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From Paper Production to Traction Motors: Transfer Patterns for the FOREST Digital Twin Framework

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Abstract

The paper industry is highly energy intensive and exposed to volatile energy markets and strict decarbonisation targets. Digital twins can couple operational data with engineering and simulation models for energy and CO_2eq management, yet many solutions remain domain-specific. This paper summarises FOREST (Framework for Resource, Energy, and Sustainability Treatment) as a modular digital twin framework that integrates plant data, Asset Administration Shell (AAS)-based models, and executable simulations to provide consistent energy and material flow views, time- and product-resolved CO_2eq indicators, and scenario evaluations. Based on an industrial tissue implementation, three domain-independent architectural patterns are derived: flow and state tracking, asset-centric semantics, and co-execution of models and services. These patterns are conceptually mapped to electric traction motor manufacturing and End-of-Use (EoU) testing within industrial data spaces (IDS), illustrating how plant-level optimisation logic can be extended towards lifecycle-oriented decisions on value-retention strategies.

Keywords

Digital twin; CO_2eq accounting; Electric traction motor manufacturing; Paper production; Data management

1. Introduction

The decarbonisation of manufacturing is driven by two intertwined developments: the electrification of processes and products, and the increasing use of data-driven methods for monitoring, optimisation and reporting. Energy- and emission-intensive industries such as paper production must reduce fuel use, integrate volatile renewable electricity and provide verifiable product carbon footprints [1–4]. At the same time, electrified products such as traction motors are deployed at scale, creating new requirements for lifecycle assessment, EoU decisions and circular economy strategies [5–7].

Digital twins are key enablers of this transition because they couple operational data with engineering and simulation models for diagnostics, forecasting and scenario analysis [8]. In practice, many solutions remain limited to specific assets or platforms and focus on either production or downstream lifecycle services. A consistent, semantics-based chain from sensor data to lifecycle-oriented services is often missing. This limits comparability across plants and complicates integration into cross-organisational data spaces [9–12].

A Framework for Resource, Energy, and Sustainability Treatment (FOREST) is introduced as a modular digital twin framework. By combining automation data, semantic asset models and simulation units, FOREST generates energy and material flow views, time- and product-resolved CO_2eq indicators and

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scenario evaluations in tissue manufacturing, providing actionable guidance while satisfying transparency and auditability requirements. [10,13,14] In parallel, IDS and AAS initiatives are establishing federated infrastructures for sovereign data exchange along supply chains, which are particularly relevant for traction motors when deciding between remanufacturing, reuse and recycling at EoU [15,16,12,17].

Against this background, this paper asks how a framework such as FOREST can be generalised from its original process-industry context to discrete assembly and EoU services, and how it can be embedded into data-space-based infrastructures. The contributions of this work are threefold:

1. FOREST is summarised as a domain-agnostic digital twin architecture with core layers for data acquisition, semantic asset modelling, model integration and application services [10,13].
2. Experiences from an industrial tissue implementation are used to derive domain-independent patterns, including consistent flow and state tracking, asset-centric semantics and the co-execution of models and services [13,14].
3. These patterns are mapped to a traction motor use case in which an EoU test service operates on data provided via an IDS, illustrating how FOREST concepts can support circular strategies in discrete manufacturing [18,6,19,7].

To address this gap, this paper applies a pattern-based generalisation approach. The FOREST architecture, as implemented in an industrial tissue mill, is analysed to identify recurring solution elements that are not specific to fibre-based processing. These elements are generalised into three reusable patterns: flow and state tracking, asset-centric semantics, and co-execution of models and services. The patterns are then conceptually instantiated for a representative discrete-manufacturing use case, electric traction motor production with EoU testing. This demonstrates how the same architectural logic supports lifecycle-oriented services within IDS. The mapping specifies transferable design decisions and required interfaces rather than reporting a completed deployment.

The remainder of this paper is organised as follows. Section 2 reviews related work on digital twins for energy and CO_2eq management, industrial data ecosystems and AAS-based interoperability, and traction motor manufacturing and EoU services. Section 3 describes the FOREST framework and derives the three domain-independent patterns. Section 4 positions IDS as the federated environment for cross-organisational sharing of FOREST-generated information. Section 5 outlines the traction motor EoU test scenario as a pattern instantiation. Section 6 discusses limitations and practical deployment constraints, and Section 7 concludes with an outlook and concrete validation steps.

