

# From Tacit to Explicit: Using Live Documentation and Feedback Loops to Facilitate Knowledge Transfer

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**Abstract:** The preservation and structured use of tacit knowledge (TK) is a critical challenge in industrial environments contending with increasing automation and a skilled labor shortage. The loss of undocumented expertise, especially in circular economy applications such as disassembly processes, threatens process efficiency, adaptability and quality. This paper presents a knowledge management approach that combines industrial engineering methods with Industry 4.0 technologies to capture and integrate TK into semiautomated disassembly systems digitally. Taking Fraunhofer IFF's iDeaR project as a case study, a demonstrator is developed to document and convert experts' actions during PC disassembly into machine-readable formats. The approach integrates live documentation, feedback loops and digital twins to systematically capture contextual problem-solving strategies, enabling their reuse and continuous learning in technical systems. Tacit knowledge is structured using a dedicated Asset Administration Shell (AAS) submodel, comprising situational context, problem description, solution, guidance and benefit. This facilitates contextual reuse across diverse scenarios. The demonstrator architecture links captured knowledge with product, process and resource twins and provides context-sensitive support through modular software applications. Expert-reviewed feedback loops transform raw data into validated disassembly instructions, checklists and training content. A user-friendly interface facilitates intuitive data entry and practical applicability in industrial settings. Results from a workshop-based analysis of disassembly steps confirm that both implicit and explicit knowledge can be meaningfully structured and evaluated for automation capability. The approach preserves expertise, enhances organizational learning and contributes to more adaptive, error-resistant processes. Future developments include AI-assisted storytelling and enhanced sensor integration to further improve feedback quality and reduce editing. This paper thus contributes to the design of intelligent knowledge systems for (semi)automated environments and highlights the value of digital knowledge models in industrial transformation.

**Keywords:** Knowledge transfer, Knowledge preservation, Tacit knowledge, Industry 4.0 technologies, Circular economy, Automated disassembly, Live documentation, Feedback loops

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## 1. Introduction

The preservation and transfer of tacit knowledge (TK) are vital for companies to ensure long-term efficiency, quality and innovation. Industrial settings in which complex machinery and processes require extensive expertise particularly raise the question of how to document and utilize such valuable knowledge sustainably. The growing skilled labor shortage and demographic change are further increasing this challenge: Experienced employees leave companies and qualified replacements are often scarce, creating a risk that knowledge accumulated over years may be lost (Ottersböck et al, 2024).

One particularly complex issue is the transition from implicit to explicit knowledge. Systematic methods must be used to transfer implicit knowledge and structured accessibility to semiautomated processes must be ensured. This is especially true of disassembly processes, which are growing increasingly important in the circular economy (Saenz et al, 2024). Product reuse and recycling require efficient disassembly strategies based on experts' TK. Failure to preserve specific knowledge entails the risk of losing specific operational knowledge and problem-solving strategies and consequently not integrating them into future process chains (Polany, 1985).

Ongoing technological advances are necessitating targeted actions that impart hitherto elusive TK of disassembly processes to new employees while simultaneously preserving departing experts' knowledge. The combination of industrial engineering methods and advanced Industry 4.0 technologies offers novel opportunities to capture, document and leverage knowledge in real time.

Taking Fraunhofer IFF's intelligent Disassembly for Remanufacturing and Recycling (iDeaR) project as an example (Fraunhofer IFF b, 2025), this paper shows how expert knowledge from disassembly processes can be systematically captured and digitally formatted. A key element of this approach is the use of digital twins—virtual models that mirror real disassembly workflows and serve as structured knowledge agents. Digital twins can continuously incorporate practical experience and human actions, making them usable for future applications. This makes tacit knowledge part of a shared, data-based knowledge base that enhances process efficiency and facilitates learning in automated environments.

## 2. Research Background and Theoretical Framework

This section establishes the thematic and project-specific framework to highlight the study's relevance and objectives. Key concepts of and developments in knowledge management are subsequently explored in the context of automated work environments, focusing on live documentation approaches and feedback loops for organizational learning and the use of digital twins.

### 2.1 Thematic Framework

Numerous industries use automation in parts of the disassembly process, but such automated systems are often limited to specific product types and lack flexibility (Saenz et al, 2024). The iDeaR project is addressing this issue by enabling adaptative disassembly of diverse items such as electronic waste. To do so, it is drawing on Industry 4.0 technologies, such as digital twins and real-time data systems, to facilitate knowledge-driven automation.

Key challenges, aside from wide product variety, that make great demands on flexibility include automated product evaluation and adjustment of disassembly depth, the integration of tacit knowledge, the incorporation of experiential knowledge, the establishment of a knowledge base and the transferability of the methods developed to other use cases. The evaluation process determines if and to what extent a particular product is disassembled. Market demand for reusable components, raw materials, plant costs and availability and the carbon footprint of disassembly are consequently included in the evaluation. Disassembly steps are automatically adapted and performed based on this evaluation.

