North American
Pultrusion Conference

In-situ pultrusion of nylon 6 based profiles

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ACMA American Composites Manufacturers Association | EPTA

Fraunhofer Gesellschaft

- Based in Germany
- World's leading applied research organization
- Founded in 1949
- 76 institutes and research units
- 30,000 employees, predominantly scientists & engineers
- annual research budget of €2.9 billion

Michael Wilhelm (ICT)

Material Properties and Recycling of Nylon 6-based Profiles

David Löpitz (IWU)

From Small Colorful Elements to the Final Profile: A Simulation of the Pultrusion Process

Simon Schwab (IGCV)

Thermoplastic Pultrusion Paves the way to Mass Applications

Fraunhofer

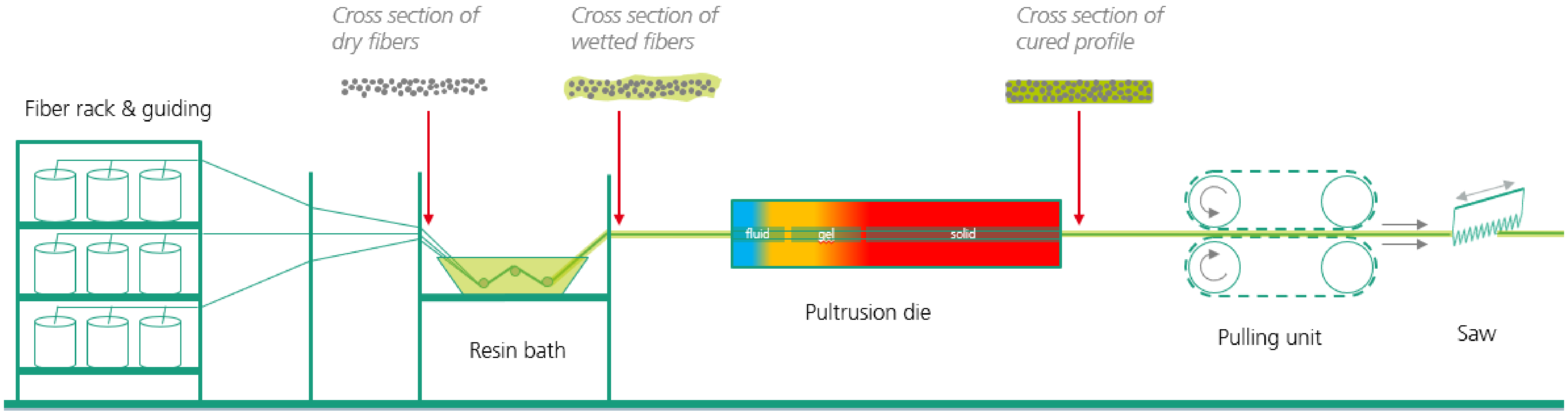
ACMA American Composites Manufacturers Association
EPTA

Pultrusion
Process

State of the art Pultrusion with resin bath

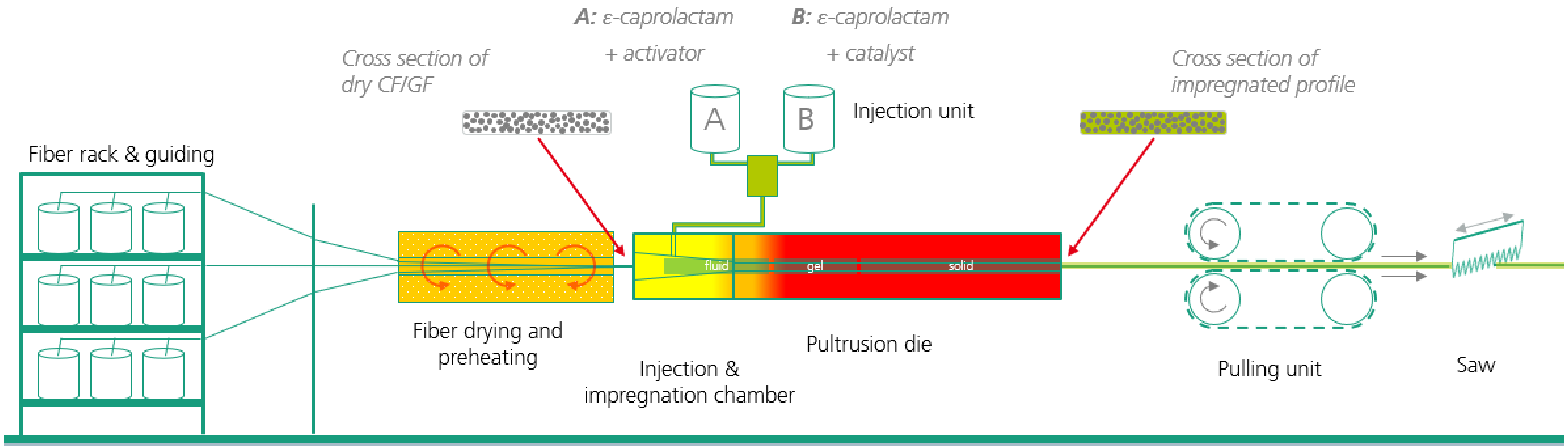
- Wetting of fibers usually in an open impregnation bath with thermoset matrix
- Almost all pultrusion profiles are based on thermoset matrices up to now

→ **Functionalization and recyclability is limited**

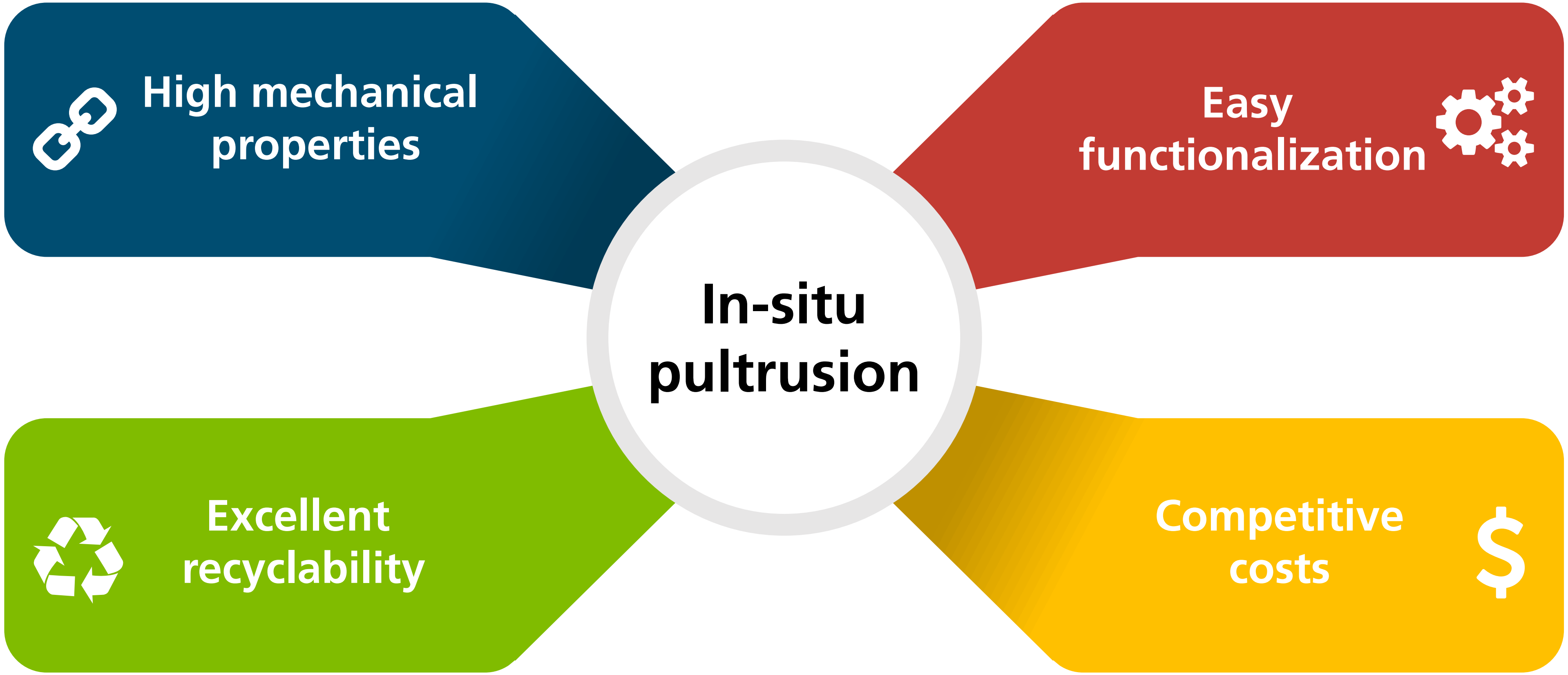


In-situ Pultrusion
Process

In-situ-Pultrusion for the production of high-performance, thermoplastic FRP profiles