2. Background and Related Work

Digital twins, industrial data ecosystems and circularity-oriented services have been widely studied, but largely in separate communities. Process industry research focuses on model-based optimisation of continuous plants, including energy systems and CO_2eq management [1–4]. Manufacturing science addresses equipment, line and product twins in discrete assembly [5,6,19]. Parallel to this, IDS and AAS-based semantics have emerged from the Industrie 4.0 and Gaia-X context as a basis for sovereign, interoperable data exchange along supply chains [15,16,12,20,17]. In traction motor research, design and production aspects are increasingly linked to remanufacturing and recycling concepts, yet EoU testing is often treated as a stand-alone diagnostic step rather than as part of a continuous, data-driven lifecycle twin [19,7].

This paper connects these strands. Section 2.1 summarises the characteristics of fibre-based web production and reviews digital twin approaches for energy and CO_2eq management. Section 2.2 introduces industrial data ecosystems and the AAS as enablers of semantic interoperability and federated data sharing. Section 2.3 outlines traction motor production, information modelling and EoU testing, with a focus on how production and lifecycle data can inform R-strategies [21] such as remanufacturing, reuse and recycling.

2.1 Digital Twins for Energy and CO_2eq Management in Manufacturing

The paper industry is energy-intensive and characterised by tightly coupled, multi-stage processes. Thermal units such as hoods and cylinders dominate fuel consumption and direct CO_2eq, while drives, vacuum systems and auxiliaries add substantial electrical demand. Small changes in product mix, operating strategy or technology configuration can therefore significantly affect specific energy use and carbon footprint [1,2].

Although mills collect large amounts of process and energy data via automation systems, historians and business applications, information is often fragmented and primarily used for aggregated monthly reporting. Transient losses, cross-machine interactions and product-specific footprints remain difficult to analyse, and systematic scenario evaluation for electrification or fuel switching is rare due to missing operational models. [3]

State-of-the-art reviews highlight the largest levers for data and artificial intelligence enabled savings in mechanical refining, dewatering and drying, alongside condition monitoring and maintenance improvements [4]. Digital twins address these gaps by linking plant data with physics-based and data-driven models to create executable representations of selected assets or process sections [8]. Existing work in the paper industry typically focuses on unit operations or quality optimisation and is often tied to proprietary platforms, which limits reuse and cross-vendor integration [10,11,3].

With FOREST, energy, resource, and emission flows are represented through modular, interoperable digital-twin components that can be instantiated and combined to reflect site-specific mill configurations [10]. A pilot in tissue manufacturing showed that FOREST can realise tangible energy savings and support energy flexibility [14,22]. The underlying requirements, i.e. traceable energy and material flows, asset-centric semantics, integrated executable models and transparent CO_2eq calculations [13], are not specific to paper and apply to discrete domains such as traction motor production. This motivates the generalisation of FOREST beyond paper industry.

2.2 Industrial Data Ecosystems and Semantic Interoperability

Industrial data ecosystems constitute socio-technical environments in which multiple actors generate, exchange, and use data across organizational boundaries. Their central feature is a federated architecture that preserves data sovereignty while enabling secure and interoperable data sharing. This is achieved through standardized interfaces, semantic models, and shared governance mechanisms [12]. Core building blocks include data sources, integration connectors, identity and access management, semantic interoperability components, and data governance services. Together these components ensure that heterogeneous information from different systems can be exchanged and interpreted reliably [15].

A recurring challenge in industrial practice is the heterogeneity, inconsistency, and limited availability of data, which often inhibit cross-organizational collaboration. To address these limitations, current industrial initiatives emphasize standardization [16,23,9]. The AAS has emerged as a central interoperability concept in industrial data ecosystems. It is often described as an integration connector because it provides a unified semantic representation of assets across their lifecycle [16]. According to its formal definition, the AAS enables secure access to asset-related information through structured submodels, standardized identifiers, and machine-readable semantics [24]. These characteristics make the AAS a key enabler for consistent data exchange and reduce manual mapping efforts across heterogeneous system landscapes.

