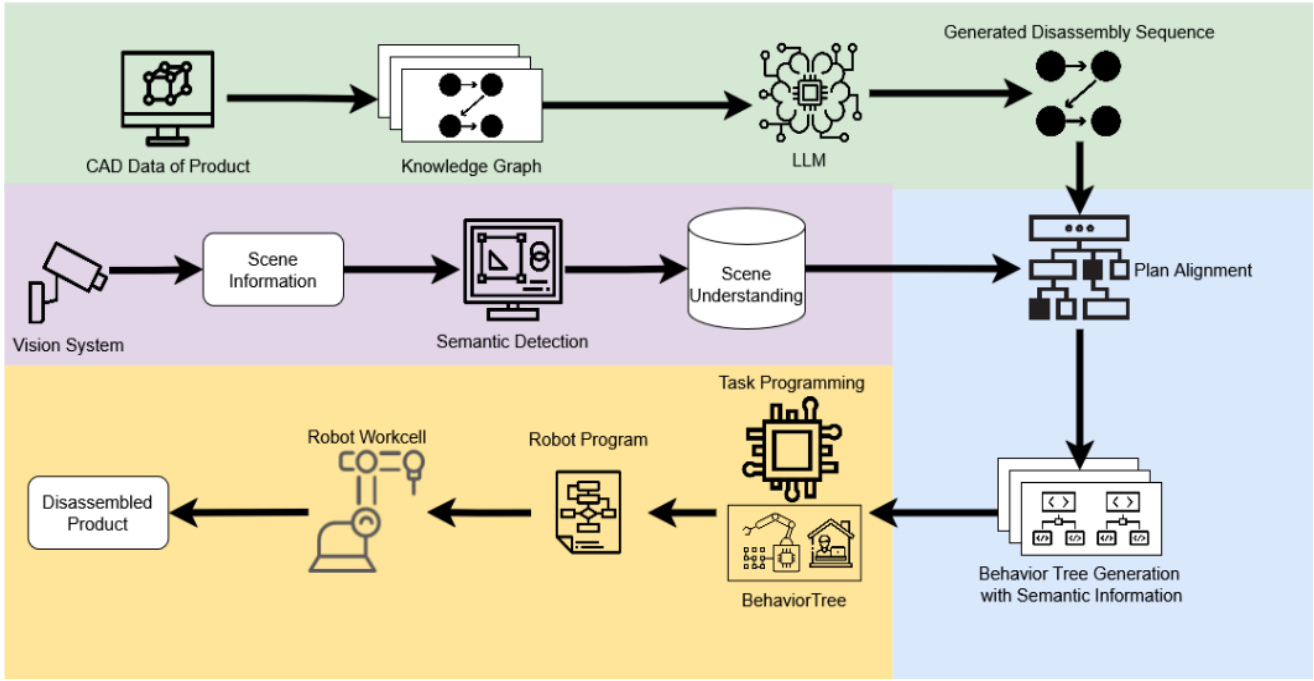
Research Questions

- How can a robotic **disassembly sequence** be **generated for an unknown product**?
- How can a generic **disassembly strategy** be **adapted to the current product** condition?

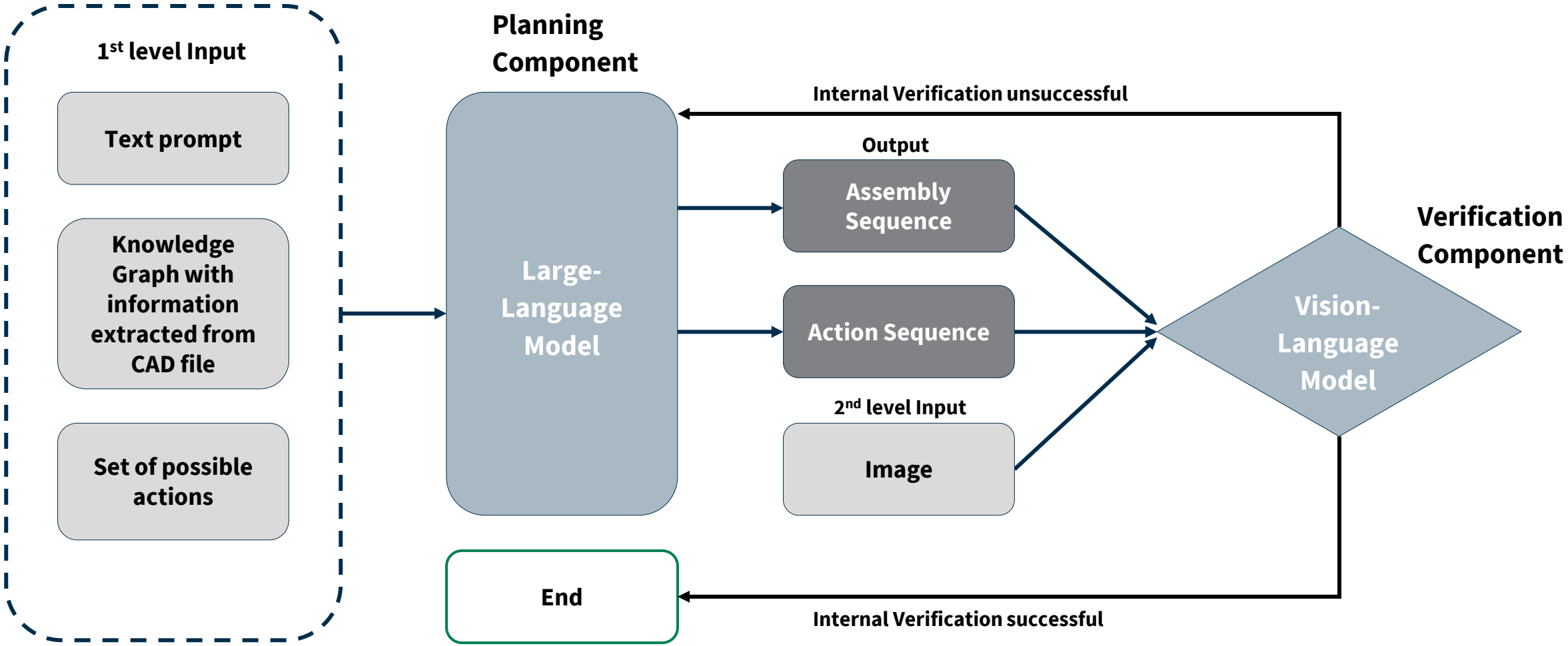


Proposed Approach - Overview

- **High-Level Planning**
  - CAD converted into **Knowledge Graph**
  - **LLM** generates a symbolic disassembly sequence
- **Semantic Scene Understanding**
  - Vision captures current product state
  - Extract spatial and semantic infos
- **Plan Refinement & Task Programming**
  - **VLM-based** plan **refinement**
  - Automatically generate **Behavior Trees**
- **Intelligent Execution**
  - Behavior Trees are executed and compliance compensates uncertainties

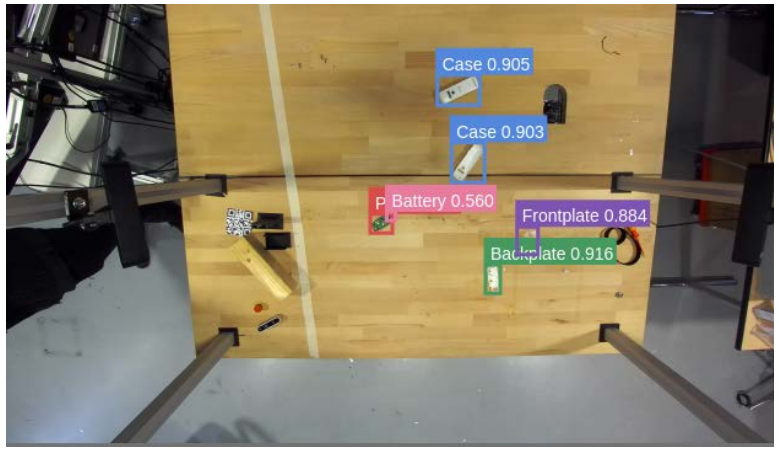


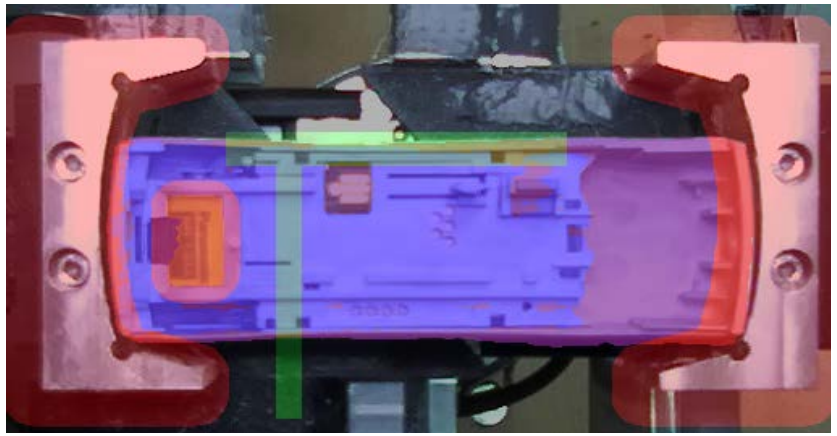
Generation of General Disassembly Sequences



Semantic Scene Understanding

- **Multi-Camera Environment Perception**
  - **Global view** of the complete work cell
  - **Close-up view** for detailed product inspection
- **AI-Based Scene Analysis**
  - Product type classification
  - 6D pose estimation
  - Detection of batteries and retaining tabs
  - Grasp verification
  - Battery removal verification

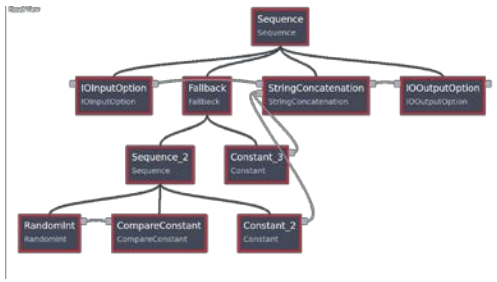


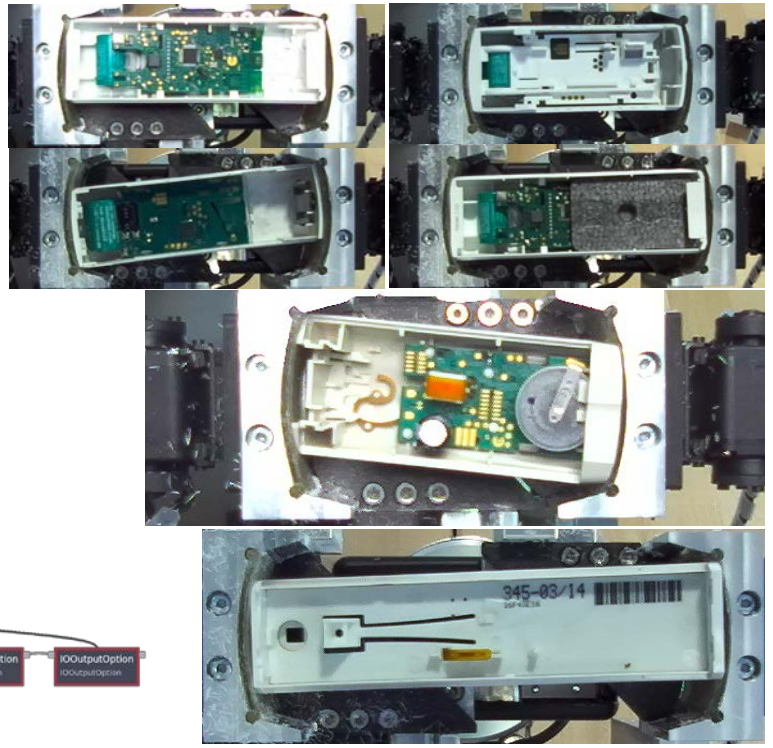


Plan Refinement

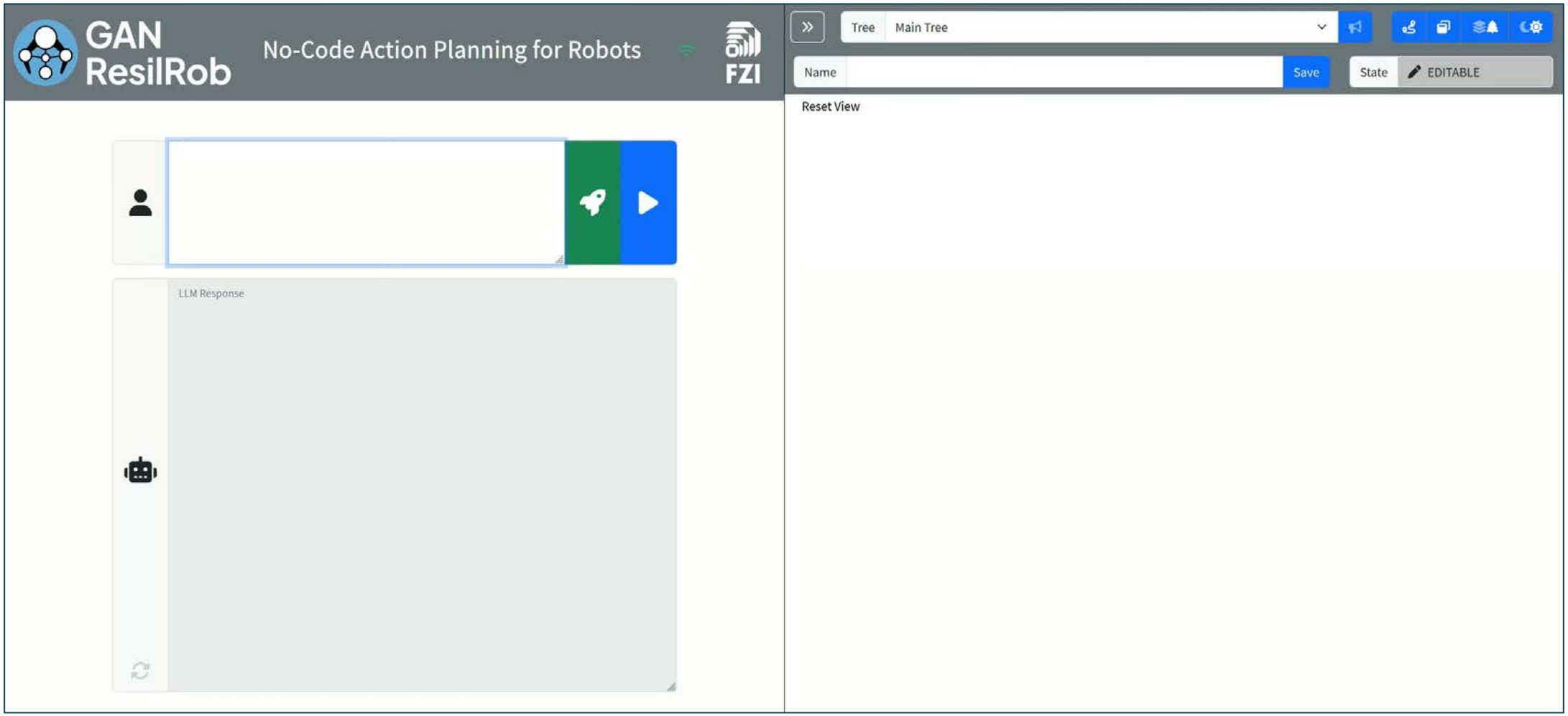
- **No-Code Robot Programming**
  - Tasks are specified in natural language
  - Example: *“Remove the battery from the housing”*
- **Context-Aware Behavior Generation**
  - **LLMs** interpret task instructions
  - **VLMs** analyse the current environment
  - Grounding: robot capabilities and tools
- **AI Generates Executable Program Sequence**
  - LLM understands how to “speak” **Behavior Trees**
  - Resulting programs can be executed directly on the robot







Skill-Based Robot Programming



Field Test Evaluation at Electrocycling GmbH Gosla





Illumination and Camera System

Illumination and Camera System

Robot UR10e

Mil

Gripper

Conveyor belt

Infeed ramp and light barrier

Field Test Evaluation at Electrocycling GmbH Gosla



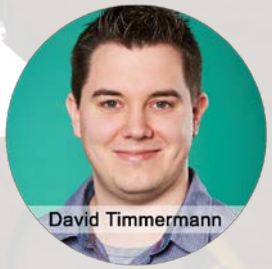
Field Test Evaluation at Electrocycling GmbH Gosla

Metric	Kalo	Metrona
Total Count of Individual Devices	93	11
Type Recognition	93	11
Battery Milling Success Detection	90	9
Battery Milling Success Rate	90	9
Removal of Battery from Housing Rate	71	9
Minimum Time [s]	271	422
Maximum Time [s]	566	597
Average Time [s]	307	455
Manual Restarts	0	0

Conclusion and Outlook

- **Conclusion**
  - Combined **Knowledge Graphs, LLMs, VLMs, and Behavior Trees** in a unified pipeline
  - Simply generate new disassembly programs for new/individual workpieces
  - Demonstrated robust operation in simulation and field test evaluation
  - Enabled **fully autonomous, end-to-end disassembly** without human intervention
- **Outlook**
  - Integration of newer and specialised foundation models
  - Extension with **Vision-Language-Action (VLA)** capabilities
  - Improved adaptability for unknown products and situations
  - Transfer of the framework to **mobile robots and other application domains**

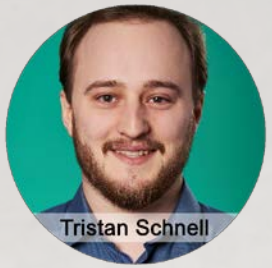












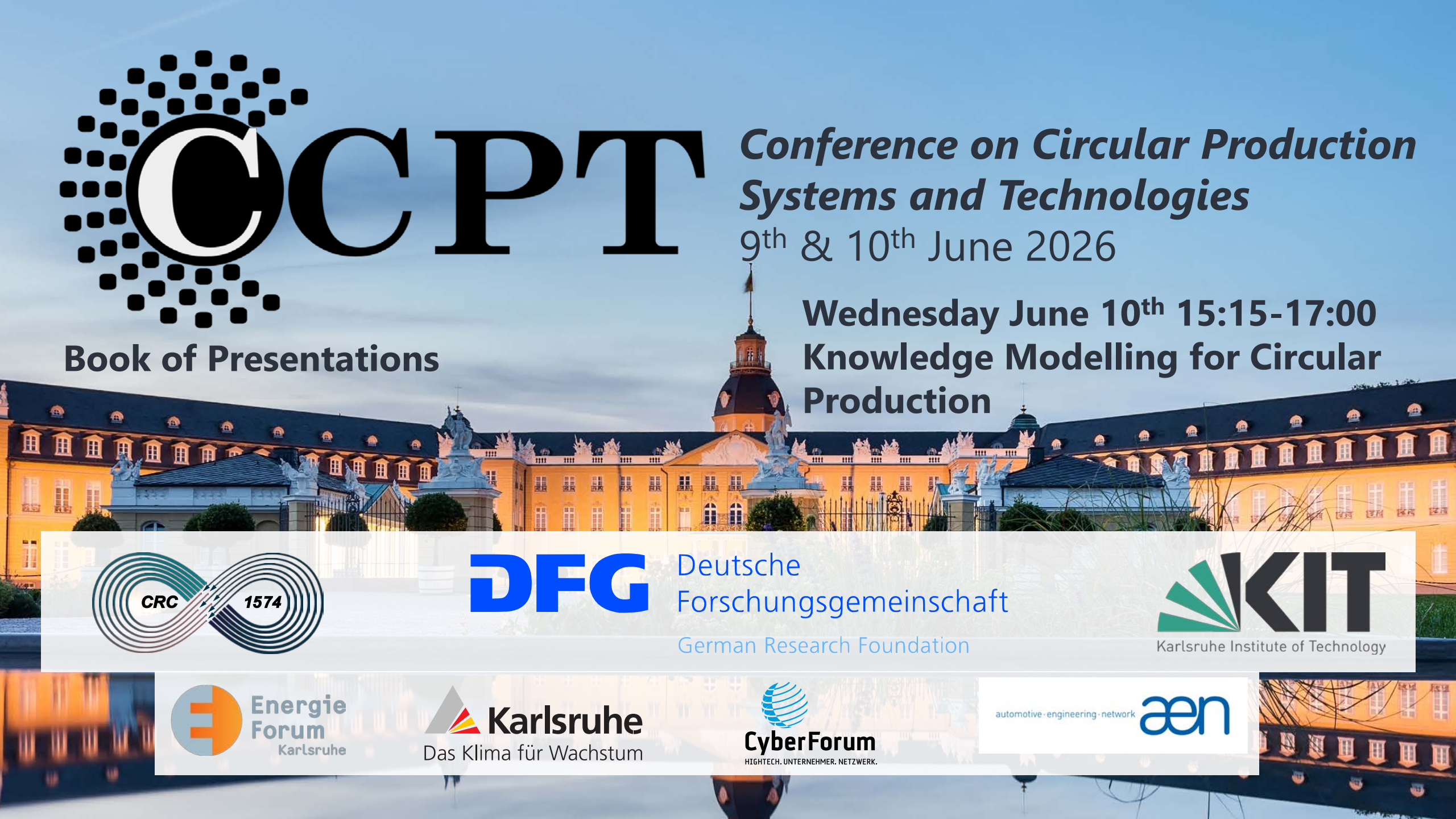


Thanks to the great team behind this work!

Thank you for your attention!

Questions?

Supported by the GANResilRob project (Grant No. 01MJ22003A, BMWE) and the AIDeCo project (Intel Corporation donations).



CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 15:15-17:00
Knowledge Modelling for Circular Production

CRC 1574

DFG Deutsche Forschungsgemeinschaft
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KIT Karlsruhe Institute of Technology

Energie Forum Karlsruhe

Karlsruhe Das Klima für Wachstum

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automotive · engineering · network aen



CCPT 2026

Development of Circular Economy-Specific Capability Profiles for Human Workers

Matthias Schmidt, Iris Graessler, **Tim Meinecke**,
Felix Vollenkemper, Thomas Hesse

10.06.2026 | Karlsruhe

Agenda

DECAP

DFG SPP 2443
Hybride Entscheidungs-unterstützung in der Produktentstehung

1. Motivation
2. Methodology
3. Derivation CE-specific capability profiles
4. Conclusion

In order to reuse and recycle products, the necessary capabilities must be taken into account.

DFG SPP 2443
Hybride Entscheidungs-unterstützung in der Produktentstehung

capabilities

- ~20% of global material input ends in landfill
- global circularity rate ~7%

RQ: Which capabilities do employees in production need to meet requirements of the CE?

capabilities

assembly

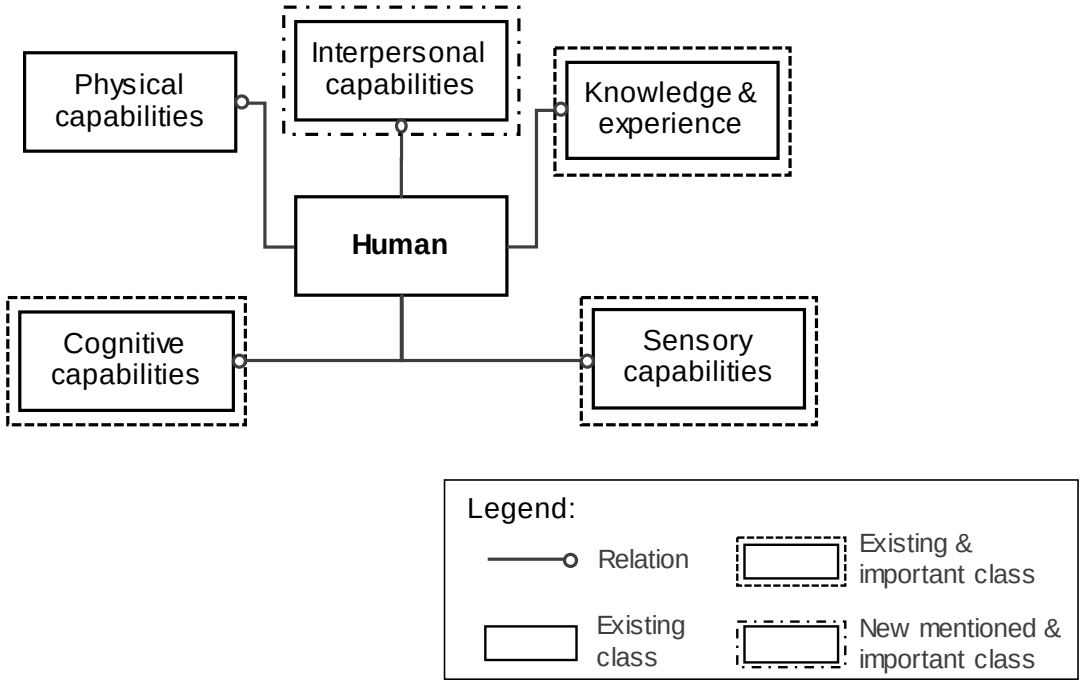
assembly

[Circle Economy 2025]

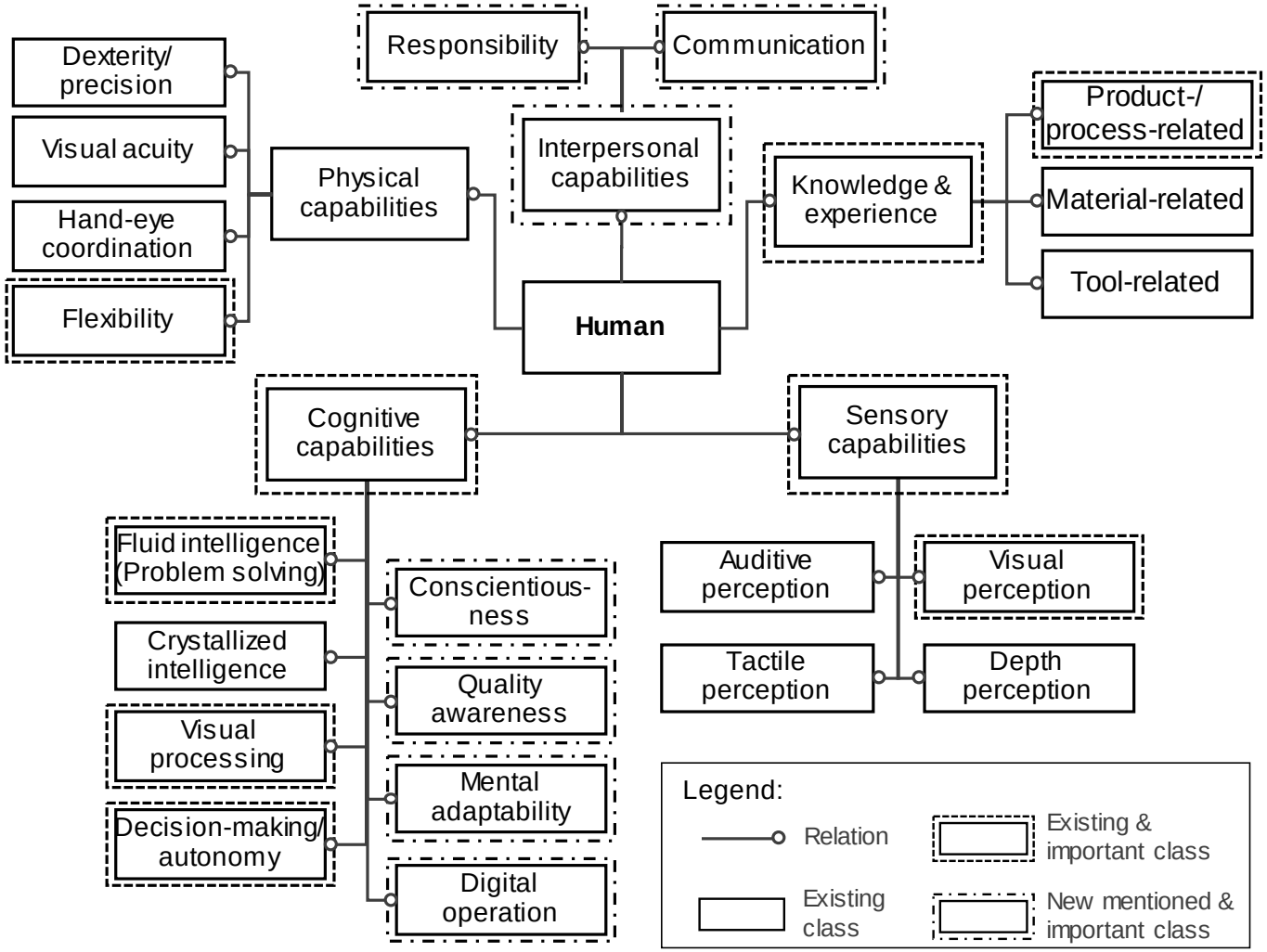
The literature search was supplemented by semi-structured interviews.

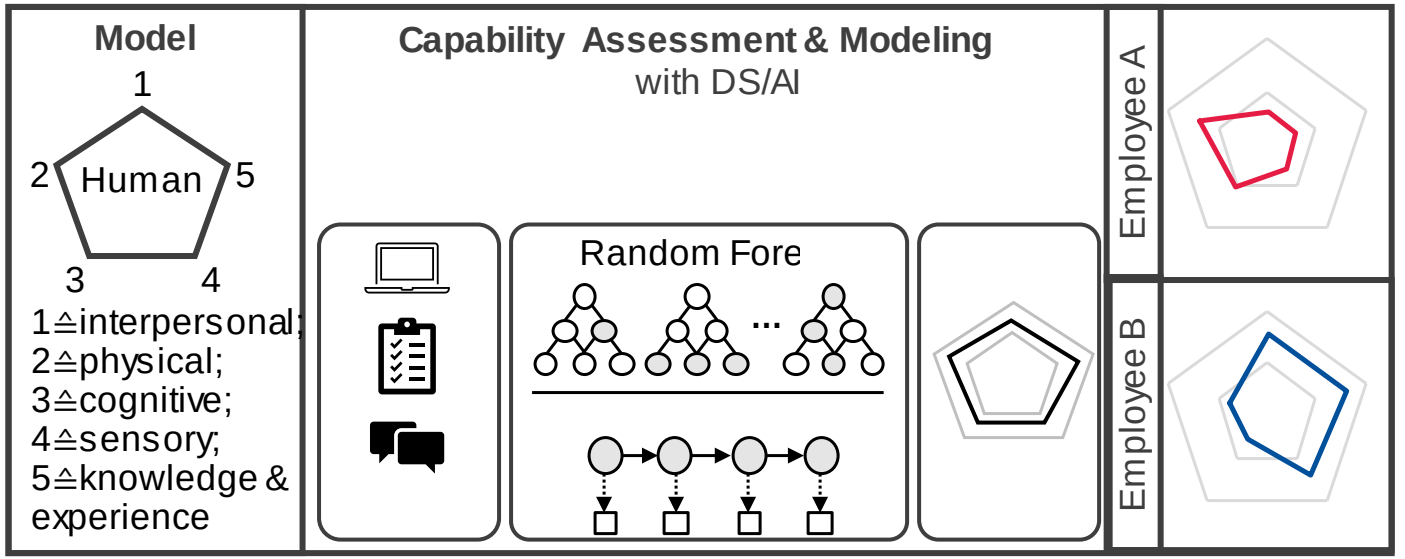
Based on the initial model, additional classes were introduced.

- observable body characteristics as well as organic processes
- non-observable processes and settings that are captured, e.g., via predictors
- gained through years of experience and training
- perception of the environment
- connection between humans



Particularly important capabilities were identified from both studies.




Model
1
2
Human
5
3
4
1≙interpersonal;
2≙physical;
3≙cognitive;
4≙sensory;
5≙knowledge & experience
Capability Assessment & Modeling
with DS/AI
Random Fore
...
Employee A
Employee B

The developed profiles still needs to be further investigated in practice.

DFG SPP 2443
Hybride Entscheidungs-unterstützung in der Produktentstehung

Need for additional interviews and data collection



further implementation in a decision support system



companies in a similar sector that were surveyed;

Thank you for your attention.
Questions can now be answered.



M. Sc.
Tim Meinecke

Research Associate
Institute of Production Systems and
Logistics

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TECHNISCHE UNIVERSITÄT WIEN

INSTITUTE OF MANAGEMENT SCIENCE
Research Unit of Production and Maintenance Management

A Knowledge-based System for Standardised Visual Inspection Documentation in Safety-Critical Assets

Andreas Steiner[1], Florian Gombotz, Samuel Herrnstein and Fazel Ansari
[1]andreas.steiner@tuwien.ac.at

© Faculty of Mechanical and Industrial Engineering

Motivation

Why Visual Inspections Matter in a Growing Transport Sector

Global travel demand in the public transport sector continues to grow by 4–7% annually (IATA Safety Report, 2022).

Visual inspections ensure regulatory compliance and enable condition assessment (Cabour et al., 2022).

PHASES OF VISUAL INSPECTIONS:

01 **Preparation:** Collect and review asset history and compliance documents

02 **Visual inspection:** Assessment of the condition

03 **Follow-up:** Documentation and reporting



INDUSTRIAL CHALLENGES OF VISUAL INSPECTIONS IN AVIATION:

- Incidents in complex socio-technical systems rarely have a single cause; they often stem from latent failures that lie dormant until a specific event triggers them (Clare & Kourousis, 2021).
- Human error is a major contributor to such failures, and manual visual inspection stays highly subjective, shaped by individual experience and perception (Clare & Kourousis, 2021).
- Dynamic, multi-stakeholder environments produce inconsistent knowledge, leading to data misinterpretation and weakened operational integrity (Abbas & Khare, 2024).
- No dedicated tools yet standardise the documentation of first-level inspections (Koch et al., 2023).

International Air Transport Association (IATA), 20-Year Air Passenger Forecast, 2022.
G. Cabour, Ledoux, and S. Bassetto, "Aligning work analysis and modeling with the engineering goals of a Cyber-Physical-Social System for industrial inspection," Applied Ergonomics, vol. 102, 2022.
J. Clare and K. I. Kourousis, "Learning from incidents in aircraft maintenance and continuing airworthiness," Aircraft Eng. and Aerospace Technology, 93(2), 338–346, 2021.
J. Abbas and A. Khare, "Identifying and categorizing errors in the final inspection and certification process of aircraft components," Aircraft Eng. and Aerospace Technology, 96(4), 564–572, 2024.
J. Koch et al., "A human-centered IIoT platform approach for manual inspections," Procedia CIRP, 120, 762–767, 2023.

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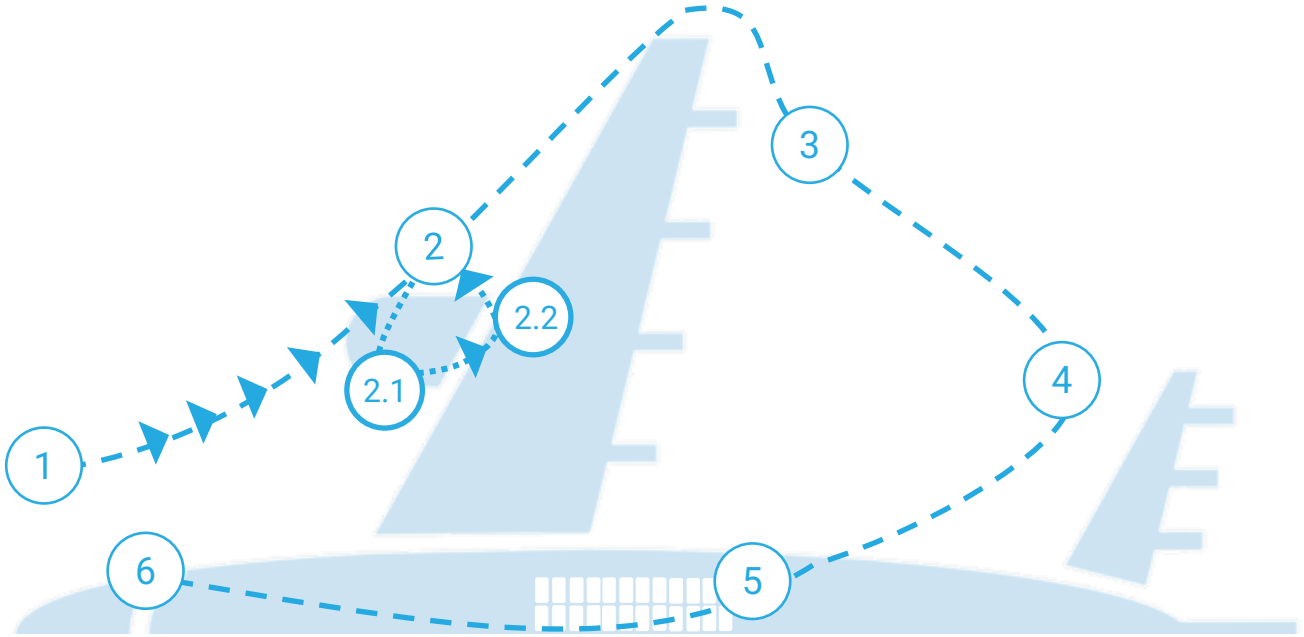
Motivation
Visual Inspection Process and Task

Types of inspection:

- Airworthiness inspection
- Pre-flight inspection
- Weekly inspection
- ...

Inspection process (regions):

1. Exterior: Nose
2. Exterior: Engine
3. Exterior: Wing
4. Exterior: Vertical stabiliser
5. Interior: Galley
6. Interior: Cockpit
- ...



Inspection tasks:

1. Exterior: Nose

1.1. Check for damage and deformation

- ...

2. Exterior: Engine

2.1. Check for damage and deformation

2.2. Check the serial number

2.3. Ensure freedom from foreign objects (FOD)

- ...

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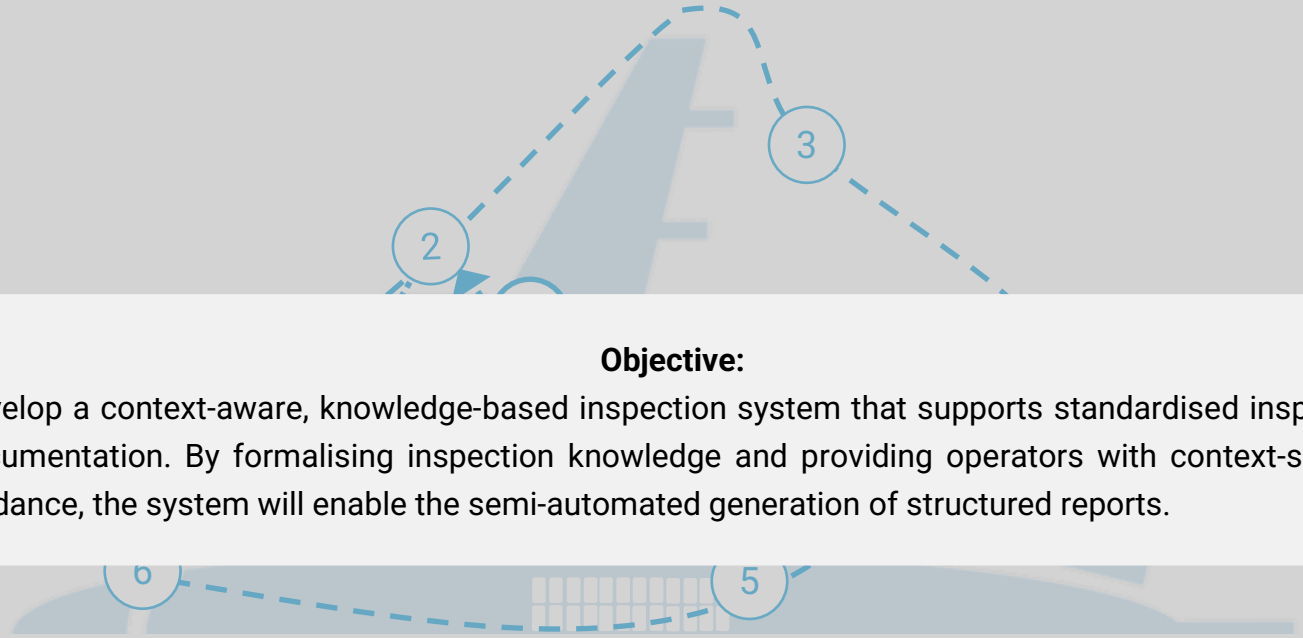
Motivation
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Types of inspection:

- Airworthiness inspection
- Pre-flight inspection
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- ...

Inspection process (regions

1. Exterior: Nose
2. Exterior: Engine
3. Exterior: Wing
4. Exterior: Vertical stabiliser
5. Interior: Galley
6. Interior: Cockpit
- ...



Objective:

Develop a context-aware, knowledge-based inspection system that supports standardised inspection documentation. By formalising inspection knowledge and providing operators with context-specific guidance, the system will enable the semi-automated generation of structured reports.

Inspection tasks:

1. Exterior: Nose

1.1. Check for damage and deformation

- ...

xterior: Engine

Check for damage and rmation

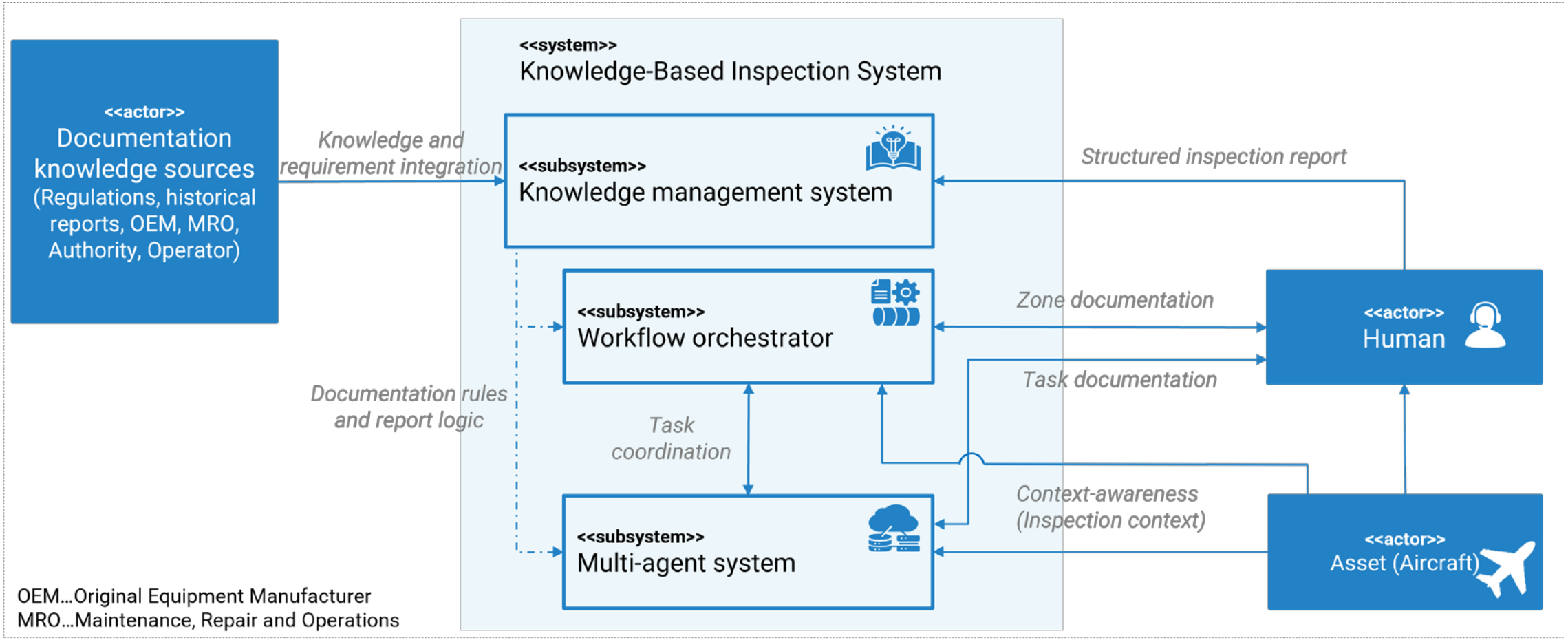
Check the serial number

2.3. Ensure freedom from foreign objects (FOD)

- ...