In-situ Pultrusion
Key benefits



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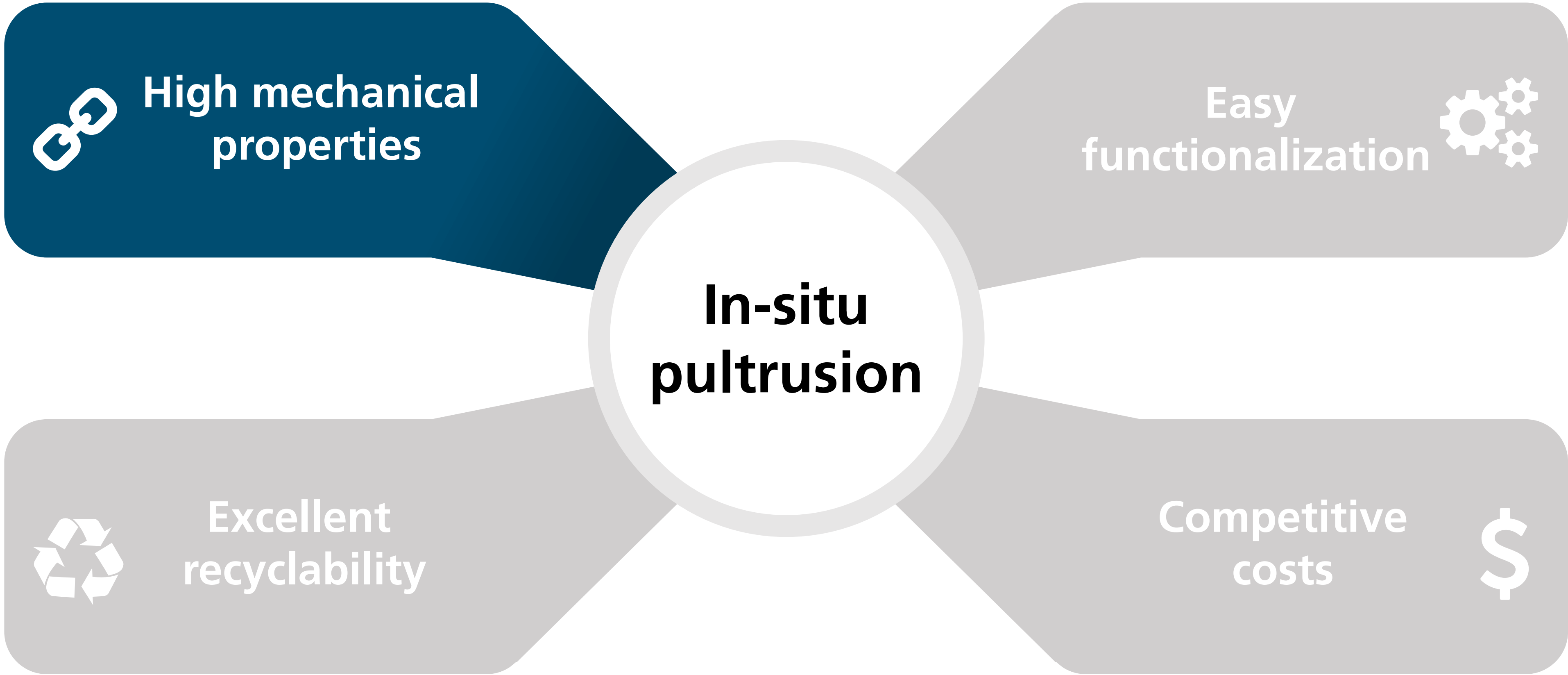


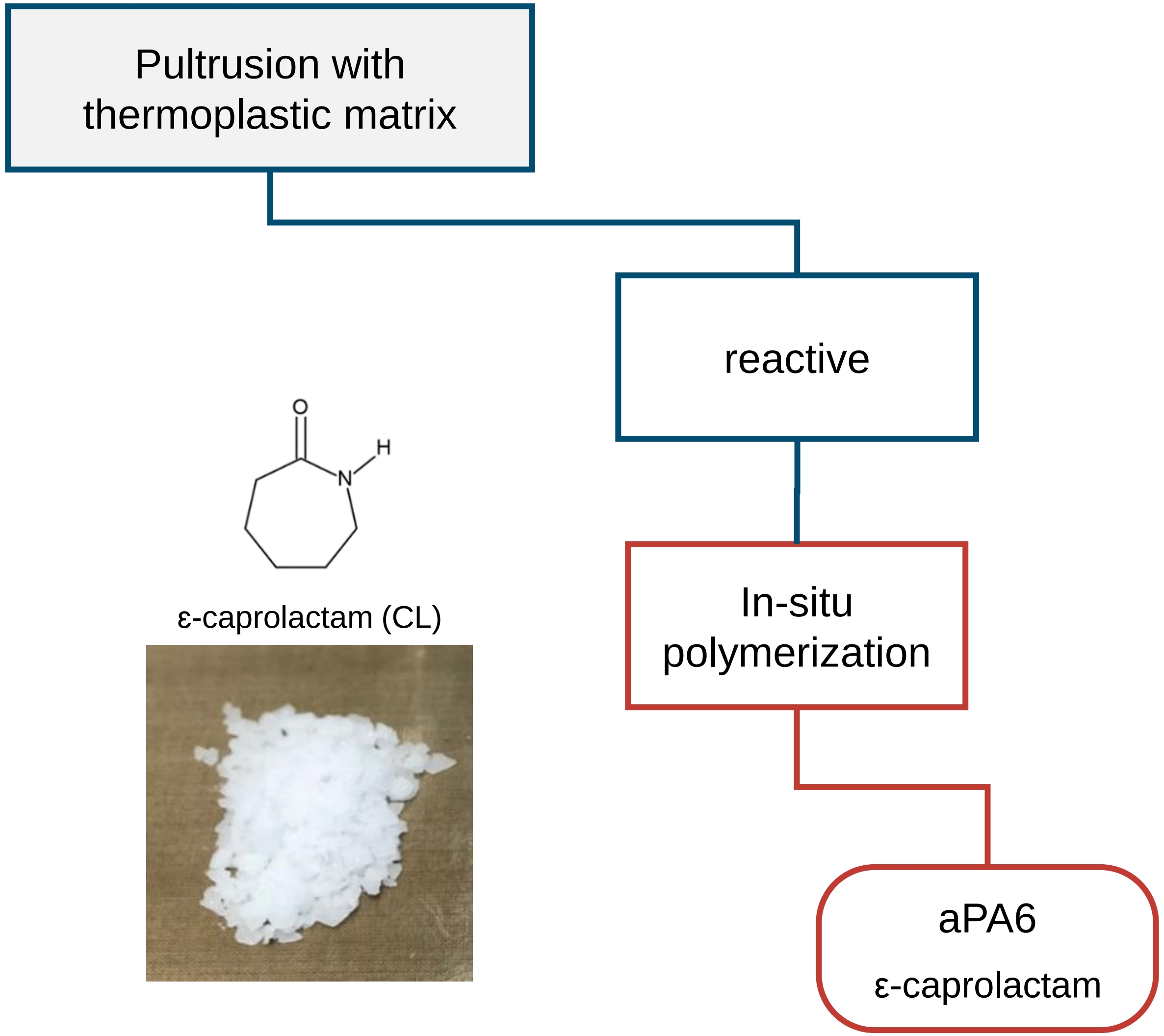
In-situ Pultrusion
Matrix

Properties of the aPA6 matrix

- Extremely low viscosity: 5-10 mPa*s @ > 70°C
- Adjustable reactivity via activator and catalyst
  - → Short curing time and high haul off speeds
- Good polymer properties
  - Extremely high molar mass (10^5 – 10^6 g/mol)
  - High degree of crystallinity
- Modification with additives (Impact, UV, color, flame retardants, chemical stabilizers, …)

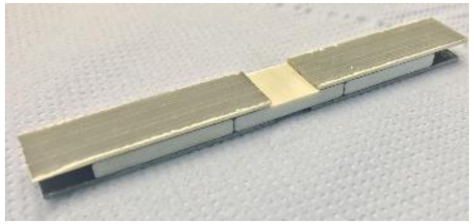
Challenges

- Sensitive to environmental influences (e.g. H_2O)
- Suitable sizings for FRP required