Data ecosystems have become essential for industrial transformation, particularly in sustainability-related applications where traceability, transparency, and trustworthy data provision are required across supply chains. They allow the integration of production, quality, and environmental data, enabling advanced analyses and evidence-based decision-making. However, the successful implementation still depends on scalable, partially automated data connectors and harmonized semantic standards, since many enterprise systems are not natively compatible with interoperable architectures. [25–28]

2.3 Electric Traction Motor Manufacturing and Lifecycle

Electric traction motors are a key technology for battery electric vehicles and strongly shape performance, efficiency and sustainability. Permanent magnet synchronous motors, especially interior permanent magnet designs with hairpin windings, dominate automotive traction due to high power density, high-speed efficiency, compact design and low noise. Their laminated stator, magnet rotor and integrated housing create high product and process complexity, requiring detailed process-chain analysis across rotor and stator production and final assembly. [5,6]

Original equipment manufacturers demand end-to-end documentation and traceability for safety- and quality-critical components. This requires continuous data capture across suppliers, manufacturing, inspection, and logistics. To achieve motor-level traceability aligned with ISO 9001 and ISO 26262, legacy IT systems must be integrated into a consistent production landscape [19,29]. This makes information modelling and service-oriented IT integration central to traction motor production. In this context the AAS provides a standardised digital twin implementation. It utilizes modular submodels for technical, production, traceability, and bill-of-materials data. Industrial pilots indicate that AAS-based approaches support scalable, reconfigurable production and consistent real-time mapping of product, process, and machine parameters [29].

Beyond production, lifecycle-oriented information modelling remains essential. It enables a unified and traceable representation of product architecture, functional behaviour, manufacturing and test processes, and lifecycle data. The remanufacturing of electric powertrains relies on integrating condition information from the use phase, such as thermal loads, vibration exposure, operating cycles, and fault histories, because key components including magnets, hairpin windings, insulation systems, and bearings are difficult to recover and highly sensitive to prior loading and degradation mechanisms [7].

The EoU phase is central to techno-economic and environmental assessment. EoU testing, including insulation resistance, torque–speed evaluation, vibration-based bearing diagnostics and thermal analysis, provides the empirical basis for assessing technical condition, determining remanufacturing potential and feeding back into design, quality assurance and lifecycle optimisation. Sustainable traction motor systems therefore require systematic integration of production, operation, EoU testing and remanufacturing within a consistent, AAS-based, traceable information model. [7]

3. The FOREST Digital Twin Framework

FOREST (Framework for Resource, Energy, and Sustainability Treatment) is conceived as a domain-agnostic, yet industry-proven, digital twin architecture for energy and CO_2eq management. It provides a structured way to connect heterogeneous data sources, semantic asset models and executable simulations to generate actionable indicators and decision support services. While it has been developed and validated initially in tissue production, its concepts are deliberately formulated in a way that allows transfer to other manufacturing domains [10,11,13].

3.1 Objectives and Scope

The primary objective of FOREST is to enable real-time and historical analysis of energy and CO_2eq performance at asset, line and product level, and to support scenario-based evaluation of technology and operating changes. Concretely, the framework aims to

- capture and harmonise production, energy and quality data from existing automation and IT systems,
- map these data onto asset-centric semantic models that represent the structure and behaviour of the production system,
- couple the semantic models with executable simulation units to explore alternative configurations and operating windows, and

- derive key performance indicators for energy use and CO_2eq emissions, suitable for operational guidance and external reporting.

In doing so, FOREST explicitly targets use cases such as root-cause analysis of energy deviations, identification of best-practice operating windows, evaluation of electrification, and assessment of product-specific footprints along different routing options or life-cycle scenarios.

3.2 Architectural Layers and Data Management

FOREST is conceived as a gate-to-gate, mill- or line-level advisory framework. It links process data, engineering models and energy and CO_2eq accounting, while remaining deployable in existing brownfield environments, modular, evolvable and economically viable. Monolithic one-off solutions and purely cloud-based system landscapes are therefore excluded. Instead, a layered microservice architecture is adopted in which FOREST is decomposed into a small set of coarse-grained services that can be deployed, scaled and updated independently.

The services follow the responsibility clusters data acquisition and integration, semantic modelling and asset management, simulation and scenario analysis, energy and CO_2eq calculation, and visualisation and decision support, complemented by cross-cutting services and tools. Each service owns its data and exposes a stable interface. The services are arranged in layers that separate core data and semantics, analytical services and user-facing decision support, as depicted in Figure 1, in line with the entity-based digital twin reference model for manufacturing [30]. An AAS-based semantic layer and Functional Mock-up Unit (FMU)-based model integration are employed so that assets, data sources and simulation models can be linked consistently across services [31]. The layers can be distinguished as follows:

1. **Data acquisition & semantic modelling and asset management**: The need to connect control systems and production IT, and to cope with high-frequency signals and inconsistent tag naming, calls for a data integration layer with connectors, buffering, and basic data quality services. Requirements for a consistent representation of machines, sections, sensors and energy systems result in AAS based asset models and an asset registry that provide a shared semantic layer and enable reuse of digital twin descriptions.
2. **Simulation and scenario analysis**: Requirements for offline and online studies of speed changes, retrofits and energy supply options lead to a simulation engine that loads and executes FMUs, manages parameter sets and orchestrates multi model scenarios.
3. **Energy and CO_2 calculation**: Requirements to convert energy flows into CO_2eq indicators under different system boundaries lead to a dedicated energy and emissions calculation service.
4. **Visualisation and decision support**: Requirements for dashboards, key performance indicators, operator guidance and reporting lead to a visualisation layer with interfaces for web dashboards, reports and external applications.
5. **Services and tools**: Requirements for configuration, exploration and integration lead to supporting components such as explorers, data services, optimisation tools and message brokers that interact with all layers and extend the FOREST core for specific tasks.

Supporting services and tools implement data management and governance, configuration management, user management and technical infrastructure functions. The figure also shows how the FOREST services interact with existing shopfloor and enterprise systems as well as external energy-market data sources via secure data connections, thereby preparing the architecture for integration into IDS.

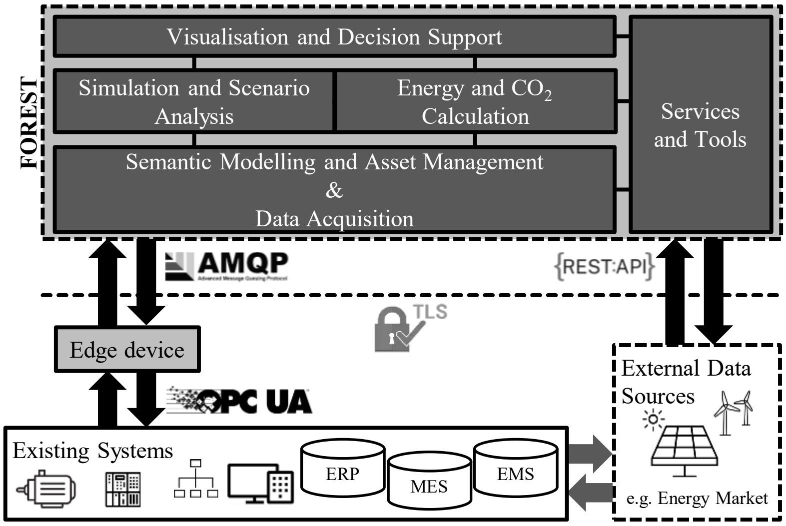

Figure 1: FOREST architecture with layered services

3.3 Domain-Independent Patterns

A set of domain-independent patterns can be abstracted from Figure 1 that enable the transfer of FOREST from paper manufacturing to traction motor manufacturing and data-space-based EoU services:

Flow and state tracking across assets and time, in which material, energy and footprint flows are represented consistently along the process topology and associated with operating states and events. In continuous paper production this corresponds to mass and energy balances across sections, whereas in traction motor assembly it corresponds to component- and process-step tracking along alternative routing variants and test stages.

Asset-centric semantics, realised by AAS-based asset models and the asset registry. This establishes a shared, machine-readable language for internal and cross-organisational applications. It can be used when a traction motor producer exposes product and process twins into a federated data space or when an EoU test service consumes lifecycle data to derive remanufacturing or recycling recommendations [16,17].

Co-execution of models and decision-support services. Data streams from the acquisition layer are coupled with FMU-based and data-driven models as well as with calculation services via stable interfaces. In paper production, this allows energy demand and CO_2eq effects of alternative drying concepts or energy supply options to be estimated. In traction motor production, analogous configurations can estimate residual lifetime, remanufacturing effort or CO_2eq impacts of different R-strategies [21] based on combined production, usage and EoU test data.

Taken together, these patterns show that the FOREST architecture is not limited to a specific process type but can act as a reusable digital-twin backbone that can be instantiated across continuous and discrete domains and prepared for secure integration into IDS.

4. Data Spaces

Building on the architectural patterns described above, this section positions IDS as the federated environment in which the FOREST framework can extend its functionality beyond plant-level optimisation. While FOREST harmonises operational, energy and CO_2eq data through semantic asset models, data spaces provide the decentralised infrastructure required to make these information assets securely available to downstream lifecycle services.