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Knowledge-Based Inspection System
Core modules



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Knowledge-Based Inspection System

Time-Structured Inspection Documentation

Zones (z_i)	Inspection task(T_i)
z_1	
	T_1
	T_2
	T_i
z_i	
	T_1
	T_2
	T_i
z_t	



time **t**

z_1 T_1 T_2 T_i

z_i T_1 T_2 T_i

z_t z_t z_t

Frame Extraction Layer F_s ($\Phi(f_t)$)

Report Generating Function G(F_s,c)

ϕ_{zone} $f_t \rightarrow z_i$

ϕ_{task} $f_t \rightarrow q_i, c_i(z_i)$

Inspection Report

z_t... non relevant zone
q_i... inspection task
$c_i(z_j)$... inspection requirements
F_s... annotated frames
c... documentation requirements

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Knowledge-Based Inspection System

Inspection Report Structure

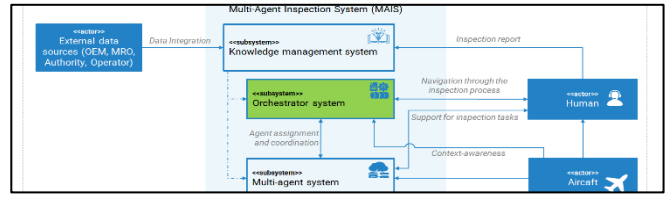
- **Hierarchical & time-based:** the top level defines the inspection context.
- **Zones** are bounded temporal segments, each set by a start and end frame.
- **Tasks** carry a minimum requirement, a status and a set of findings.
- **Findings** link to individual frames. Termination criteria (stop_if) define when a task is complete.
- **Human input** enters during the inspection (feedback) and at the end (oversight → finalised report).

```
Inspection Report
├─ type: time_based
└─ zones
   └─ Zone 1
      ├─ frames: 34-85
      └─ tasks
         └─ Task 1
            ├─ min: ""
            ├─ status: ongoing
            ├─ findings
            │  └─ frame 34: ""
            └─ stop_if: min, coverage
```

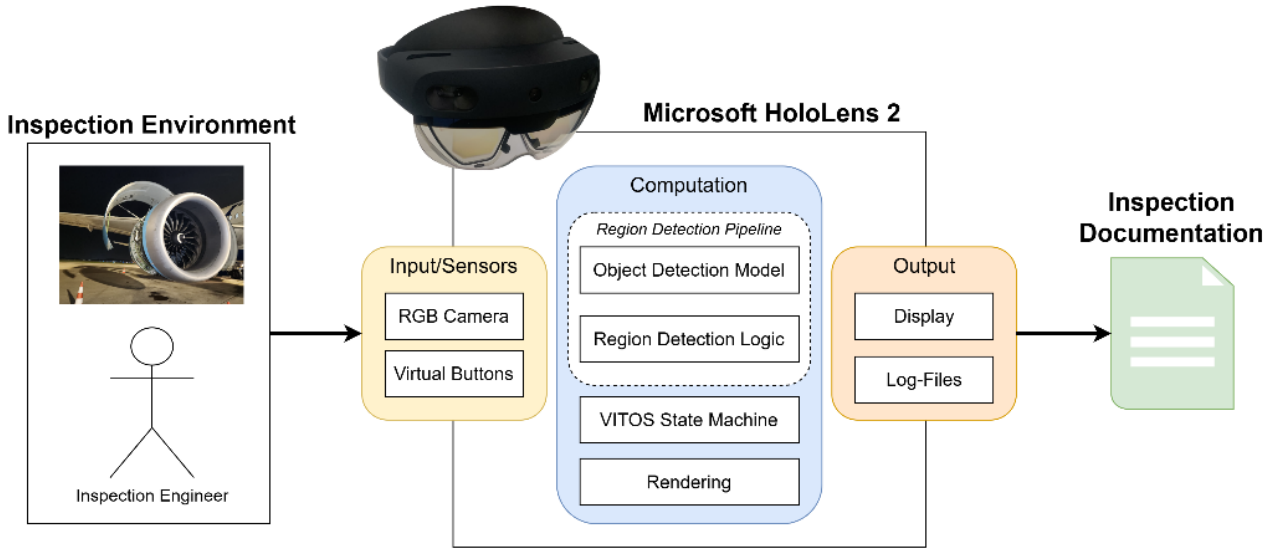

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Evaluation Scenario

Experimental Setup and VITOS Prototype



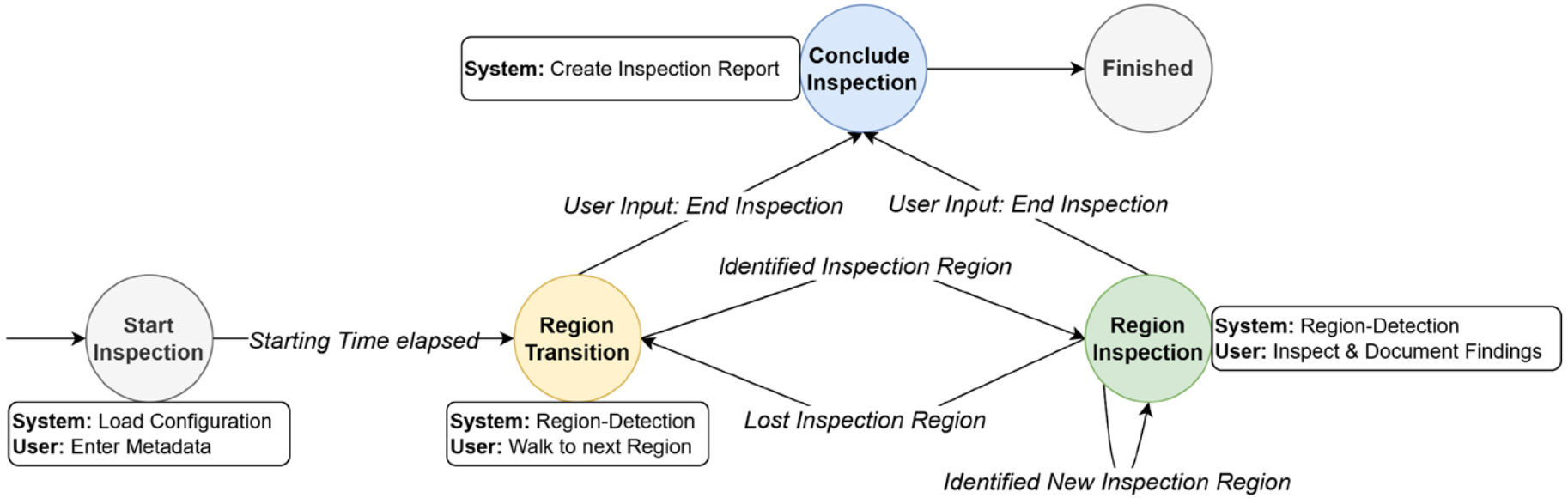
- **PoC** of a context-aware inspection system for transparent process documentation.
- **Hardware:** VITOS runs on a Microsoft HoloLens 2 AR HMD (RGB camera, see-through display, on-device SoC).
- **Software:** Unity 2022.3.62f1 with Sentis 2.1.3; a YOLOv12-Nano pipeline detects aircraft parts and the VITOS state machine derives the zone.
- **Evaluation:** Tested on a real aircraft under controlled conditions; logged states drive report generation.





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Evaluation Scenario
VITOS – State Machine logic



- **Region Detection** identifies the current inspection region from the inspector's field of view.
- The **VITOS state machine** switches between **Region Transition**, **Region Inspection**, and **Conclude Inspection**.
- Logged system states enable **time-aligned task documentation** and **structured inspection report generation**.

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Evaluation Scenario

VITOS – Technical Performance

$$Region\ Accuracy = \frac{TP + TN}{TP + TN + FP + FN} = \frac{Correct\ Predictions}{Evaluated\ Frames}$$

-	Landing Gear	Engine	Wing	Door	Nose	Total
Eval. Frames	89	90	26	23	21	320
Corr. Predictions	45	85	14	15	2	224
Region Accuracy	**51%**	**94%**	**54%**	**65%**	**10%**	**70%**

$$Region\ Precision = \frac{TP}{TP + FP} = \frac{Correctly\ Predicted\ Region\ Frames}{Total\ Predictated\ Region\ Frames}$$

-	Landing Gear	Engine	Wing	Door	Nose	Total
Predicted Frames	49	88	18	15	2	172
Corr. Predictions	45	85	14	15	2	161
Region Precision	**92%**	**97%**	**78%**	**100%**	**100%**	**94%**

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Evaluation Scenario

VITOS – Excerpt of inspection report

```
=== Inspection Report ===
Inspection Start: 2026-04-29 11:28:10
Inspection End: 2026-04-29 11:37:37
Inspection Duration: 09:26
Total Regions Inspected: 11

----- Region Entry 1 -----
Region: Engine, Start: 2026-04-29 11:29:50, End: 2026-04-29 11:31:29,
Duration: 01:38, Damage Images: 1

Damage Images:
U:/Users/holol/AppData/Local/Packages/VITOS_pzq3xp76mxafg/LocalState\Vito
sDamageReport_Images_20260429_1128\Damage_Engine_20260429_113041.png

----- Region Entry 2 -----
Region: LandingGear, Start: 2026-04-29 11:31:29, End: 2026-04-29
11:32:19, Duration: 00:50, Damage Images: 0


----- Region Entry 3 -----
```

- **VITOS test output** from simulated visual inspection.
- State logging provides the basis for structured report generation.

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Evaluation Scenario
Limitation & Outlook

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LIMITATIONS

- **Camera-only sensing:** zones or defects that are not visually distinguishable, or fall outside the inspector's field of view, cannot be captured.
- **Detection reliability:** (70% accuracy, 94% precision) bounds the reliability of the resulting documentation.
- **Human remains the decision authority:** the system acts as a guidance and documentation layer, not a replacement.

KNOWLEDGE-BASED INSPECTION SYSTEM FOR DOCUMENTATION

- Core contribution: a **time-structured workflow** that segments the video into region-specific states and produces structured, frame-traceable findings for a PDF report.

BENEFITS

- Reduced subjectivity: Finding tied to zones and tasks
- Coverage: The completeness of the inspection can be made visible
- Traceable: Time-based logging allows reproducibility

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[7] Huang, L., Wu, G., Tang, W., & Wu, Y. (2021). Obstacle distance measurement under varying illumination conditions based on monocular vision using a cable inspection robot. IEEE Access, 9, 55955–55973.

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INSTITUTE OF MANAGEMENT SCIENCE
Research Unit of Production and Maintenance Management



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Technische Universität Braunschweig

Institut für Werkzeugmaschinen und Fertigungstechnik



Development of a variant-flexible gripper system for automated battery disassembly

Conference on Circular Production Systems and Technologies (CCPT)

Maximilian Liedtke and Leif Tönjes

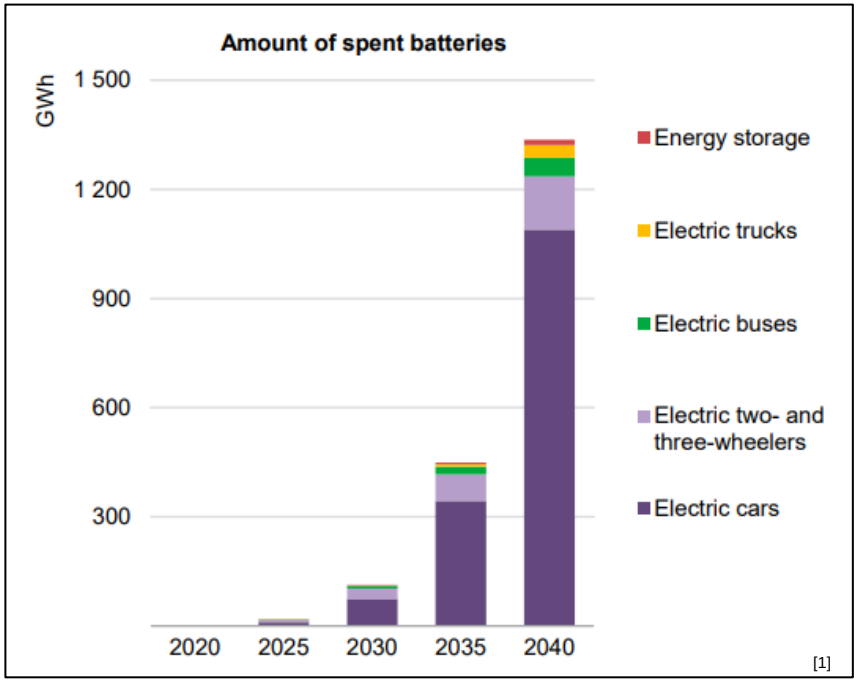
Introduction

Motivation for Efficient Recycling of End-of-Life Lithium-Ion Batteries

Environmental Challenges

- Improper disposal
- Health, fire and environmental risks

→ Goal: Hazard avoidance



Introduction

Motivation for Efficient Recycling of End-of-Life Lithium-Ion Batteries

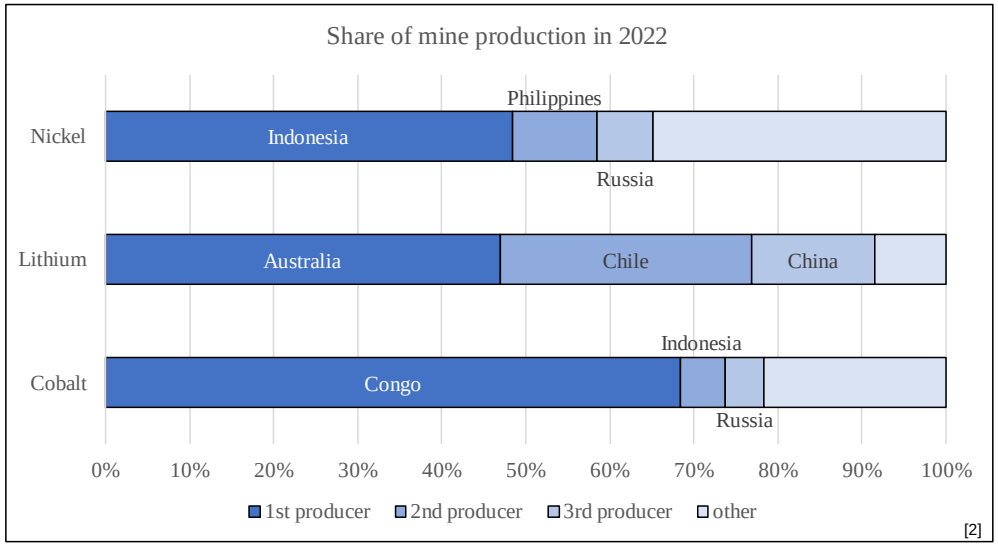
Environmental Challenges

→ Goal: Hazard avoidance

Primary Material Limitations

- Production is concentrated in few countries
- Mining has negative environmental, social and health impacts

→ Goal: Reduce dependencies



Introduction

Motivation for Efficient Recycling of End-of-Life Lithium-Ion Batteries

Environmental Challenges

→ Goal: Hazard avoidance

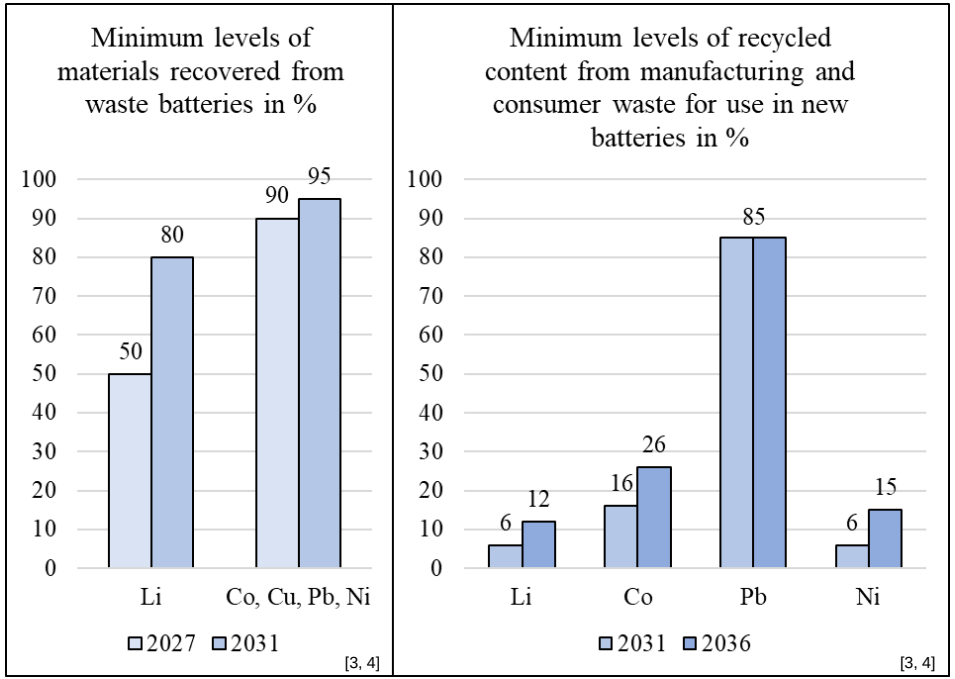
Primary Material Limitations

→ Goal: Reduce dependencies

Legal Regulations

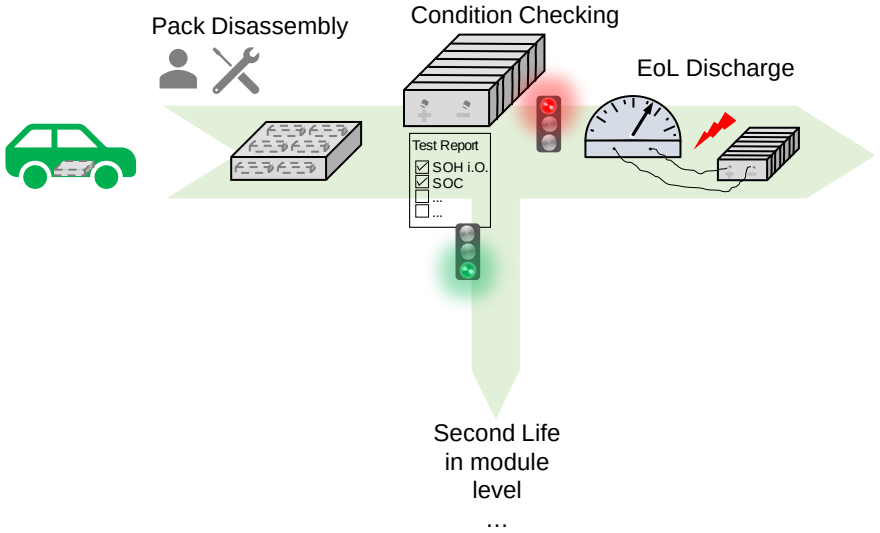
- More stringent targets for waste collection, recycling efficiency, and material recovery

→ Goal: Sustainable and self-sufficient circular economy



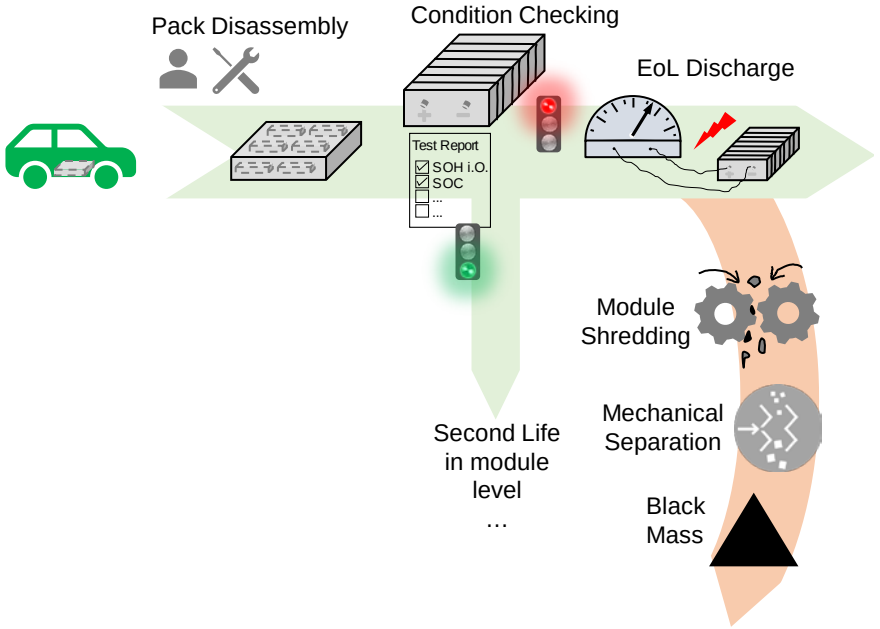
Introduction

State of the Art of Efficient Recycling for Lithium-Ion Batteries



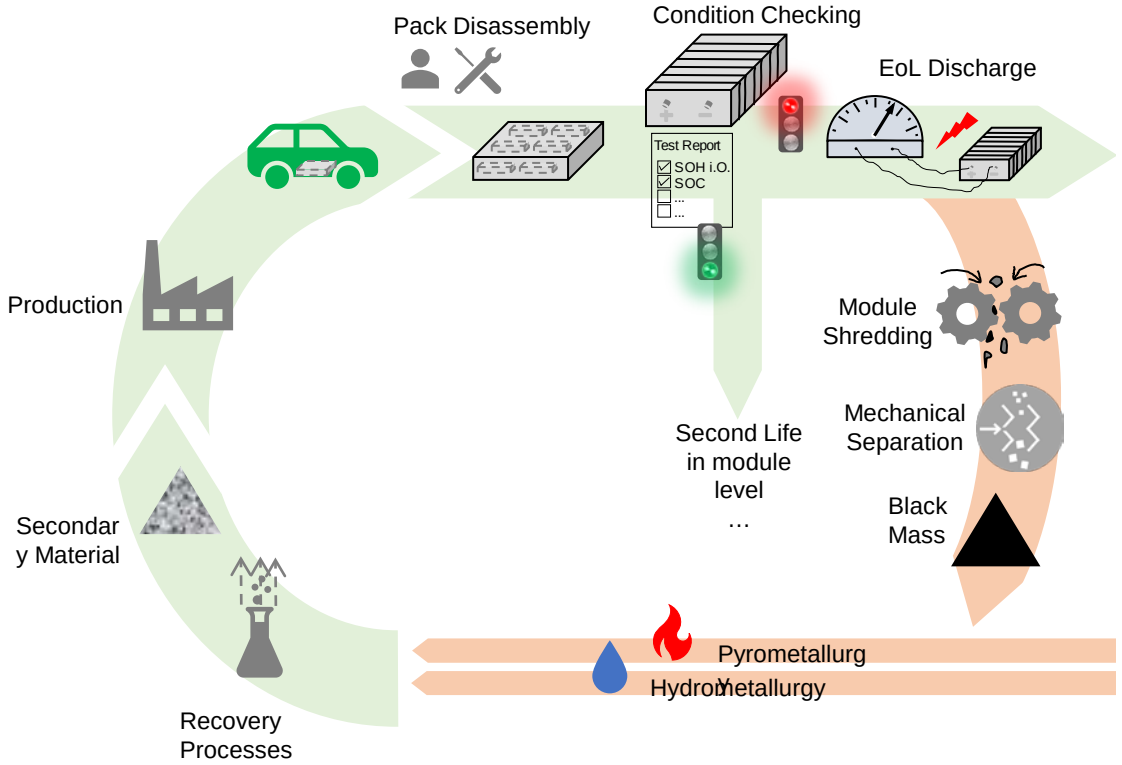
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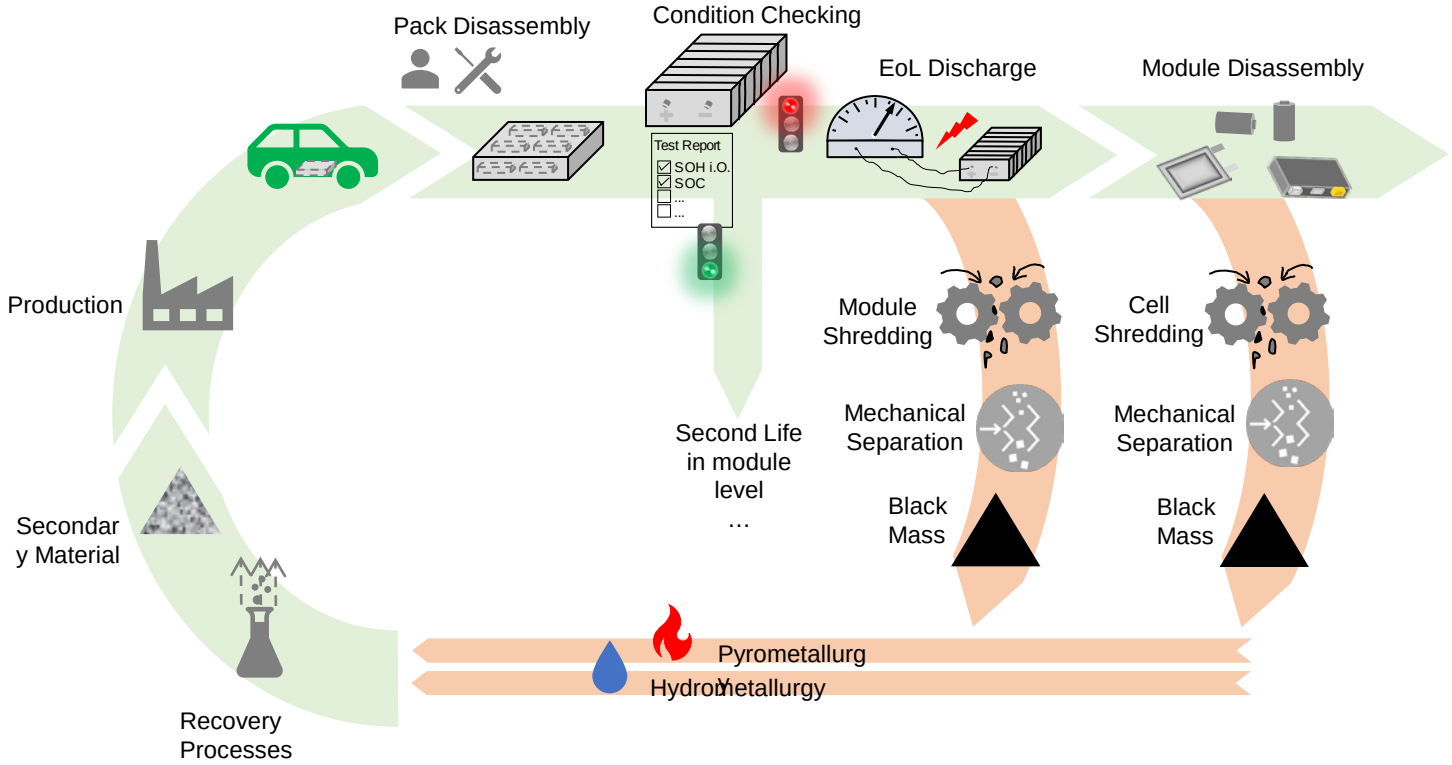
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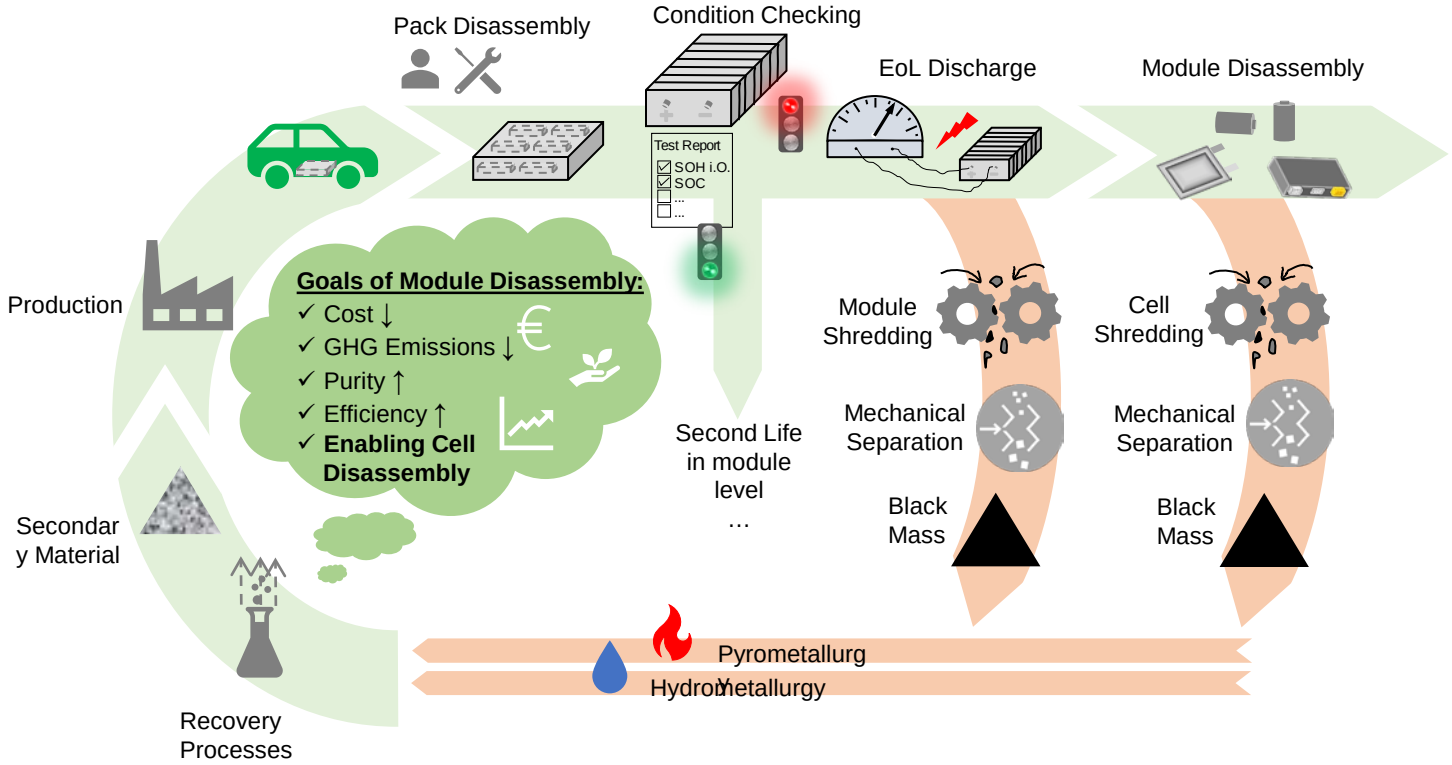
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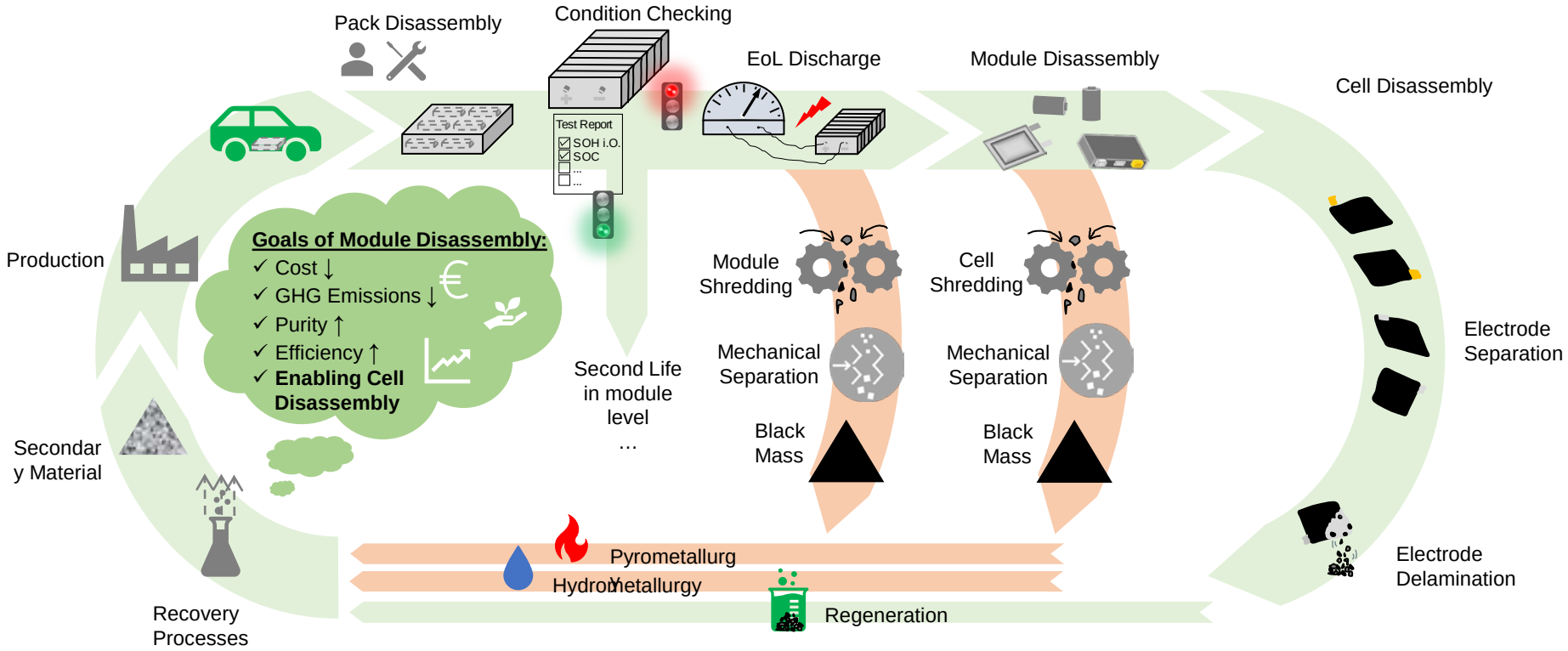
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Introduction

State of the Art of Efficient Recycling for Lithium-Ion Batteries



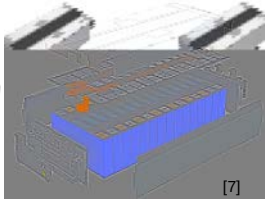
Introduction
Challenges of Battery Module Disassembly

Challenges

- Very high diversity in module and cell design
  - Cylindrial, prismatic and pouch
  - No established standards
- Various applied joining technologies
  - Adhesives and welded seams
- Minimal data available from OEMs
  - No design for disassembly
  - No battery passport


[5]


[6]


[7]

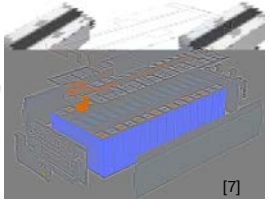
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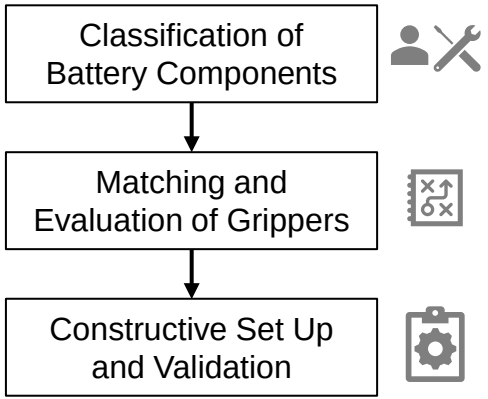

[6]


[7]

Approaches and Methods

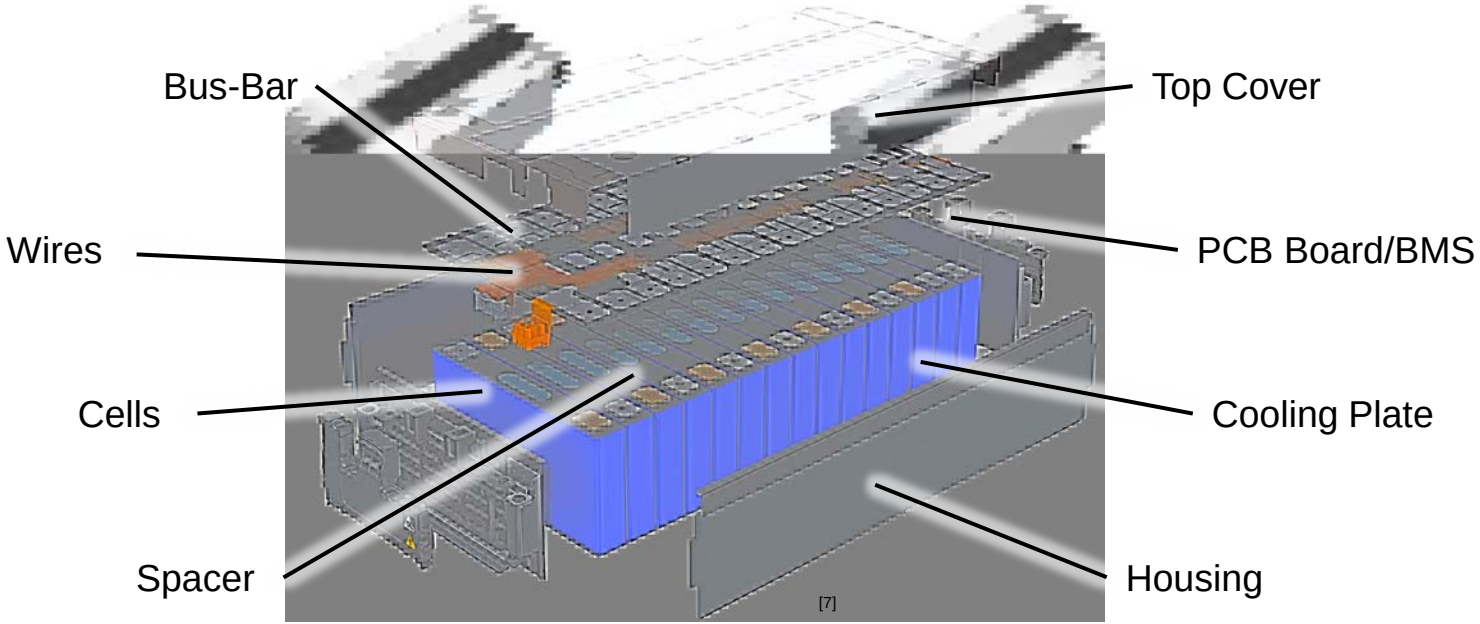
- Developing a variant-flexible gripper system for automated battery disassembly





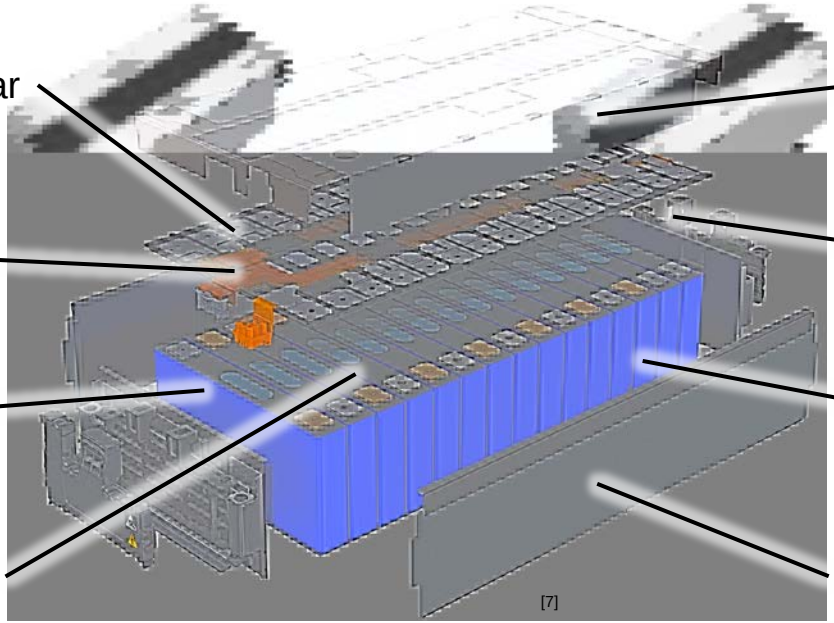
Development of a variant-flexible gripper system

Methodological Classification of Battery Components



Development of a variant-flexible gripper system

Methodological Classification of Battery Components



How can the different components be handled

Development of a variant-flexible gripper system

Methodological Classification of Battery Components

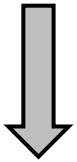
1. Defining Classification Categories

Category	1	0
Accessibility (A)	Three sites	One Site (vertical)
Magnetizability (M)	Yes	No
Surface property (S)	Smooth, large enough	Rough, too small

Development of a variant-flexible gripper system

Methodological Classification of Battery Components

1. Defining Classification Categories



2. Classifying the Components

Category	1	0
Accessibility (A)	Three sites	One Site (vertical)
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A	M	S	Component	Class
1	0	1	Top Cover, Housing, Cells	Plane surface
1	0	0	Wires, Spacer, PCB Board/BMS	Irregular surface
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Development of a variant-flexible gripper system

Methodological Classification of Battery Components

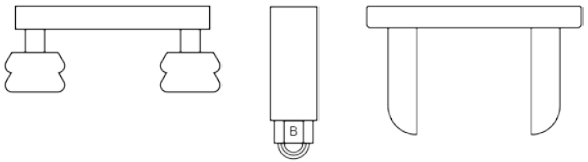
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3. Matching with Gripping Principles



		A = 1			A = 0		
S = 1	M = 1	1	1	1	1	1	0
	M = 0	1	0	1	1	0	0
S = 0	M = 1	0	1	1	0	1	0
	M = 0	0	0	1	0	0	0
		SG	MG	PG	SG	MG	PG

* SG (Suction Gripper), MG (Magnetic Gripper), PG (Parallel-jaw Gripper)

Development of a variant-flexible gripper system

Methodological Classification of Battery Components

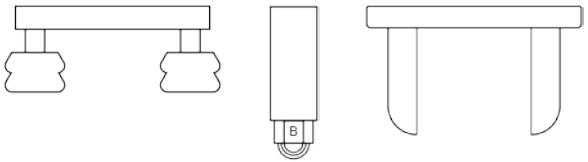
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Development of a variant-flexible gripper system

Methodological Development and Concept Selection



List of Requirements



Morphological Matrix

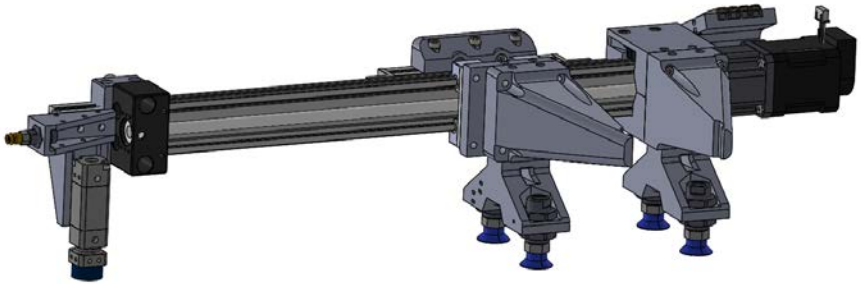


Simple Additive Weighting (SAW)

Development of a variant-flexible gripper system

Methodological Development and Concept Selection

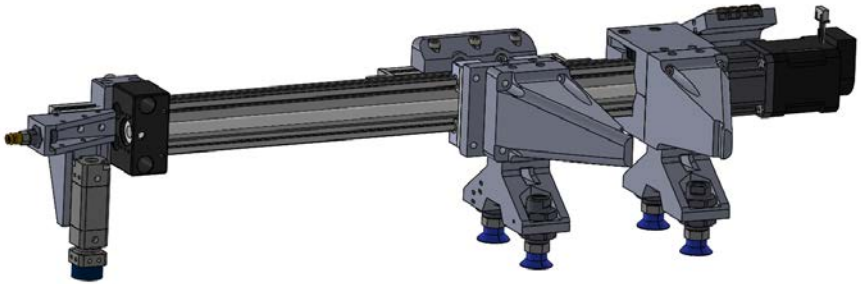
List of Requirements → Morphological Matrix → Simple Additive Weighting (SAW)

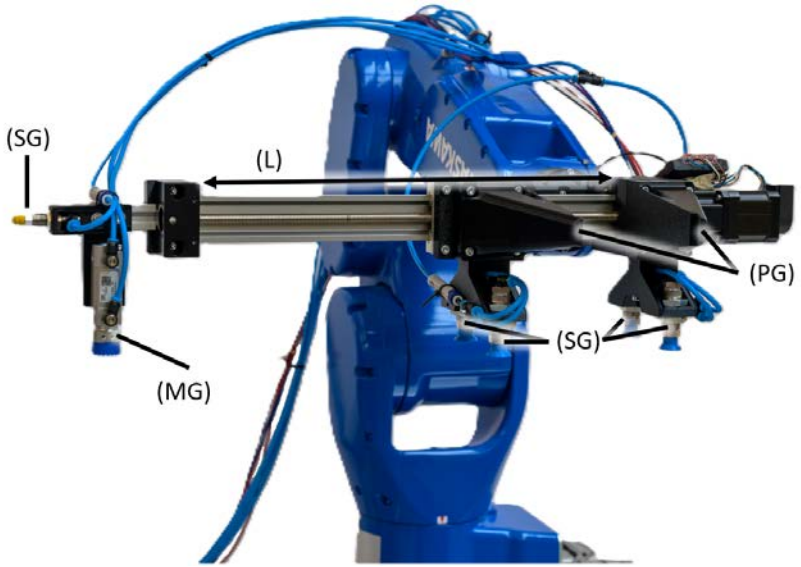


Development of a variant-flexible gripper system

Methodological Development and Concept Selection

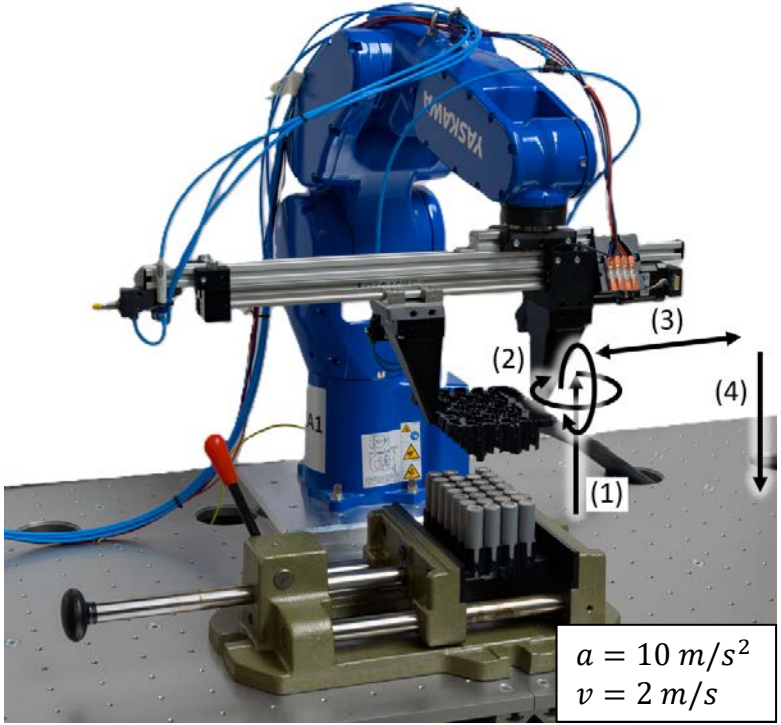
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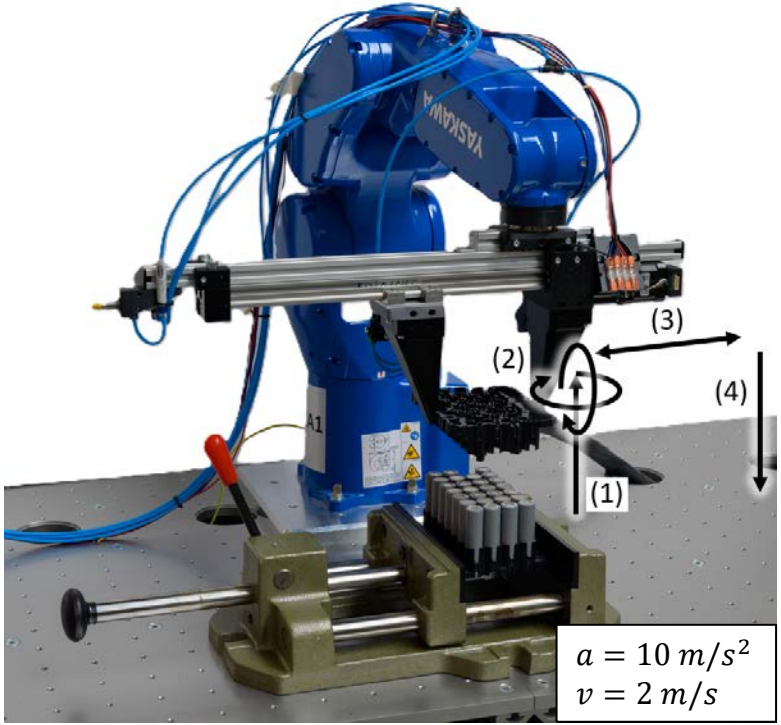
Development of a variant-flexible gripper system