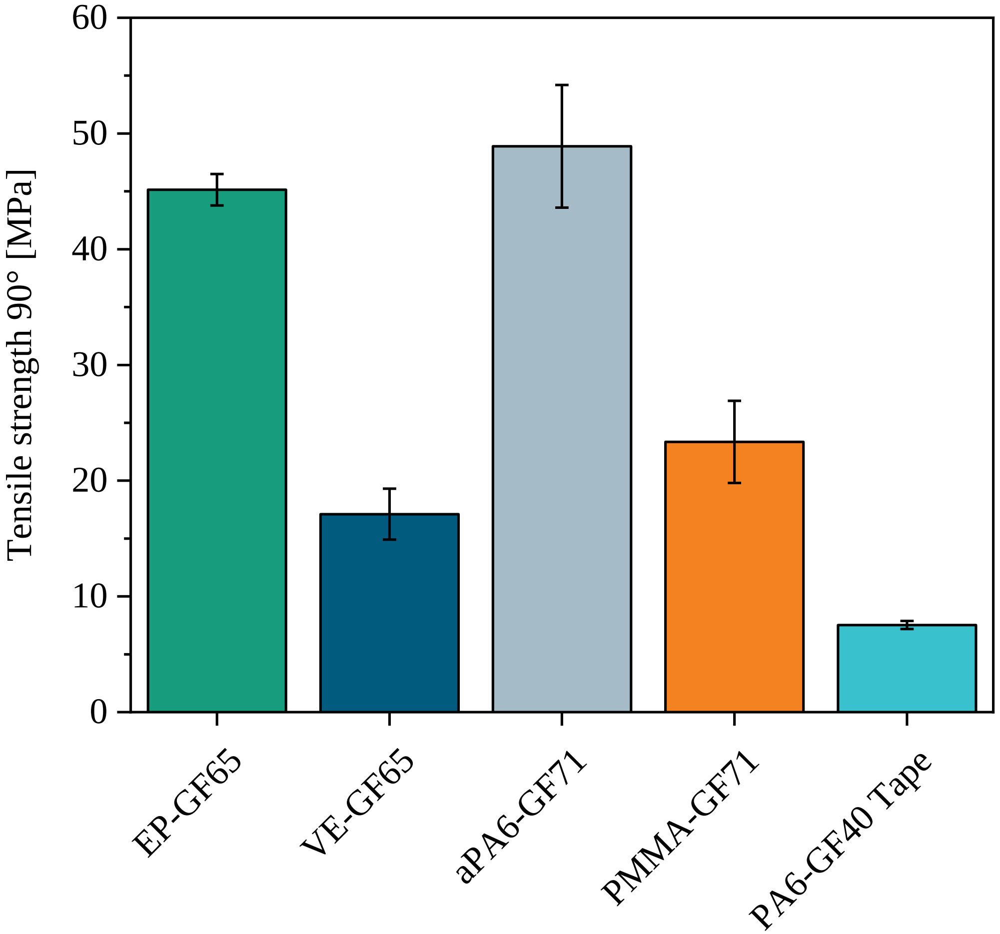


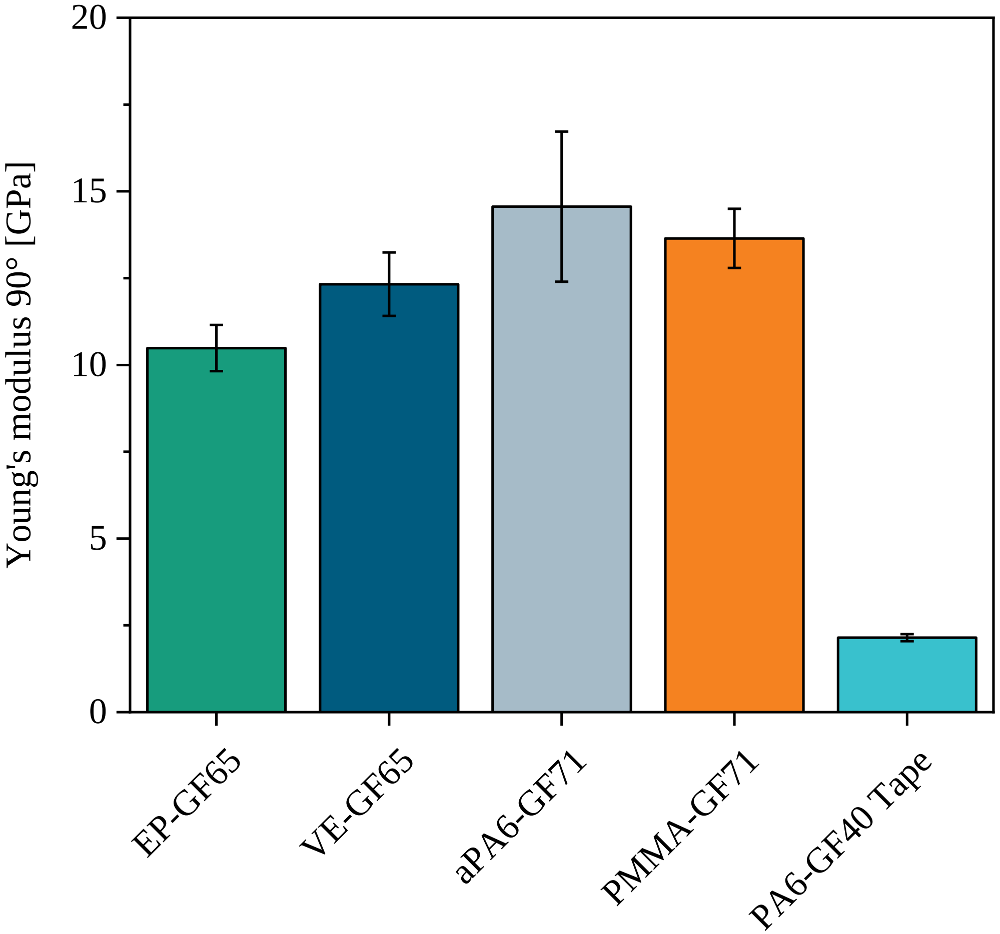
Benchmark of mechanical properties

Matrix



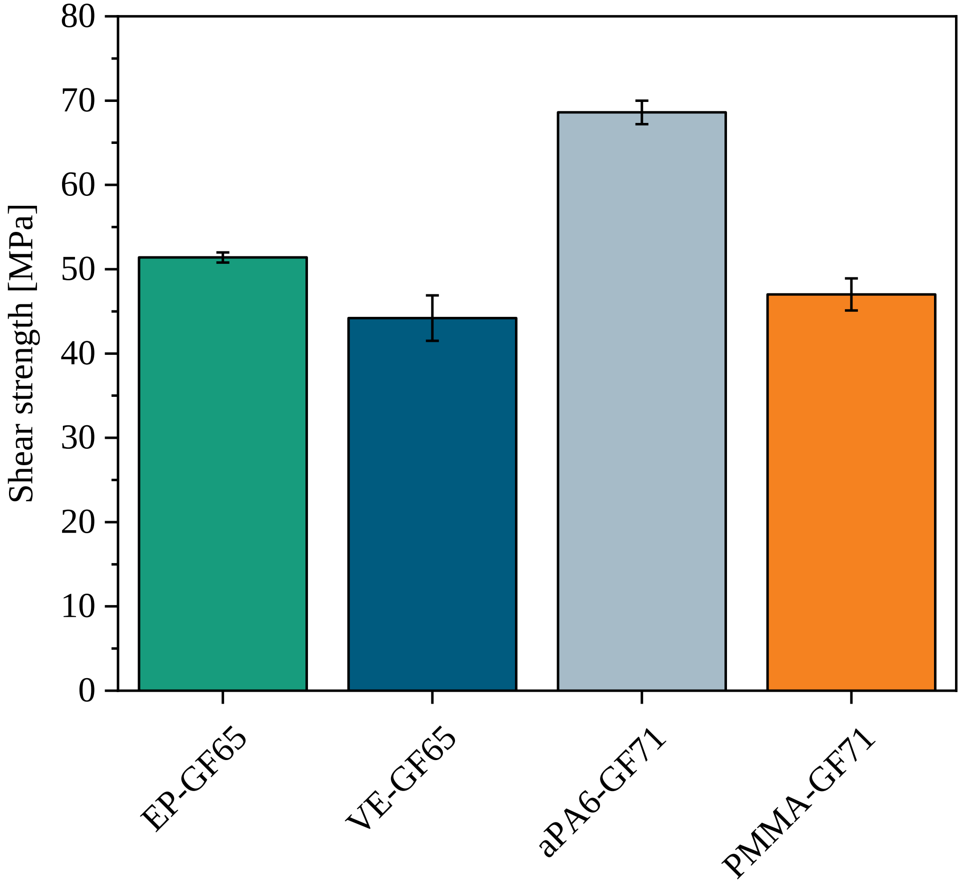
Bonded and cut tension/
compression 90° specimen

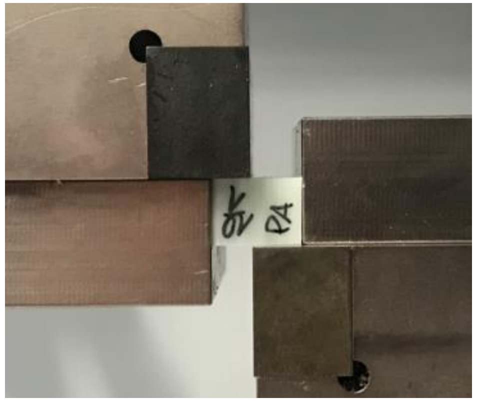




Benchmark of mechanical properties
Matrix

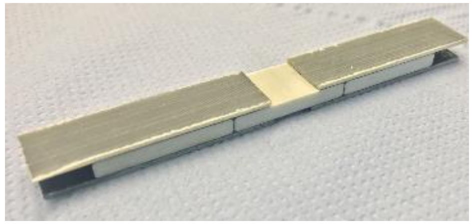
Competitive mechanical performance of thermoplastic and thermoset profiles