Tacit knowledge is essential for adapting disassembly processes, managing manual actions and solving problems whenever automated systems experience errors. A key element of this is the *disassembly sequence*—a step-by-step procedure that defines how a product is taken apart. Such sequences often rely on practical experience and are refined by hands-on problem-solving. To preserve and reuse such knowledge, information on items, processes, resources and expert actions must be collected in a structured knowledge base. Digital tools such as interconnected disassembly twins and appropriate software systems are needed to ensure data consistency.

### 2.2 Tacit Knowledge and Its Role in Automation

Even though it is difficult to formalize, tacit (or implicit) knowledge acquired through experience and embedded in practical routines is essential for automated work environments. This section defines tacit knowledge and explains why its integration into technical systems requires specific strategies beyond conventional documentation. The goal is to preserve valuable knowledge and structure it for machine accessibility and readability.

Explicit knowledge provides the formal basis for work processes (e.g., instructions or documented information), whereas implicit knowledge acquired through years of practical experience is often intuitively applied without explicit documentation. Explicit knowledge sourced from manuals or training programs is more accessible and easily transferable. Implicit knowledge's deep integration in specific machines, processes and corporate cultures make it indispensable to automated work environments (Polany, 1985).

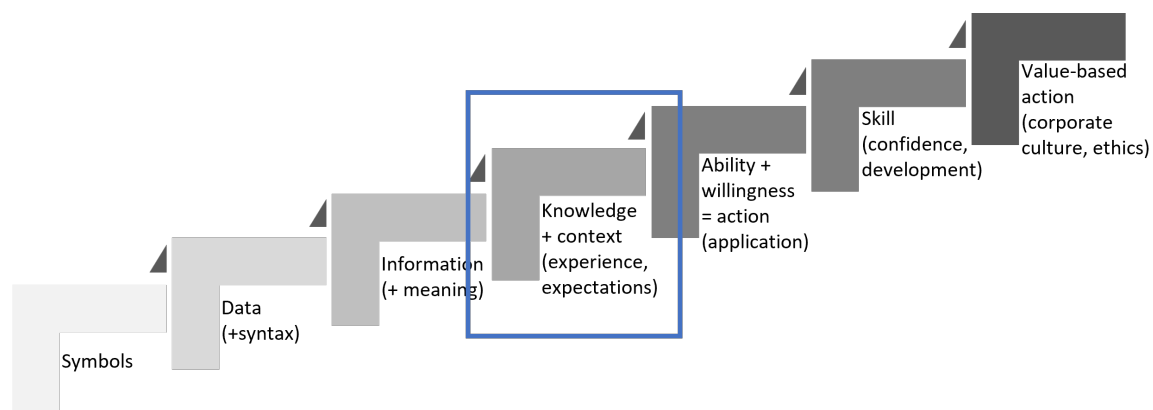


Figure 1: Stepped information processing model (Reisach et al, 2025)

Human expertise and everyday work practices are far more challenging to capture than machine data that are automatically recorded in structured formats such as sensor data logs (BIDT, 2021). Tacit knowledge, on the other hand, is often concealed in routines and difficult to articulate. All the same, making this kind of knowledge usable in automated environments is becoming increasingly important (Reisach et al, 2025). Narrative methods

such as storytelling or triadic conversations, a specific form of guided conversations, offer promising ways to transfer TK by conveying not only facts but also the reasoning and decision-making behind them.

Research stresses the irreplaceability of humans as knowledge agents, even in an increasingly digital world, and the need for technological support. Designing user-friendly human-machine interfaces is crucial: They must facilitate learning, be intuitive to understand and facilitate decision-making in complex situations, particularly when human TK is integrated into digital processes (BIDT, 2021).

### **2.3 Live-Documentation as a Capture Strategy**

Live documentation techniques make it possible to capture tacit knowledge, even though it is often unstructured. This section presents technological approaches and practical implementations of live documentation, emphasizing their role in preserving expert knowledge during disassembly processes.

Practical methods of live documentation include technologies such as IoT sensors, internet-connected devices that collect and transmit real-time data continuously, and automated image analysis and data capture systems. In logistics, for instance, employees can use mobile devices to send live images of damaged goods to central systems, improving both the speed and accuracy of tracking (Flicono, 2025). In manufacturing, embedded real-time systems help monitor and prioritize processes, reducing disruptions and keeping product quality consistent (Intel 2025).