Results and Discussion



Development of a variant-flexible gripper system

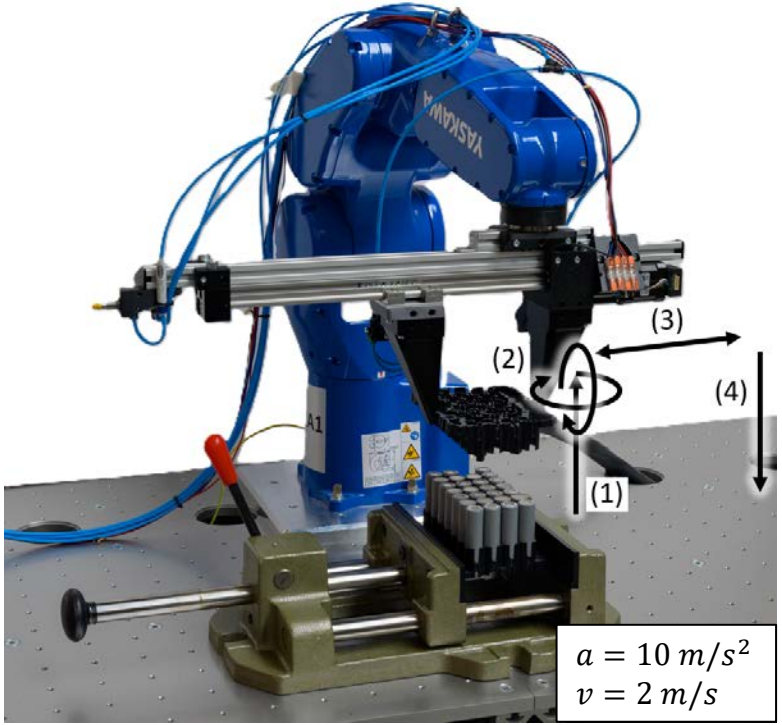
Results and Discussion



- All Battery Module Components can be gripped with at least one of the three gripping principles
- None of the Battery Module Components came loose during the handling tests

Development of a variant-flexible gripper system

Results and Discussion



- All Battery Module Components can be gripped with at least one of the three gripping principles
- None of the Battery Module Components came loose during the handling tests
- Expand to include joint separation process for holistic disassembly
- Consider further R-Strategies with varying depth of disassembly
- Analysis of depth of disassembly and cost-effectiveness

Acknowledgement and Contact Details

This research was conducted within the research project “VaTreBat” (FKZ: 16BZF309B)

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Project Partners:



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- [5] https://electrichasgoneaudi.net/models/e-tron/drivetrain/battery/
- [6] https://www.bbsautomation.com/de/branchenloesungen/battery/batteriemodule
- [7] https://gycxsolar.com/de/what-you-need-to-know-about-the-battery-module/



Implementation of a Flexible Robotic Disassembly Concept for Remanufacturing

C. Weckendrup, *J. Elsner, S. Saeed, O. Melnychuk, H. Behnen, L. Bergs, A. Moriz and Prof. Dr.-Ing. R. H. Schmitt*

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Motivation, Research Gap & Objective

Current Challenges & Motivation

- over 20 million tons of EoL-batteries by 2040[1]
- Critical raw materials must be returned to the cycle[2]
- Disassembly: essential first step, yet still manual[3]
- High variability in product type and condition[4]

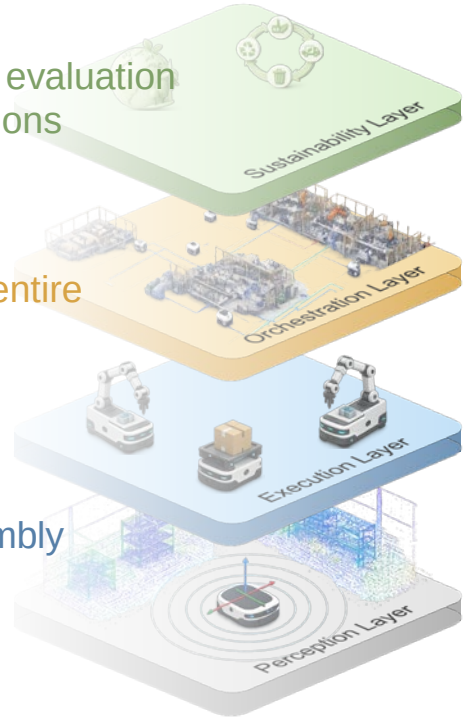
Research Gap

- No system combining flexibility, condition assessment and automated execution [4]
- Existing implementations are rarely validated under near-industrial conditions [5, 6]
- The environmental impact of individual disassembly decisions is largely ignored [7]

Remanufacturing of variant-rich battery modules with automated assembly and testing processes - **REVAMP**

Use case - electric trucks, buses and transporters

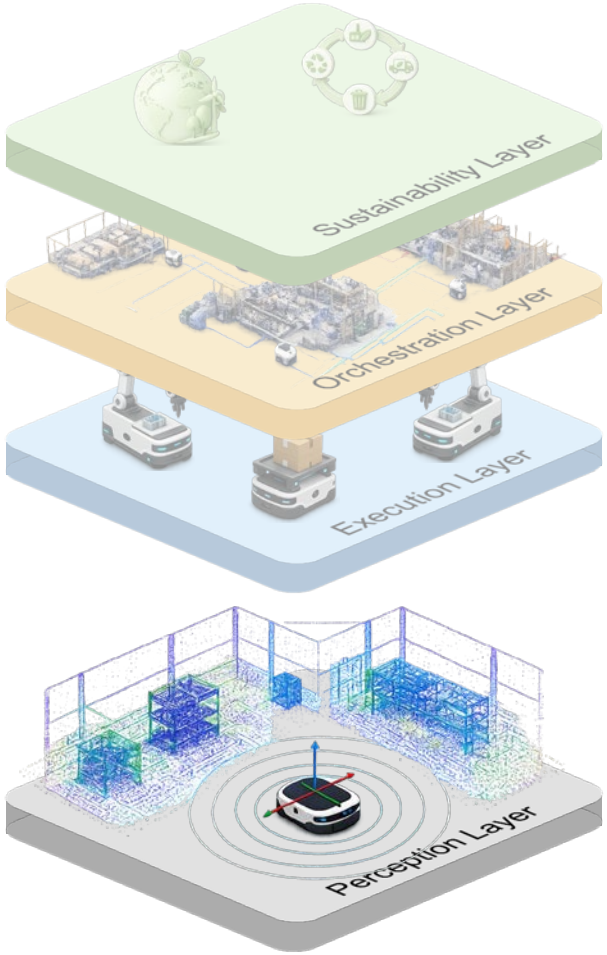
- LCA-based sustainability evaluation of remanufacturing decisions
- Digital twin covering the entire battery lifecycle
- Flexible, automated disassembly and reassembly



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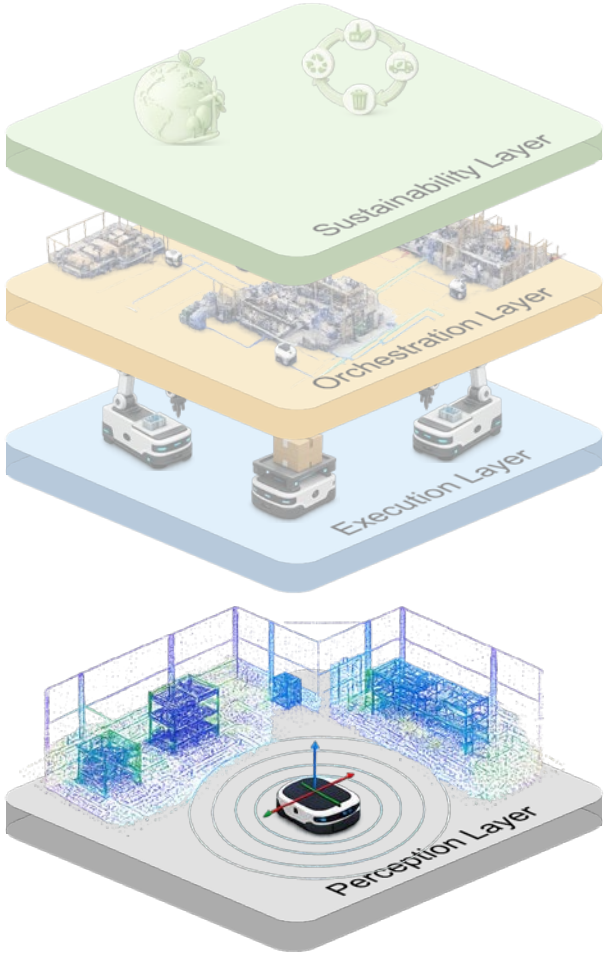
Perception Layer

- How does the system perceive its components and agents?



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Perception Layer
- How does the system perceive its components and agents?



Global Tracking

OptiTrack PrimeX 41

- Tracks mobile manipulators & AGVs via passive markers
- Real-time pose across entire workspace
- 180 Hz, ±0.1 mm accuracy, 5.5 ms latency [8]

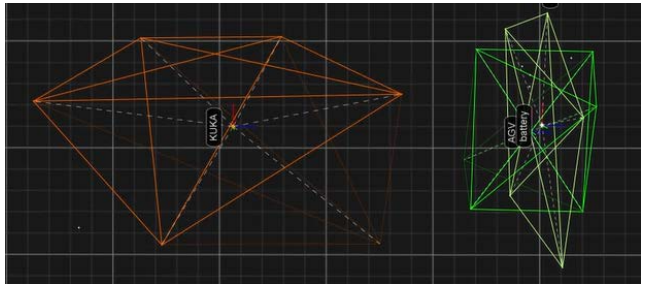


Fig.1: *OptiTrack tracking of mobile robots*

Local Object Detection

Zivid 2+ MR60

- Mounted on robot arm for occlusion-free acquisition
- High-resolution RGB-D output
- SAM-6D: training-free pose estimation
- 96.4% grasping success rate

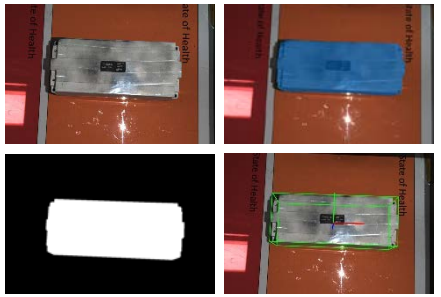
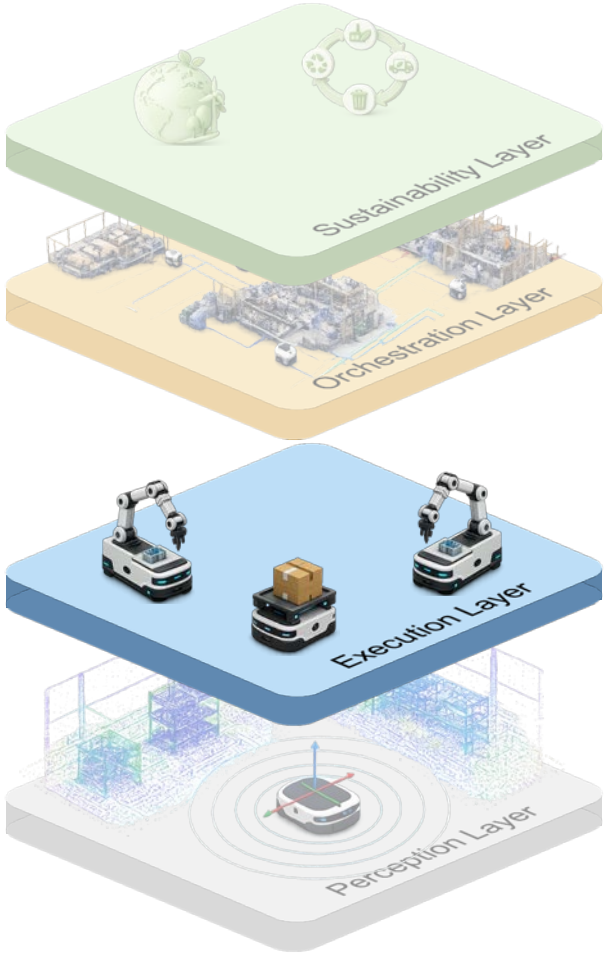


Fig.2: FoundationPose evaluation pipeline

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Execution Layer
- How does the robot physically execute the disassembly?



Agents & Their Capabilities

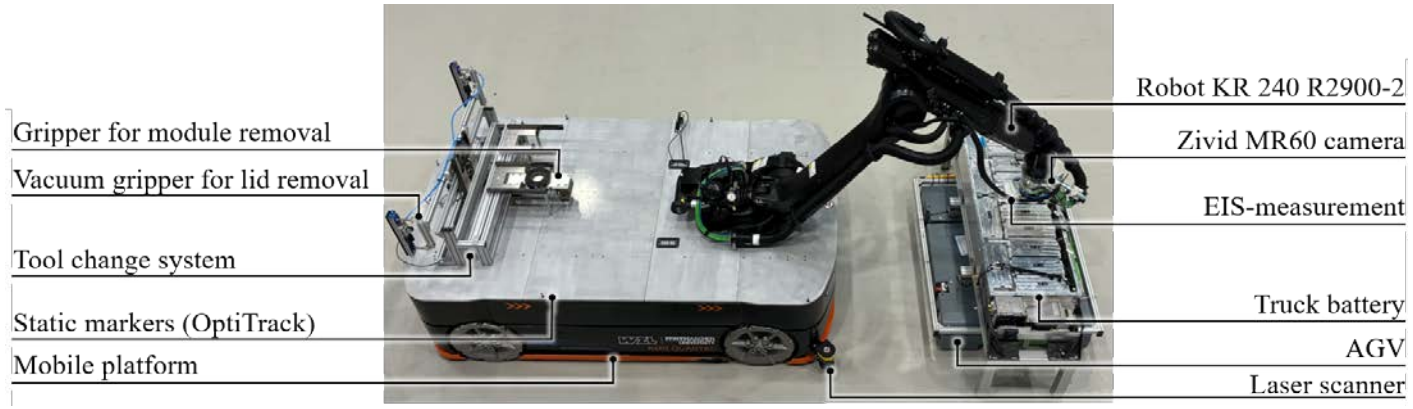


Fig.3: *KMR Quantec performing disassembly operations*

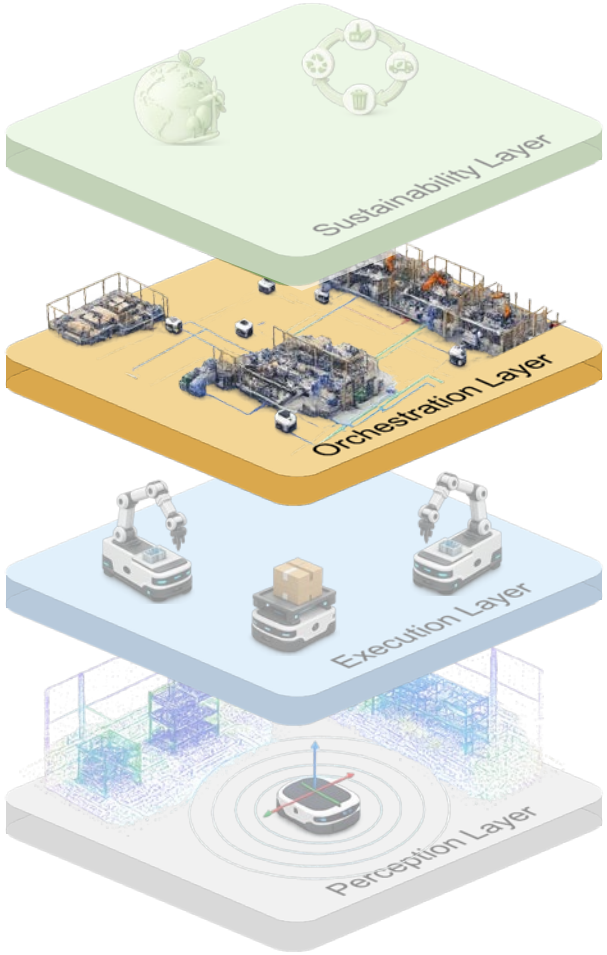
Disassembly stations

Table 1: Cycle times per disassembly operation

Station	Tool change	Remove Lid	Tool change	EIS-Measm.	Tool change	Remove modul
Time [s]	150	140	150	122	150	112

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Orchestration Layer
- Who is the conductor of the system?



Connecting Physical & Digital World

- MQTT protocol connecting all agents
- Real-time synchronization via OptiTrack
- Discrete-Event Simulation model as core of the digital twin
- Dynamic task allocation and process sequencing

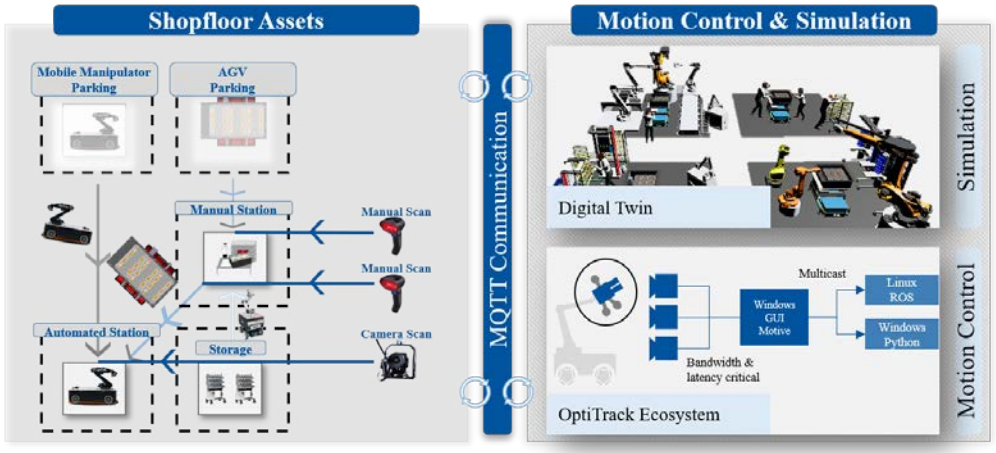
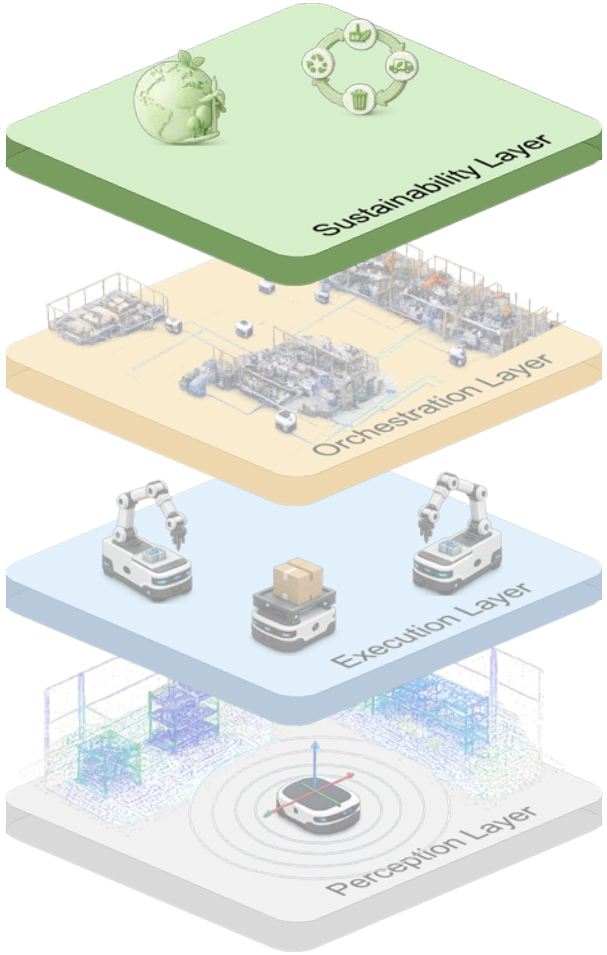


Fig.4: *Physical and digital system connected via MQTT*

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Sustainability Layer

- How does the system evaluate the environmental impact of each decision?



Condition-Based Sustainability

- EIS measurement → State of Health (SoH) per individual module
- SoH as decision point: Second Life, Second Use or Recycling
- LCA according to DIN EN ISO 14040/44: Product-specific primary data from all system levels

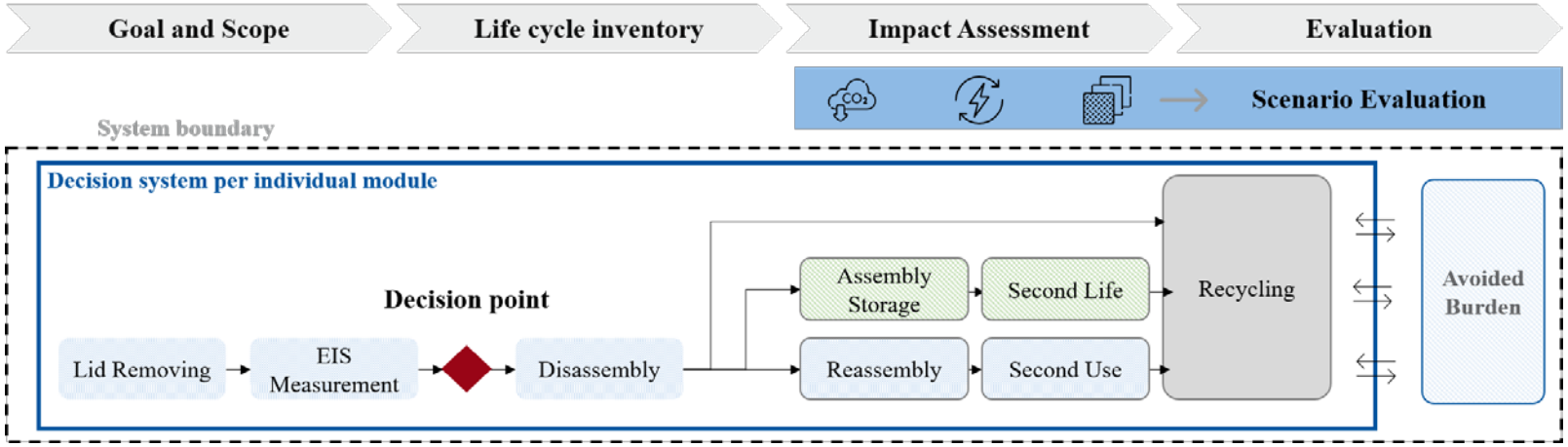


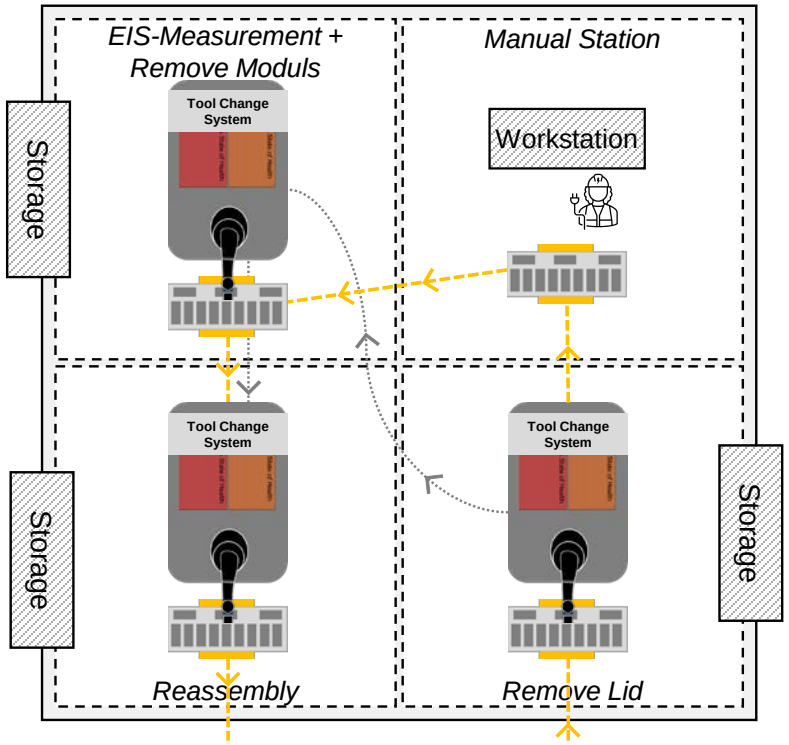
Fig.5: *LCA-integrated decision system per module*

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Results
– *Reference run at WZL laboratory*





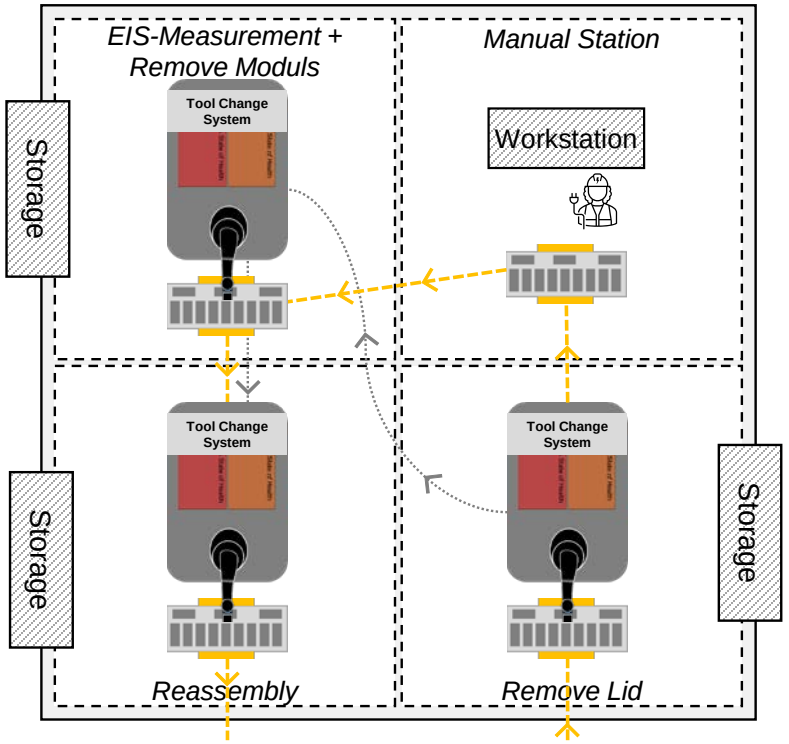






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Limitations & Outlook



Limitations

- Pose estimation validated on a single module type only
- Electrical connectors not yet automated – process not fully autonomous
- Digital twin synchronization is still partially manual
- Sustainability assessment validated on a prototype basis only

Outlook

- Scale-up to higher component volumes
- Automation of the remaining manual station
- Improved real-time coupling between physical system and digital twin
- Transferable blueprint for other products and remanufacturing scenarios

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Thank You!

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2. E. Kristoffersen, F. Blomsma, P. Mikalef, and J. Li, “The smart circular econ-omy: A digital-enabled circular strategies framework for manufacturing companies,” Journal of Business Research, vol. 120, pp. 241–261, 2020.

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5. E. Gerlitz, T. Fuchs, F. Kößler, and J. Fleischer, “Flexible Roboterzelle für Traktionsbatterie-Demontage,” *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, vol. 118, no. 12, pp. 853–857, 2023.

6. A. A. Assadi, T. Götz, A. Gebhardt, O. Mannuß, B. Meese, J. Wanner, S. Singha, L. Halt, P. Birke, and A. Sauer, “Automated Disassembly of Battery Systems to Battery Modules,” *Procedia CIRP*, vol. 122, pp. 25–30, 2024.

7. Baum, J., Elsner, J., Kern, J, Göppert, A., Sauer, D.U., Schmitt, R.H., “Remanufacturing variantenreicher Batterien,” *QZ – Qualität und Zuverlässigkeit*, no. 69(9), S. 16–19, 2024.

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Conference on Circular Production Systems and Technologies (CCPT)

A Manufacturing Capability-Aware Supplier Mesh Network Framework for Changeable Production Systems

Shreyes N. Melkote[1,*] | Suyoung Park[1,*]

CCPT, June 9-10th, 2026, Karlsruhe, Germany

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Georgia Tech

Motivation: Capability Visibility for Changeable Production Networks

Why Manufacturing Capability Visibility Matters

- Changeable production networks require flexible supplier reconfiguration.
- Disruptions and demand variability continuously change supplier availability.
- Requirement–capability mismatch limits product-specific feasibility assessment.

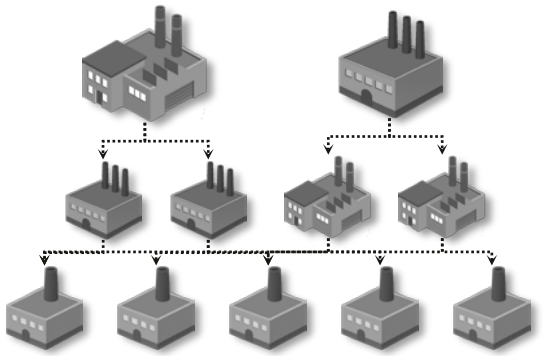
Demand Variability / Disruption



“Supplier availability changes”

[1]

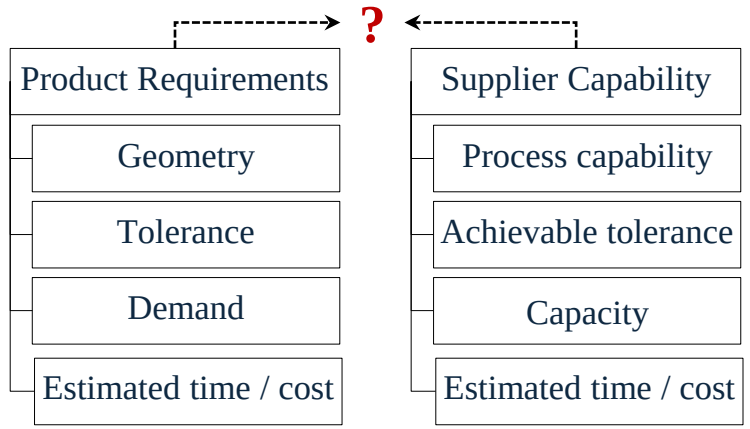
Distributed Supplier Network



“Multiple suppliers and tiers”

[2]

Requirement - Capability Mismatch



“Heterogeneous evaluation criteria”

[3]

[1] Ivanov, Dmitry, and Alexandre Dolgui. "A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0." Production Planning & Control 32.9 (2021): 775-788.
[2] Kalaiarasan, Ravi, et al. "The ABCDE of supply chain visibility: A systematic literature review and framework." International Journal of Production Economics 248 (2022).
[3] Saputro, Thomy Eko, Gonçalo Figueira, and Bernardo Almada-Lobo. "A comprehensive framework and literature review of supplier selection under different purchasing strategies." Computers & Industrial Engineering 167 (2022): 108010.

Motivation: Capability Visibility for Changeable Production Networks

Why Manufacturing Capability Visibility Matters

- Changeable production networks require flexible supplier reconfiguration.
- Supplier decisions often overlook manufacturing-specific feasibility.
- Product-specific feasibility is difficult to compare across suppliers.

Demand
Variability / Disruption



“Supplier availability changes”

[1]

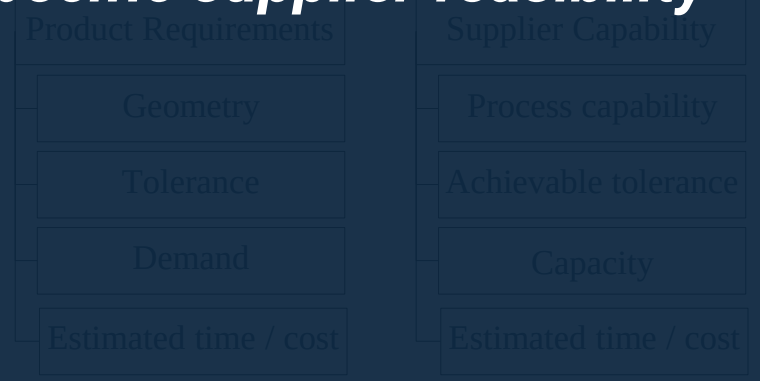
Distributed Supplier Network



“Multiple suppliers and tiers”

[2]

Requirement - Capability Mismatch



“Heterogeneous evaluation criteria”

[3]

Need: Quantitative methods to evaluate product-specific supplier feasibility

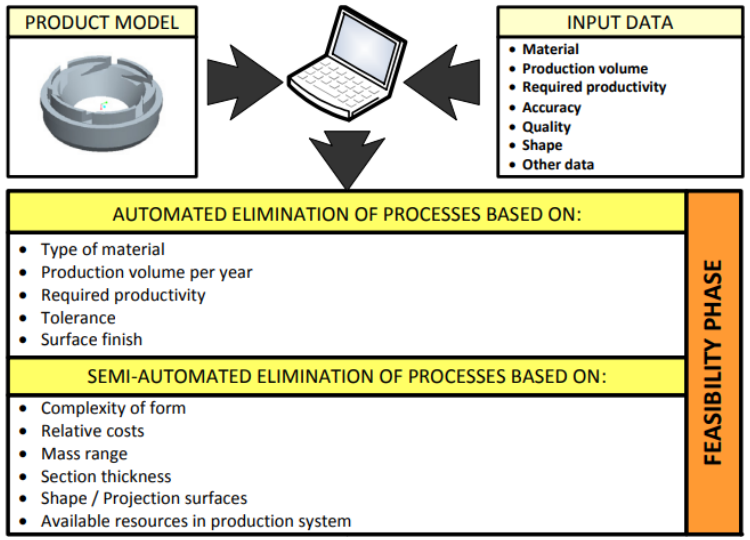
[1] Ivanov, Dmitry, and Alexandre Dolgui. "A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0." Production Planning & Control 32.9 (2021): 775-788.
[2] Kalaiarasan, Ravi, et al. "The ABCDE of supply chain visibility: A systematic literature review and framework." International Journal of Production Economics 248 (2022).
[3] Saputro, Thomy Eko, Gonçalo Figueira, and Bernardo Almada-Lobo. "A comprehensive framework and literature review of supplier selection under different purchasing strategies." Computers & Industrial Engineering 167 (2022): 108010.

Research Gap

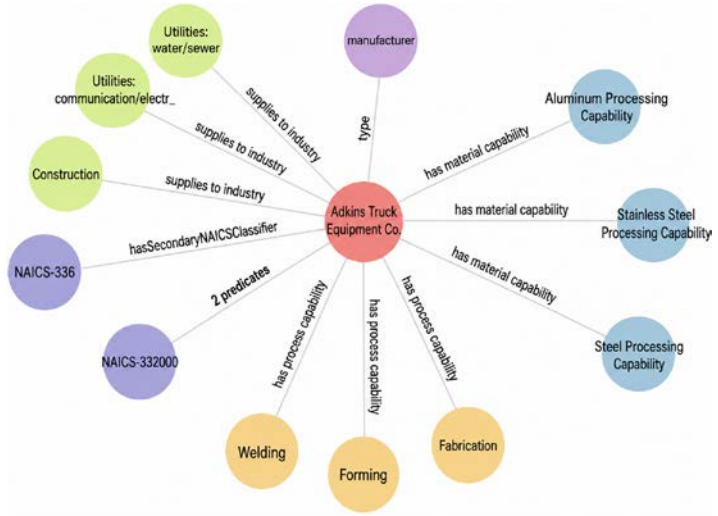
Capability Comparison Methods

- **Feature-based:** process-level feasibility, but **limited supplier-specific comparison**.
- **Knowledge graph-based:** semantic capability representation, but **limited quantitative comparison**.
- **Deep learning-based:** supplier identification, but **limited allocation and disruption response for changeable production**.

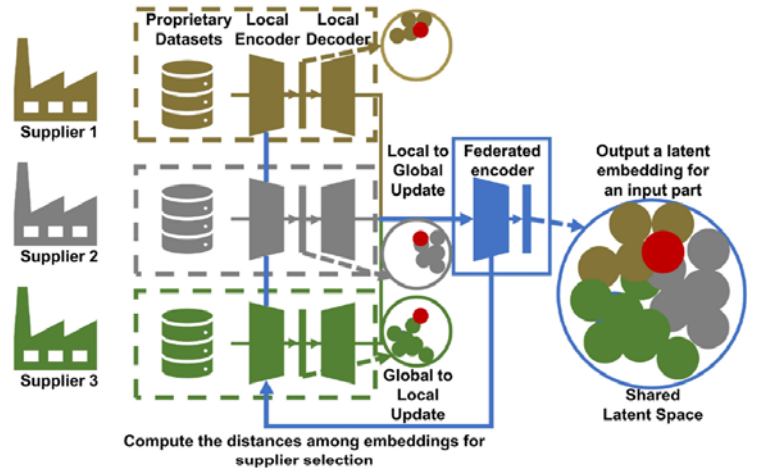
Feature-based [1]



Knowledge Graph-based [2]



Deep Learning-based [3]

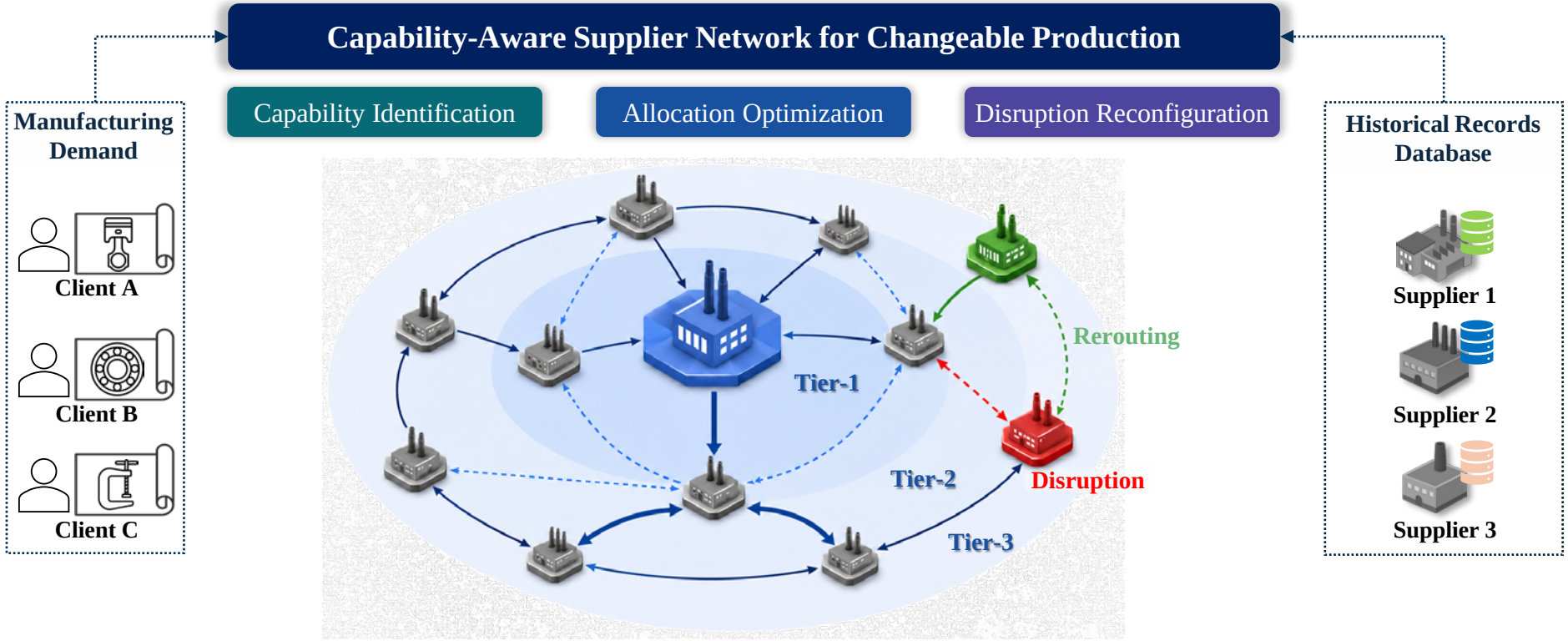


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[2] Ameri, Farhad, et al. "Open Manufacturing Capability Network Supported by Formal Ontologies." IFIP International Conference on Advances in Production Management Systems. Cham: Springer Nature Switzerland, 2024.
[3] Yan, Xiaoliang, et al. "A federated learning approach to automated and secure supplier selection in cyber manufacturing as-a-service." Journal of Manufacturing Systems 77 (2024): 170-183.

Objective

Manufacturing Supplier Mesh Network (SMN)

- End-to-end decision-making framework for supplier identification, allocation, and disruption response for changeable production system
- **Objective 1:** Identify feasible suppliers based on multi-attribute capability
- **Objective 2:** Optimize allocation with cost, time, and sustainability-related objective
- **Objective 3:** Re-route and re-balance to maintain performance under disruption



[1] S. Park et al., "Cyber Manufacturing Mesh Network: A Manufacturing Capability-Aware Supplier Decision Support Framework", Manufacturing Letters, 2026 (Under revision)

Dataset Construction

Dataset Configuration for Experimental Evaluation

- Industrial 3D designs with DFM[1]-based and ISO[2,3]-referenced manufacturing attributes
- Twelve suppliers were defined with paired capability profiles to evaluate identification, allocation, and reconfiguration.
- Product-specific attributes include tolerance, cost, time, recycled content, and carbon footprint.

Manufacturing Attribute Assignment Process

Preprocessing	Extract component size and assign handling, insertion, and fastening operations
↓	
Supplier	Assign supplier capability profile (High, Low)
↓	
Material	Assign corresponding material types
↓	
Tolerance	Assign ISO 286 fit based on assembly complexity
↓	
Time	Estimate manual assembly time scaled by supplier capability
↓	
Cost	Calculate cost using time × average U.S. wage × capability factor
↓	
Environment	Calculate **recycled contents (RC)** and **carbon footprints (CFP)**

Table. Dataset configuration used in this study

Supplier	Product Category		Relative Capability Profiles					
			Tolerance	Cost	Time	Material	RC	CFP
A_1, A'_1	Bearing Cage, Ball		Tight	High	High	High	**High**	**High**
A_2, A'_2			Loose	Low	Low	Low	**Low**	**Low**
B_1, B'_1	Clamp PinScrew, Rivet		Tight	High	High	High	**High**	**High**
B_2, B'_2			Loose	Low	Low	Low	**Low**	**Low**
C_1, C'_1	Piston Head, ConnectingRod		Tight	High	High	High	**High**	**High**
C_2, C'_2			Loose	Low	Low	Low	**Low**	**Low**

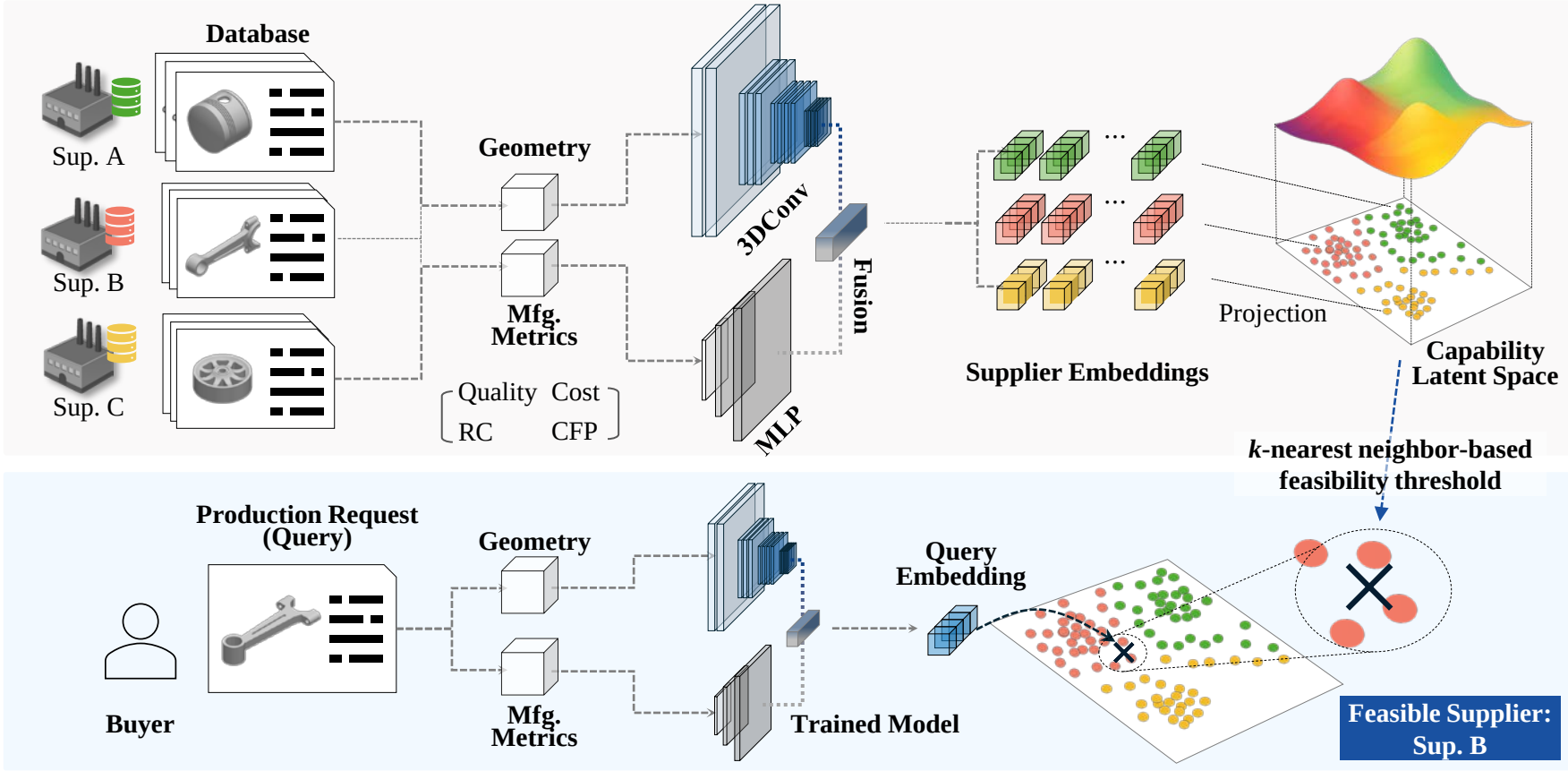
Note: Primed suppliers indicate paired suppliers with twice the capacity of the corresponding unprimed suppliers.