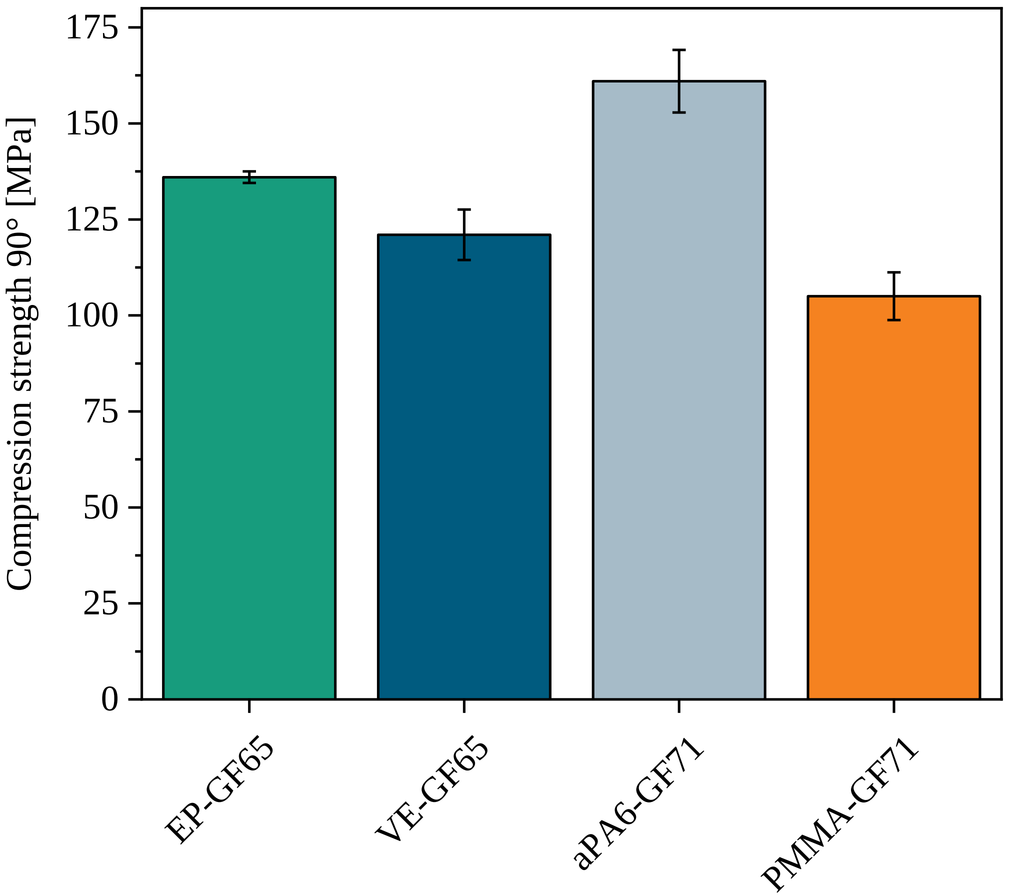


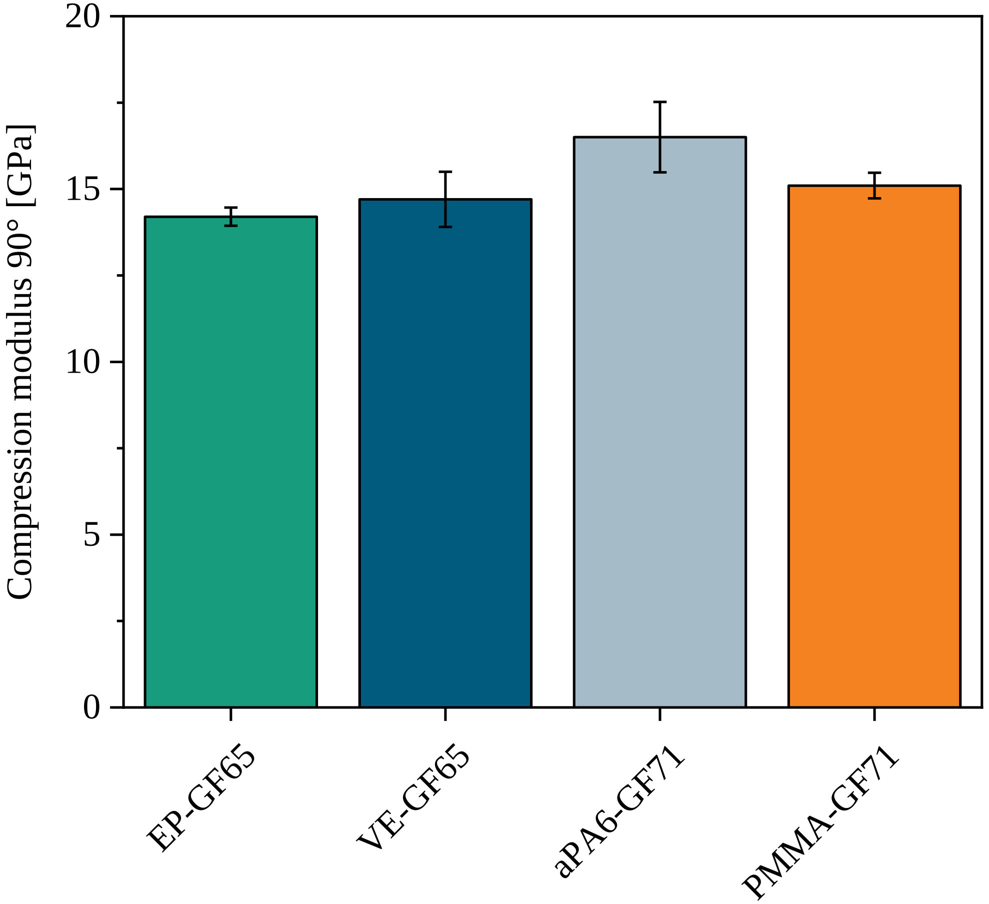
Edge-Shear-Test specimen

Benchmark of mechanical properties
Matrix



Bonded and cut tension/ compression 90° specimen



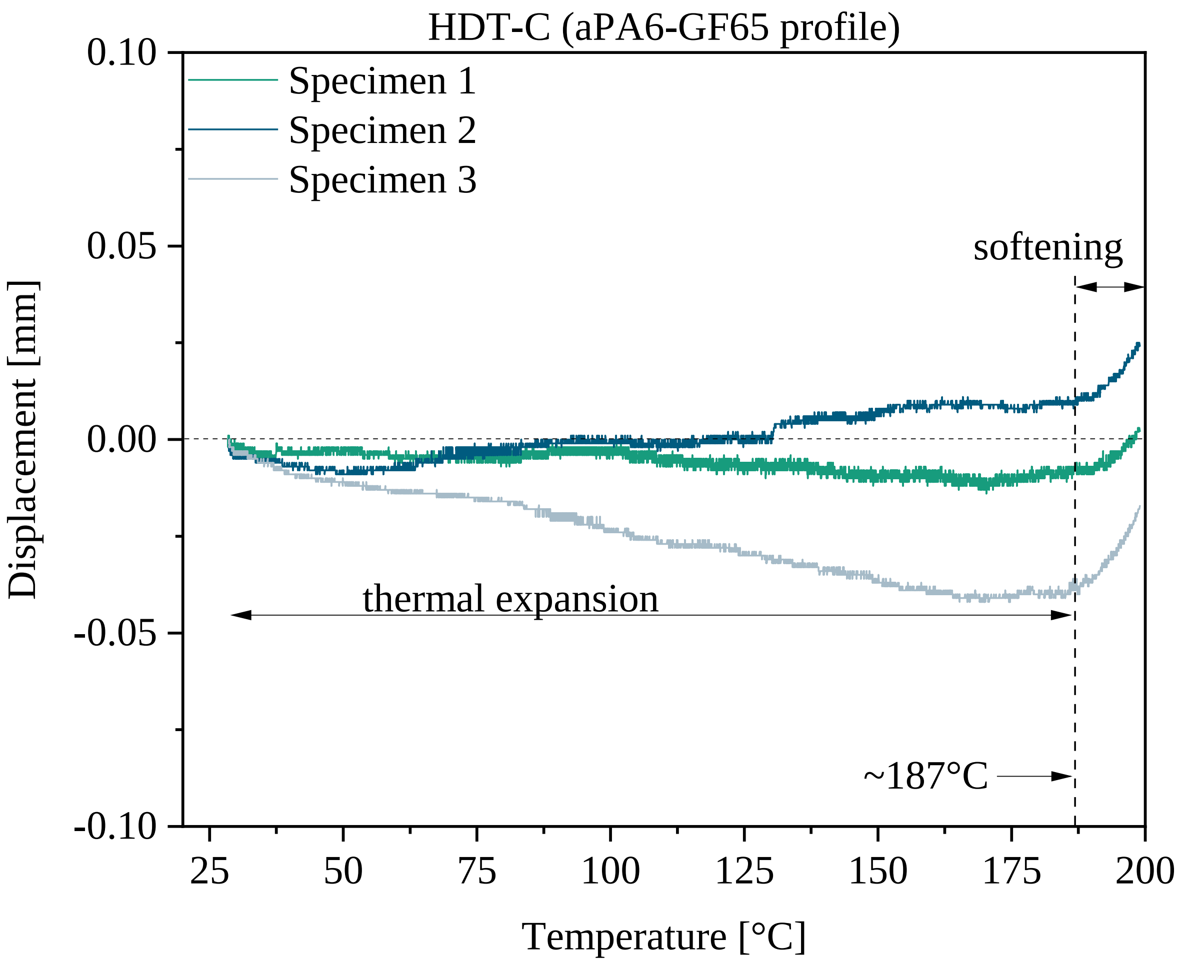


Benchmark of mechanical properties
Matrix

High Heat Deflection Temperature, even at

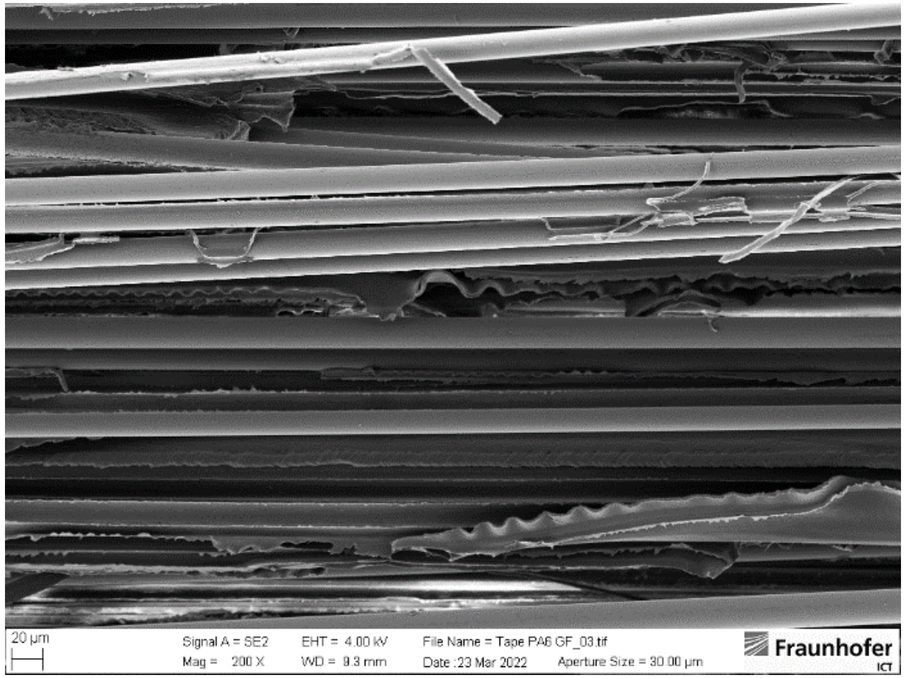
$T_{G,\ aPA6}$ ~ 60°C

due to semi-crystalline polymer structure

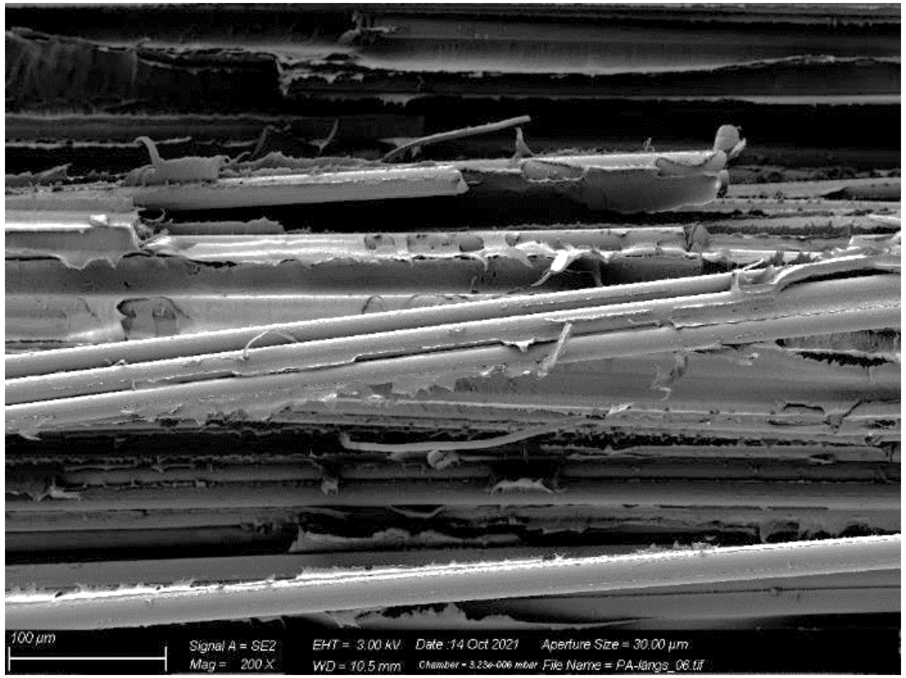


Benchmark of mechanical properties
PA6 non-reactive vs. reactive

Reactive processing with suitable sizing increases fiber-matrix bond significantly