Current manufacturing IT landscapes are characterised by fragmented systems, bilateral interfaces and limited interoperability, which hinder the integration of operational and environmental data across organisational boundaries [32–34]. Data spaces address these limitations through decentralised architectures, shared governance and interoperable standards that enable sovereign data exchange across value chains [35,36,17]. In this context, the AAS functions as a semantic interoperability layer, allowing FOREST-generated indicators, events and models to be exposed in a machine-readable and standardised form [15,20].

Established reference architectures, such as the IDS RAM with its security, certification and governance perspectives [12] and the Data Spaces Support Centre (DSSC) building blocks for identity, metadata and connector services, provide the structural basis for integrating FOREST into federated data ecosystems (see Figure 2). Through these components, production data and derived indicators can be shared with lifecycle applications without compromising data ownership or confidentiality.

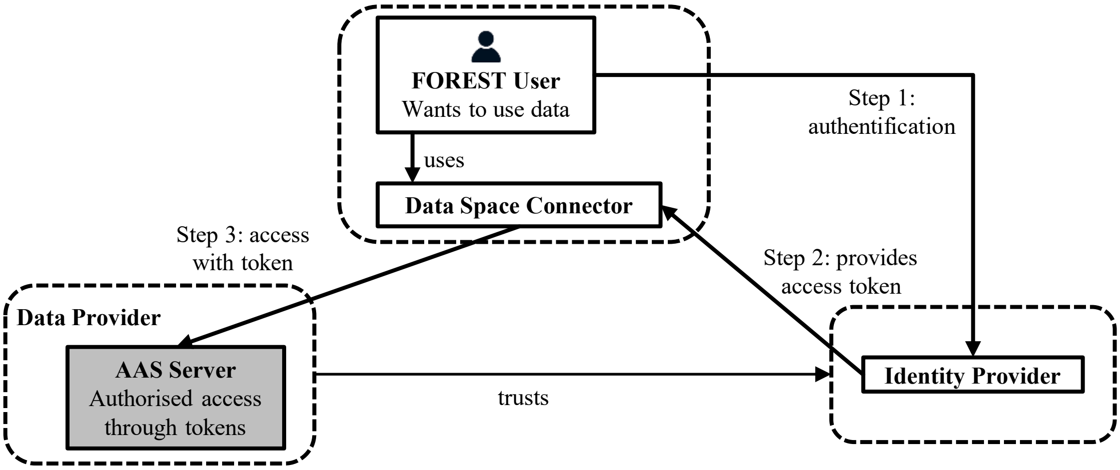

Figure 2: Conceptual integration of FOREST and AAS-based twins into an IDS

For the traction motor EoU test, data spaces enable the controlled combination of production, quality and material data with lifecycle-relevant information to derive robust R-strategies. Requirements regarding data quality, semantic consistency and reproducible calculation rules ensure that CO_2eq and performance indicators remain trustworthy when transferred between actors [18].

In this role, data spaces operationalise the cross-domain transfer envisioned in this paper: they create the conditions under which a generalised digital twin framework like FOREST can support both operational guidance in manufacturing and lifecycle-oriented decision-making in traction motor manufacturing. In this context, FOREST can be seen as a service of the data space platform.

5. Conceptual EoU Testing in Traction Motor Production Using FOREST Patterns

In the traction motor context, FOREST is applied through a pattern instantiation rather than by transferring a fibre-specific solution. The goal is to consistently link product identity, process and quality states, and energy/CO_2eq indicators across multi-stage manufacturing chains, for example for permanent magnet synchronous machines manufactured with hairpin technology. The three patterns structure this mapping. Flow and state tracking relates material and energy flows to process events and quality states across stations and batches. Asset-centric semantics represent motors, components, and test artefacts as interoperable, AAS-based digital twins with shared identifiers and controlled vocabularies. Co-execution couples these semantic representations with simulation and analytics services to compute derived indicators and support scenario-based assessments.

EoU testing is treated as a lifecycle event that generates decision-relevant evidence for value retention. Typical test sequences include insulation resistance measurements, torque-speed characterisation, vibration-based bearing diagnostics, and thermal measurements. These signals become decision-relevant only when contextualised with manufacturing and usage history. Relevant context includes component genealogy, process deviations, quality gates, repairs, and operating conditions. In the proposed architecture, this linkage is realised through AAS-described data structures and governed data exchange via IDS. This enables role-specific and cross-organisational access without centralising data.