[1] S. Park., et al., "DFM-based Synthesized Component Dataset for "Manufacturing Capability-Aware Supplier Identification and Optimization".", https://hdl.handle.net/1853/79946 (2025).
[2] ISO 14067:2018, Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.
[3] ISO 14021:2016, Environmental labels and declarations — Self-declared environmental claims (Type II environmental labelling), Clause 7.8, "Recycled content."

Objective1: Manufacturing Capability-Aware Supplier Identification

Data-driven Supplier Selection Methodology

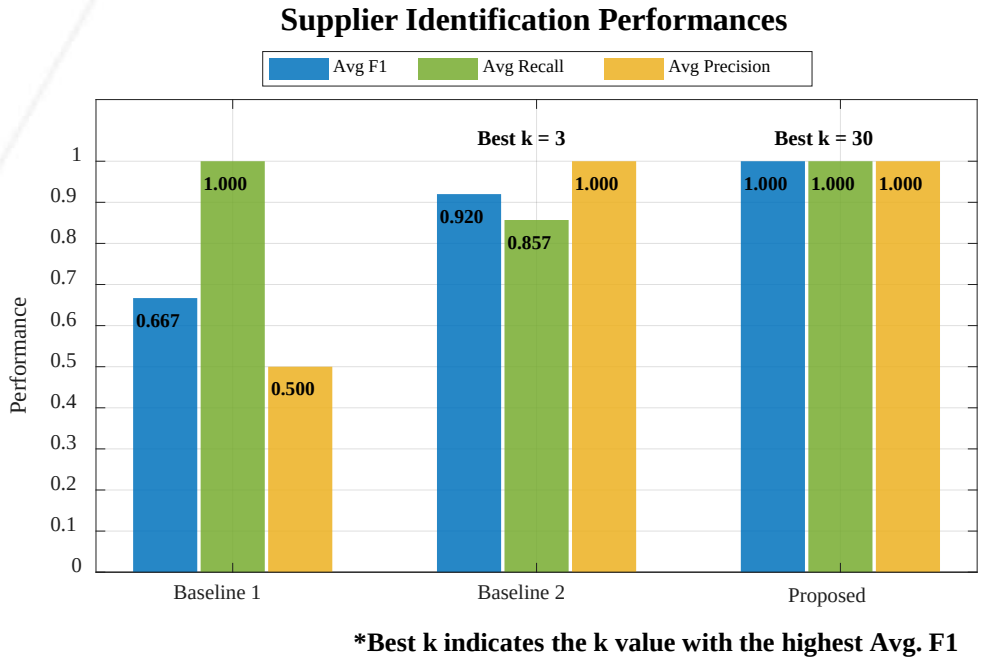
- Shared latent-space mapping of supplier records and buyer requests
- *k*-nearest-neighbor Euclidean distance threshold for feasible supplier selection
- Suppliers within this pre-defined threshold identified as feasible



Objective1: Manufacturing Capability-Aware Supplier Identification

Comparison with Baseline Methods

- **Baseline 1 (Capability-Unaware):** Product-level identification selects infeasible suppliers (C_2, C'_2).
- **Baseline 2 (Non-Learning):** Shape-descriptor-based identification misses feasible suppliers (C_1).
- **Proposed:** Capability-aware embedding identifies feasible suppliers more consistently.



***Best k indicates the k value with the highest Avg. F1**

Table. Supplier Identification Example across Methods

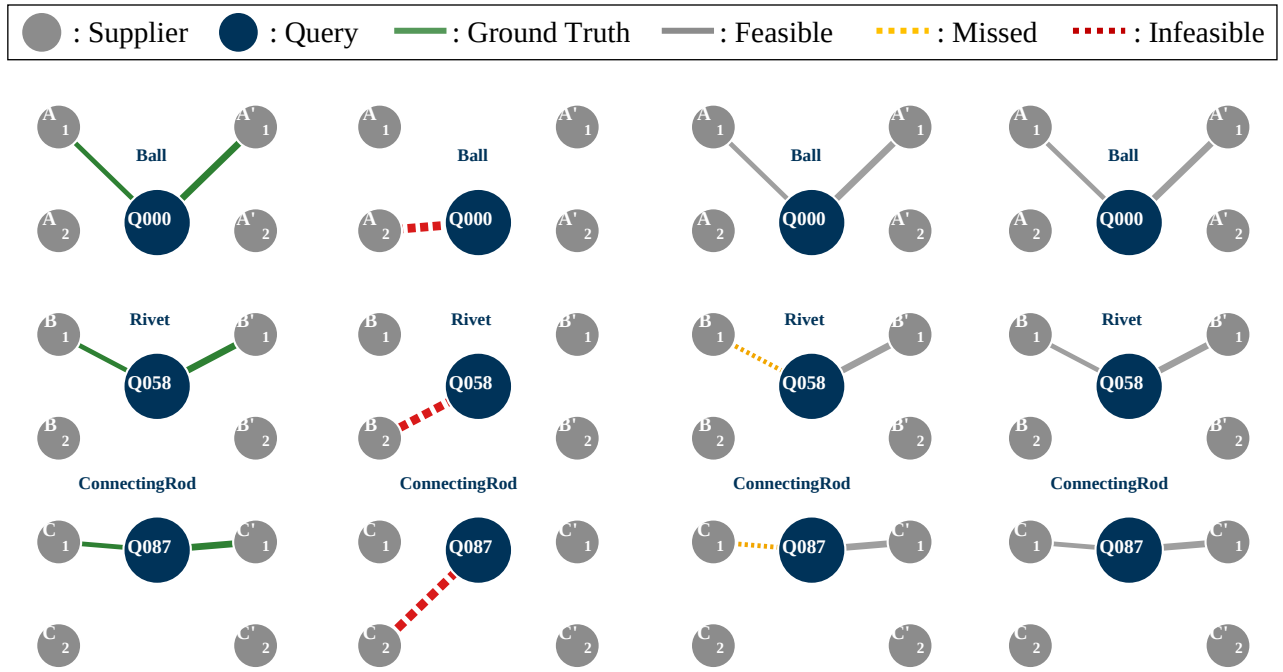
Method	Retrieved Instance	Similarity	Supplier	Manufacturing Attributes (Log-scaled normalization)				
				Tol	Cost	Time	RC	CFP
Query	Rivet_idx#0058	-	C_1, C'_1 (Ground Truth)	**0.407**	**-0.861**	**-1.022**	**0.823**	**-0.912**
Baseline 1	Rivet_idx#0126	-	C_1	0.389	-0.881	-1.021	0.805	-0.709
	Rivet_idx#0734	-	C'_1	0.401	-0.886	-1.016	0.812	-0.697
	Rivet_idx#0430	**-**	***C_2**	**1.949**	**-1.422**	**-1.603**	**0.374**	**-0.838**
	Rivet_idx#1038	**-**	***C'_2**	**1.950**	**-1.445**	**-1.595**	**0.402**	**-0.823**
Baseline 2	Rivet_idx#0736	0.964803	C'_1	0.386	-0.881	-1.016	0.820	-0.741
Proposed	Rivet_idx#0171	0.999899	C_1	0.407	-0.882	-1.007	0.826	-0.946
	Rivet_idx#0779	0.999886	C'_1	0.390	-0.880	-1.010	0.817	-0.934
	Rivet_idx#0741	0.999790	C'_1	0.383	-0.884	-1.017	0.825	-0.953
	Rivet_idx#0190	0.999103	C_1	0.393	-0.893	-1.039	0.837	-0.937

*Infeasible suppliers

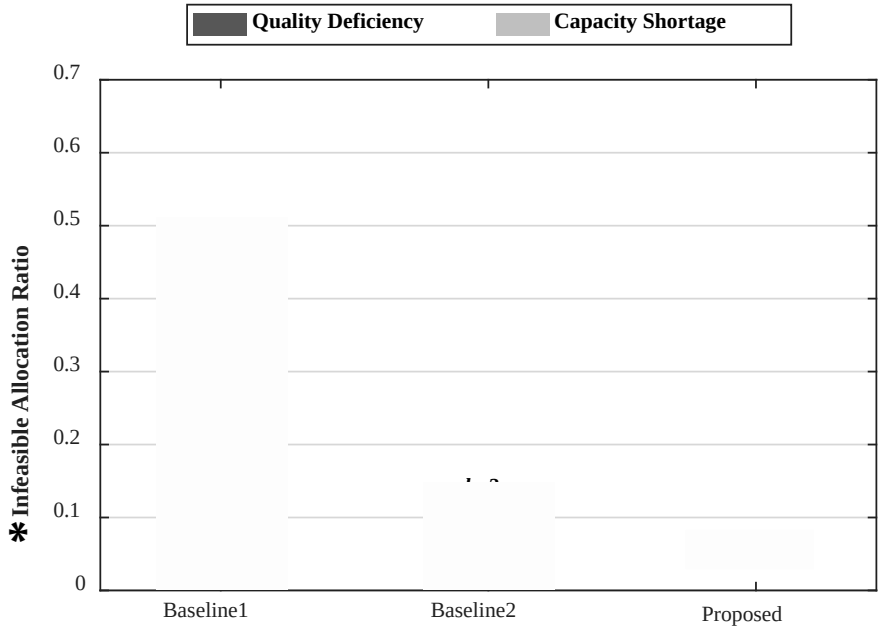
Objective2: Optimization-based Production Allocation

Production Allocation Optimization based on Identified Suppliers

- **Baseline 1 :** Optimization minimizes carbon footprint (CFP) and assigns demand to low-CFP suppliers (X_2), but they are infeasible (Quality Deficiency)
- **Baseline 2 :** Missed feasible suppliers prevent full demand allocation (Capacity Shortage)
- **Proposed :** Capability-aware supplier pool enables full allocation without infeasible allocation



Example of Production Allocation

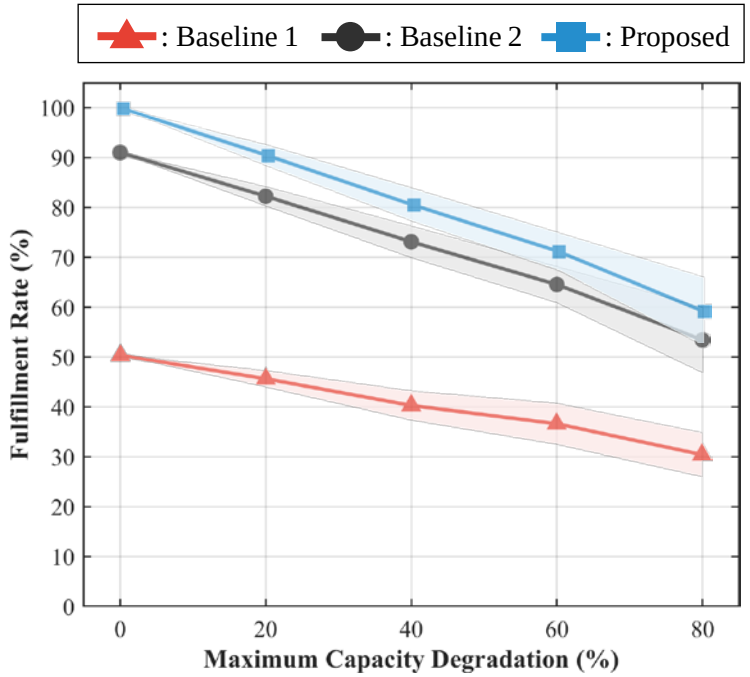


***Ratio of demand assigned to infeasible suppliers or left unmet**

Objective3: Disruption-Responsive Supplier Reconfiguration

Reallocation Evaluation under Capacity Degradation

- **Capacity degradation:** Supplier capacity decreases from 0% to 80%
- **Baseline 1 :** Continues assigning demand to infeasible suppliers
- **Baseline 2 :** Insufficient feasible supplier pool leaves demand unmet
- **Proposed :** Secured feasible supplier pool maintains higher fulfillment under disruption



Allocation Fulfilment across Capacity Disruption

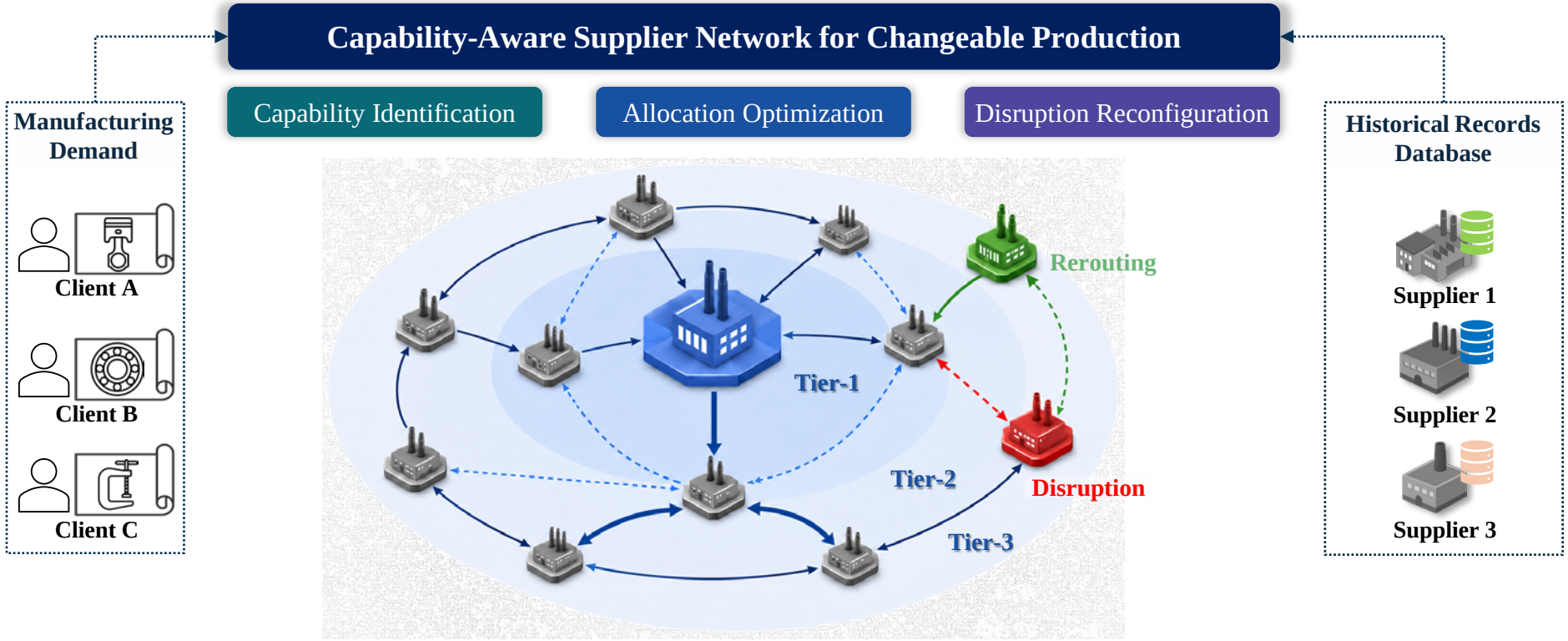
Table. Example of Production Allocation across Disruption Rates

Query	Product Type	Disruption rate	Ground Truth	Baseline 1	Baseline 2	Proposed
Q058	Rivet	0%	{B'_1, B_1}	{B_2*}	{B'_1, ∅}	{B'_1, B_1}
		20%	{B'_1, B_1, ∅}	{B_2*}	{B'_1, ∅}	{B'_1, B_1, ∅}
		40%	{B'_1, B_1, ∅}	{B_2*}	{B'_1, ∅}	{B'_1, B_1, ∅}
		60%	{B'_1, B_1, ∅}	{B'_2*}	{B'_1, ∅}	{B'_1, B_1, ∅}
		80%	{B'_1, B_1, ∅}	{B'_2*}	{B'_1, ∅}	{B'_1, B_1, ∅}
Q087	Connecting Rod	0%	{C'_1, C_1}	{C_2*}	{C'_1, ∅}	{C'_1, C_1}
		20%	{C'_1, C_1, ∅}	{C_2*}	{C'_1, ∅}	{C'_1, C_1, ∅}
		40%	{C'_1, C_1, ∅}	{C_2*}	{C'_1, ∅}	{C'_1, C_1, ∅}
		60%	{C'_1, C_1, ∅}	{C'_2*}	{C'_1, ∅}	{C'_1, C_1, ∅}
		80%	{C'_1, C_1, ∅}	{C_2*}	{C'_1, ∅}	{C'_1, C_1, ∅}

*: Capability-infeasible allocation
∅: Unmet demand due to capacity shortage

Conclusion

- Proposed an **SMN framework** for changeable production system
- Enabled **capability-aware supplier identification** and allocation
- Supported **disruption-responsive supplier reconfiguration** under capacity degradation
- **Future Works:** Multi-tier supplier selection, Realistic changeable production scenarios, Privacy-preserving Architecture



This work was funded by a **National Science Foundation Future Manufacturing Research Grant (Award # 2229260).**

Q&A

Georgia Tech

Appendix

3D Geometry and Manufacturing Attributes

- Collected 3D models from industrial catalogs and augmented through feature-based parameterization of dimensions and shapes
- Defined supplier capability profiles: High and Low based on material types
- Computed supplier-specific product attributes using DFM and ISO standards: **Tolerance, cost, time and environmental metrics** (ISO 14021, 14067)

3D Geometries



Mfg. attributes assignment process

Preprocessing	Extract component size and assign handling, insertion, and fastening operations
Supplier	Assign supplier capability profile (High, Low)
Material	Assign corresponding material types
Tolerance	Assign ISO 286 fit based on assembly complexity
Time	Estimate manual assembly time scaled by supplier capability
Cost	Calculate cost using time × average U.S. wage × capability factor
Environment	Calculate carbon footprints (CFP) and recycled contents (RC)

[1] S. Park., et al., "DFM-based Synthesized Component Dataset for “Manufacturing Capability-Aware Supplier Identification and Optimization”." (2025).

Appendix

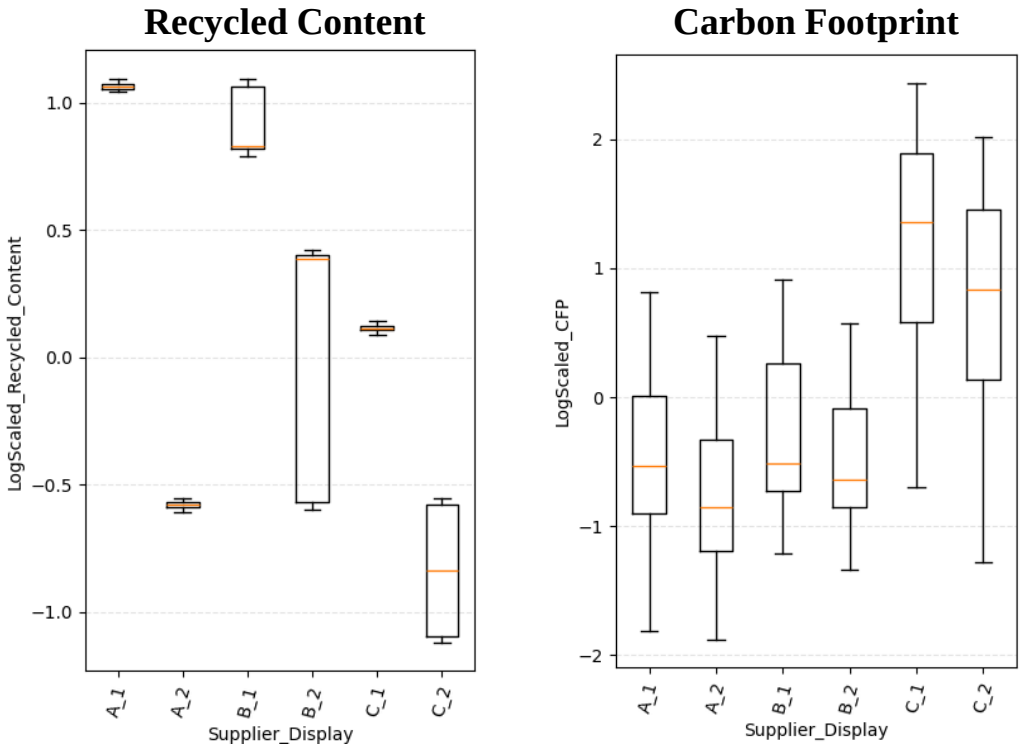
Dataset Configuration for Experimental Evaluation

- 12 suppliers and 6 product categories
- High: Tighter tolerance, higher cost, time, recycled content (RC) and carbon footprint (CFP)
- RC and CFP are not always inversely correlated because both depend on material type.
- A high-capability supplier can have higher CFP if it uses high-emission materials such as titanium.

Table. Dataset configuration used in this study

Group	Product Category	Capability Profiles	
		High	Low
A	Bearing Cage, Ball 	{A_1, A′_1}	{A_2, A′_2}
B	Clamp PinScrew, Rivet 	{B_1, B′_1}	{B_2, B′_2}
C	Piston Head, ConnectingRod 	{C_1, C′_1}	{C_2, C′_2}

Note: Entries in braces denote supplier indices. Primed suppliers indicate paired suppliers with twice the capacity of the corresponding unprimed suppliers.



Distribution of Attribute Values

Appendix

Environment-Related Metrics (Carbon Footprint, CFP)

- Defined as a partial CFP metric, motivated by **ISO 14067:2018**.

$$CFP_i^{mat} = M_i EF_m \quad (M: Mass, EF_m: Emission\ Factor\ of\ material)$$

$$M_i = r_{occ,i}\, V_{bbox,i} \rho_i \quad (r_{occ}: voxel\ occupancy\ ratio, V_{bbox}: bounding\ box\ volume, \rho: material\ density$$

- Excludes process energy, transportation, use phase, and end-of-life impacts.

Material type	EF_m	Reference basis
High carbon steel	**1.46**	Matched to ICE v2.0 "Steel, General" factor due to its carbon steel category.
Low carbon steel	**1.46**	Assigned the same general steel factor, as carbon factor is mainly affected by production route and recycled content rather than carbon grade.
Stainless steel	**6.15**	Matched to ICE v2.0 "Stainless" representative embodied carbon factor.
Cast iron	**2.03**	Approximated using ICE v2.0 "Iron, General" as a proxy factor.
Aluminum alloys	**9.16**	Matched to ICE v2.0 "Aluminium, General"; virgin and recycled aluminum factors are also available in ICE.
Copper alloys	**3.52**	Matched to the Climatiq/GEMIS copper emission factor, reported per kg of refined copper metal.
Titanium alloys	**29.4**	Estimated from the ICE v2.0 titanium virgin range; midpoint value used due to large uncertainty.
Polypropylene	**4.49**	Matched to ICE v2.0 "Polypropylene, Injection Moulding"; Climatiq/GEMIS provides a comparable PP factor.
Polyamid / Polyamide	**9.14**	Matched to ICE v2.0 "Nylon (Polyamide) 6 Polymer"; PA6 and PA66 may differ.
Polyurethane	**4.84**	Matched to ICE v2.0 "Polyurethane Flexible Foam"; rigid foam has a slightly lower factor.
Natural rubber	**7.50**	Based on tyre-grade natural rubber cradle-to-gate LCA; value is consistent with the upper range of generic rubber factors.

Hammond, Geoff, and Craig Jones. "Inventory of carbon & energy (ICE) version 2.0." *University of Bath* 19.20 (2011): 386.

Appendix

Environment-Related Metrics (Recycled Content Capability, RC)

- Defines the supplier's capability to provide a material with recycled content, based on **ISO 14021, Clause 7.8, "Recycled content."**

$$\text{Recycled content (\%)} = \frac{mass\ of\ recycled\ material}{mass\ of\ product} \times 100$$

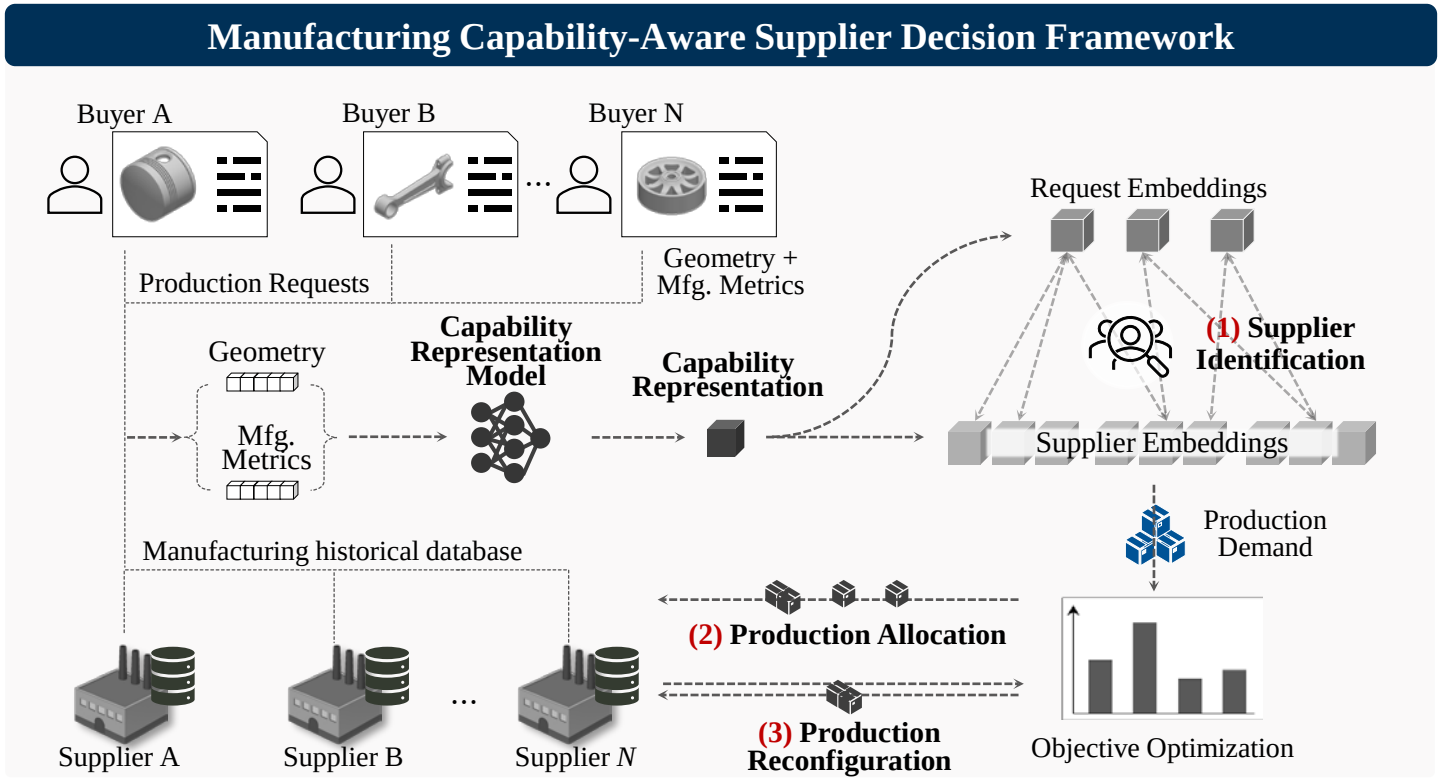
- Material-specific ranges are based on industry statistics, association reports, and certification-based evidence.
- Two capability profiles are used: low and high.

Material type	Possible range	Reference
High carbon steel	**23–82%**	AISI/SMA *Steel Recycling Rates Report*. BOF: 23%, EAF: 82%. (American Iron and Steel Institute)
Low carbon steel	**23–82%**	AISI/SMA *Steel Recycling Rates Report*. Same steelmaking-route basis. (American Iron and Steel Institute)
Stainless steel	**48–85%**	World Stainless reports global stainless recycled content around 48%; Stainless Steel World summarizes Europe/USA values around 83–85%. (worldstainless)
Cast iron	**50–95%**	Ferrous casting/foundry scrap input references and high recycled-content cast iron product claims. This one is weaker than steel/stainless/aluminum/copper and should be treated as an assumption range.
Aluminum alloys	**15–70%**	International Aluminium Institute reports global aluminium Recycling Input Rate of 32%; higher values are possible for closed-loop/product-specific supply. (International Aluminium Institute)
Copper alloys	**20–50%**	International Copper Association states copper products contain more than 30% recycled content on average; ICA/Fraunhofer reports 35% of global copper use sourced through recycling. (International Copper Association)
Titanium alloys	**0–40%**	Titanium recycled-content default is weak. Use as a closed-loop recycling capability assumption, not as a generic average.
Polypropylene	**0–30%**	Plastics Europe discusses a 30% EU recycled-content target for plastics packaging by 2030; generic PP material does not imply recycled content. (Plastics Europe)
Polyamid / Polyamide	**0–30%**	Use ISO 14021 / recycled-content certification logic. SCS certification evaluates manufacturing data, chain of custody, material quantification, and mass balance. (ISO)
Polyurethane	**0–20%**	Same certification-based logic as polymer materials. Generic PU label does not imply recycled content without supplier evidence. (SCS Global Services)
Natural rubber	**0–20%**	Reclaimed rubber is possible, but tire/automotive applications often use little reclaimed rubber; one industry report notes 3–5% in tire production due to technical constraints. (GovInfo)

Appendix

Overview of Decision Framework

- Extended supplier identification to production allocation and disruption response
- **Step 1:** Identify feasible suppliers using comparable request and supplier representations
- **Step 2:** Optimize production allocation among identified suppliers
- **Step 3:** Reconfigure production under disruption via supplier re-identification

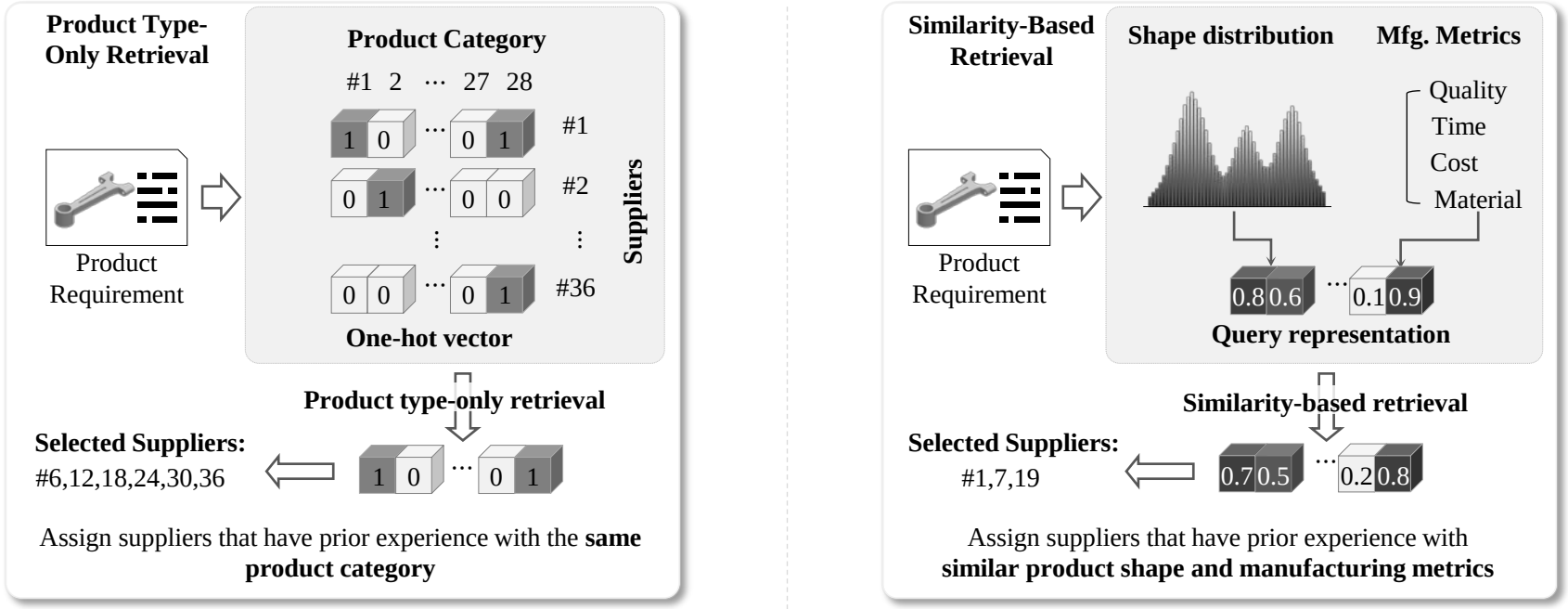


[1] S. Park et al., "A Manufacturing Capability-Aware Supplier Decision Framework for Resilient Production Allocation and Disruption Response," Journal of Manufacturing Systems, 2026 (Under Review)

Appendix

Benchmark Models and Dataset Configuration

- **Baseline 1 (Product type-only retrieval):** Selects suppliers with prior experience in the same product category
- **Baseline 2 (Similarity-based retrieval):** Selects suppliers using rule-based shape and metric similarity



Benchmark models

[1] S. Park et al., "A Manufacturing Capability-Aware Supplier Decision Framework for Resilient Production Allocation and Disruption Response," Journal of Manufacturing Systems, 2026 (Under Review)

Appendix

Optimization Equations

Effective Metric Ratio Effective Metric Ratio $= M_{\text{eff}}/M_{\text{Ground Truth}}$

Effective Metric $M_{\text{eff}} = M_{\text{pred}} + M_{\text{capacity}}^{\text{penalty}} + M_{\text{quality}}^{\text{penalty}}$

Predicted Metric $M_{\text{pred}} = \sum_{s \in S_q} x_s m_s^{\text{pred}}$

Objective Function $\min_{x_s} \sum_{s \in S_q} x_s m_s^{\text{pred}} + \lambda\, \mu_{\text{demand}} \cdots \quad \lambda = \alpha \cdot m_q^{\max}$

Subject to $\sum_{s \in S_q} x_s + \mu_{\text{dem}} = \text{total demand}, \qquad 0 \le x_s \le \text{Capacity}_s$

An Integrated Ontology for the Perpetual Innovative Product in the Circular Factory

Kristian Vlajic[1]*, Gabriel Moser[1], Jonas Hemmerich[1], Victor Leon Mas[1], Nehal Afifi[1], Etienne Hoffmann[2], Ratan Bahadur Thapa[3], Patric Grauberger[1], Sven Matthiesen[1], Albert Albers[1], Tobias Düser[1]

1 IPEK - Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany.

2 Institute for Material Handling and Logistics (IFL), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany.

3 Analytic Computing, Institute for Artificial Intelligence, University of Stuttgart, Stuttgart, Germany.

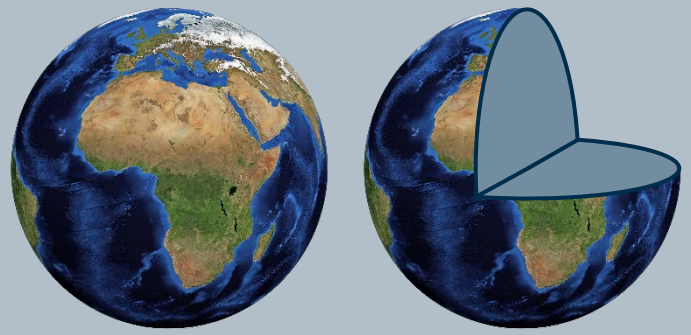
*Corresponding author. E-mail: kristian.vlajic@kit.edu.

This publication was created as part of the Collaborative Research Centre 1574 “Circular Factory for the Perpetual Innovative Product.”

Decoupling Prosperity and Resource Consumption

Linear economic patterns need to be reconsidered

1,75 Earths



are necessary to cover **global resource consumption** in 2022.

[1]

7,2 % (2023)

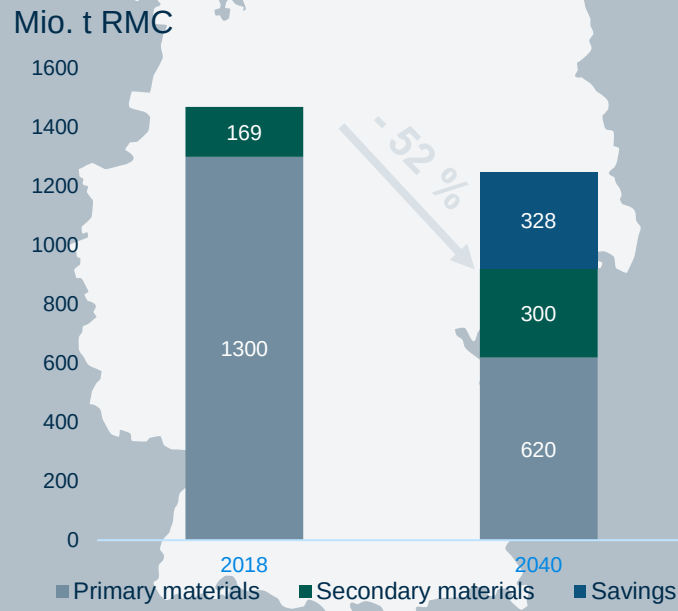
9,1 % (2018)



of the total materials used worldwide are **recovered materials**.

[2]

Circular Economy Potential Germany



RMC: Raw material consumption

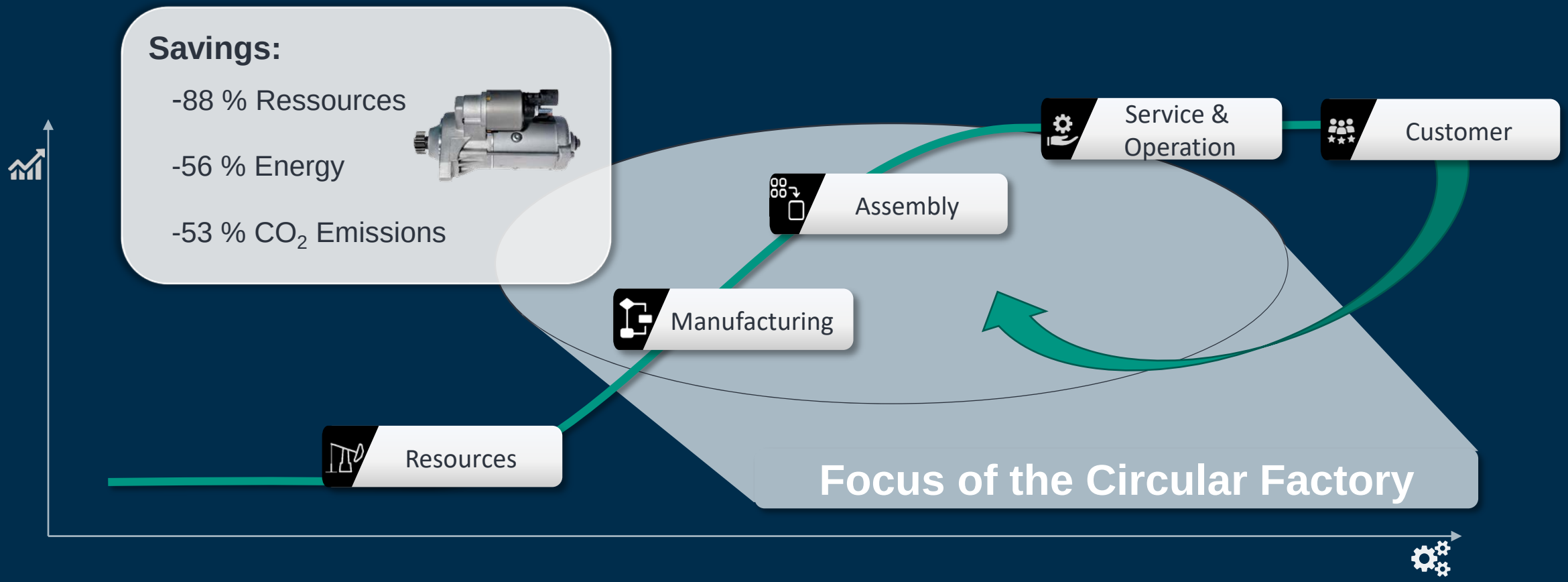
[3]

Our CRC 1574 addresses research and innovation demands to enable the **circular economy**.

[1] Global Footprint Network (2022), [2] Circle Economy (2023), [3] Circular Economy Initiative Deutschland (2021)

Ensuring Maximum Retention of Added Value

Preservation of the material composition enables great savings potential



Based on Khor & Udin (2012), Parker et al. (2015), Ellen MacArthur Foundation (2013), Benoy, et al. (2014), Tolio et al. (2017)

Vision of the „Perpetual Innovative Product“

Maximum value retention through Product-Production-CoDesign



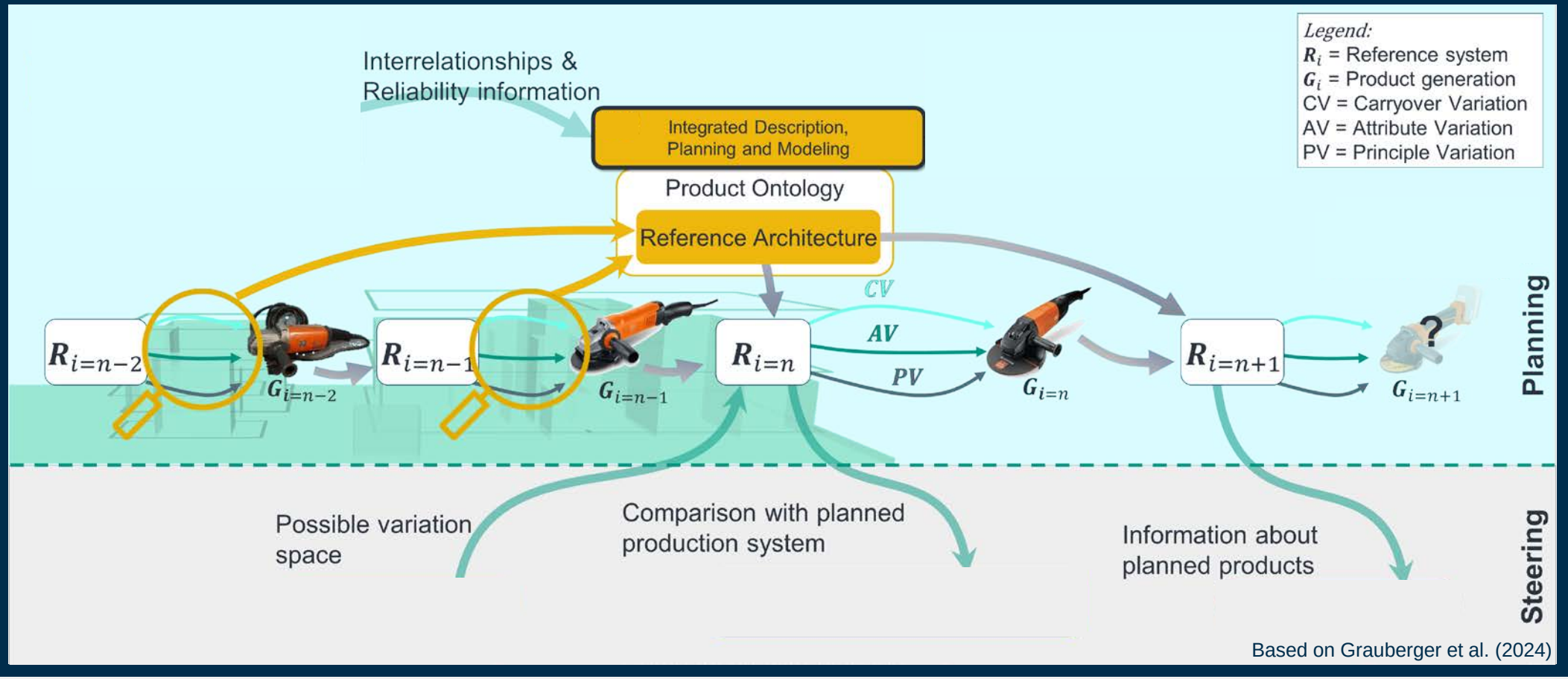


New products with individual processing content

Used product instances (their subsystems, components) are constantly transferred to the same or a new product generation. This enables **theoretically perpetual innovative product use**.