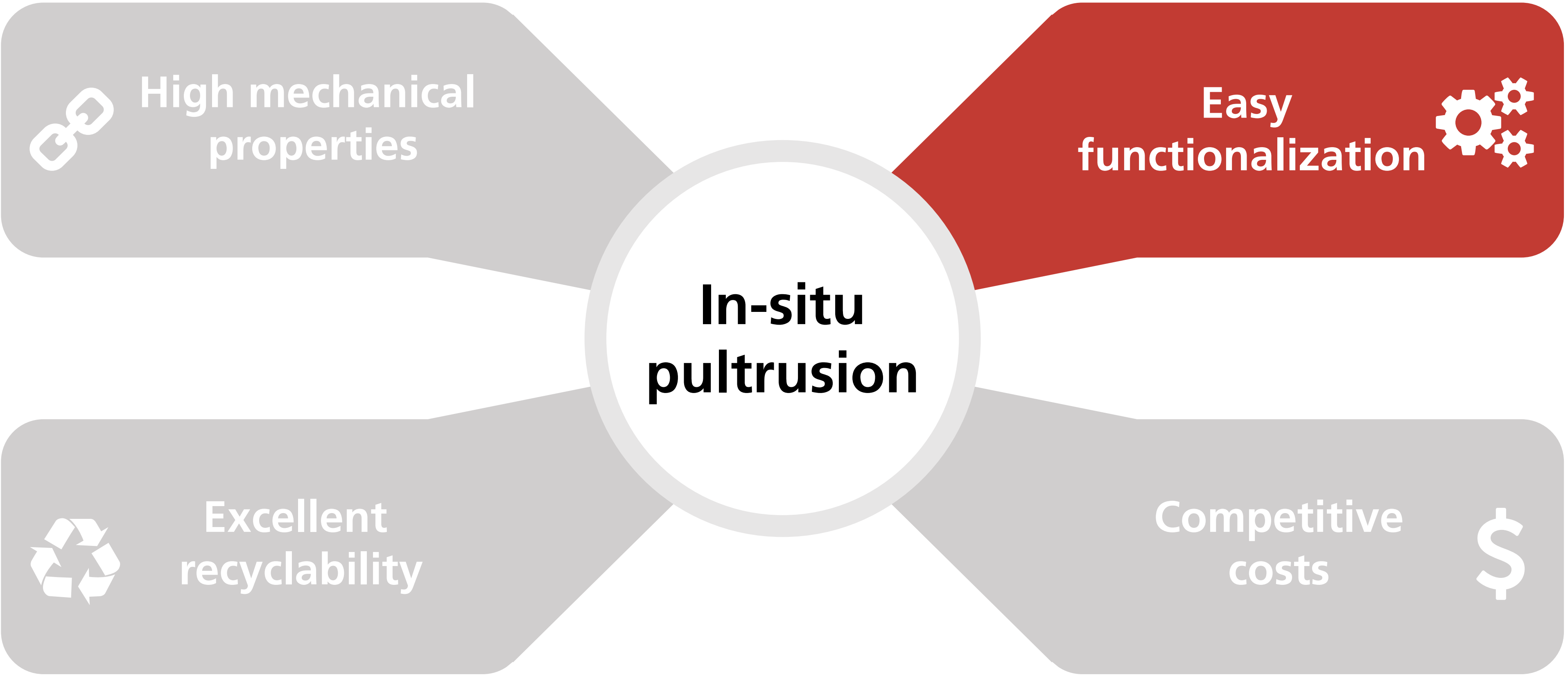


Non reactively processed PA6GF tape



In-situ-pultrusion profile aPA6GF

In-situ Pultrusion
Key benefits



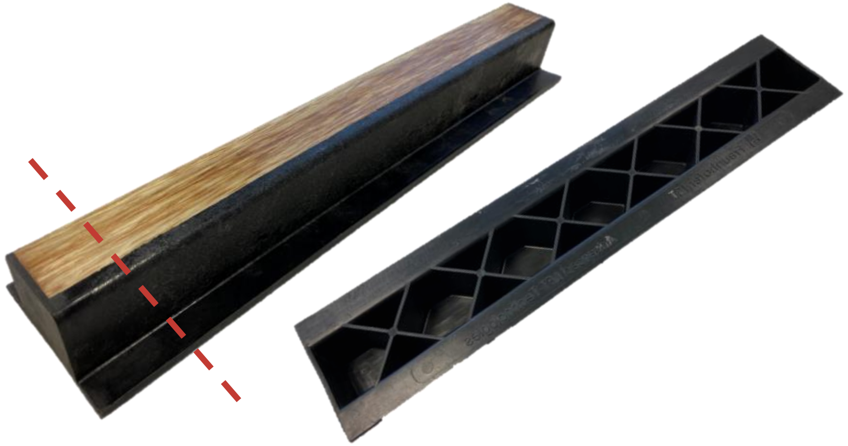
Functionalization

Demonstrator example

Co-molding of in-situ-pultrusion profiles and LFT-D

“Erlanger Träger”

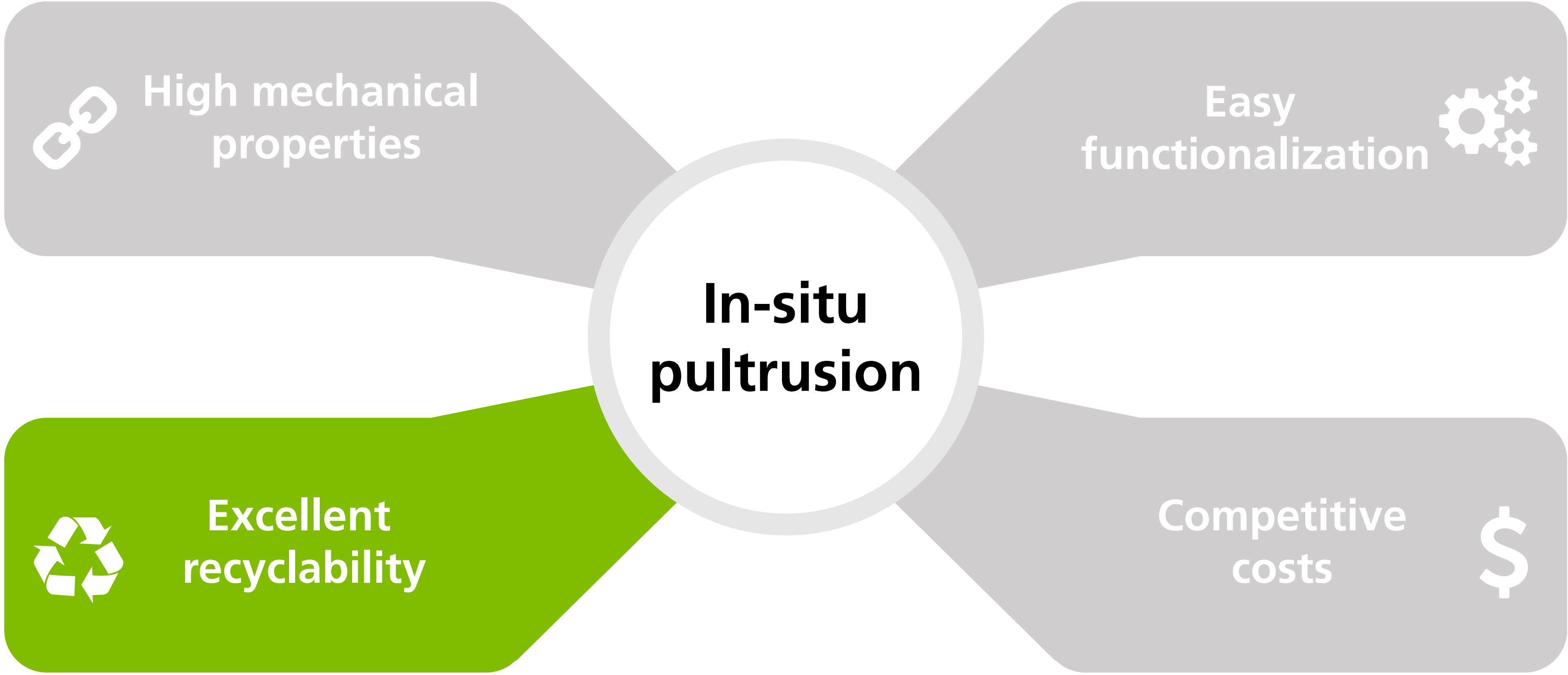
- PA6 profiles with 65 vol.% GF
- t = 2 mm/ 3 mm
- PA6 GF45 D-LFT



Replacing expensive tapes with flat, cost-efficient profiles for local reinforcement?