Decision-support services are parameterised by EoU findings and contextual histories to evaluate value-retention pathways such as remanufacturing, component reuse, and recycling. The same service layer can estimate associated effort, expected residual lifetime, and feasibility constraints. It can also quantify comparative CO_2eq impacts. The focus therefore extends from production-only optimisation to lifecycle-integrated assessment, while retaining the same architectural interfaces and pattern logic.

To illustrate the quantitative impact of the proposed approach, a representative traction motor scenario is considered. Life-cycle assessment studies on electric traction motors and remanufactured electrical machines show that manufacturing-related impacts can amount 300–500 kgCO_2eq [37], while remanufacturing can substantially reduce these emissions; for example, one study reports emission reductions of 26.75% to 65.13% depending on the remanufacturing case [38]. This implies that, depending on the dedicated assessment conducted during the end-of-use testing phase, a substantial potential for CO_2 savings can be achieved. In particular, significant reductions are possible when complete components, such as the magnet-equipped rotor, which is associated with a high carbon footprint of approximately 250 kgCO_2eq [39], can be reused following the replacement of wear-prone elements such as bearings.

6. Discussion

The results from the tissue pilot and the traction motor EoU service illustrate that the digital twin framework originally developed for fibre-based web production can be generalised to a discrete manufacturing domain and integrated into data-space-based infrastructures. The three patterns from the tissue implementation, namely flow and state tracking, asset-centric semantics and co-execution of models and services, are transferable to traction motor production and EoU services. However, domain-specific specialisations such as magnet composition, insulation systems or dedicated test submodels remain necessary.

Embedding FOREST into IDS highlights the central role of standardisation and governance. AAS-based semantics and IDS connectors provide a solid interoperability stack yet deploying them in brownfield environments remains effort-intensive due to modelling, connector setup, and data governance, which can be especially challenging for SMEs. The EoU service concept illustrates how plant-level twins can support lifecycle decisions such as R-strategy selection and product carbon footprint communication, but practical rollouts must address incomplete data and organisational barriers to cross-company sharing. Hybrid approaches that combine model-based estimation, partial measurements, and expert knowledge will therefore often be necessary. Overall, FOREST can connect shop-floor optimisation with lifecycle services, provided interoperability, semantics, and governance are developed and maintained.

7. Conclusion and Outlook

The FOREST digital twin framework is conceptually adapted from fibre-based web production to discrete manufacturing and lifecycle services. It is achieved via three reusable patterns, namely flow and state tracking, AAS-based asset-centric semantics, and co-execution of models and services. The framework is instantiated for traction motor manufacturing and EoU testing in an IDS context to link operational indicators with lifecycle diagnostics for value-retention decisions and CO_2eq assessment.

Key remaining challenges concern the effort required for AAS-based semantic modelling, IDS-compliant connectors, and governance in heterogeneous brownfield environments. Future work will focus on industrialisation and scaling. This includes traction-motor-specific AAS submodels, integration with MES and quality and test infrastructures, and validation using representative motor populations. In parallel, hybrid physics- and data-driven methods under incomplete data will be investigated, together with additional domain applications and alignment with product carbon footprint and digital product passport regulations.

Future work should operationalise this instantiation through implementation of traction-motor-specific AAS submodels (product, process, test, and condition-history). This includes integrating existing MES/quality/test infrastructure and connector-based provision within an IDS-compliant data space. In addition, calculation rules for lifecycle- and remanufacturing-related indicators are defined and validated under conditions of incomplete data. The approach is evaluated on representative motor populations. The evaluation considers integration effort, runtime performance, and decision-quality impacts compared with baseline EoU testing workflows.

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Biography

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Florian Pohlmeyer (*1998) has been a Research Associate at the Institut für Textiltechnik (ITA) of RWTH Aachen University. Additionally, he has been the Head of Digitalisation at the ITA since 2023. His main areas of expertise include data ecosystems and sustainability in the fiber-based process industries with a special focus on transformation processes in small and medium-sized enterprises

Jürgen Fleischer (*1961) obtained his doctorate at the Institute of Production Science (wbk) in 1989. From 1992 on, he held several leading positions in industry before being appointed professor and head of the wbk at today's Karlsruhe Institute of Technology (KIT) in 2003. His current scientific research focuses on intelligent production machines and components, the automation of immature processes and agile production systems.

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