Vision of the „Perpetual Innovative Product“

Cross-generational product and production system planning

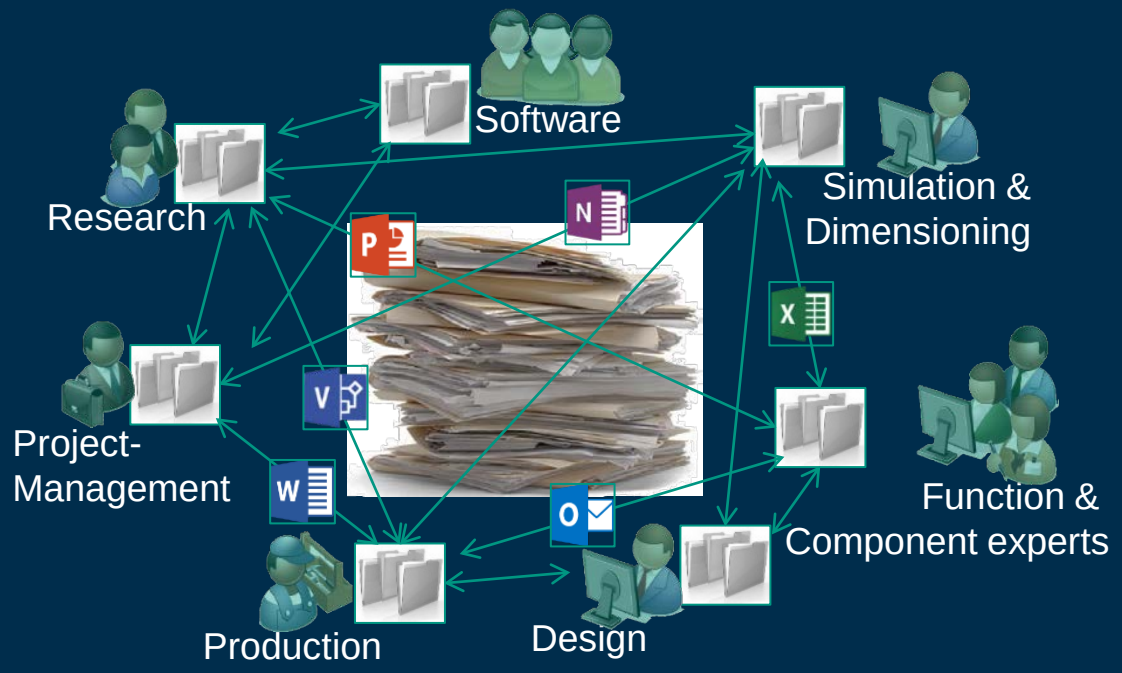


Based on Grauberger et al. (2024)

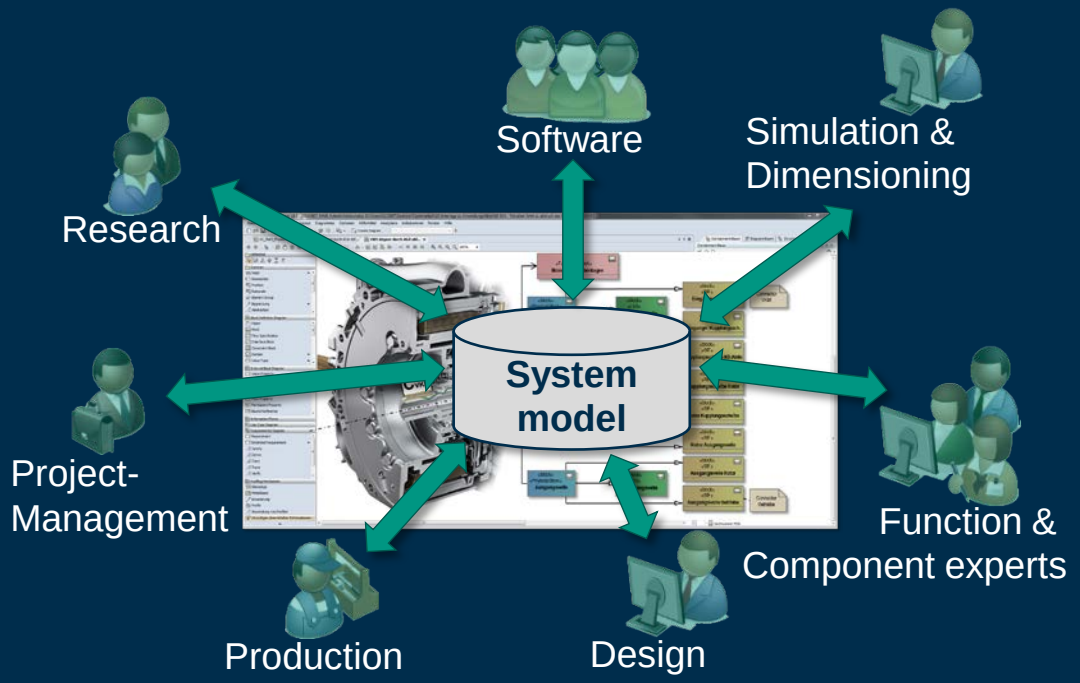
How can we **deal** with the high **complexity?**

Managing Complexity with Model-Based Systems Engineering

Document-based vs. model-based systems engineering



Document-based

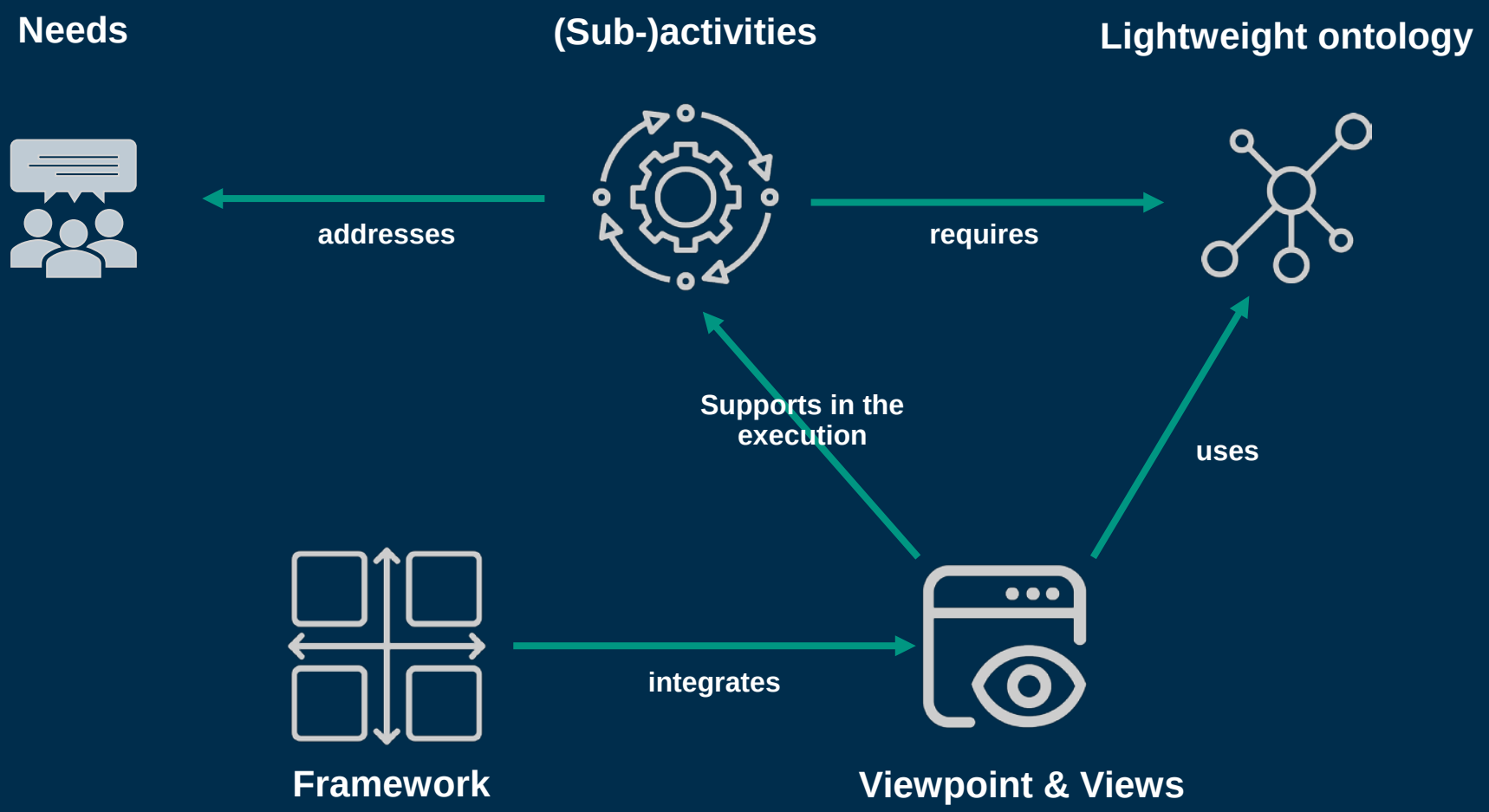


Model-based

Improved consistency, availability, reusability

Procedure for the Development of MBSE Approaches

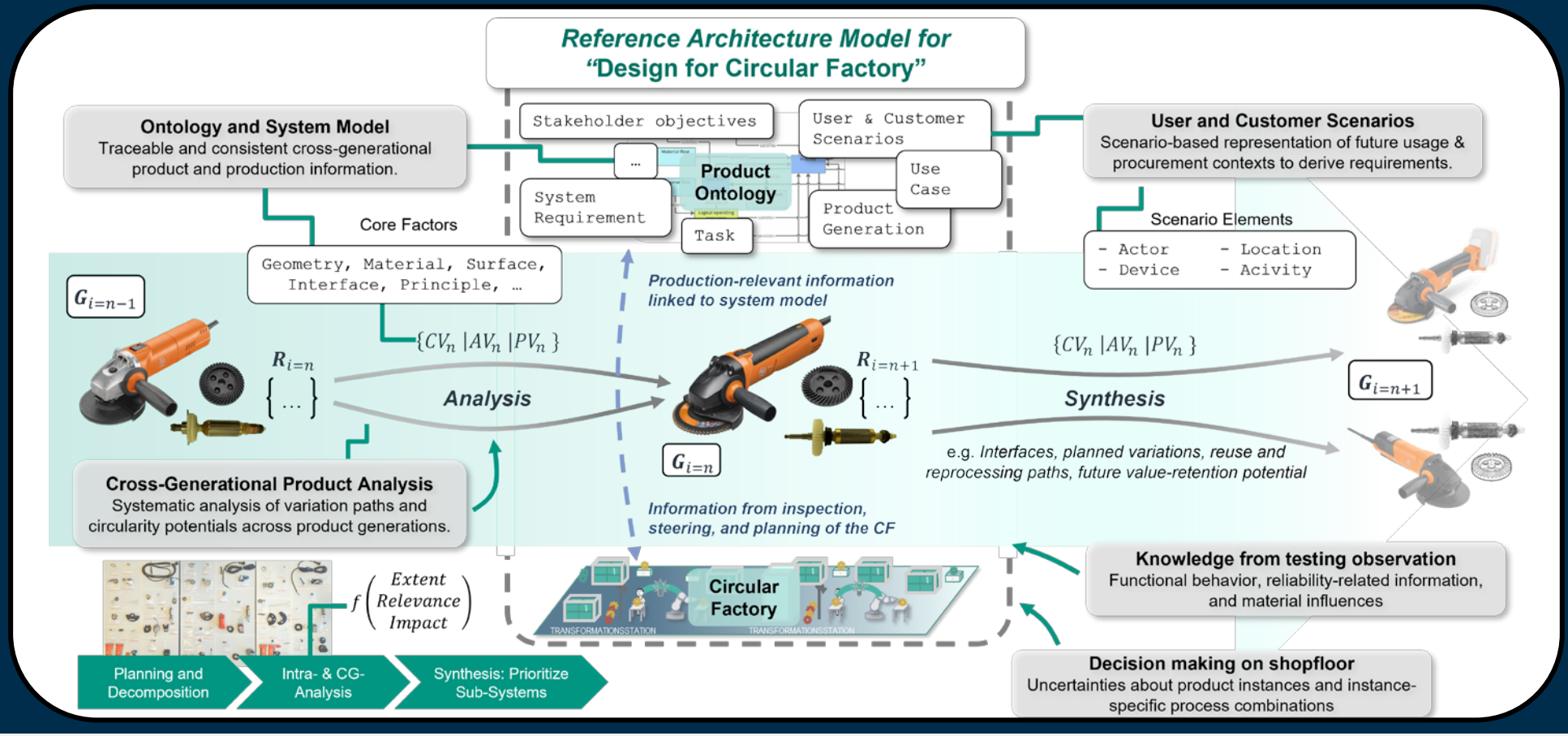
The relationship between the method, framework, and ontology



Based on Holt & Perry (2019)

Vision of the „Perpetual Innovative Product“

Prediction of the product function of new product generations



How exactly are the **domains interrelated** within the Circular Factory?

The Perpetual Product in the Circular Factory

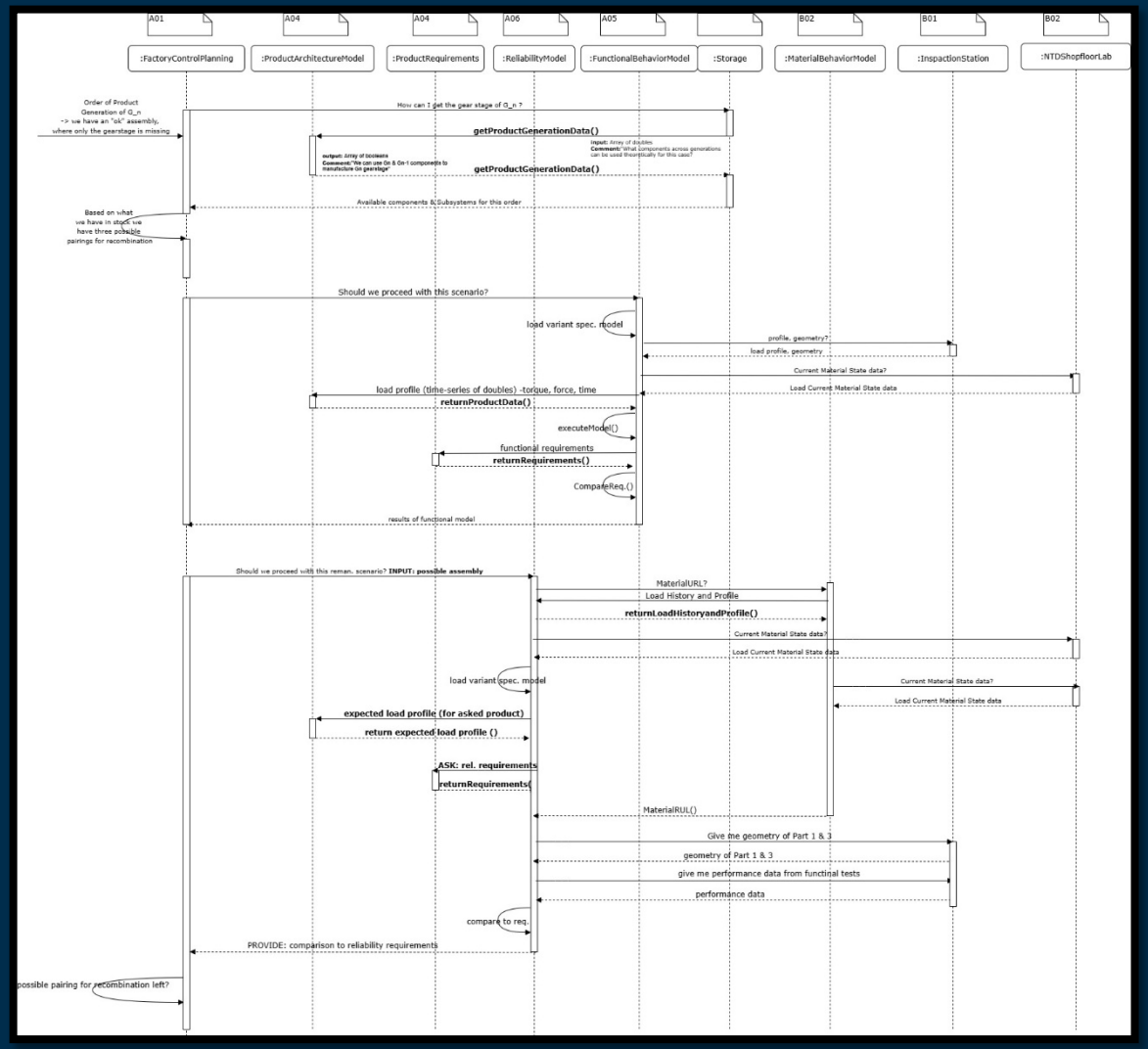
Scenario for the angle grinder in a circular factory

Component identification and compatibility check: Factory Control identifies that a suitable gear stage is missing and queries Storage and product knowledge to find compatible components from available stock and past product generations

Functional validation:
The functional model evaluates the proposed component combinations to determine which options fulfill the required performance and functional criteria

Reliability assessment:
The reliability model checks the selected assemblies using material monitoring data to confirm that reliability requirements are met

- **Decision-making:** Factory Control uses the information of the possible recombination pairings to decide whether to proceed with the step.



Competency Questions for the Ontology

Meta-competency questions based on a full set of competency questions

Formalized System Integration:
Establishes a semantic foundation that maps the critical interfaces and dependencies between the product, validation, and production systems within a Circular Factory

Cross-Generational Development:
Links stakeholder needs and product requirements directly to architecture at the instance level, allowing teams to map out and trace future product development paths

Value-Retention & Decision Making:
Identifies potential remanufacturing and value-retention paths early on, providing data-driven decision support across multiple product generations

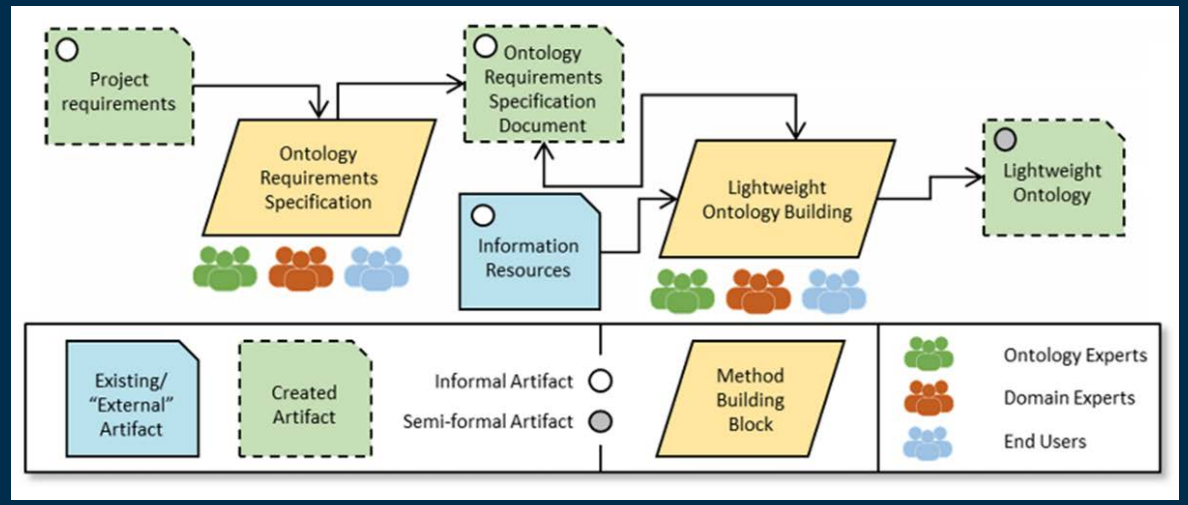
- **Define Competency Questions:**
  A set of competency questions across multiple domains to establish clear functional boundaries and requirements for the ontology, represented here as meta competency questions

Table 1. Meta competency questions that the ontology intends to satisfy.

Domains	Meta Competency Question
Problem Space	How do stakeholders' needs and boundary conditions within a user and customer scenario derive and trace to specific system requirements and functions?
Cross-Generational Remanufacturing Potential	Which assemblies and components are viable for the requirements of new product generations, and does the embodiment characteristic allow direct reuse or require technological updating?
Cross-Generational System Architecture	Which variations are executed on reference system elements across generations, and how are system elements impacted regarding their system requirements fulfillment and functions?
Functional Behavior	Does the assembly meet the expected behavior, and how does the individual embodiment of components alter the functional behavior of an assembly from its expected nominal performance under load?
Reliability Prediction	Does the assembly satisfy the reliability requirement, and what is its remaining useful life based on the current wear states and cumulative load exposures of its individual components?
Product-Production-CoDesign	Which configuration of returning component instances or newly manufactured components satisfies the system requirements for a specific product generation variant?

Research Approach
Objective and methodology

An integrated ontology that connects cross-generational product architectures, remanufacturing potential, instance-specific functional behavior, and reliability prediction with a circular production system to provide decision support for reuse, update, or reject returned components.



Based on Hildebrandt et al.(2018)

I Applied a domain-expert-centric ontology-building methodology specifically designed for cyber-physical systems, structuring development through iterative, requirement-driven building blocks

II Conducted literature reviews and participatory workshops with researchers and MBSE experts to identify industry challenges and establish competency questions, which were refined with the "Perpetual Innovative Product" scope using an angle grinder scenario.

III Collaborated with researchers via semi-structured questionnaires to formalize domain viewpoints, converting the knowledge into a machine-readable OWL 2 ontology over an RDF graph

Ontology for the Perpetual Innovative Product in the Circular Factory

Domains and Elements



Problem Space:
- **Stakeholders and objectives:** Map out the Stakeholder, Stakeholder Need, Stakeholder Benefit, and Stakeholder Objective classes
- **Constraints and scenarios:** Utilize the System Context and User and Customer Scenario to establish operating limits through a defined Use Case
- **System requirements:** Combine objectives with restrictions from the Constraint class to formulate the final System Requirement

Cross-Generational System Architecture:
- **Product hierarchy:** Blueprint the physical and functional architecture across generations using Product Type, Product Generation, Assembly Type, and Component Type
- **Knowledge:** Track legacy data by linking the system to a Reference System and its corresponding Reference System Element
- **Design changes:** Use the Variation superclass to strictly differentiate evolutionary updates into Carryover Variation, Attribute Variation, or Principle Variation

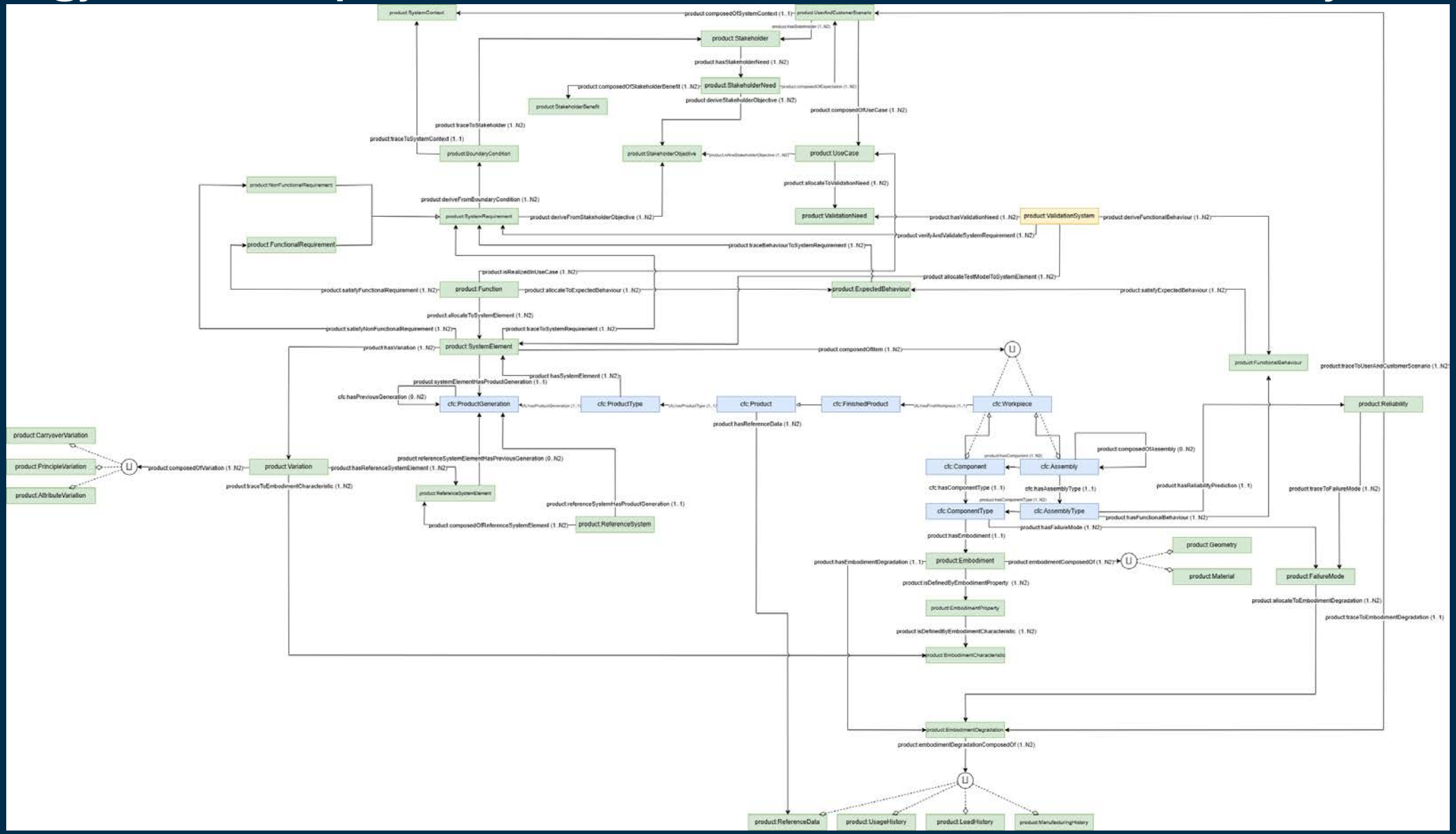
Cross-Generational Remanufacturing Potential:
- **Value-retention paths:** Assess whether a returned assembly can be directly reused or must undergo additive/subtractive remanufacturing based on its cross-generational Variation
- **Technical shifts:** Map physical transitions across generations by tracking changes in the Embodiment, Embodiment Property, and Embodiment Characteristic classes
- **Match condition to requirements:** Link instance-specific data of a returned System Element to the latest System Requirement to justify production integration

Functional Behavior:
- **Specify targets:** Allocate the Expected Behavior directly to a defined Function to anchor what the system must deliver under operational conditions
- **Formalize physical response:** Connect intended design characteristics (Embodiment Characteristic and Embodiment Property) to the actual Functional Behavior of an assembly
- **Capture wear:** Model how a physical structure deviates from its initial state over time using the Embodiment Degradation class

Reliability Prediction:
- **Track physical degradation:** Document structural wear indicators over time using the Embodiment Degradation class
- **Formalize failure mechanisms:** Identify exactly how an assembly fails under stress over time by mapping its active Failure Mode
- **Calculate remaining useful life:** Process history data through the Reliability class to output a mathematical probability of satisfying requirements over a given time-in-use

Product-Production-CoDesign:
- **Establish the co-design interface:** Map physical product variants directly to shop-floor tasks by linking the Product Type with the factory Workpiece
- **Sequence manufacturing operations:** Use workpiece properties to define the exact production capabilities and operations needed to assemble cross-generational parts
- **Support factory control systems:** Enable central controllers to query live inventory and verify if a specific combination of old and new component instances meets system requirements

Ontology for the Perpetual Innovative Product in the Circular Factory

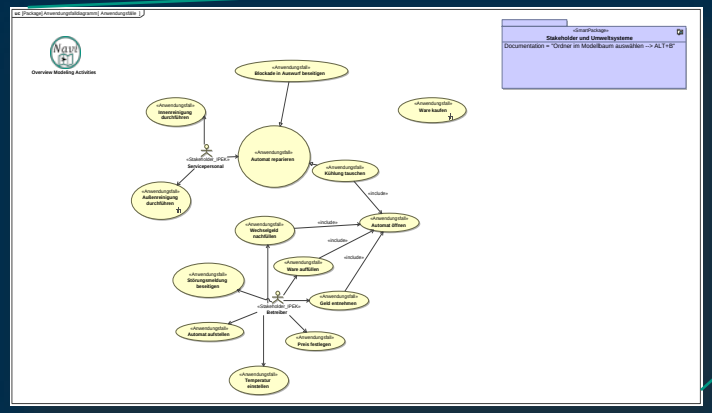


Activity-based Modeling Approach

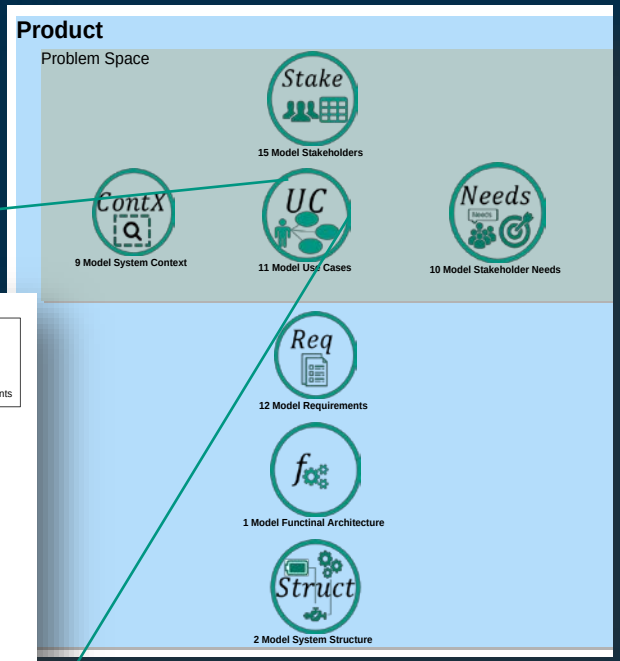
Modeling activities for products

***Detailed description** of modeling activity*

View** used for **modelling step







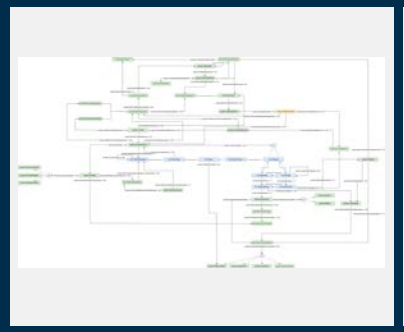
Framework** of modeling activities in a **structured tool-template

Based on Mandel et al. (2022)

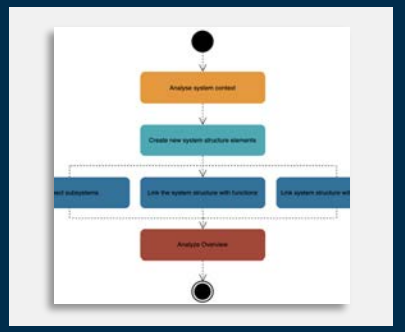
Summary and Outlook

Next steps

Developed an ontology for the PIP

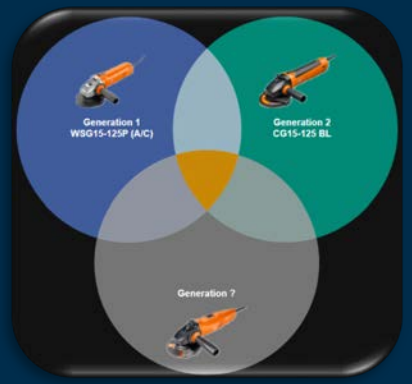


Expand the MBSE methodology

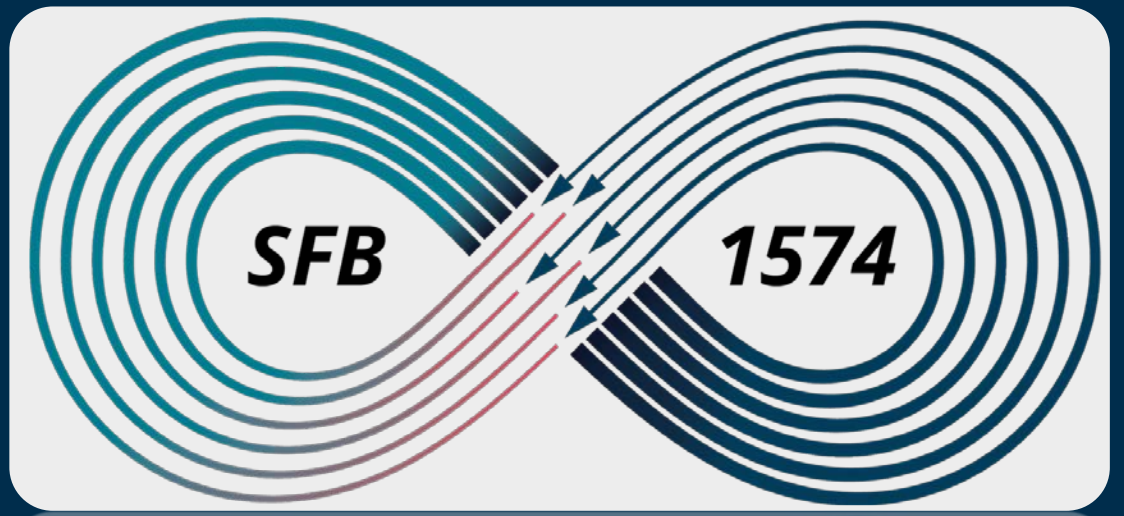


Implement the findings in a system model

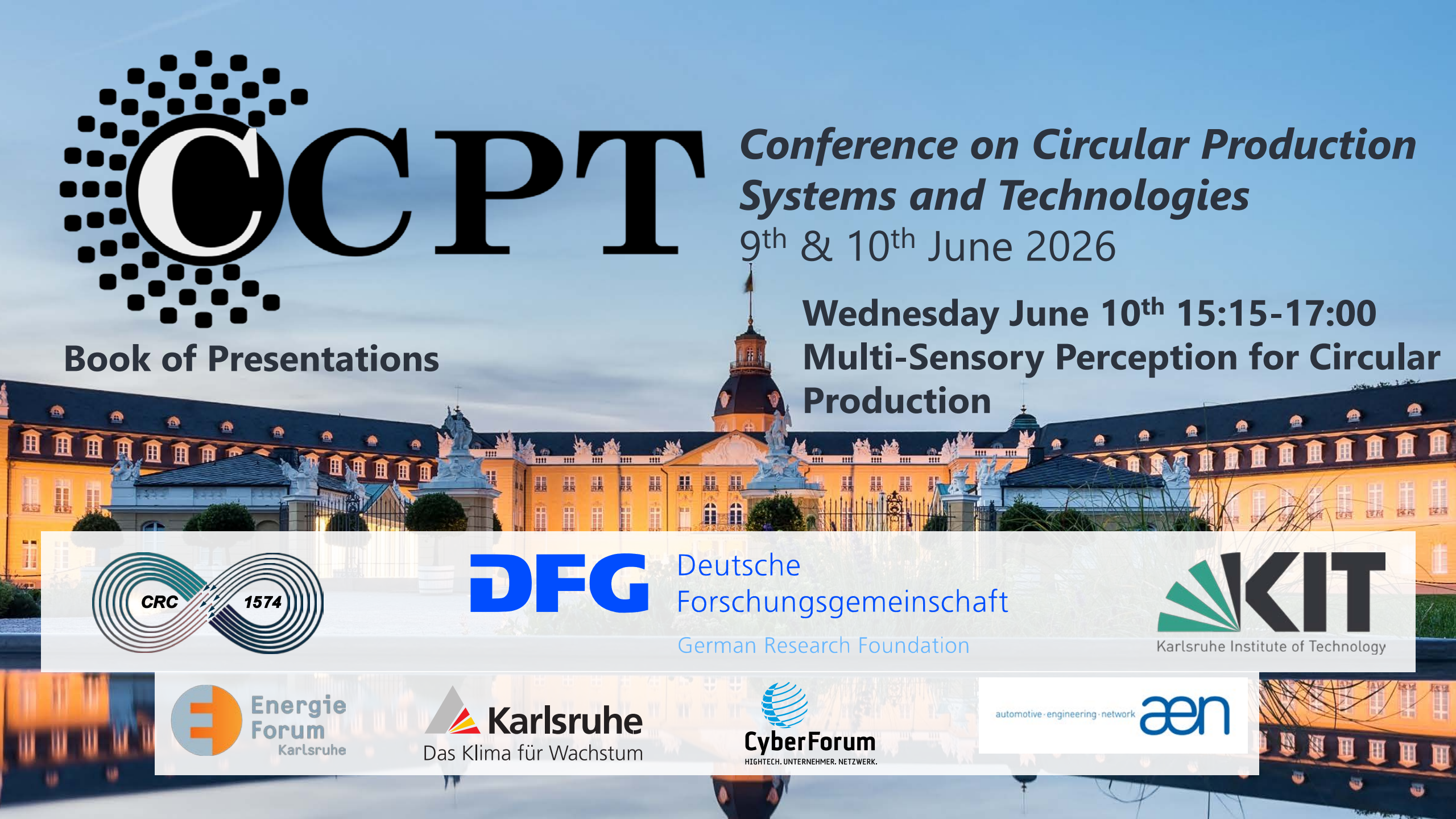




Laying the foundation for future research to address these challenges:



https://www.sfb1574.kit.edu/



CCPT

Conference on Circular Production Systems and Technologies

9th & 10th June 2026

Book of Presentations

Wednesday June 10th 15:15-17:00
Multi-Sensory Perception for Circular Production

CRC 1574

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German Research Foundation

KIT Karlsruhe Institute of Technology

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1st Conference on Circular Production Systems and Technologies (CCPT)

Information Lead Time and Sustainability in Biointelligent Production: A Comparative Assessment of Quality Control Strategies in Viral Vector Manufacturing

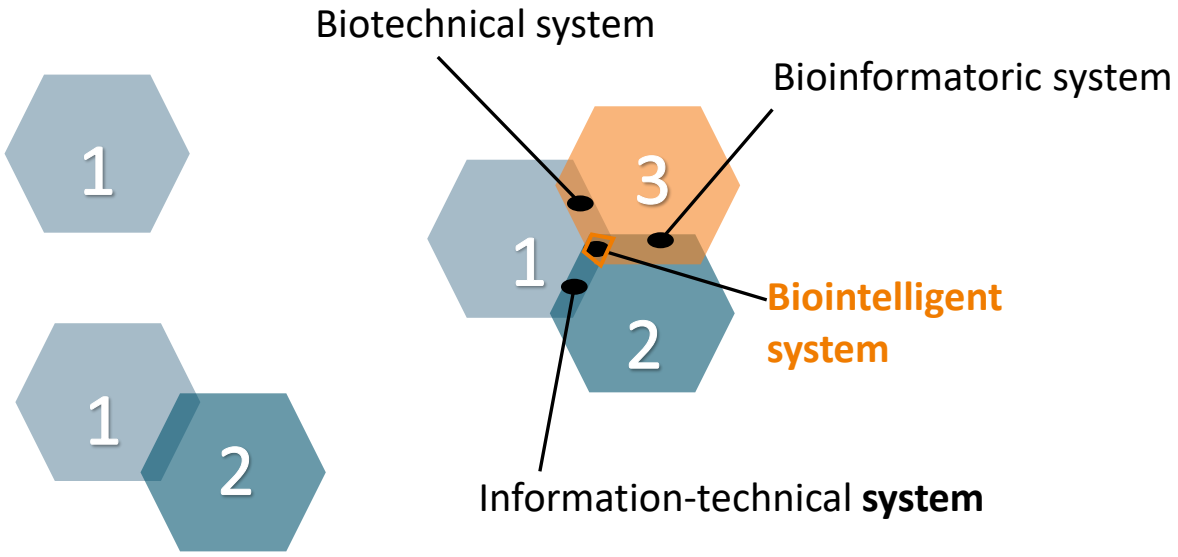
Edgar Gamero[1,2,*], Arber Shoshi[1,2,3], Thomas Bauernhansl[1,2], Robert Miehe[1,2]

1 Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart, Germany
2 Institute of Industrial Manufacturing and Management IFF, University of Stuttgart, All-mandring 35, 70569 Stuttgart, Germany
3 Graduate School of Excellence advanced Manufacturing Engineering GSaME, University of Stuttgart, Nobelstraße 12, 70569 Stuttgart, Germany

*Corresponding author

The „Biointelligent Manufacturing System“

Convergence of three different technology areas



1 - Technical system

2 - Information system

3 - Biological system

Levels of biointelligent value creation

BVS / BIS / BHS	Macro level	Macroeconomics - National economy	e.g. supraregional economic regions
		Entire production network	e.g. decentralized production with heterogenous stakeholders
	Meso level	Production System	e.g. intelligent biorefinery, Smart Biointelligent Manufacturing Devices
	Micro level	Product (stand alone)	e.g. (intelligent) bioreactor
		Product component (non stand alone)	e.g. biosensor, bioactuator
		Fundamentals	e.g. enzyme, microbial cells, cell cultures

BVS = Biointelligent Value Creation Systems BIS = Biointelligent Systems BHS = Biohybrid Systems

Current understanding: biointelligent systems integrate technical, information and biological compounds and allow direct, bi-directional communication between different building blocks.