In-situ Pultrusion

Key benefits



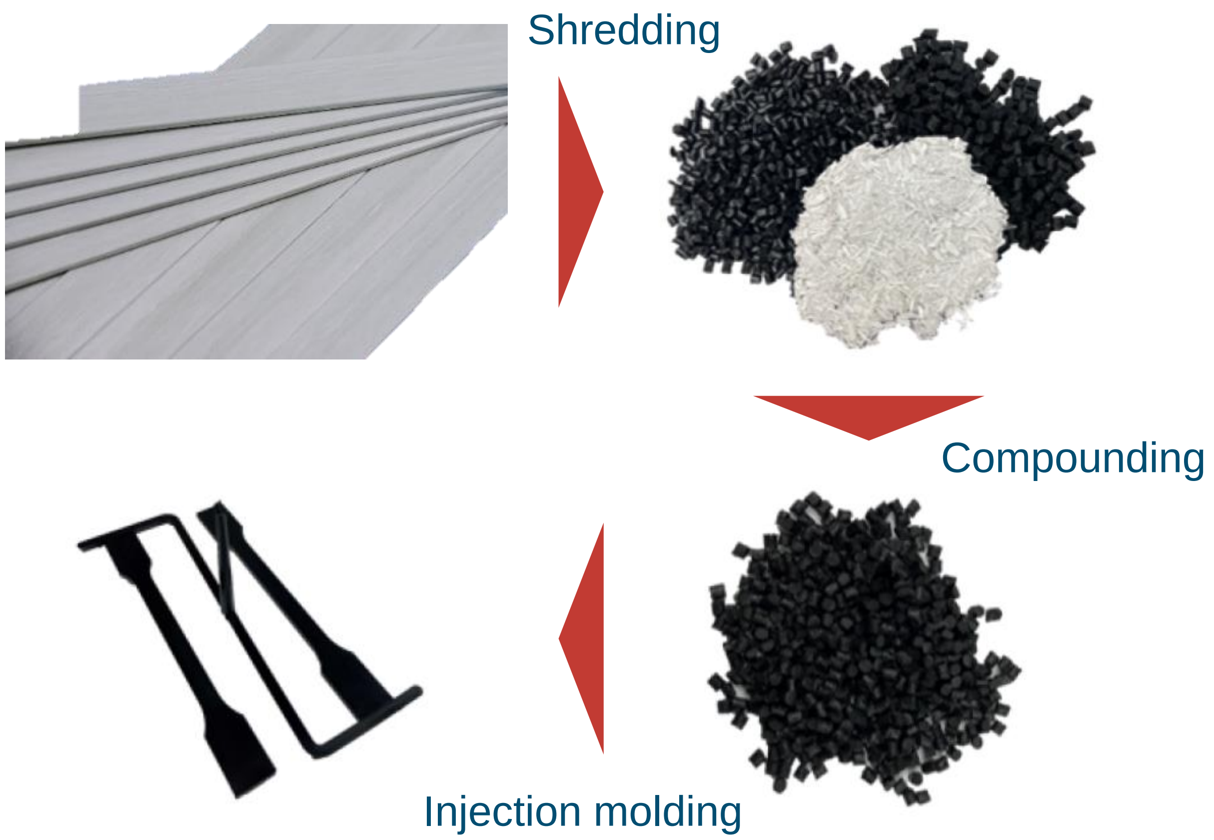
Recycling
General approach

Different options for recycling routes

- Mechanical recycling
- Chemical recycling

Mechanical recycling

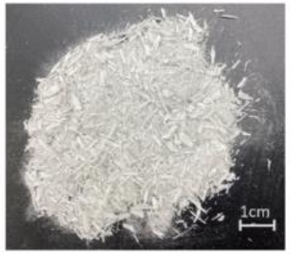
1. Shredding
2. Separation of fractions
3. Compounding
4. Injection molding
5. Testing



Recycling
Shredding of in-situ profiles

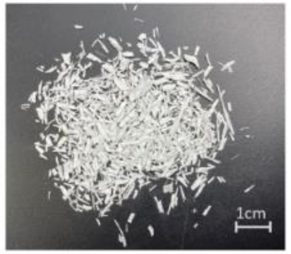
Dust fraction

~22%



Mixed fraction

100%



Coarse fraction

~78%

Machinery

Cutting mill

Cutting blades

Shredded aPA6-GF profiles

Recycling
Tensile properties

Investigation of varying:

- Fraction (D – M – C)
- Amount (10/ 20/ 30/ 37%)
- Processing route (Compounding + IM vs. direct IM)