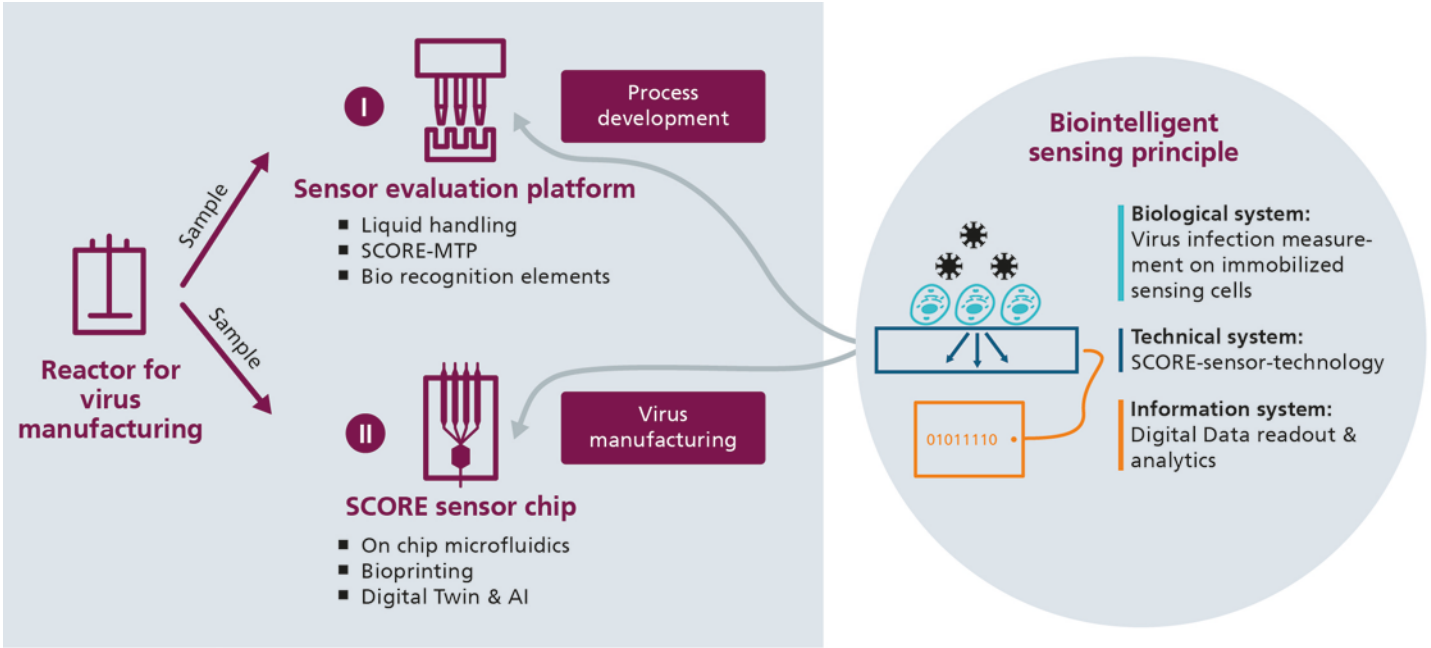
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BioProS Project Outline

Biosensor for an in-line quality check of viruses

Real-time capable biohybrid sensor technology to monitor viral activity as in-line quality control

SCORE-device with a functionalized surface on which living cells, bacteria or other biological binding components (ligands) are attached that function as the sensing element



SCORE = Single-Colour Reflectometry

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Major challenges in viral vector manufacturing

Classical test methods

Measured property	Viral Vectors for Gene Therapy		Oncolytic Viruses
	Adeno-associated viruses (AAV)	**Lentivirus (LV)**	**e. g. Herpes simplex virus**
Functional virus numbers	Molecular Methods (qPCR, ddPCR)	Molecular Methods (qPCR, ddPCR)	Cell-based Methods (Plaque/TCID50 Assay)
Total virus numbers	Biochemical Methods (ELISA, HPLC)	Biochemical Methods (ELISA, HPLC)	Molecular Methods (qPCR, ddPCR)
Biological activity	Cell-based Methods (Transduction Assay)	Cell-based Methods (Transduction Assay)	Cell-based Methods (Plaque/TCID50 Assay)

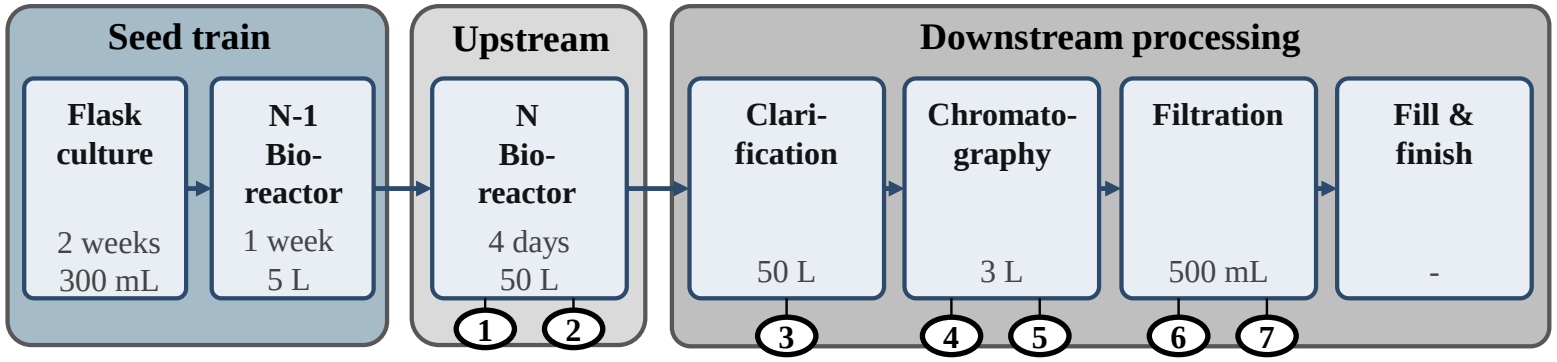
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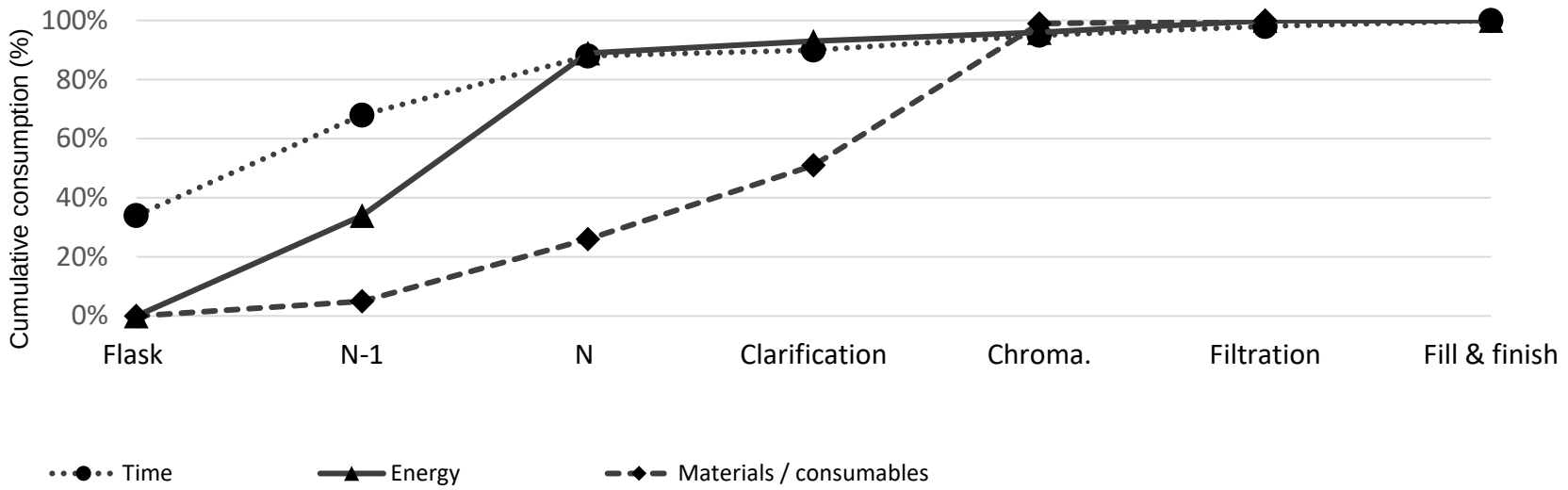
Offline, slow and non-digital readout

© Fraunhofer IPA

Viral vector manufacturing

Process sequence, measurement points, replaced assays and cumulative consumption model





Conventional assays replaced

1–2
- 2× ELISA
- 2× PCR

3
- Functional titration
- ELISA
- PCR

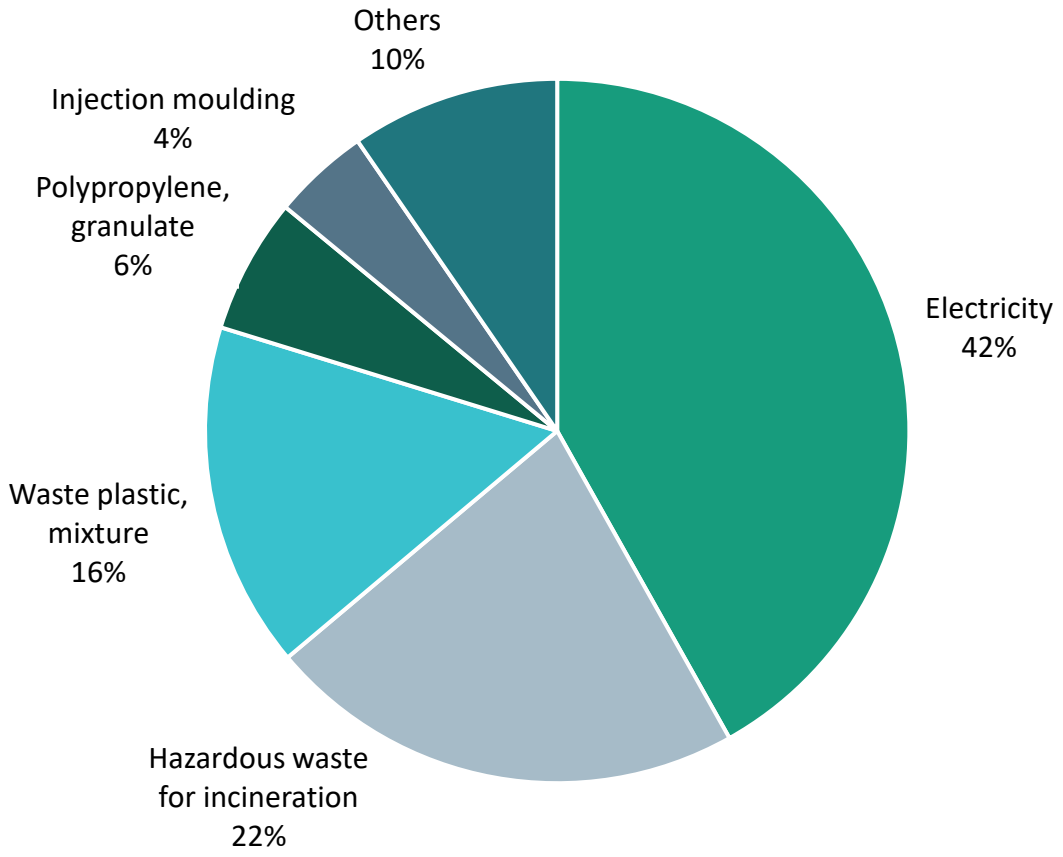
4–5
- Functional titration
- 2× ELISA
- 2× PCR

6–7
- Functional titration
- ELISA
- PCR

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Conventional assay vs biosensor case

Global warming potential and avoided resources



- Biosensor use: 3.3 kg CO_2-eq (Gamero et al. 2026)
- Conventional assay case: 75.9 kg CO_2-eq
- ~96% reduction of impacts with biosensor use

Avoided resources:

Unit operation	Buffers [L]	Single-use assemblies	Filters	Electricity [kWh]
Clarification	60	3	4	5.2
Chromatography	115	3	0	4.9
TFF	0	1	0	5.3
Fill & Finish	0	0	1	0.2
Total	175	7	5	15.7

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Information Logistics

Definition, building blocks, and its role as the binding constraint

Information logistics delivers the right information to the right person, at the right time, in the right form, and at the right place.

Building blocks

An information logistics system is modelled as typed elements along the value stream:

- Information Sources & Sinks: where information originates and is consumed
- Transformations: processing and interpretation steps
- Interfaces: hand-overs between systems or actors
- Archives: auditable storage (LIMS / MES records)
- Triggers: events that initiate an action

Information lead time

Elapsed time from the physical event (the sensor measurement) to the moment the decision-maker can act on it.

Why it is the binding constraint

The interval: resources accumulate during the lead time, so the sensor's benefit depends on the lead time, not on the hardware.

The mechanism: automating routing and escalation cuts post-sensor propagation from 3.0 h to 0.4 h (7.5-fold).

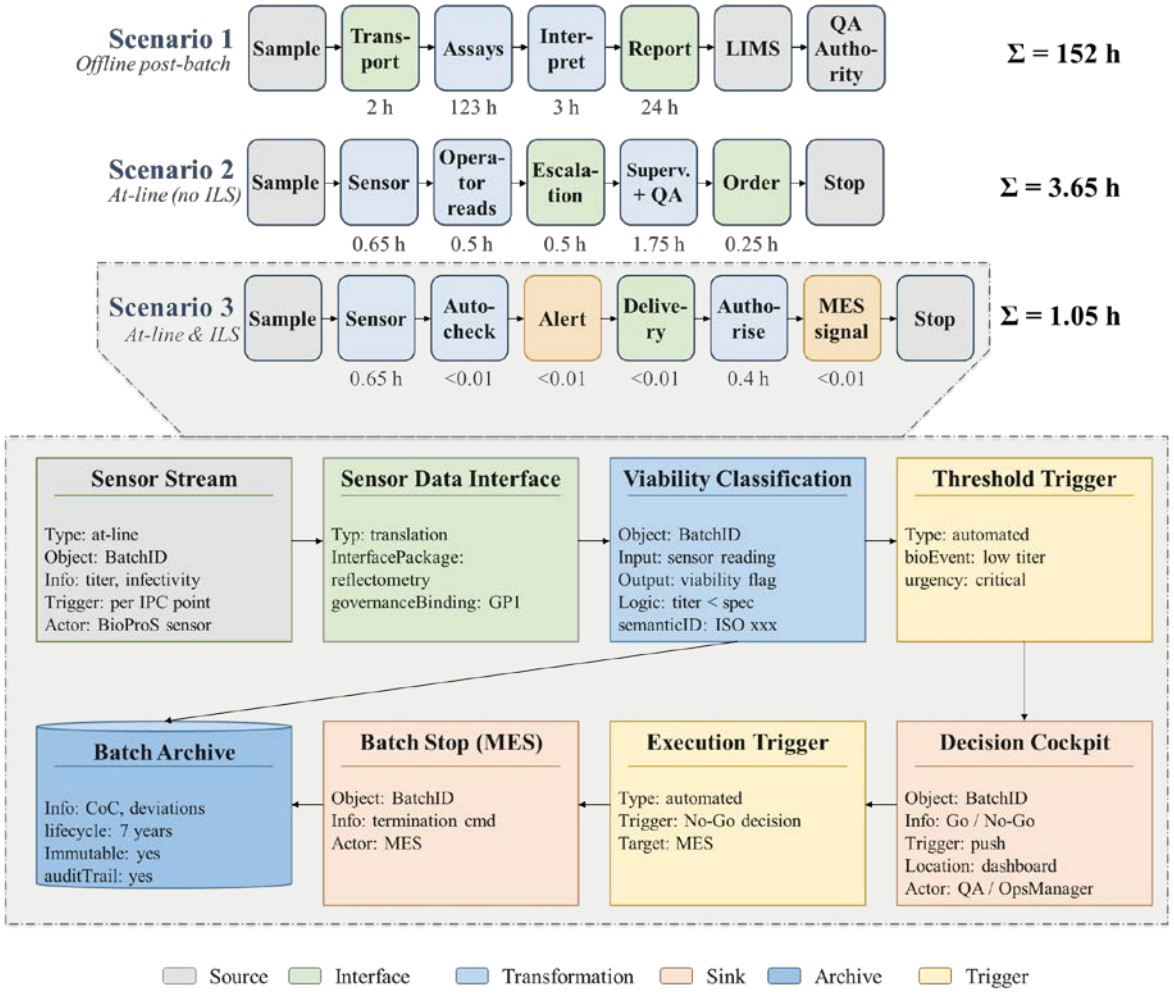
Point of no return: once a non-viable batch enters a unit operation, its single-use assemblies and buffers are committed; the IL system keeps the decision ahead of that boundary.

The sensor determines whether within-batch termination is possible; the information logistics determines how much of the avoidable investment is captured.

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Quality control scenarios

Information flow and resulting lead time per scenario



- Scenario 1 (offline post-batch testing): conventional assays in external laboratory, results after batch completion
- Scenario 2 (at-line, no ILS): BioProS biosensor without IL integration; interpretation, escalation, and authorization propagate through manual channels
- Scenario 3 (at-line, ILS-coupled): integrated system; signal is processed through standardized interfaces, addressed automatically to the decision-maker, and used for an immediate Go/No-Go gate

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Summary

Key findings and implication

- **Faster quality gating is a circular strategy:** Late detection wastes a whole batch; ~1 in 10 is non-viable.
- **The biosensor cuts the analytics footprint:** At-line sensing replaces offline assays: −96 % (75.9 → 3.3 kg CO_2-eq).
- **Early termination saves the downstream resources:** Stopping before downstream avoids 175 L buffers, 7 assemblies, 5 filters, 15.7 kWh.
- **Information lead time decides whether they are captured:** Lead time 152 h → 3.65 h → 1.05 h; post-sensor 3.0 → 0.4 h (7.5×). The sensor enables it; the ILS makes it timely.

➢ **The sensor enables within-batch termination; information lead time decides whether it prevents the waste.**

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Acknowledgments

Thank you for your attention!

This project has received funding from the European Union's Horizon Europe research and innovation program
(HORIZON-CL4-2021-DIGITAL-EMERGING-01-27: Development of technologies/devices for biointelligent manufacturing (RIA)) under grant agreement number 101070120.

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Future is our product

Sustainable. Personalized. Smart.

Verena Eichinger, Keerthana Lokesh Babu,
Moritz Parth and Bernd Meese

Towards Autonomous Disassembly: Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal



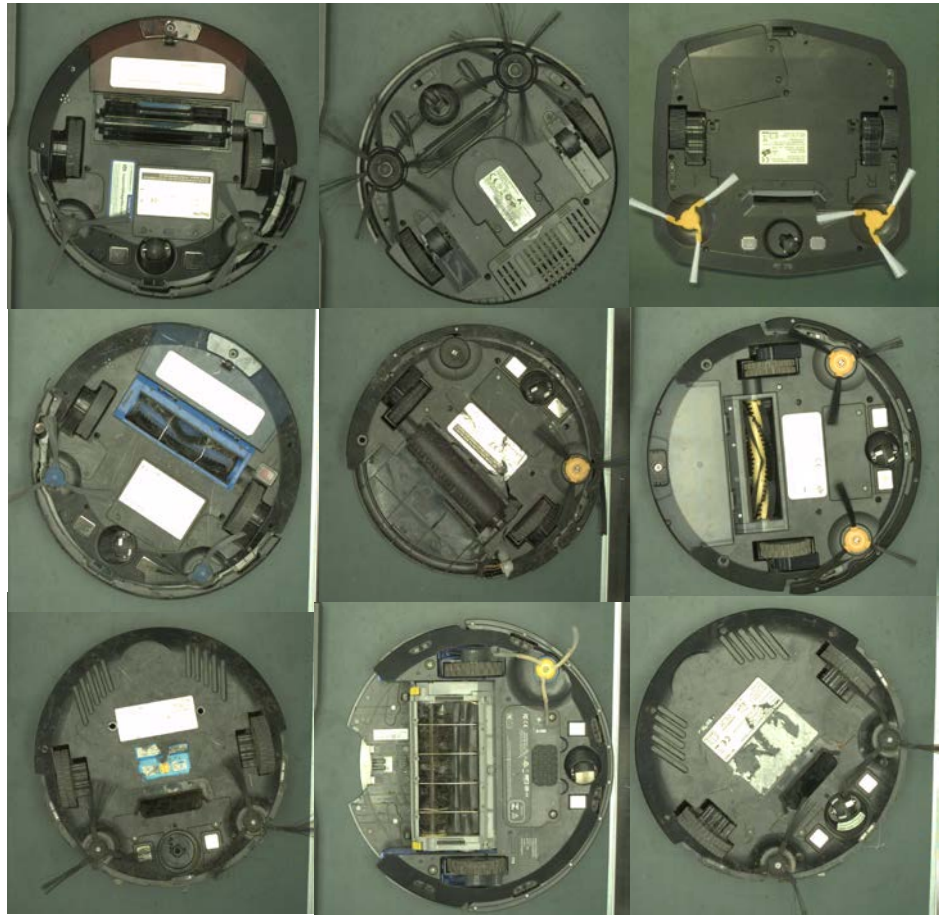
Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal

Motivation

Why Knowledge-Free Disassembly?

- Scarcity of raw materials and growing e-waste volumes
- Manual disassembly is labour-intensive and not cost-effective
- High complexity of the disassembly task:
  - Missing disassembly information
  - End-of-Life conditions are unknown
  - Big product variety

There is a need for systems that work on unknown devices and take end-of-life conditions into account



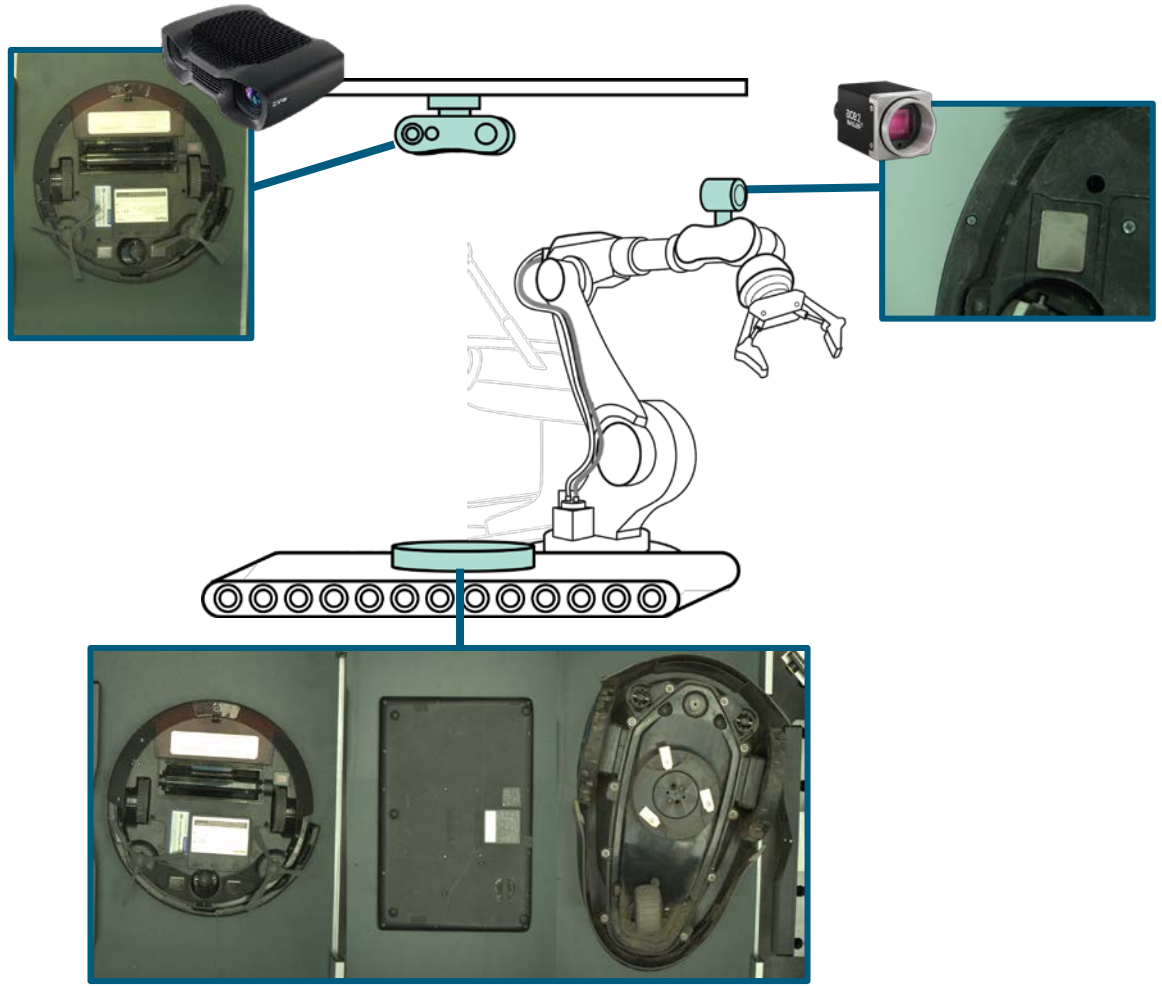
Product variations within the product group of vacuum cleaner robots

Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal

System Architecture and Experimental Setup

Robotic disassembly cell:

- 6-DoF UR10e robot with exchangeable tools
- Conveyor with device fixation
- Vision system:
  - Overhead ZividTwo+ 3D sensor (RGB + 3D point cloud)
  - Robot-mounted Basler RGB camera with 50mm lens (close-up inspection)
- All components integrated via ROS



The vision system is designed to provide all data needed for unscrewing and plug removal through cable cutting

Image sources:
https://www.baslerweb.com/de-de/shop/a2a2840-14gcip67/
https://devicebase.net/en/zivid-two

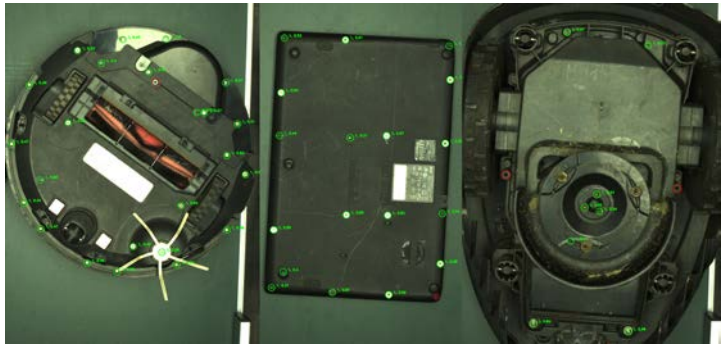
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Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal

Screw Perception Pipeline

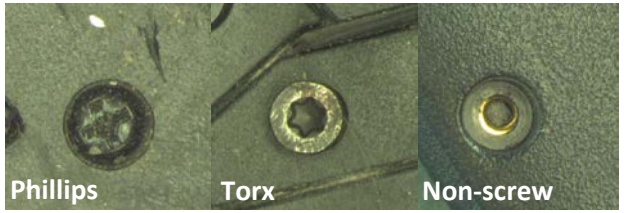
Global Candidate Detection

- EfficientDet-D1 on Zivid RGB image
- Holes and screws are detected as possible candidates
- 3D positions are acquired from the organized point cloud



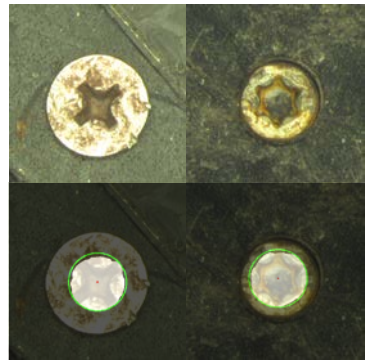
Candidate Classification

- Basler camera is moved over the candidates for close-up images
- YOLOv8m classifier on 400×400 px image crops
- Classes: Phillips / Torx / Non-screw



Drive Segmentation and Bit Size Definition

- Screw drive segmentation with YOLACT
- OpenCV contours detection and equivalent circle diameter calculation
- Bit size (PH 0/1/2, T 10/20/25) definition based on a look-up table



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Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal

Screw Results

Global Candidate Detection

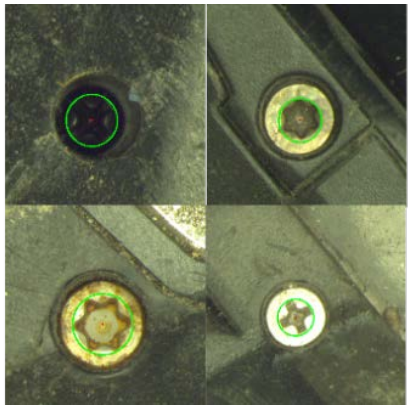
- Precision: 100 %
- Recall: 88 %
- Significant variation in brightness caused by reflection or indentation is observed in missed detections

Candidate Classification

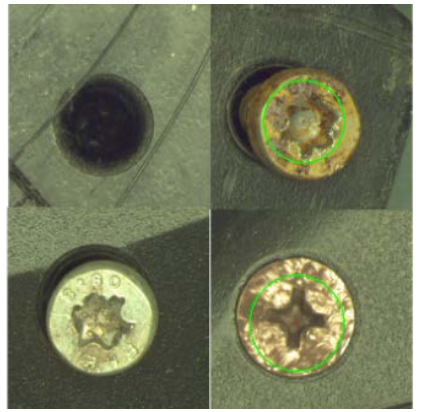
- Overall accuracy: 80 %.
- Misclassification of heavily soiled or damaged Torx screws
- Low recall for Torx and non-screw elements (likely due to insufficient training samples)

Drive Segmentation and Bit Size Definition

- Successful segmentation in 150 of 151 cases
- 85 % correct bit size definition based on the segmentation
- The second-best bit size can be used as a fallback option



Examples for correctly detected screws



Examples for screws with different errors

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Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal

Plug Perception and Cutting Pose

Method:

- Dataset collection with vacuums and lawn mowers
- YOLOv8-n pose model
- Prediction of 3 keypoints per connector:
  - P_1, P_2: cable entry points on connector housing
  - P_3: point along cable
- Keypoints are projected into 3D via point cloud

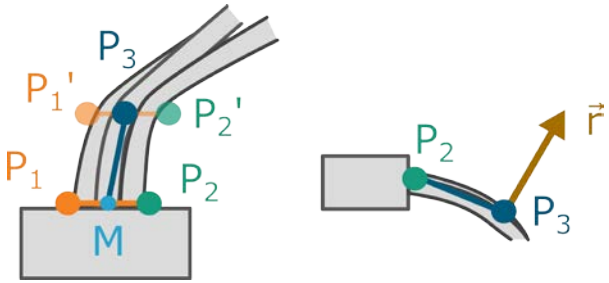
Cutting pose definition:

- Cable orientation is defined by M to P_3
- Plug orientation is defined by P_1 to P_2
- Both orientations span a plane with normal vector $\vec{r}$
- P_3 and $\vec{r}$ define the cutting pose

» 6D cutting pose generation to sever cables close to the plug



Example image from the disassembly cell



Schematic overview of the cutting pose generation

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Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal

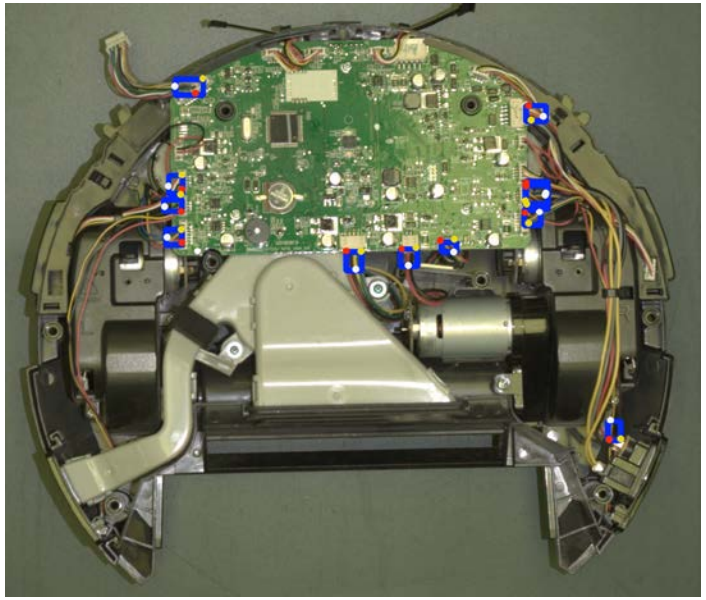
Plug Results

Keypoint detection:

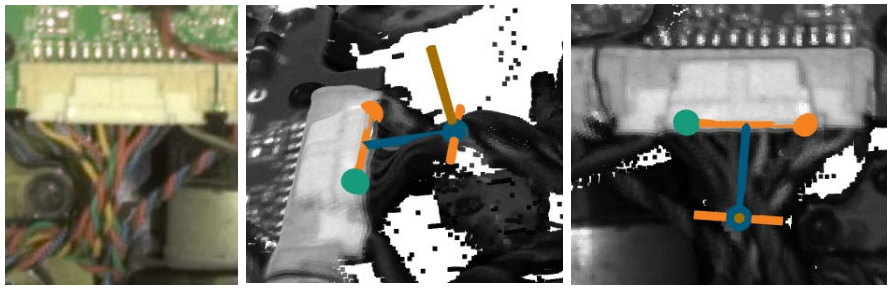
- Precision: 84 %
- Recall: 51 %
- Mean OKS: 0.63 (P1: 0.65, P2: 0.68, P3: 0.55)
- White connectors with only black cables are frequently missed

Cutting pose:

- Manual evaluation on 10 connectors regarding plausibility and reachability
- Reachable pose in 6 out of 10 cases
- 4 out of 10: pose computed, but approach vector not suitable for cutting
- For all computed poses a validity check through the range of Z-coordinates was possible



Detection result on a Zivid RGB image



Pose calculation result for one plug visualized in 3D

Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal

Discussion and Limitations

Achievements

- Knowledge-free perception: No product-specific CAD or disassembly plans
- System tested on and suitable for different product types
- Incorporation of realistic end-of-life conditions, including contamination and wear and tear
- Robust screw pipeline
- First demonstration of keypoint-based cutting poses for plugs in realistic e-waste scenarios

Limitations

- Sensitivity to extreme illumination and heavy soiling
- Data-related limitations:
  - Top down view limitation with usage of two sensors only
  - Limited datasets with potential for expansion
- Plug pose system is to be expanded for optimization

Knowledge-Free Machine Vision-Based Multi-Sensor Perception for Screw and Plug Removal

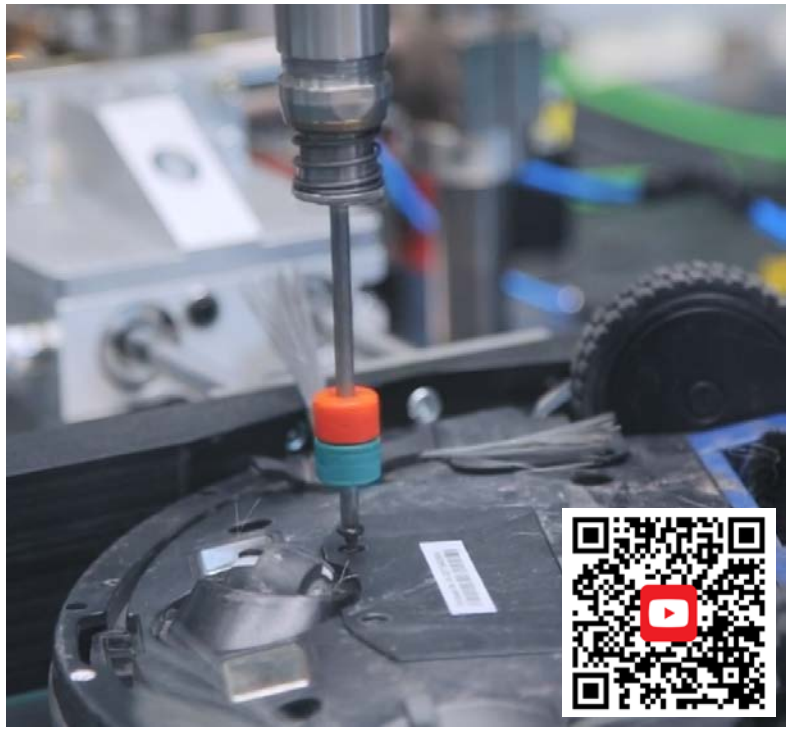
Conclusion

Conclusion

- Machine vision-based multi-sensor perception system for:
  - Screw detection with type, and bit size
  - Plug keypoints and cutting poses
  - Works across different product types without product-specific prior knowledge
  - Demonstrates feasibility of flexible, knowledge-free robotic disassembly

Future Work

- Larger, more diverse datasets: more device types and diversity in plugs and screws
- Improved plug perception: two-stage pipelines, higher-resolution local views
- Enhanced robustness



Smart battery removal with screw perception at Fraunhofer IPA

Contact

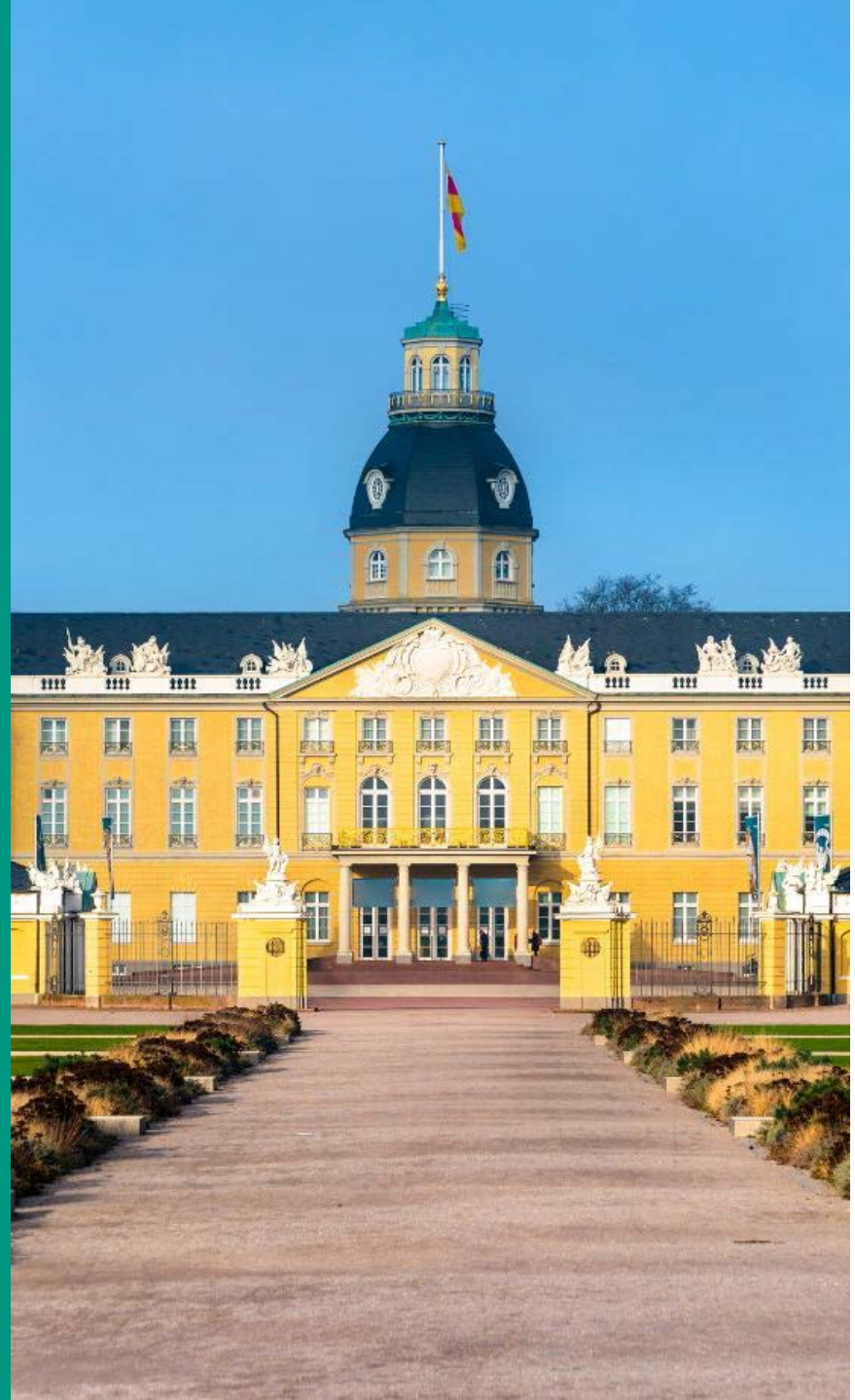
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Video Demonstration:
Smart battery removal – Fraunhofer IPA

Probabilistic Process–Structure–Property Modelling for Hardness and Porosity Estimation in High-Speed DED-Reprocessed Components



Luisa Hoffmann, Mehdi Khabou, Helena Wexel, Ali Darijani, Jürgen Beyerer, Frederik Zanger, Volker Schulze, Stefan Dietrich, and Michael Heizmann

Karlsruhe Institute of Technology (KIT), Germany

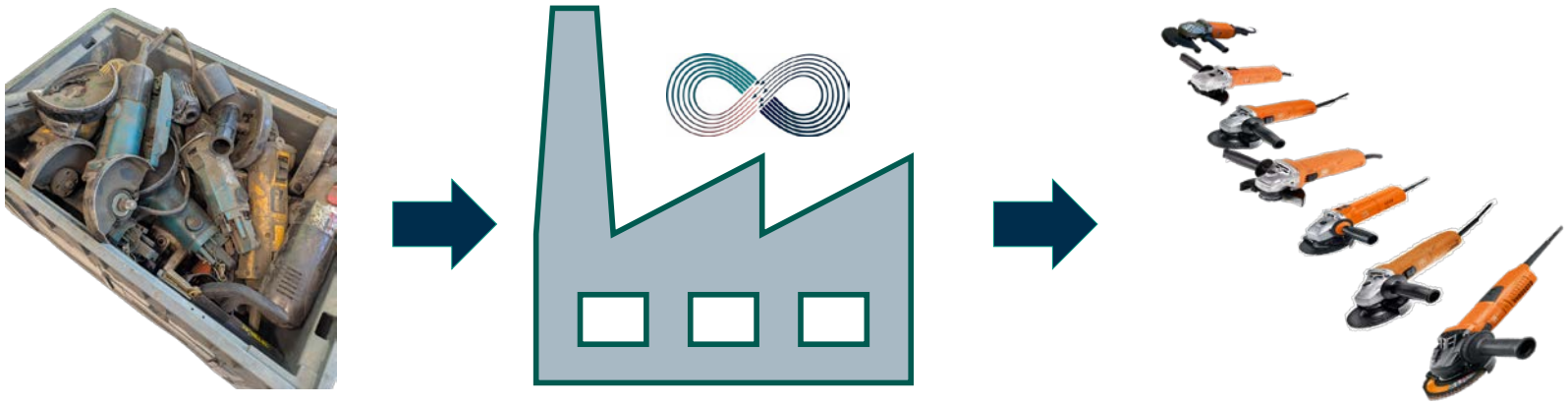
Institute of Industrial Information Technology

Content

1. Motivation
2. Process and data aquisition
3. Method
4. Results
5. Conclusion

1. Motivation

- Growing demand for sustainable production
- Reuse and remanufacturing of high-value components
- Need for reliable quality assessment after reprocessing
- Material properties must be predicted despite process variability
- Traditional deterministic models provide only point estimates and ignore uncertainty.



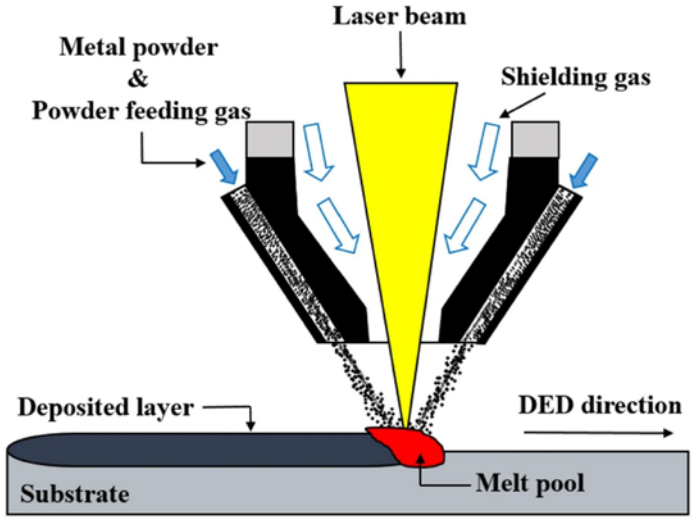
2. HS DED-LB Reprocessing
High-Speed Laser Directed Energy Deposition

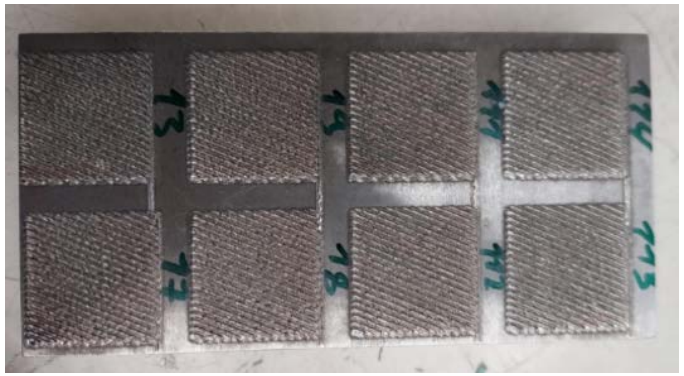
Process

- AISI 4140 powder deposited layer-by-layer
- Laser melts powder and substrate locally
- Thermal history determines final material properties

Key Process Parameters

- Laser power P
- Scan speed v
- Energy input proxy P/v





Ref.: Lim et al. (2021): *Selection of effective manufacturing conditions for directed energy deposition process using machine learning methods*, Scientific Reports, 11, 24169.

2. Sources of uncertainty

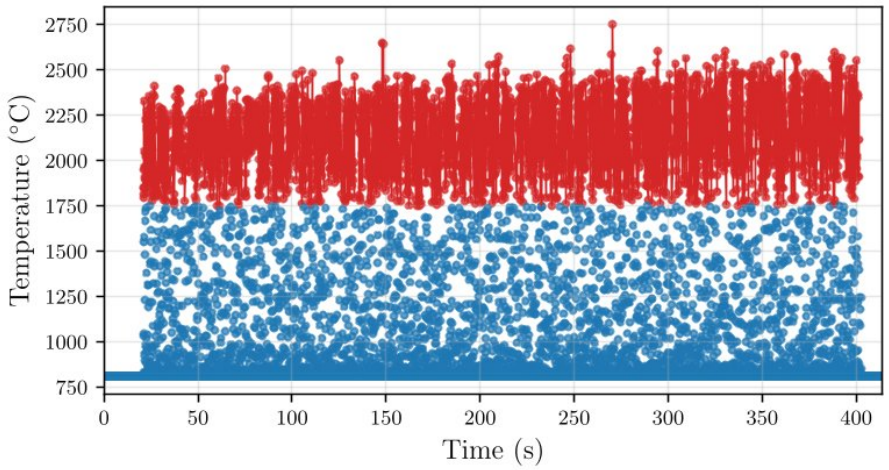
Process Variability

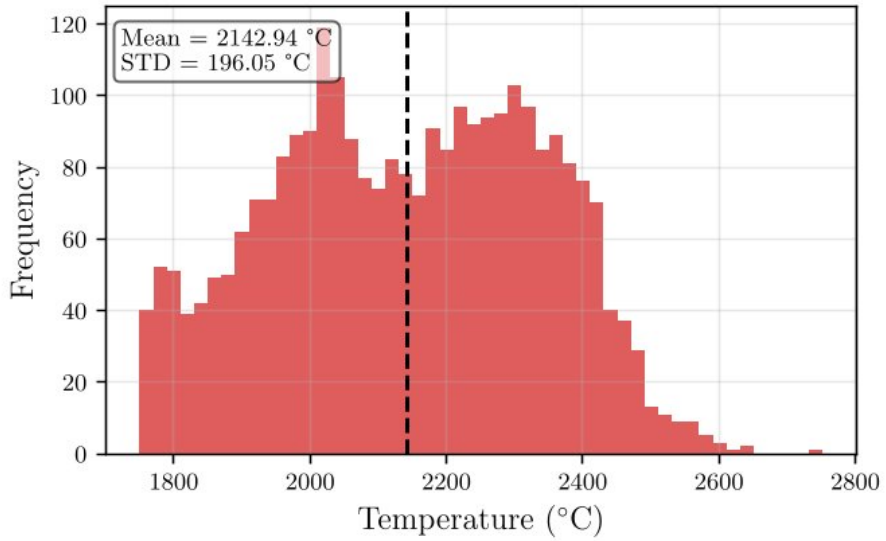
- Melt pool instability
- Powder delivery fluctuations
- Thermal variations

Measurement Uncertainty

- Spatter
- Smoke
- Plasma effects
- Changing emissivity

→ Resulting in uncertain Temperature Measurements

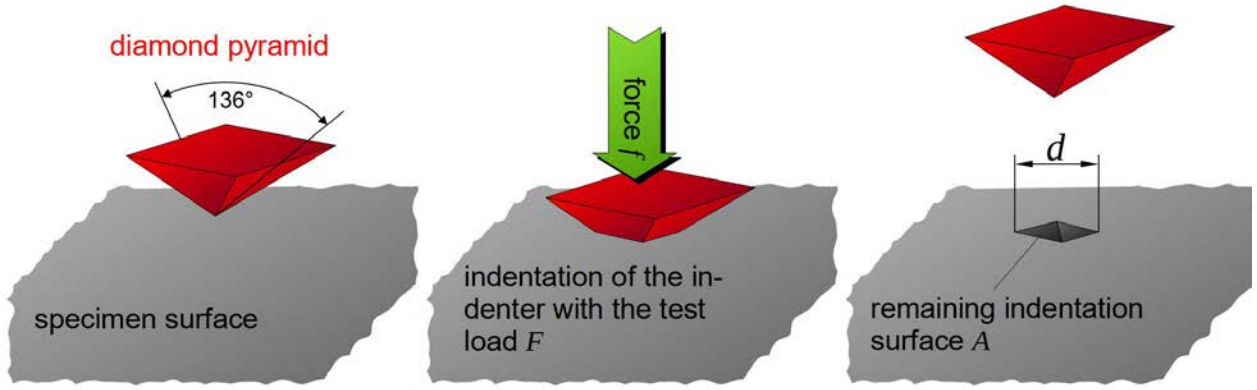




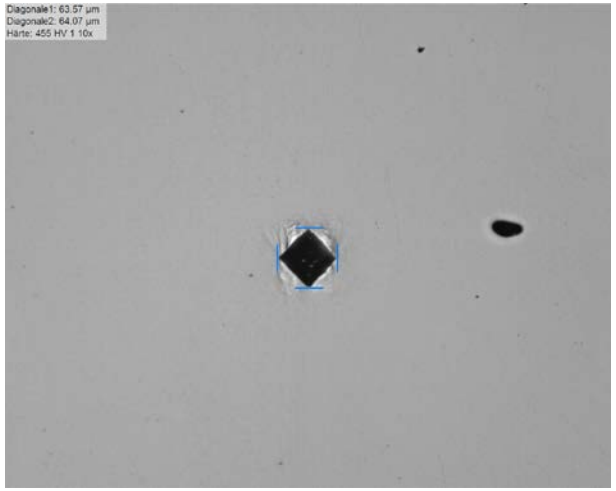
2. Quality Indicators
Material State Characterization

Hardness

- Indicator of fatigue strength
- Measured via Vickers microhardness



Microscopic section analysis



Porosity

- Stress concentrator
- Promotes crack initiation
- Reduces component lifetime
- Both are critical for remanufactured parts.