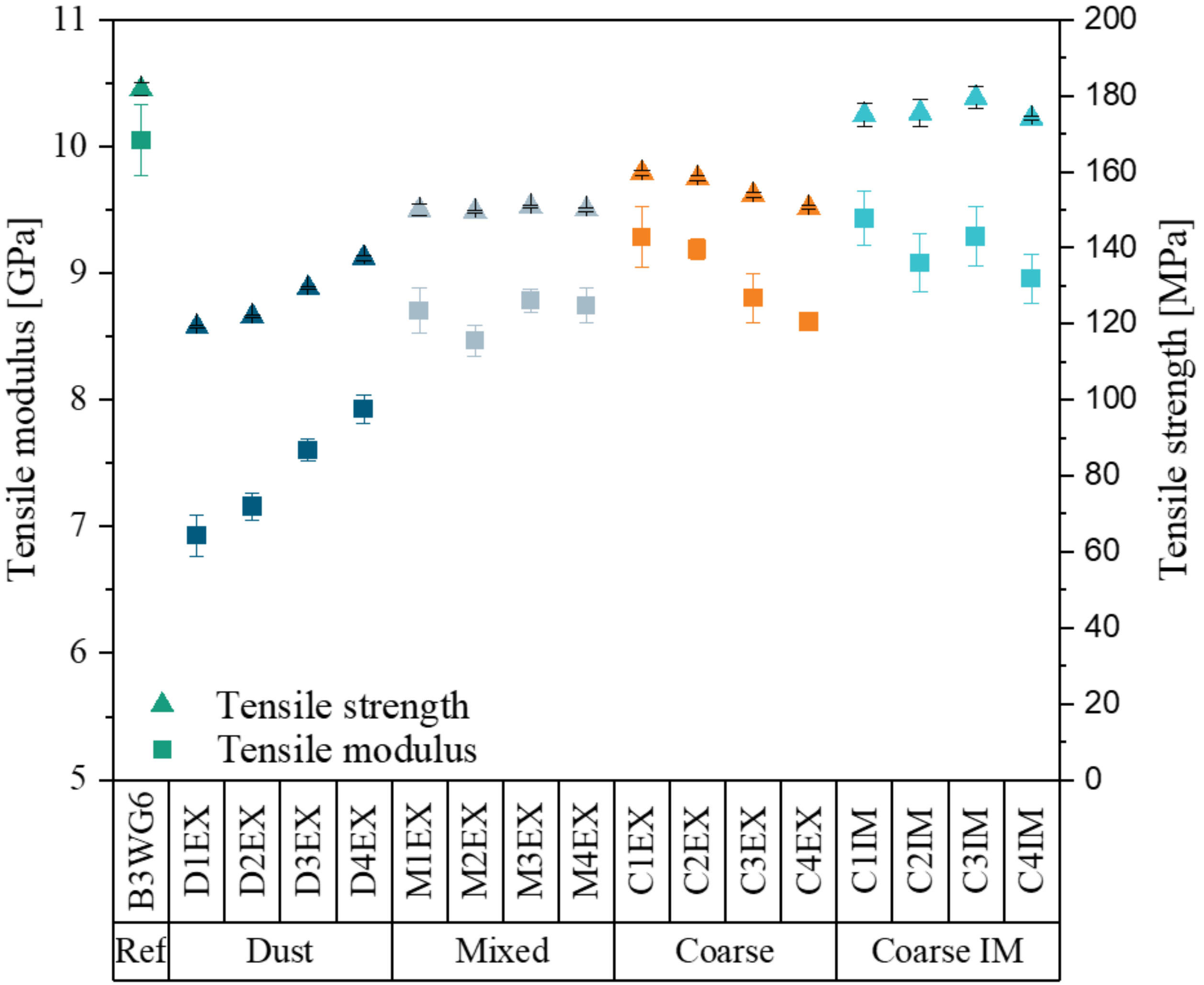
All constant at 30 wt.% GF

Variation of fraction →

Variation of recycling material amount ↓

	D	M	C	C
1	D1EX	M1EX	C1EX	C1IM
2	D2EX	M2EX	C2EX	C2IM
3	D3EX	M3EX	C3EX	C3IM
4	D4EX	M4EX	C4EX	C4IM

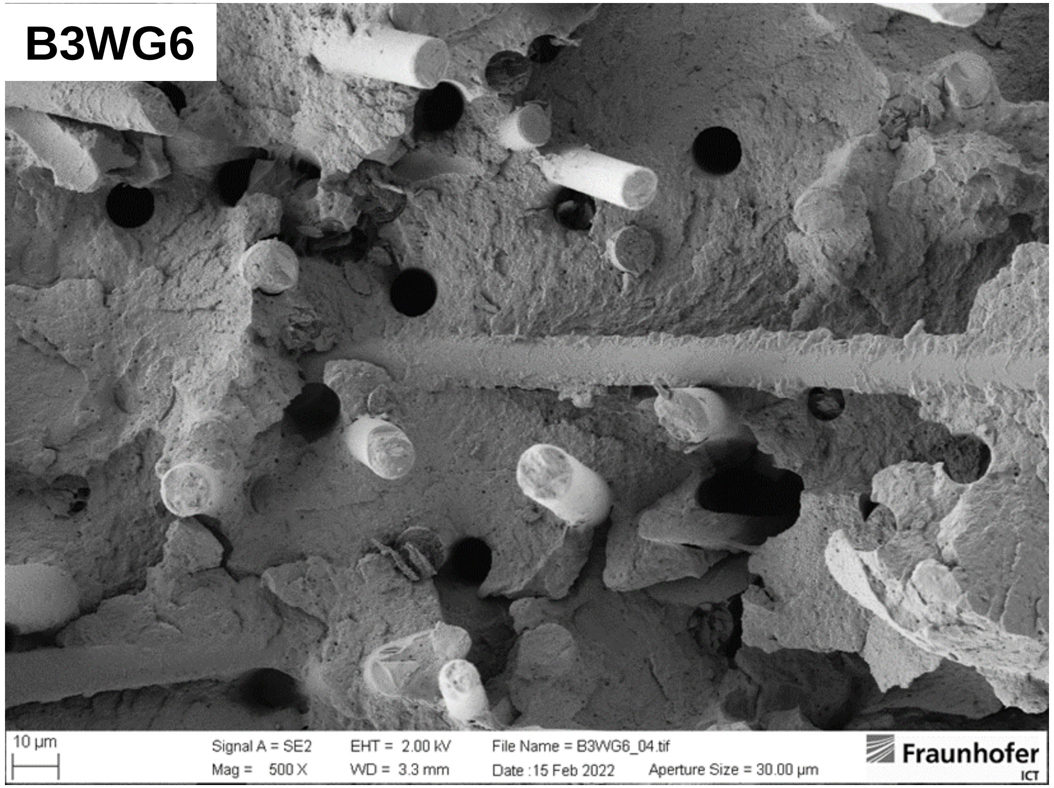
Variation of processing route

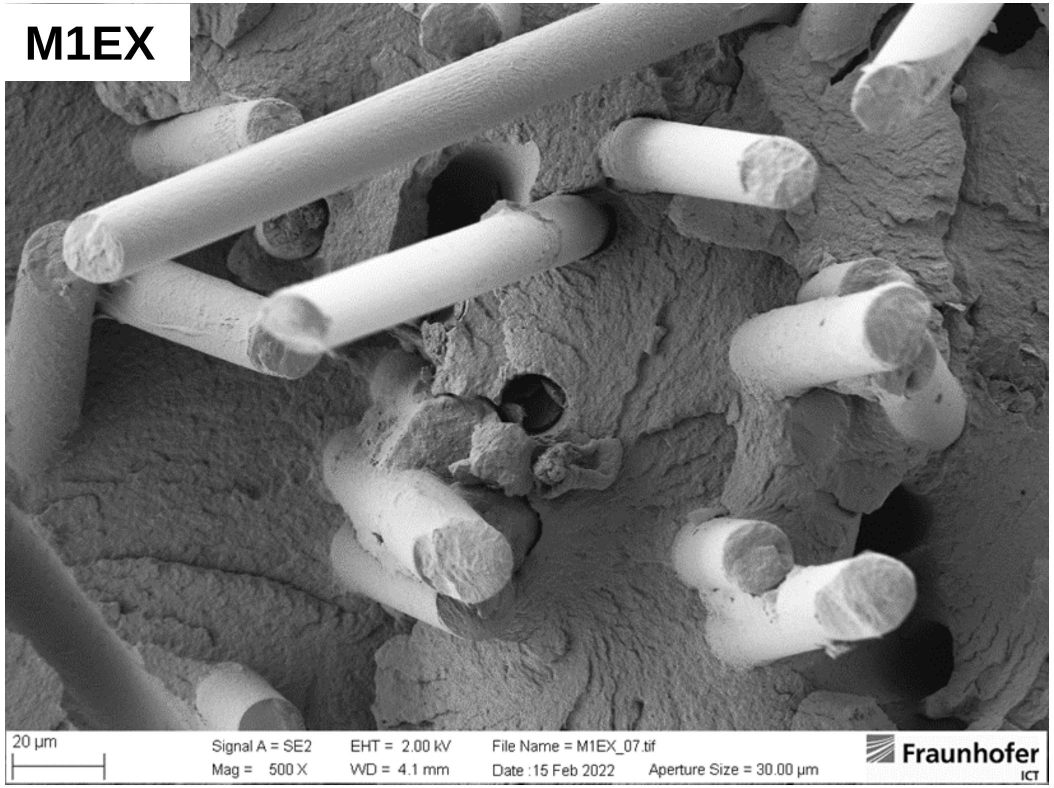


Recycling

SEM analysis

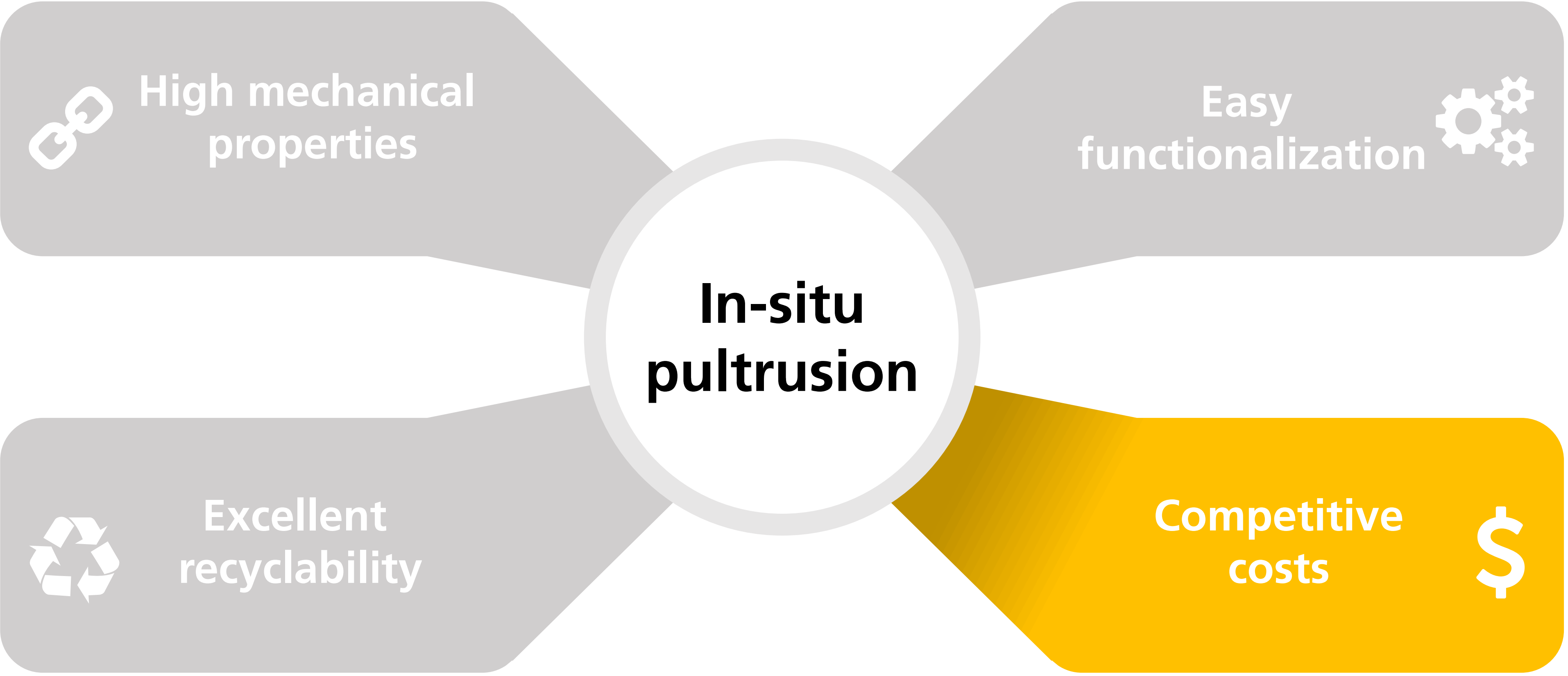
Comparison of Reference Ultramid® B3WG6 and M1EX





In-situ Pultrusion

Key benefits



Competitiveness
In-situ-Pultrusion

Machinery

- Similar machinery invest compared to thermoset
  - Dosing machine and injection + impregnation box
- Additional fiber drying and preheating unit necessary

Processing

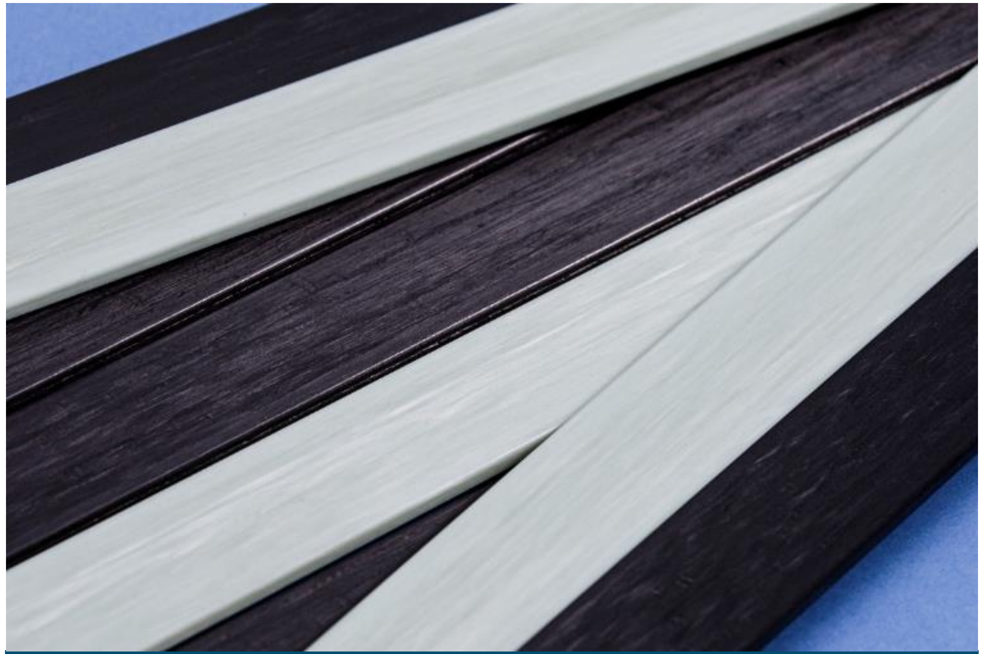
- Haul off speed up to 1.6 m/min for flat profiles successfully demonstrated
- More complex profiles are currently under investigation

Materials

- Matrix system costs are comparable to VE
- Slightly higher fiber costs
- No need for fillers

Our research topics
In-situ-Pultrusion

- Evaluation and optimization of process parameters and materials
- Design and comparison of different injection chambers
- **Process digitalization** (real time analysis, prediction, tracking)
- Functionalization & co-molding of the thermoplastic profiles
- End-of-Life processes / Recycling
- Development and adaption of new reactive TP matrices



Flat profiles made with
in-situ-Pultrusion
30 x 4 mm^2
Matrix: Nylon 6, Brüggemann Chemicals
Fibers: Johns Manville/ Zoltek (~72% FVC)

Pultrusion 4.0

Sensor selection & implementation

Standardized data acquisition

Energy- and Eco-balancing (e.g. CO_2 Eq.)