3. Method - Research Question

Goal of this Work:

Can we estimate

- Hardness
- Porosity

from

- Process parameters
- Temperature measurements

while explicitly accounting for uncertainty?

Proposed Solution
A probabilistic Process-Structure-Property (PSP) framework using Gaussian Mixture Models (GMMs)

3. Method - Gaussian Mixture Model

Why GMMs?

A single Gaussian cannot capture:

- Multiple operating regimes
- Nonlinear behavior
- Multimodal distributions

GMM Representation

- Each component represents a latent process regime

$$p(\mathbf{x}) = \sum_{k=1}^{K} \pi_k \mathcal{N}(\mathbf{x} \mid \mu_k, \Sigma_k)$$

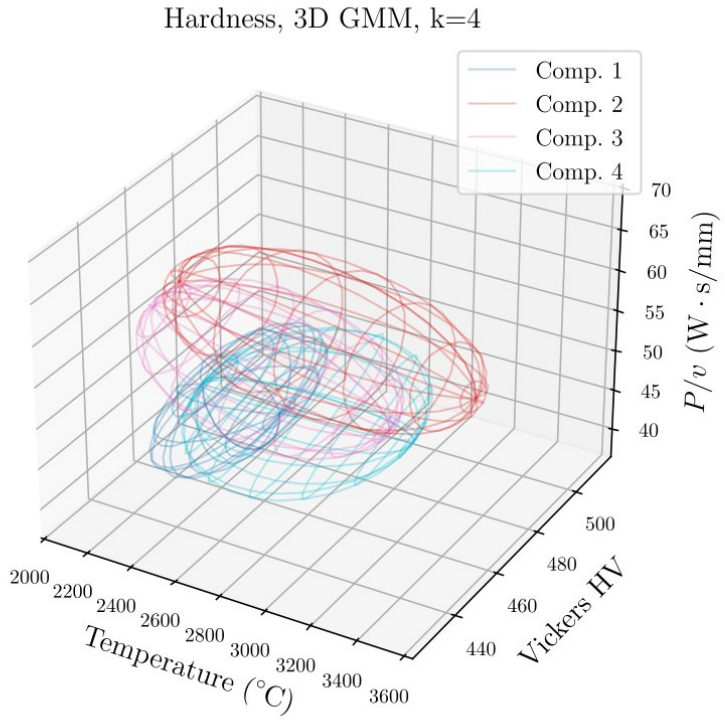
3. Method - Model learning

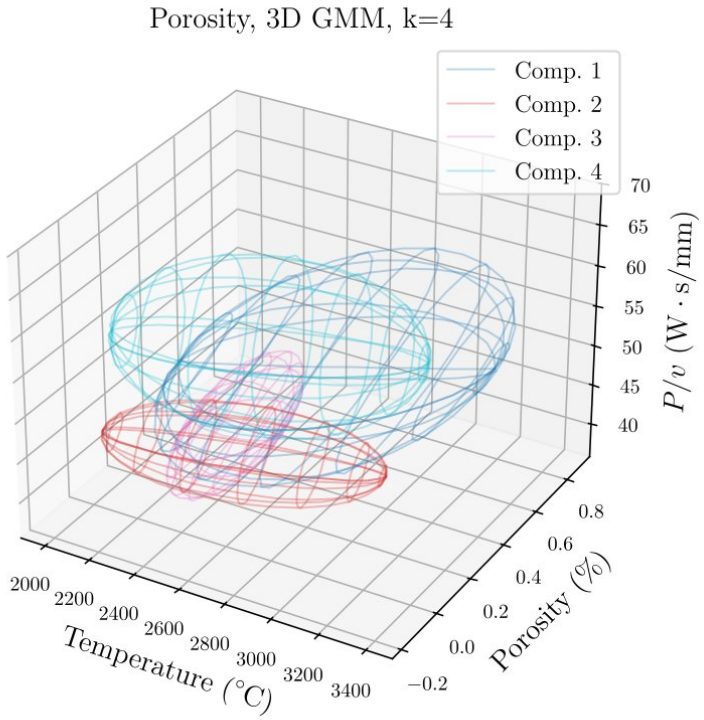
Variables:

- Temperature
- Process parameters
- Hardness
- Porosity

Training:

- Expectation Maximization (EM)
- Model selection using:
  - Akaike Information Criterion (AIC) or
  - Bayesian Information Criterion (BIC)





Outcome:

- Joint probabilistic representation of the process.

3. Method - Soft Evidence

Conditioning with Uncertainty

Traditional approach:

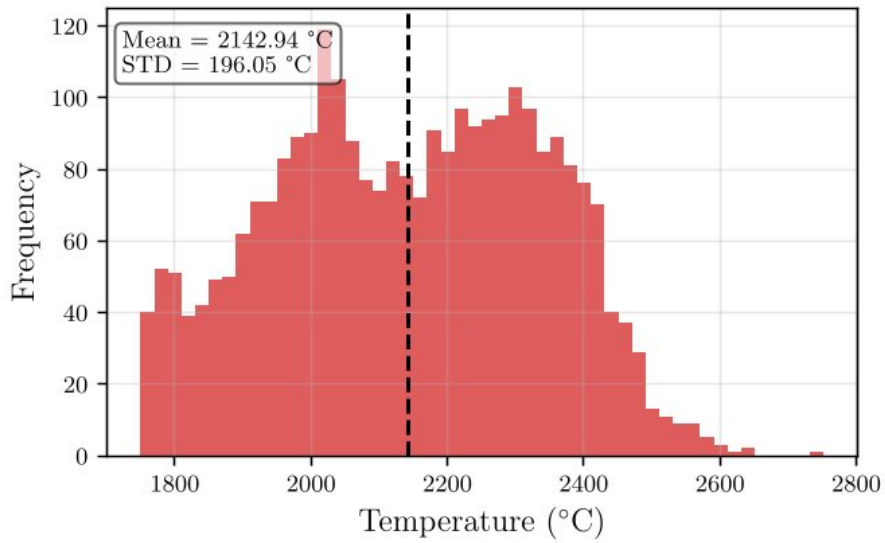
- Observed temperature = exact value

Proposed approach

- Observed temperature = probability distribution

Benefits:

- Sensor uncertainty preserved
- Consistent uncertainty propagation
- More realistic predictions



3. Method - Conditional Inference

From Measurements to Material Properties

Observed:

- Temperature distribution
- Process parameters

Infer:

- Hardness distribution
- Porosity distribution

Instead of a single prediction:

- → Full probability density functions as GMMS

4. Results

Example:

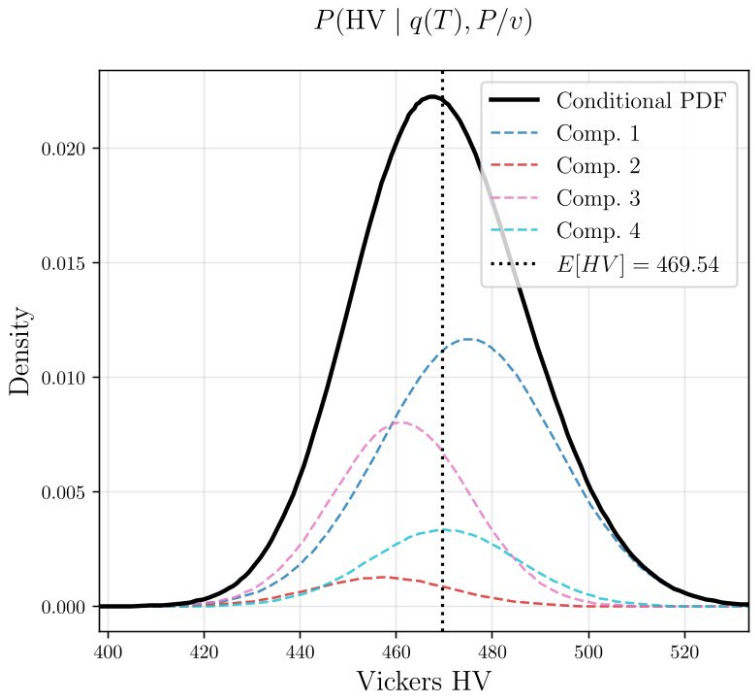
- Temperature ≈ 2200 °C
- P/v ≈ 51 W·s/mm

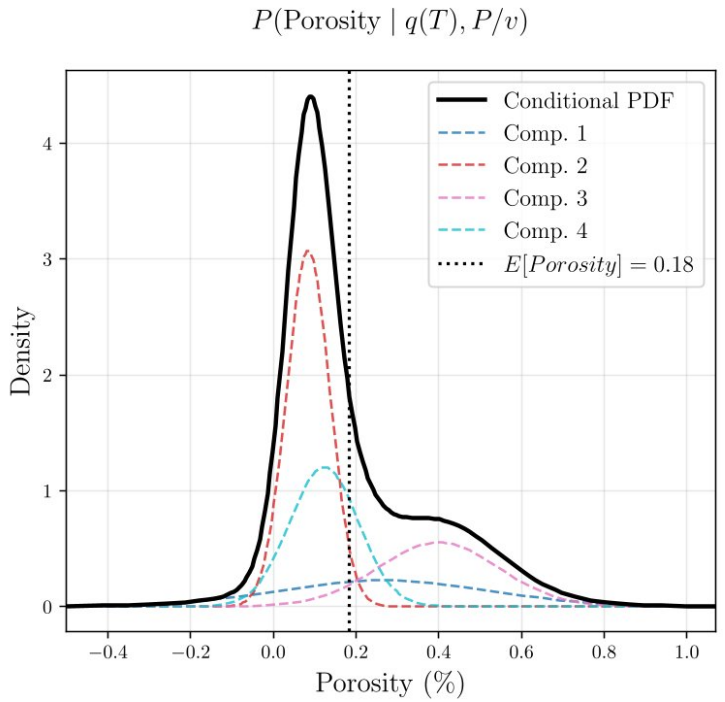
Output:

- Full hardness and porosity PDF
- Expected hardness ≈ 470 HV
- Expected porosity ≈ 0,18

Interpretation

Wider PDF = lower confidence



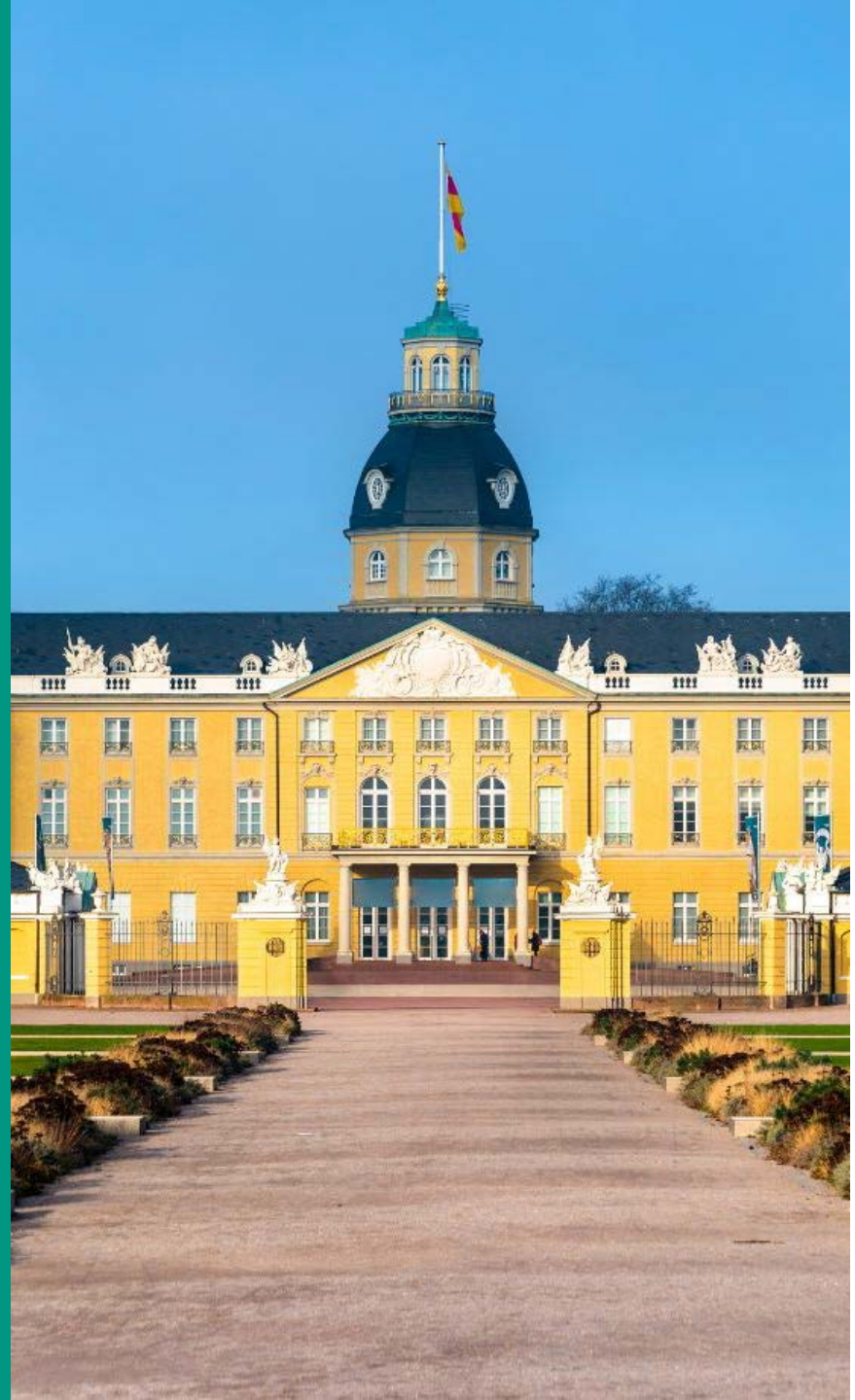


5. Conclusion

- Unified probabilistic PSP framework
- Explicit treatment of measurement uncertainty
- Hardness and porosity predicted as PDFs
- Captures multimodal process behavior
- Supports risk-aware manufacturing decisions

Thanks for your attention!

Questions?



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Karlsruhe Institute of Technology (KIT)

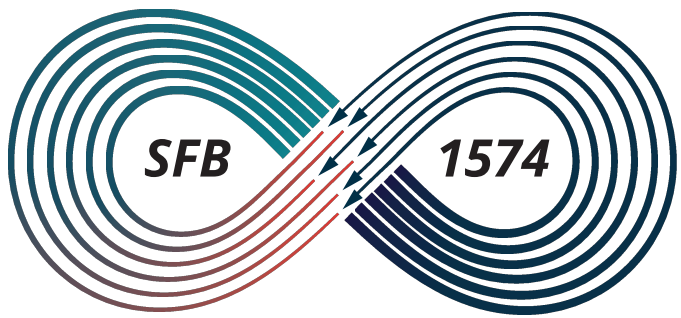
Email: luisa.hoffmann@kit.edu

Funded by DFG CRC 1574 „Circular Factory for the Perpetual Product“

Institute of Industrial Information Technology

A Mixture Based Framework for Fusion of Uncertainties of Heterogeneous Supply Chain Sources in Circular Factories

Ali Darijani



10th of June, 2026
Germany

Motivation

Remark

Circular factories rely on diverse, distributed sources along the supply chain, each having uncertainty models (such as probability densities). To optimize operations, we need a robust method to fuse these heterogeneous uncertainties into a single, actionable model.

Fusion Problem in Circular Supply Chains

Problem

Given weighted uncertainty models (w_i, p_i) from heterogeneous sources (suppliers, sensors, etc.), how can we combine them into a single global uncertainty model, respecting each source's reliability or importance, and robust to the fusion order?

Mixture-Based Fusion Rule

Remark

We use a mixture-based fusion rule for uncertainty models:

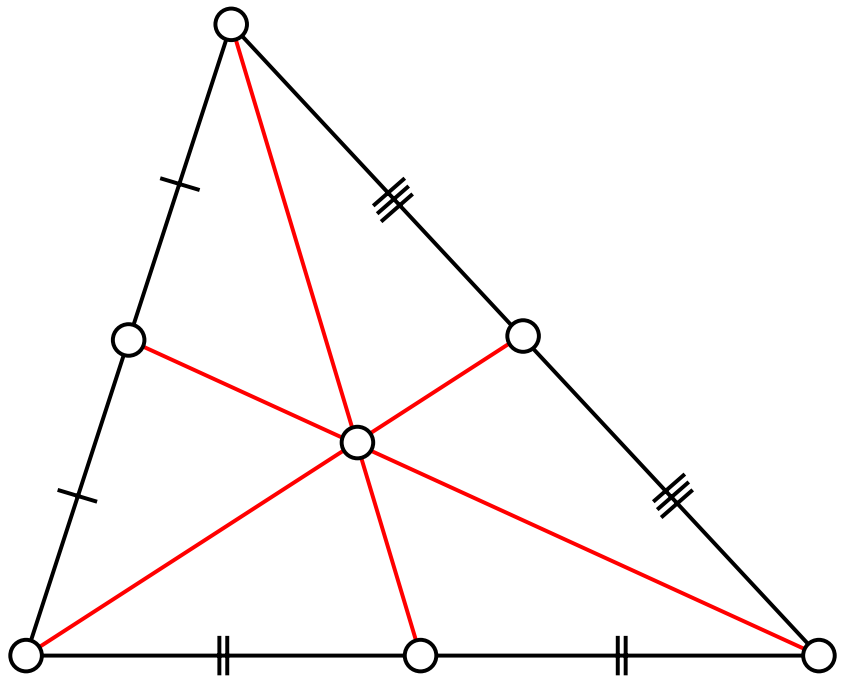
$$p_{\text{fused}} = \frac{\sum_{i=1}^{m} w_i p_i}{\sum_{i=1}^{m} w_i} \tag{1}$$

Problem

What is $2 + 4 + 6$*?*

Remark

Looking at the triangle can be enlightening into eliminating a couple of frameworks.



When is Mixture Fusion Justified?

Problem

What conditions guarantee that mixture-based fusion is consistent, interpretable, and robust to sequential or hierarchical aggregation in supply chain networks?

Segment-Balancing Principle

Solution

Fusion is restricted to the segment between two densities and requires source-weighted dissimilarity balance:

$$w_a \Delta(p_a, (1-t)p_a + tp_b) = w_b \Delta(p_b, (1-t)p_a + tp_b) \tag{2}$$

For norm-induced distances, the unique solution is mixture-based fusion:

$$(1-t^*)p_a + t^* p_b = \frac{w_a}{w_a + w_b} p_a + \frac{w_b}{w_a + w_b} p_b \tag{3}$$

where $t^* = \frac{w_b}{w_a + w_b}$.

Order-Invariance in Supply Chain Fusion

Remark

The fusion operation has an additive form:

$$(w_a, p_a) \oplus (w_b, p_b) = \left(w_a + w_b, \frac{w_a p_a + w_b p_b}{w_a + w_b} \right) \tag{4}$$

This operation is commutative, associative, and robust to the order of fusing sources—key for distributed or asynchronous supply chains.

Fusion for Gaussian Mixture Models

Solution

Mixture-based fusion preserves the Gaussian mixture structure:

$$p_{fused} = \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_i} \tag{5}$$

Summary Table

Remark

Fusion Regimes in Circular Factories:

Regime	*Pairwise point*	*Closed form*	*Order-invariance*
Norm-induced	*Unique*	*Yes*	*Yes*
Divergence	*Exists*	*Not always*	*No*
Gaussian mixtures	*Inherited*	*Yes*	*Yes*
Total Bregman Quadratic Divergence	*Unique*	*Yes*	*Yes*

Preprocessing of Weights

Remark

In practice, it is often desirable to adjust the influence of each source before fusion. This can be achieved by preprocessing the weights using a strictly increasing function $f : \mathbb{R}_{>0} \to \mathbb{R}_{>0}$.

Weight Preprocessing: Rule

Solution

Given original weights $(w_1, \ldots, w_m)$*, apply preprocessing:*

$$\tilde{w}_i = f(w_i) \tag{6}$$

Then, perform fusion using the transformed weights:

$$p_{\text{fused}} = \frac{\sum_{i=1}^{m} \tilde{w}_i p_i}{\sum_{i=1}^{m} \tilde{w}_i} \tag{7}$$

Examples of Preprocessing Functions

Remark

- ***Convex***: $f(w) = w^\gamma$, $\gamma > 1$ *(amplifies large weights)*
- ***Concave***: $f(w) = w^\gamma$, $0 < \gamma < 1$ *or* $f(w) = \log(1 + w)$ *(reduces disparity between weights)*
- ***Identity***: $f(w) = w$ *(no change)*

The choice of f allows supply chain managers to tune the influence of each source according to reliability, trust, or other domain knowledge.

Conclusion and Outlook

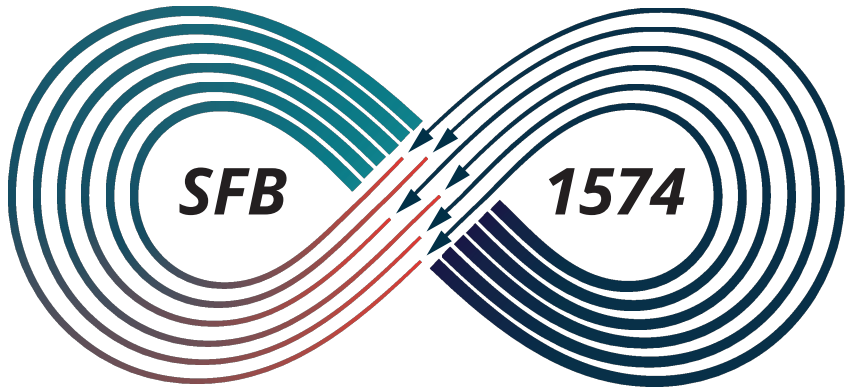
Problem

What is the boundary for order-invariant uncertainty fusion in circular factories, and what are future directions?

Remark

"Compositional Boundaries for Density Fusion" by Ratan Bahadur Thapa, Ali Darijani, Jürgen Beyerer, Steffen Staab

Fortis fortuna adiuvat

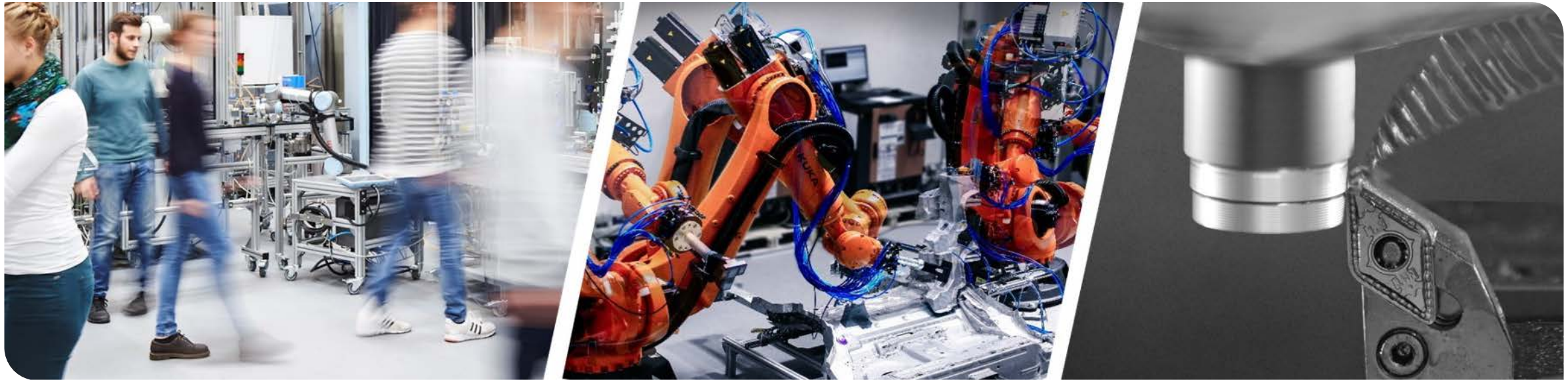


Karlsruhe Institute of Technology

Institute of Production Science

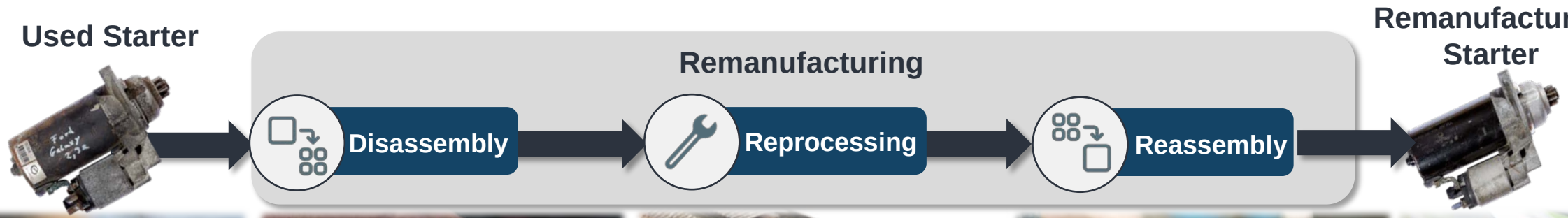
Autonomously Detecting Defects in Circular Production Using Multimodal Large Language Models and Retrieval Augmentation

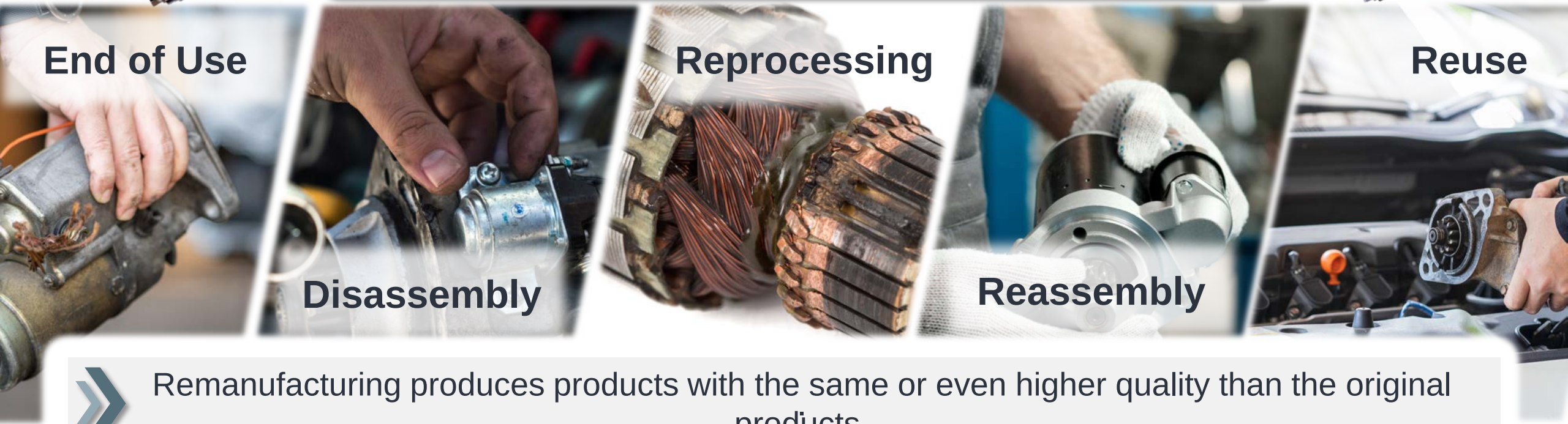
Dominik Koch*, Marvin Ohland, Di Wen, Kunyu Peng, Martin Benfer, Prof. Dr.-Ing. Rainer Stiefelhagen, Prof. Dr.-Ing. Gisela Lanza



Circular Production

Motivation

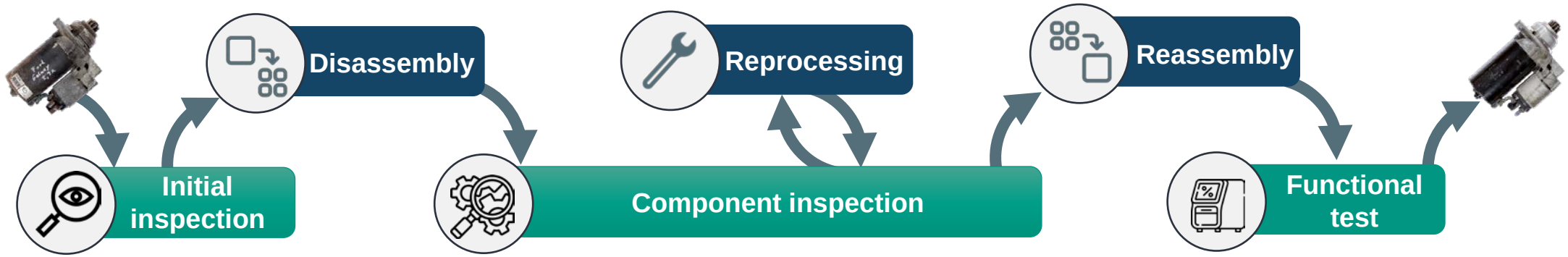




Remanufacturing produces products with the same or even higher quality than the original products.

Inspection: key component in circular production

Motivation



Inspection tasks and activities in circular production

- Determine product condition
- Determine suited processes and process sequences
- Prevent process repetitions

Challenges for automated inspection concepts

- Product variety & generational variety
- Uncertain condition of the product
- Manual and 100% inspection
- Small lot sizes
- Missing functional knowledge
- Missing product knowledge

Inspection is a **crucial point** in the automation of circular production, but to this day, many **challenges** have to be addressed to enable **autonomous inspection**.

Exemplary Use-Case: Bevel Gear

Motivation

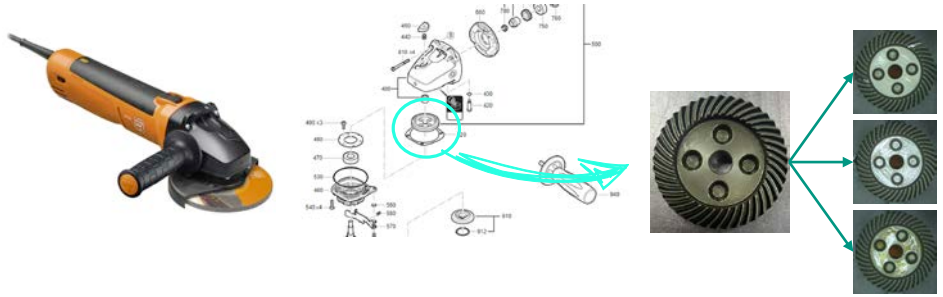


The bevel gear exhibits **diverse defect patterns.**
But with **scarce** worn samples, how can **automated** defect detection still be achieved?

Model choice under limited data availability

Case Study on the angle grinder gear wheel

CRC 1574 – Circular Factory



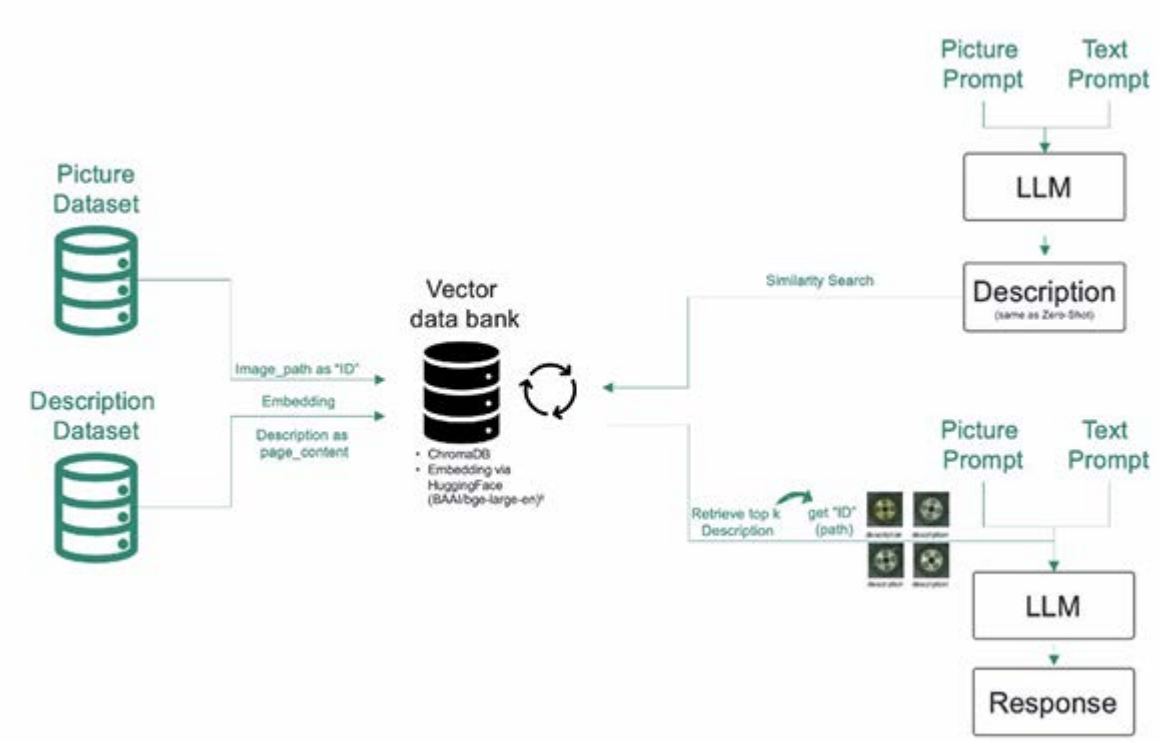
By comparing different models given the requirements of circular production, RAG looks promising

CNN-based Models like YOLO[1]	large datasets, labeled training datasets	Resource-intensive, time-consuming[2]	High for training models	Poor at unseen defects without retraining
LLMs + RAG[2]	small datasets via retrieval augmentation	No training needed, uses existing models	Low by using foundation models	Can retrieve and reason about similar cases

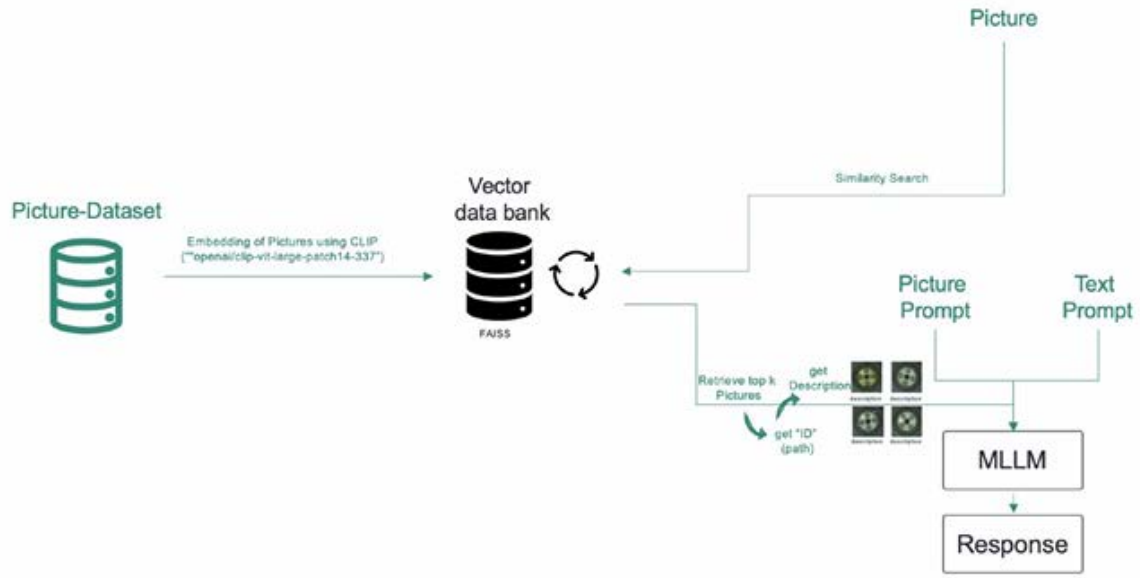
Source 1: Tulbure , et al (2025): A study on multi-modal LLM reasoning for defect detection
Source: 2 cf. Chen, et al. (2025): *A Novel Multi-Expert Framework for Industrial Anomaly Detection*,

Prompting Architectures

Text-based RAG architecture

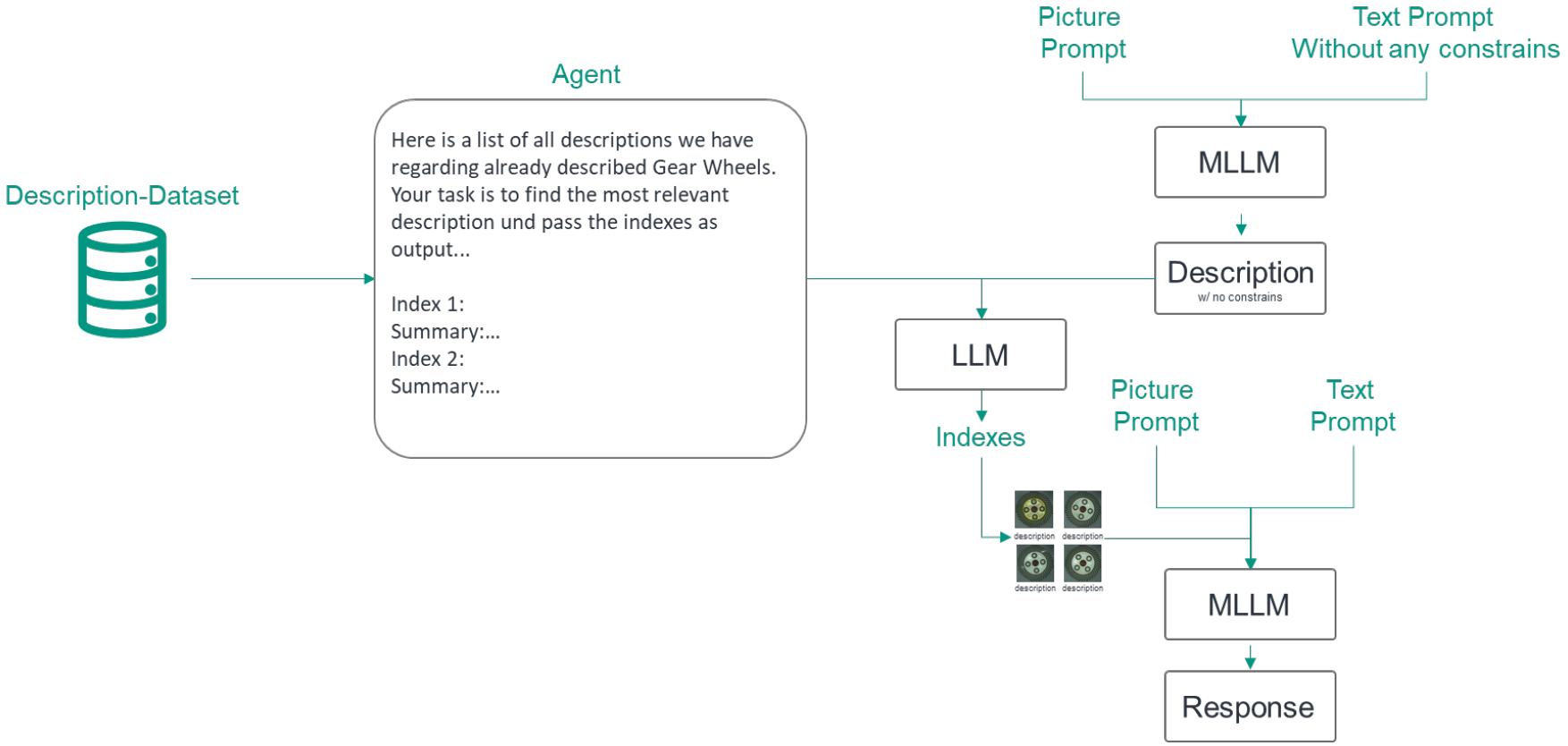


Picture-based RAG architecture



Approach to RAG based inspection

Schematic representation of the Self RAG approach



Self RAG is compared with text-based and picture-based RAG architectures. Additional, zero-shot and few-shot are tested as baselines.