Real time KPI visualization

Digital product pass

Live data analysis

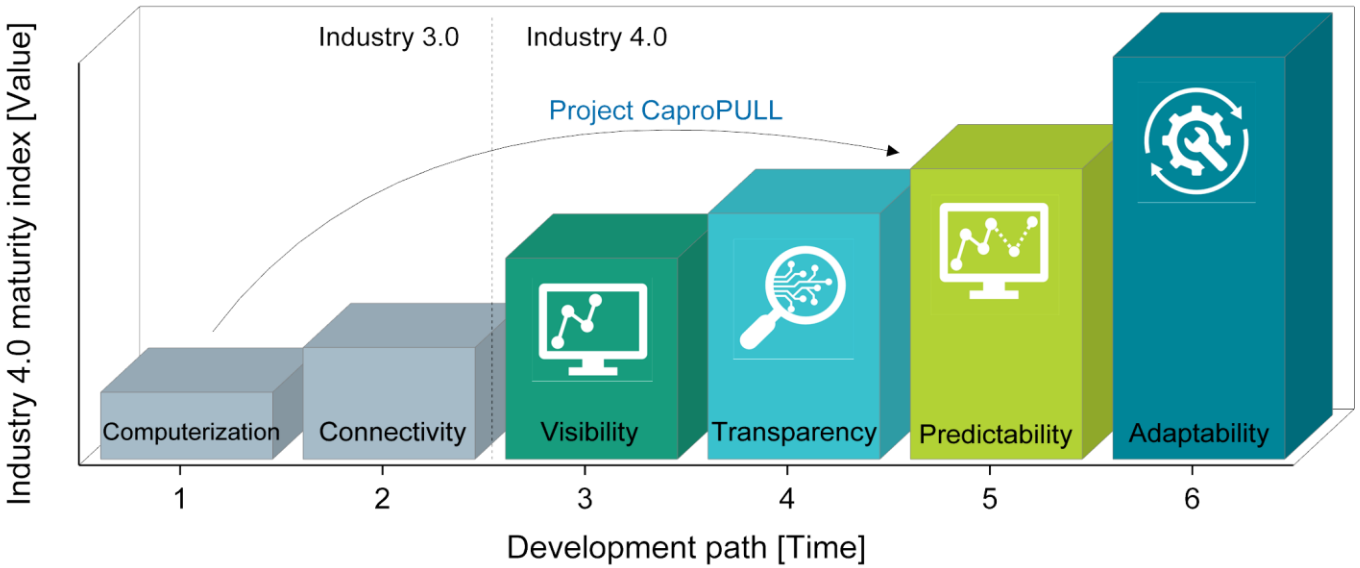
Anomaly & Missing data detection

Data-based process optimization

Track and Trace

Prediction/ Prescription

Industry 4.0 maturity index of the pultrusion process and objective in CaproPULL project



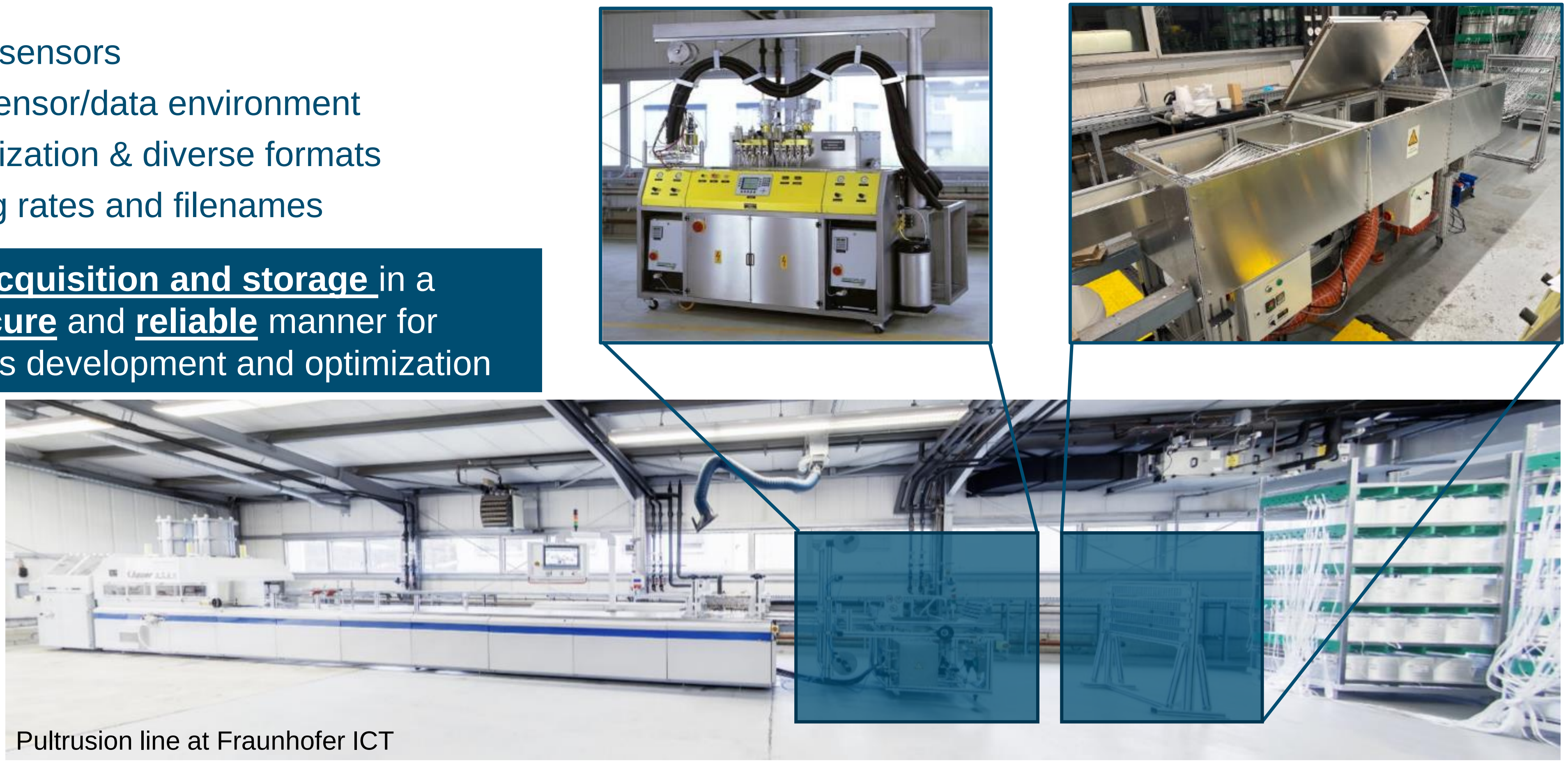
Picture Source: T. Helfrich, M. Wilhelm, O. Kuppler, P. Rosenberg und F. Henning, „Development of a standardized data acquisition prototype for heterogeneous sensor environments as a basis for ML applications in pultrusion“, *Proceedings ML4CPS Conference*, 2023

Pultrusion 4.0

Current state

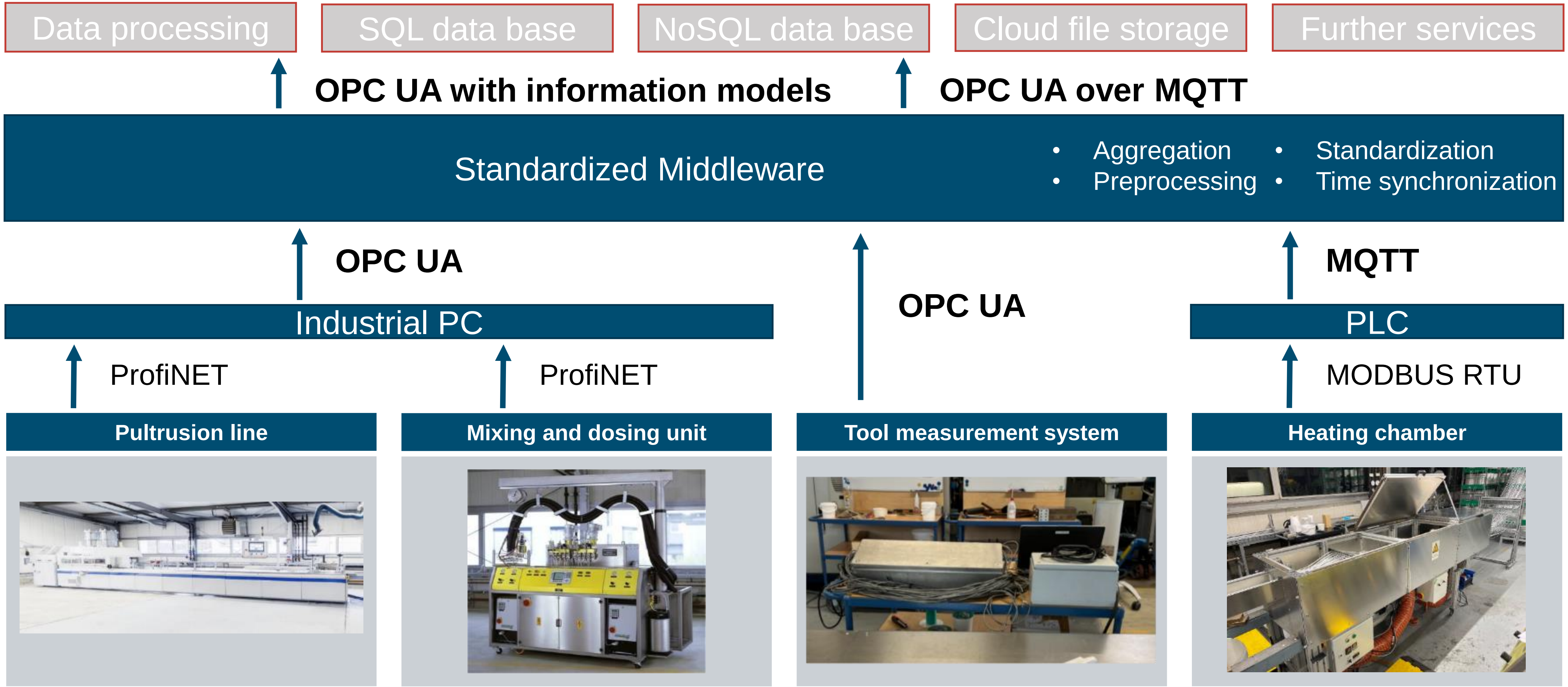
- None or only few sensors
- Heterogeneous sensor/data environment
- No time synchronization & diverse formats
- Different sampling rates and filenames

→ Need for data **acquisition and storage** in a **standardized, secure** and **reliable** manner for data-based process development and optimization



Pultrusion line at Fraunhofer ICT

Pultrusion 4.0



Pultrusion 4.0

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