Dataset Creation

Establishing six categories with different levels

Tooth Clipping

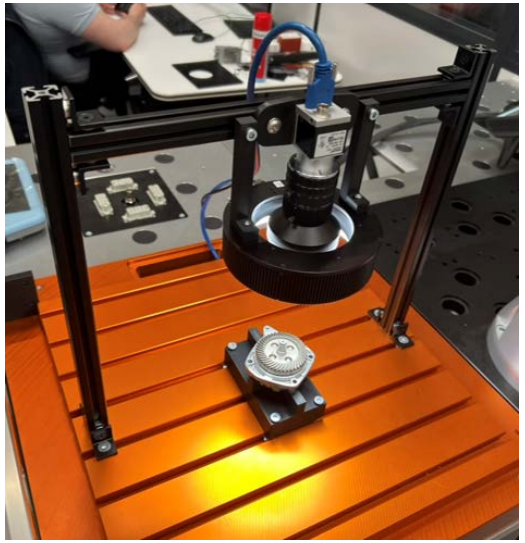


Surface Scratches



Dirt





Total of 13 gear wheels

- Defects are introduces sequentially with pictures taken after each step
- Combinatorics also enables further scenarios
- 3 versions of each scene are created (rotation // blurred // holding gear wheel in hand // light)

Knowledge Base // Evaluation Queries

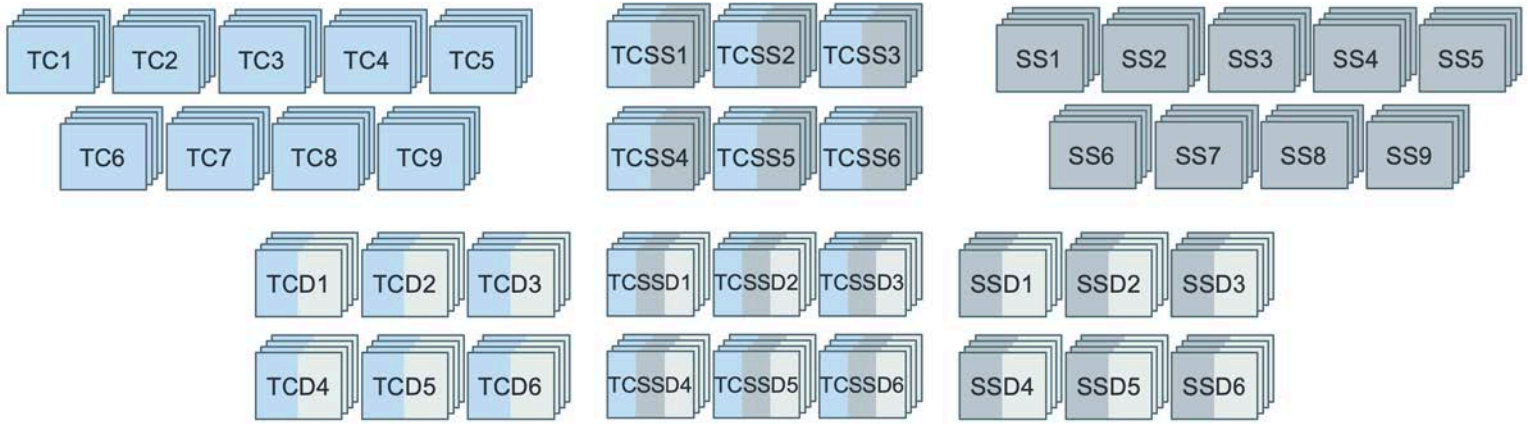
- 2-6 images (at least) are taken per Gear wheel, which will have 3 versions, meaning approx. 150 images
- 70/30 "Train"/"Test" split

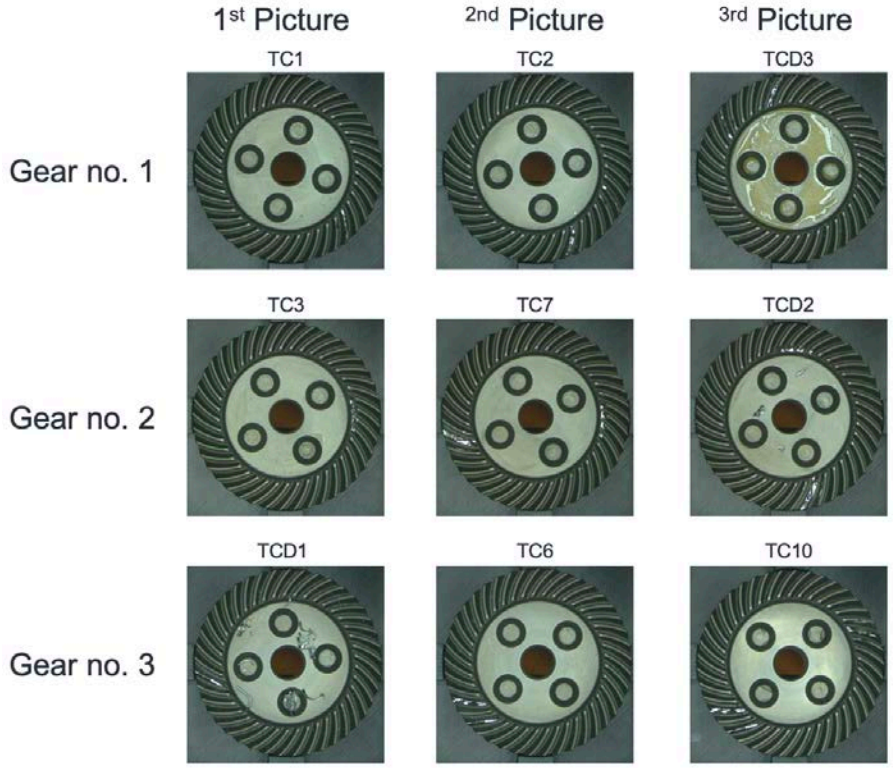
Difficulty level

- 2-3 difficulty levels are created per category to measure the performance of the VLM/RAG

Dataset Creation

Schematic dataset overview





Evaluation Dimensions for LLMs

Retriever Evaluation

Recall@K[10&11]	Precision@K[10&12]

Text Generation Evaluation

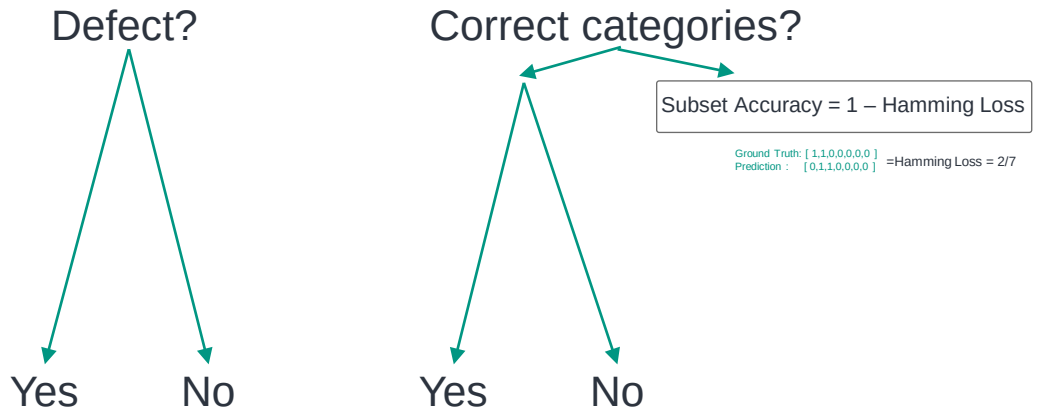
BLEU[12] (Bilingual Evaluation Understudy)	Measures N-gram overlap between reference text and generated text
Cos Similarity[13]	Measures semantic by comparing vector representations

Localization Evaluation

Localization[1] (Of Tooth Clipping Defects)	Measures the minimal distance between predicted TC and real TC

Classification Evaluation

$$\text{Accuracy} = \frac{TP+TN}{TP+TN+FP+FN}$$



Source: 10 Chen, et al. (2019): *Towards Knowledge-Based Recommender Dialog System*

Source: 11 Chen, et al. (2025): *Keyword-driven Retrieval-Augmented Large Language Models for Cold-start User Recommendations*

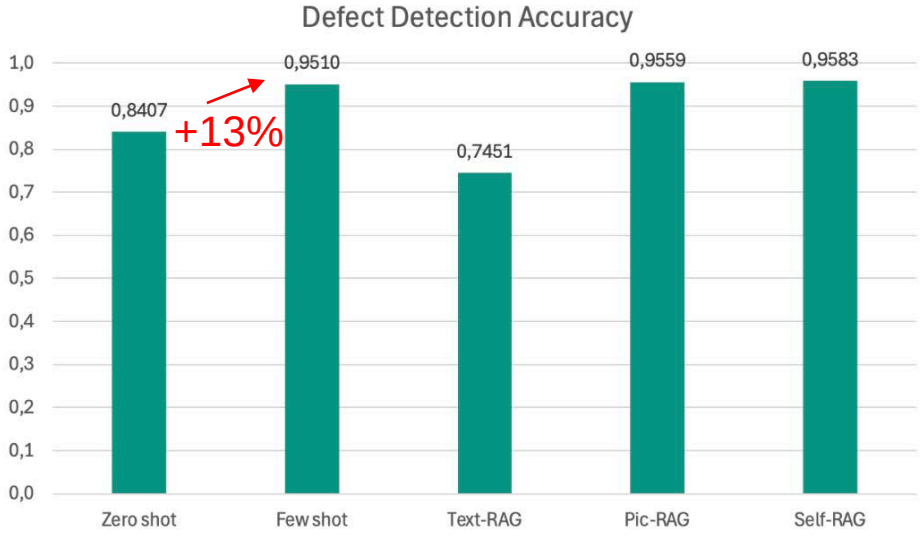
Source 12: Doris, et al.(2025): DesignQA: A Multimodal Benchmark for Evaluating Large Language Models' Understanding of Engineering Documentation

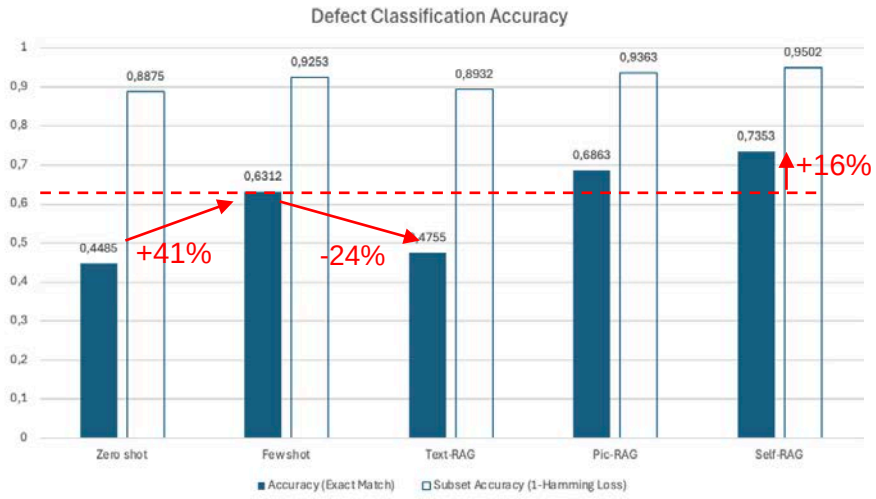
Source 13: B and Purwar (2025): Evaluating the Efficacy of Open-Source LLMs in Enterprise-Specific RAG Systems: A Comparative Study of Performance and Scalability

Source 1: Tulbure, et al. (2024): A study on multi-modal LLM reasoning for defect detection

Evaluation of RAG-Architectures

Evaluating defect detection





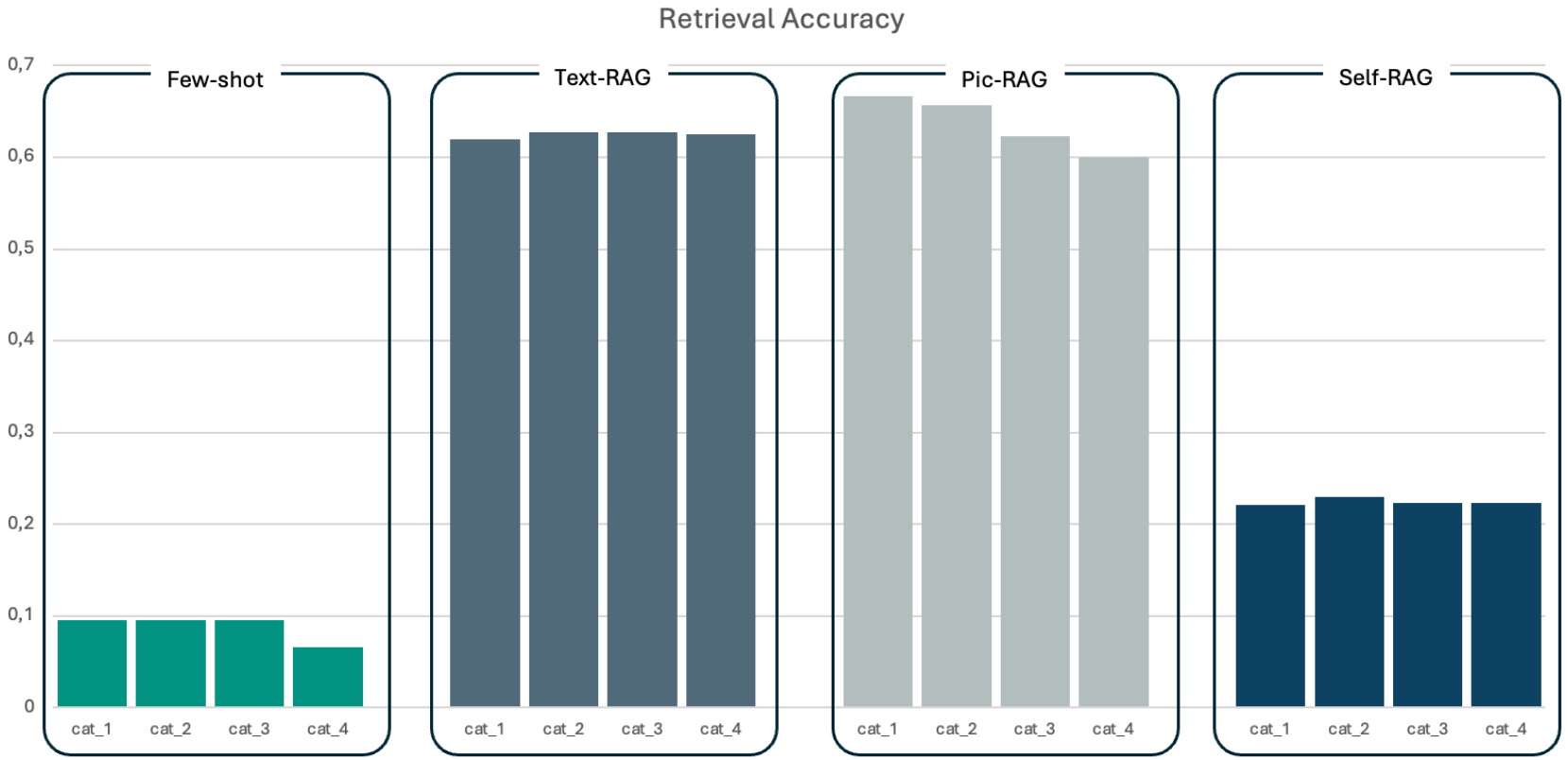
Key take aways

- As expected, when given the LMM more similar data the output gets better
- All approaches have already a high precision in detecting if the gear wheel has a defect (84%-95%)
- Text-Rag delivers same defect accuracy than the baseline “few-shot” approach
- Self-RAG delivers best result with a Total Accuracy of 95,83% (only 0,7% better result than few-shot-baseline)

- Significant difference between zero-shot and few-shot baseline (41% improvement)
- Text-Rag delivers a worse output than few-shot–baseline
- Self Rag outperforms few-shot-baseline with 16,5%

Results

Retrieval Accuracy of the top k = 4 retrieved images across all RAG approaches, using Exact Match



Picture-based RAG achieves the highest retrieval accuracy, while Text-based RAG stays high despite weak end-to-end classification. Self-RAG shows low but uniform accuracy across ranks, reflecting greater diversity among retrieved images, which ultimately supports more confident and accurate classification.

Summary & Outlook

Summary

Strengths in detection, weaknesses in localization

- Very high accuracy in answering the question "Defect yes/no" (up to 96%)
- Weak localization capabilities, regardless of classification quality
- Experiments show that input quality is not the limiting factor

RAG integration improves quality but does not solve core problems

- Better results with 5 (relevant) images per prompt
- Picture RAG as a fast and inexpensive option
- Localization problem and multiple defects remain unresolved

Very high influence of contextual data on predictions

- Strong dependence on the text and image context provided
- Categories change depending on prompt content and frequency
- Questionable whether LLMs really "understand" images or just follow patterns

Outlook

Development of an environment in which specialized LLM agents (experts) discuss specific defect categories[15]

- Each category has an expert who is solely responsible for their category
- Relevant images are distributed to the appropriate experts via RAG
- An orchestrator coordinates the discussion and creates a summarized response

Source14 : Tang et al (2024) : MedAgents: Large Language Models as Collaborators for Zero-shot Medical Reasoning

Thank you!



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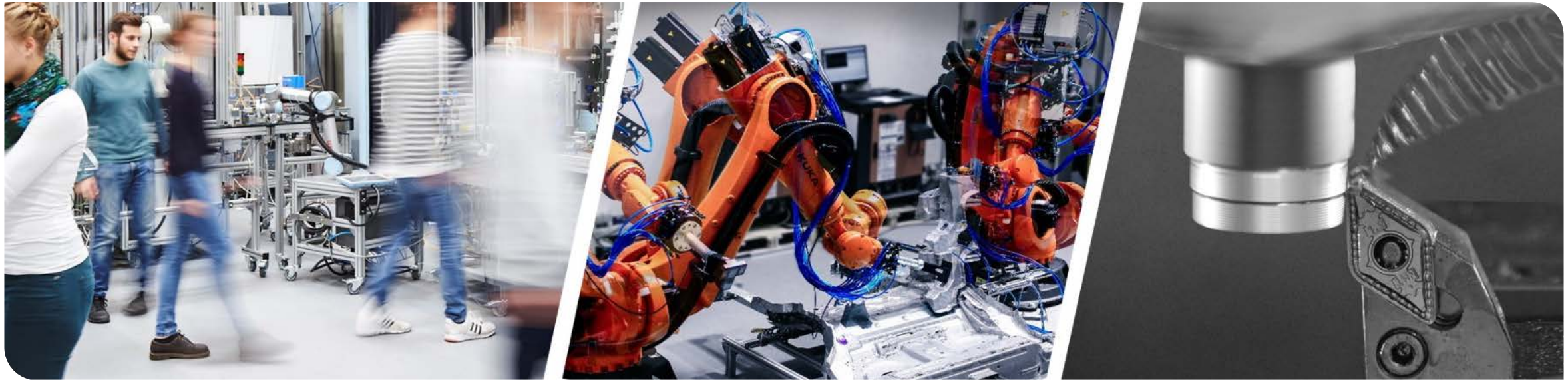
Thank you for your attention!

Karlsruher Institut für Technologie

Institut für Produktionstechnik

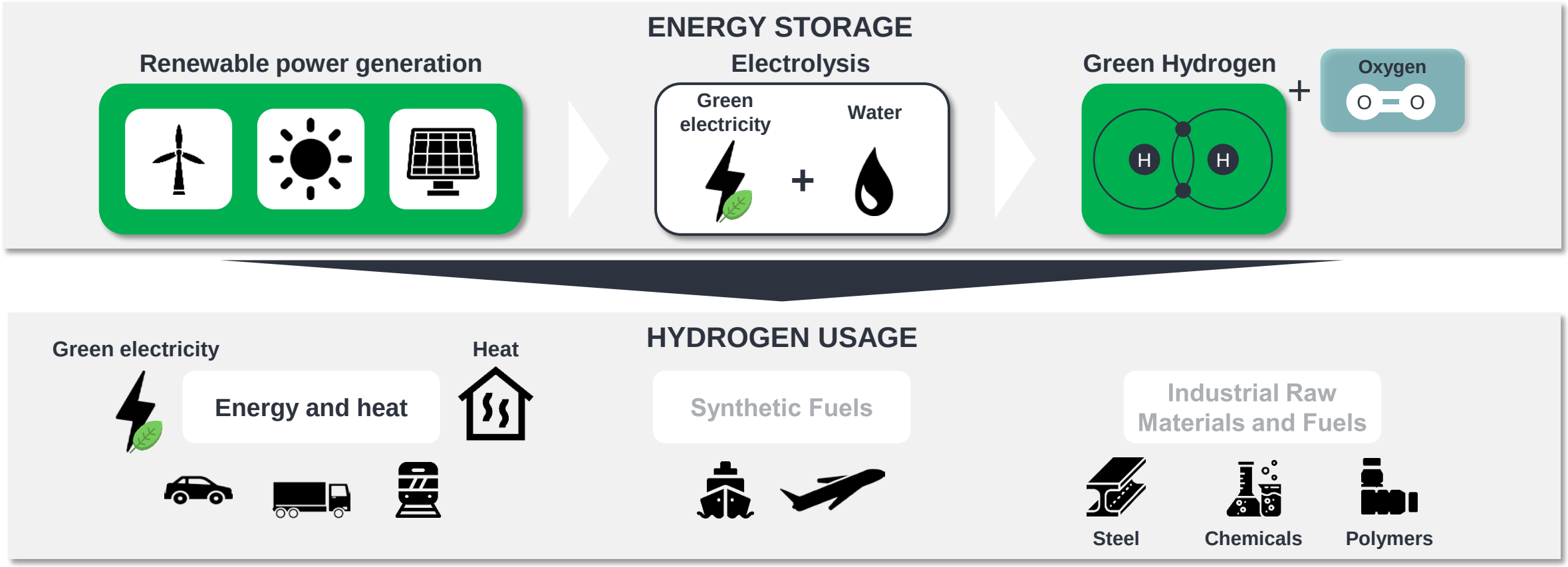
Inspection of Metallic Bipolar Plates Enabling Fuel Cell Remanufacturing

Johannes Buchholz, Dominik Goes, Martin Benfer, Gisela Lanza



Green Hydrogen as Key Element of Sustainable Energy Systems

Motivation

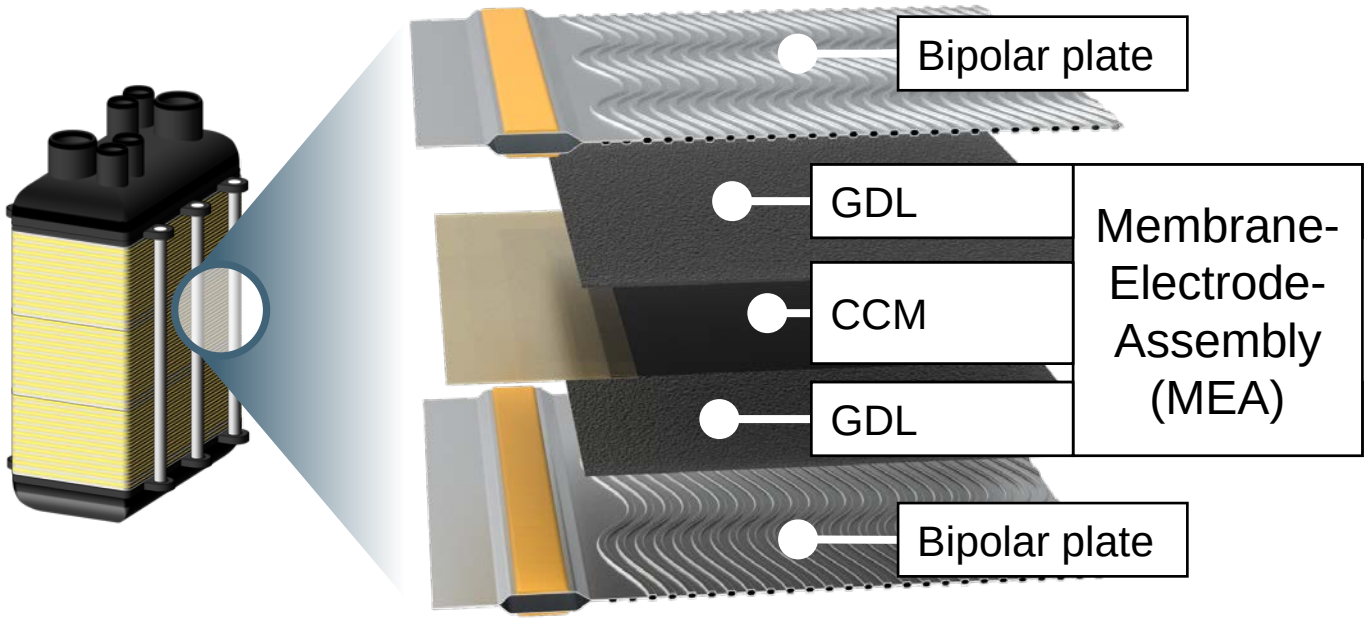


Green hydrogen is a key energy carrier for the future, with fuel cells playing a central role in converting it back into electricity.

Challenges in Scaling Fuell Cell Systems

Motivation

Exemplary Fuel Cell Design



Economical challenges

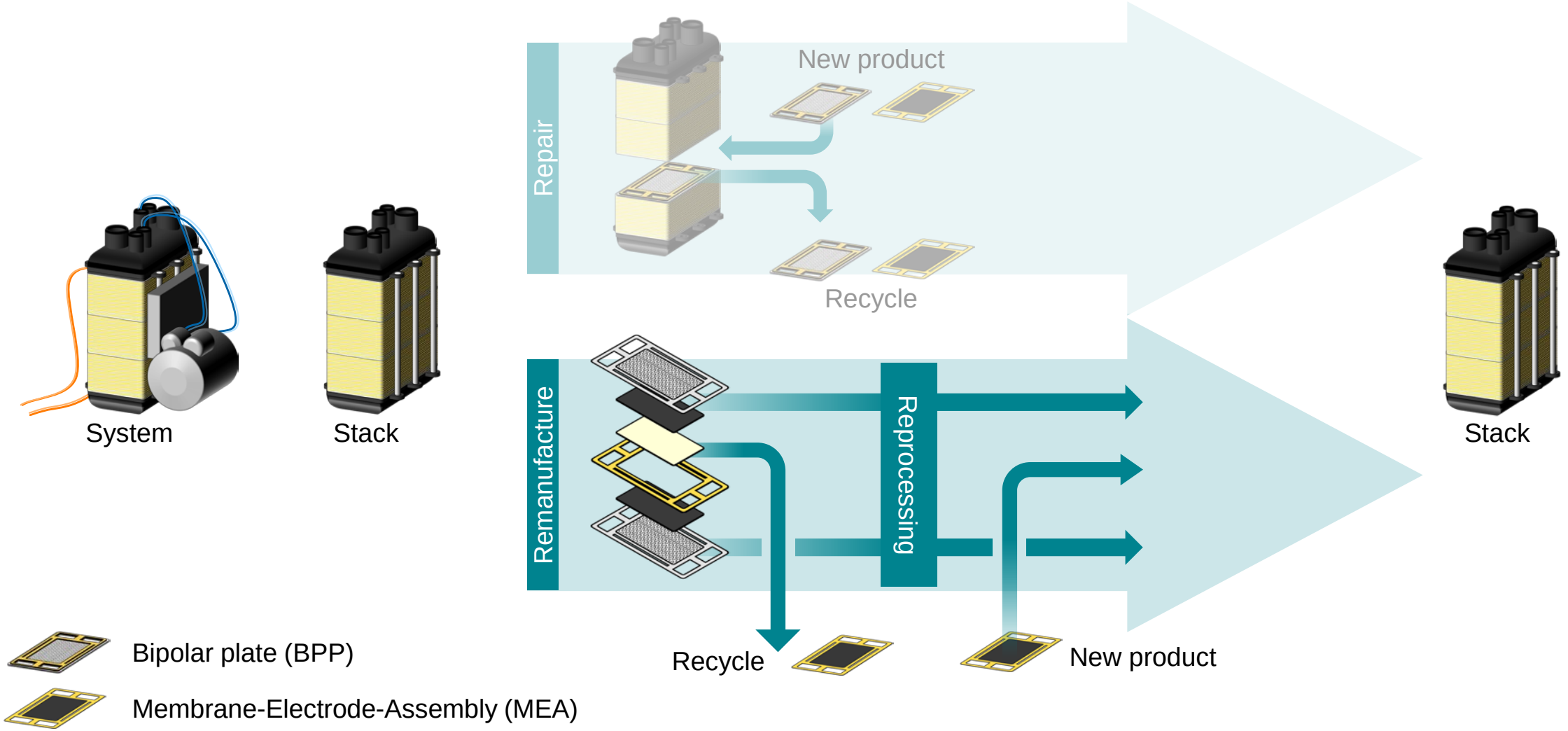
- Stagnant demand
- Manufacturing costs

- High level of value creation for bipolar plates
- High material costs due to platinum in MEAs

MEAs offer significant potential for platinum recovery, while bipolar plates are promising candidates for high-value R-strategies due to their high manufacturing value added.

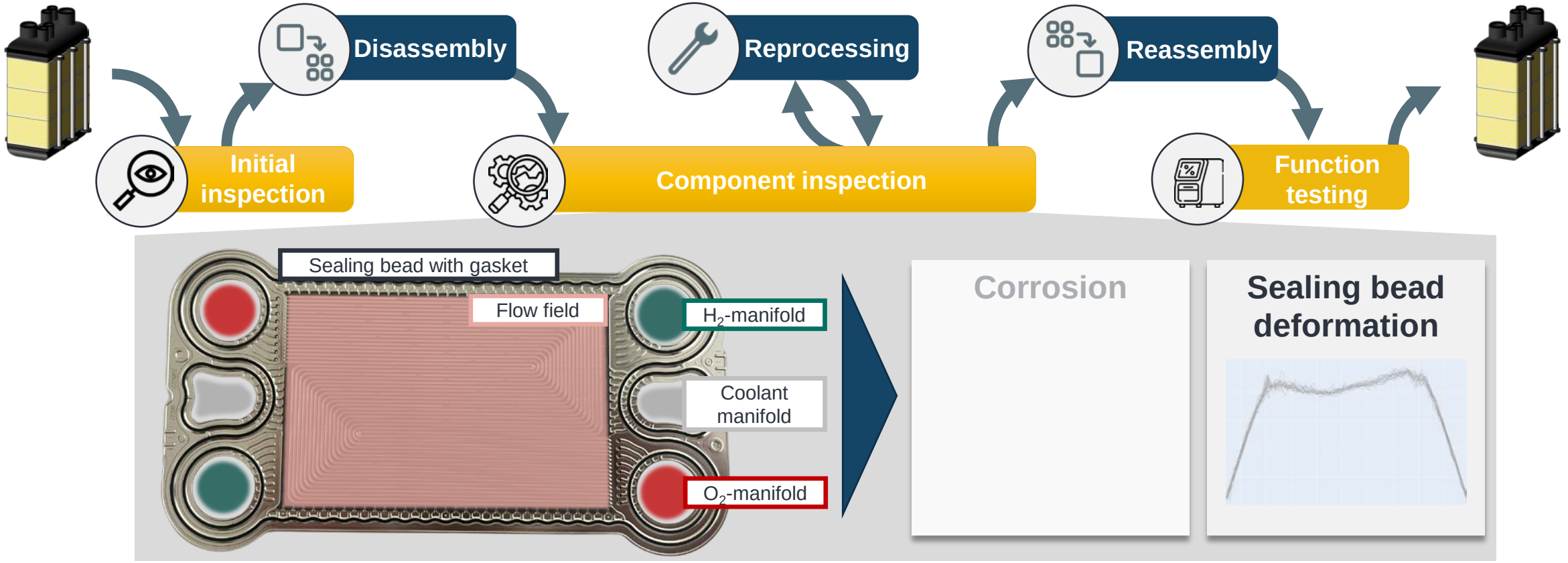
High-value R-Strategies for PEM fuel cell stacks

Objective



Remanufacturing process chain for fuel cell stacks

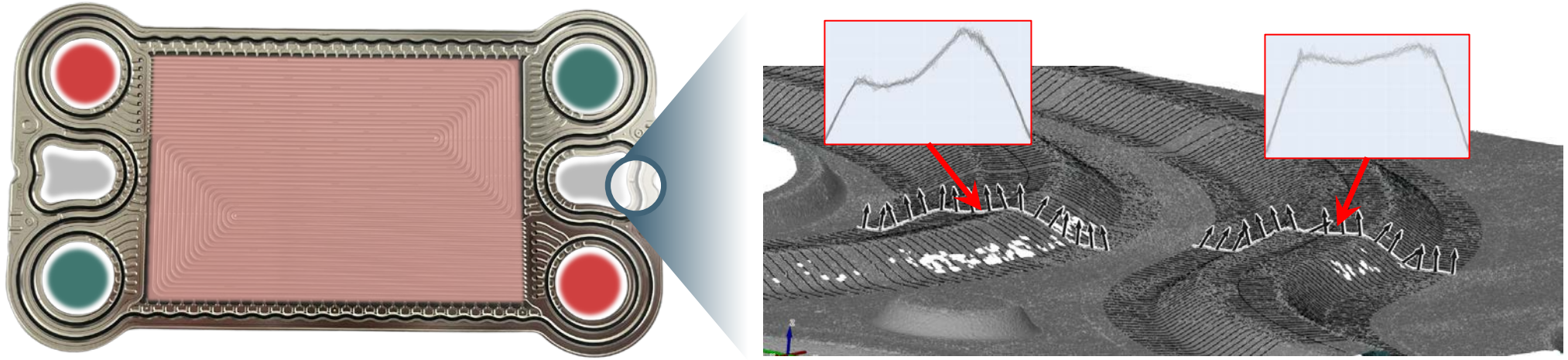
Objective



Corrosion has already been addressed by various assessment approaches, whereas sealing bead deformation remains a critical but largely unexplored condition indicator.

Challenges in assessing sealing bead deformation

Methodology



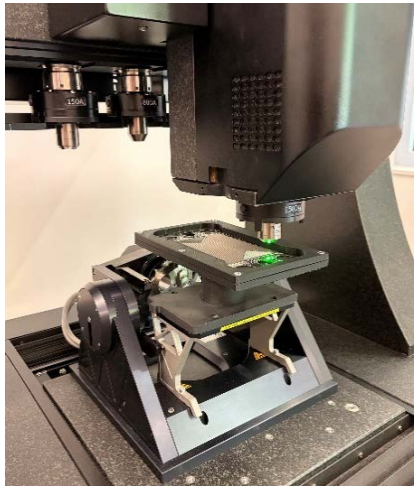
! High requirements for measurement resolution and inspection area

Optical measurement systems are promising due to their ability to inspect large areas with high precision. Focus variation is particularly suitable for first laboratory analysis.

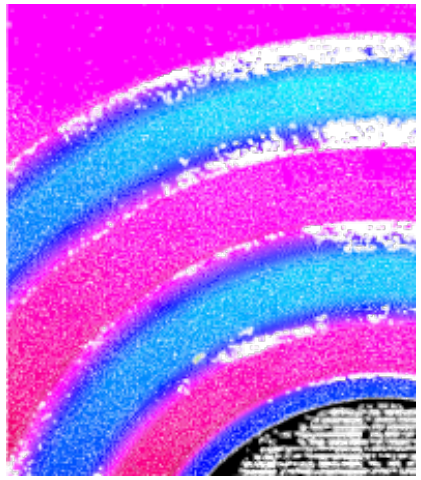
Measurement setup and evaluation pipeline

Methodology

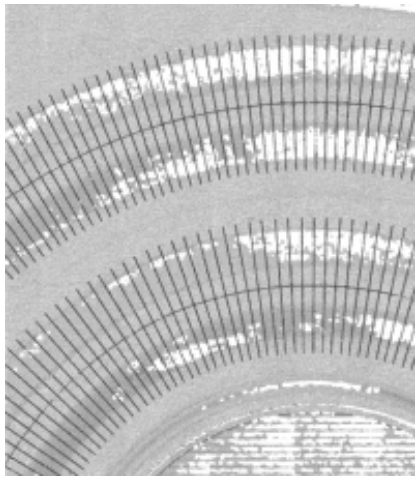
Surface data acquisition



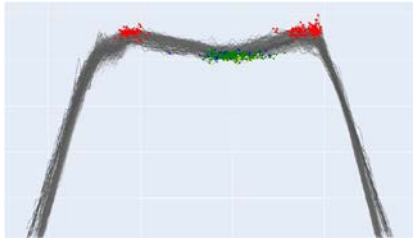
Mesh generation and fusion

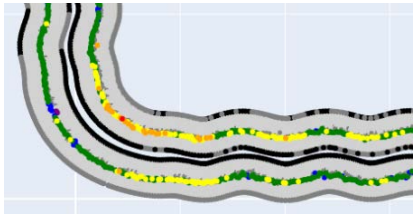


Cross-sectional profile extraction



Feature calculation and visualization

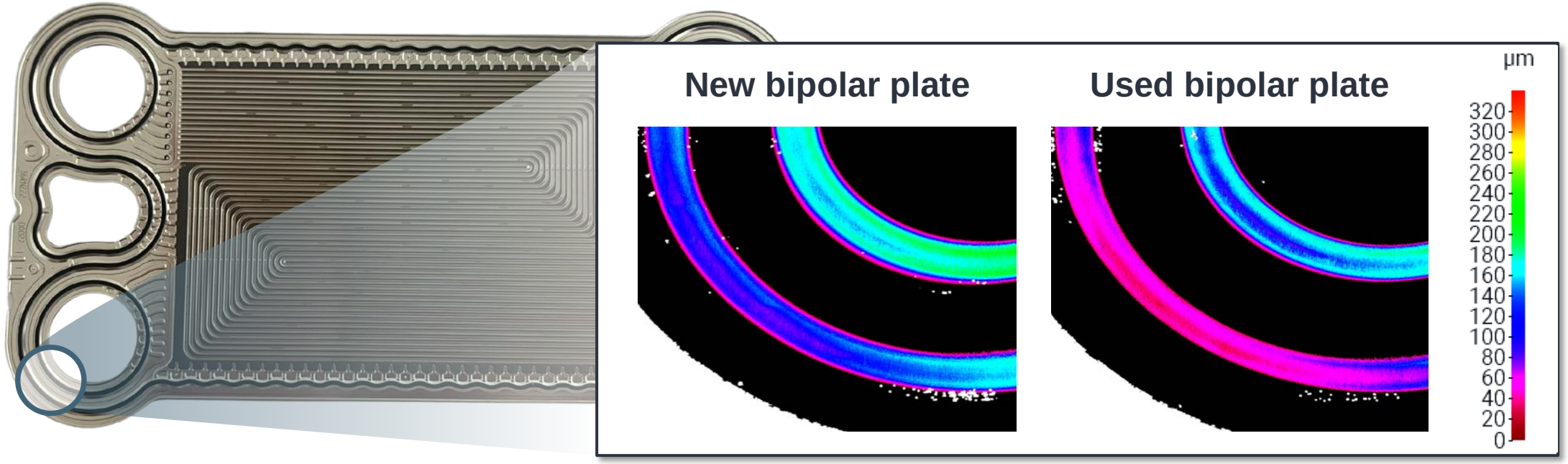




The developed workflow enables a holistic assessment of sealing bead deformation by combining qualitative and quantitative evaluation.

Qualitative evaluation using false-color representations

Results

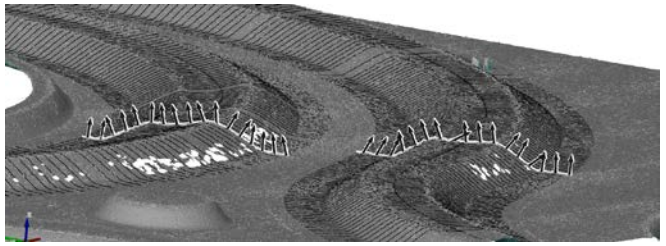


The developed workflow enables a holistic assessment of sealing bead deformation by combining qualitative and quantitative evaluation.

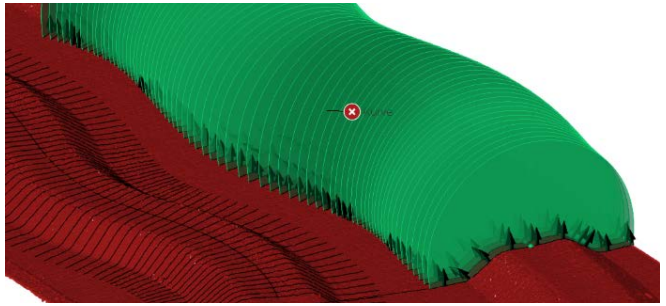
Quantitative Comparison of New and Used Bipolarplates

Results

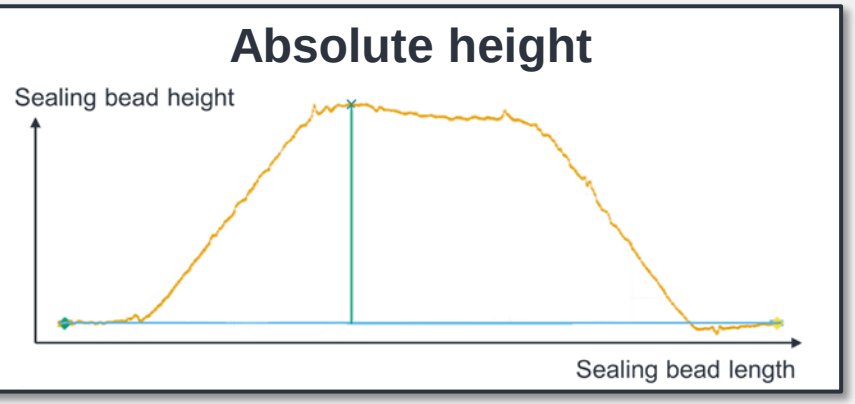
Measurement Data



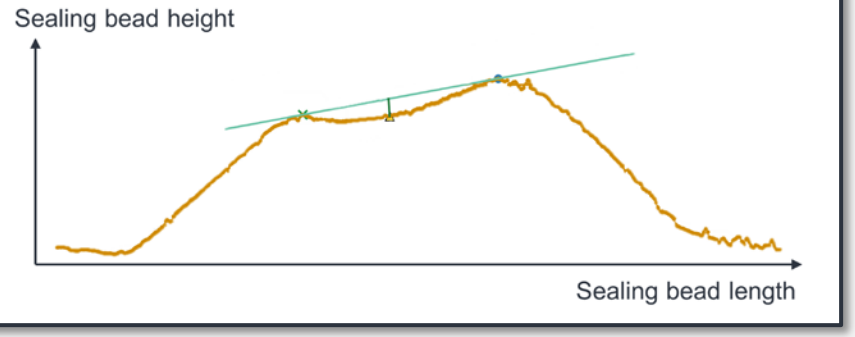
Cross-sectional profile generation



Absolute height



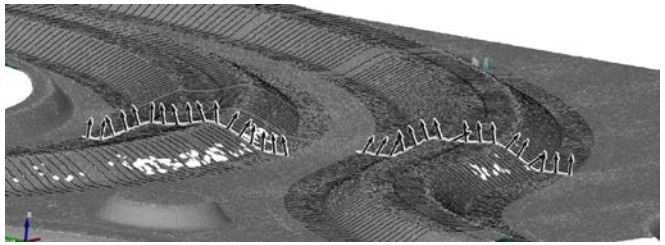
Plateau deformation



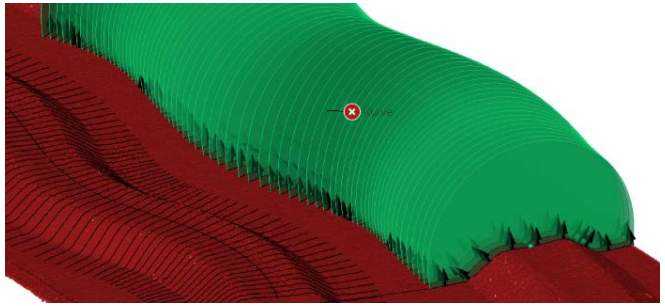
Quantitative Comparison of New and Used Bipolarplates

Results

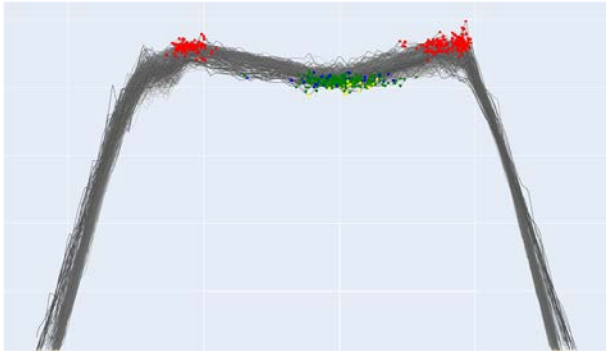
Measurement Data



Cross-sectional profile generation



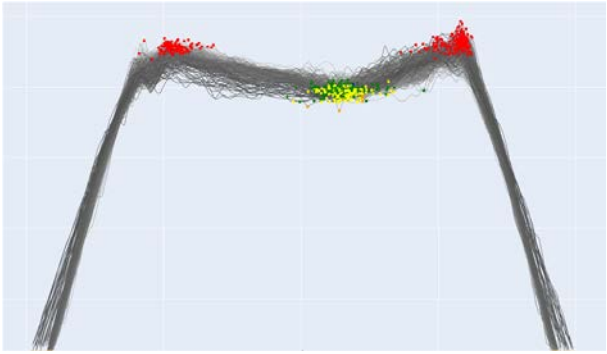
New bipolar plate



Plateau deformation: 23.6 µm

Standard deviation: 3.7 µm

Used bipolar plate



Plateau deformation: 29.8 µm

Standard deviation: 4.4 µm

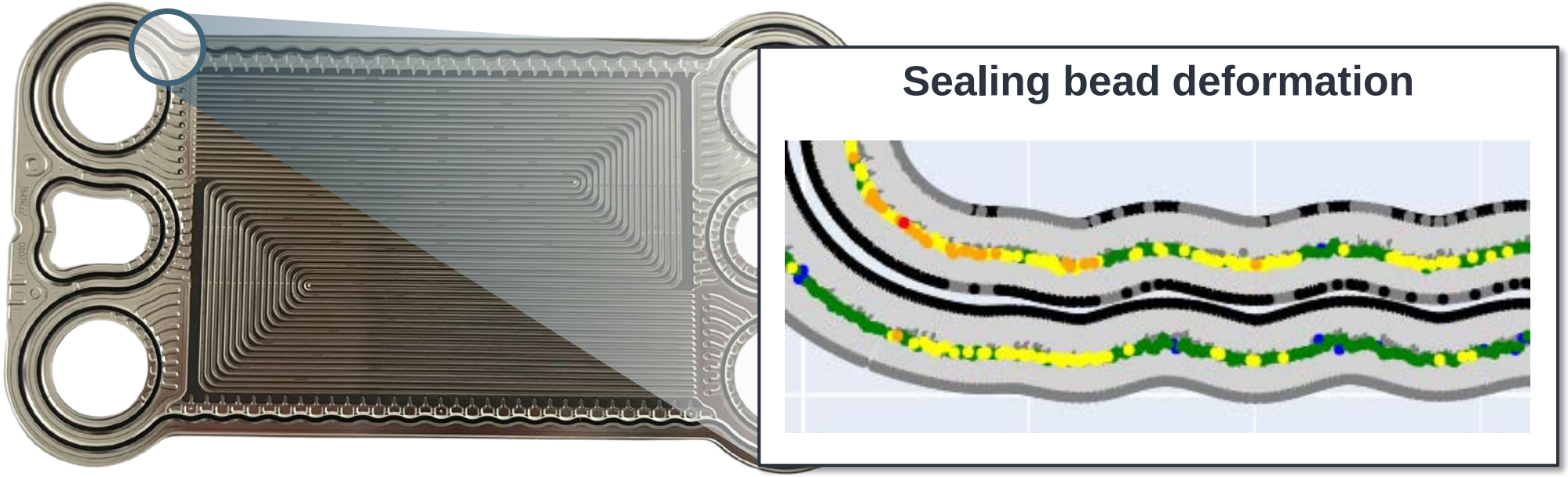
Absolute reduction: ~20 µm

The extracted metrics enable a quantitative comparison of sealing bead deformation and reveal differences between new and used bipolar plates.

Johannes Buchholz, Dominik Goes, Dr.-Ing. Martin Benfer, Prof. Dr.-Ing. Gisela Lanza

Spatial analysis of sealing bead deformation

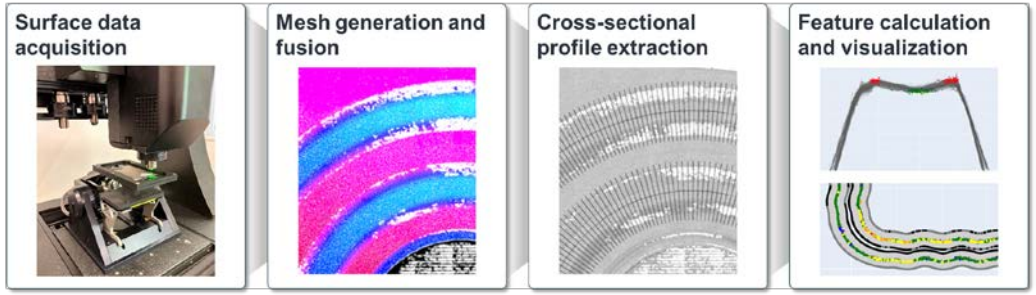
Results



The spatial mapping reveals that sealing bead deformation is not uniformly distributed along the bead. Therefore, local measurements should not be generalized to the entire bipolar plate.

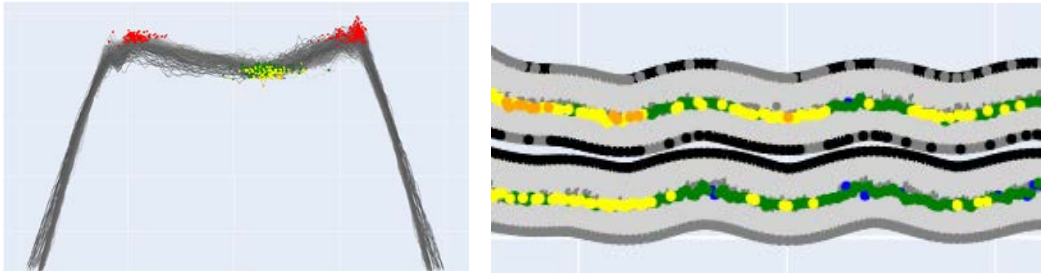
Conclusion and outlook

Reference workflow



- Reproducible bead assessment

Results for sealing bead deformation



- Spatial height loss and local deformation

Next steps

Critical region identification



Inline measure-ment validation

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Thank you very much for your attention!



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