Live documentation is particularly valuable in the circular economy, where the goal is to keep products and materials in use for as long as possible through reuse, remanufacturing or recycling. In disassembly processes, it enables the continuous capture of data on the condition of parts, helping recover valuable components and avoiding unnecessary waste (Fraunhofer IFF, 2025; Solarify, 2025). Research projects such as Fraunhofer IFF's iDeaR project demonstrate how sensors and camera systems can supply data to digital twins. Such digital twins serve as structured knowledge agents, enabling robot systems to react to changes flexibly while also preserving employees' knowledge for future tasks.

Clausthal University of Technology (TU Clausthal) is using automated disassembly cells to guide robots based on real-time tracking of components' location and condition (WissenhochN, 2024; TU Clausthal, 2024). Similarly, recycling facilities use live data, collected by various technologies, to manage material flows and recover resources more efficiently (Brother, 2020).

Overall, live documentation improves transparency, adaptability and long-term knowledge retention. Technical and organizational challenges remain, though, especially in terms of data quality, system compatibility and the training of employees to work effectively with such tools (Fraunhofer IFF, 2025; WissenhochN, 2024; Solarify, 2025).

### **2.4 Feedback Loops for Organizational Learning**

Feedback loops make captured knowledge actionable by systematically integrating practical knowledge into organizational processes. According to Willke (2001), organizational learning results when individual experiences are structured and embedded into routines. In keeping with this, feedback mechanisms enable continuous improvement and facilitate the integration of tacit knowledge into adaptive, semiautomated systems. A feedback loop is a cyclical mechanism that reintegrates operational knowledge (e.g., disruptions, effective solutions, manual adjustments) into system development or process design. Such feedback processes enable continuous adjustments consonant with single-loop learning in which routines are optimized to prevent recurring problems. Conversely, double-loop learning aims for more far-reaching structural changes. Underlying assumptions and strategies, such as those that guide automated approaches, are examined critically and revised (Argyris and Schön, 1978). Digital technologies, including IoT sensors, digital twins and AI-based analyses, significantly enhance this learning process, boosting organizational adaptability and resilience. Challenges include data quality and user acceptance of feedback systems.

Feedback loops are instrumental to the development of adaptive, learning-capable systems, strengthening organizational resilience by systematically integrating TK into technical systems.

### **2.5 Digital Twins as Knowledge Integration Platforms**

Tacit knowledge must be embedded in structured digital representations to make it accessible for automated applications. Digital twins—virtual replicas of physical objects, products or processes—serve as dynamic knowledge agents that enable real-time monitoring, analysis and contextual reuse of data and knowledge (Firstlignite, 2025; Fraunhofer IFF a, 2025). They are already widespread in industrial practice as interfaces

between physical and digital realms and play a key role in both process optimization and knowledge preservation. This section explores how digital twins can be used as integration platforms for TK, focusing on their role in facilitating interoperability and standardization in knowledge-based disassembly processes. Digital twins integrate various digital tools and standards. The Asset Administration Shell (AAS), as defined in IEC 63278-1:2022-07, is on such standard for a unified information model. It enables consistent data storage and easy integration into existing IT systems (Fraunhofer IFF a, 2025). Industrial Digital Twin Association (IDTA) standards enhance specific submodels' interoperability and data exchange (Newroom Connect, 2024; Kem, 2023).

Practical benefits of digital twin technologies include enhanced interoperability and streamlined integration through standard data models, enabling consistent data management and facilitating knowledge sharing, such as recording disassembly instructions and optimizing processes using real-time data (Gabor et al, 2020). Significant challenges remain, though, particularly in terms of data quality, system integration complexity and the work required for initial implementation (BMDV, 2024). Strategies, such as phased implementation and modular platform architectures, help companies overcome these hurdles (BVMW, 2025).

### 3. Methodological Development of the Demonstrator

The following section outlines the implementation of a demonstrator that operationalizes live documentation, feedback loops and digital twin models based on the theoretical concepts presented in section 2. This technology demonstrator focuses on knowledge digitization and preservation, demonstrating how tacit knowledge can be captured digitally and embedded into a network of digital twins for utilization in an Industry 4.0 environment.

#### 3.1 Concept

Wide product variety will inevitably result cases in which a product differs to such an extent that certain disassembly steps are not yet automatable. Such instances cause an error occurs in the disassembly system that requires manual action be taken by staff.

The first objective is to clear the blockage in the disassembly system. Staff sees whether the problem can be resolved on-site so that the system can resume operation right away or the component must be taken out and disassembled manually. The second objective is to document the manual action to automate it in the future or to plan and expedite the manual disassembly step with the aid of the knowledge base. Digital twins based on interconnected AASs for products (PC), processes (disassembly), resources (e.g., robots) and TK make contextual knowledge transfer and capture modules possible (Figure 2).

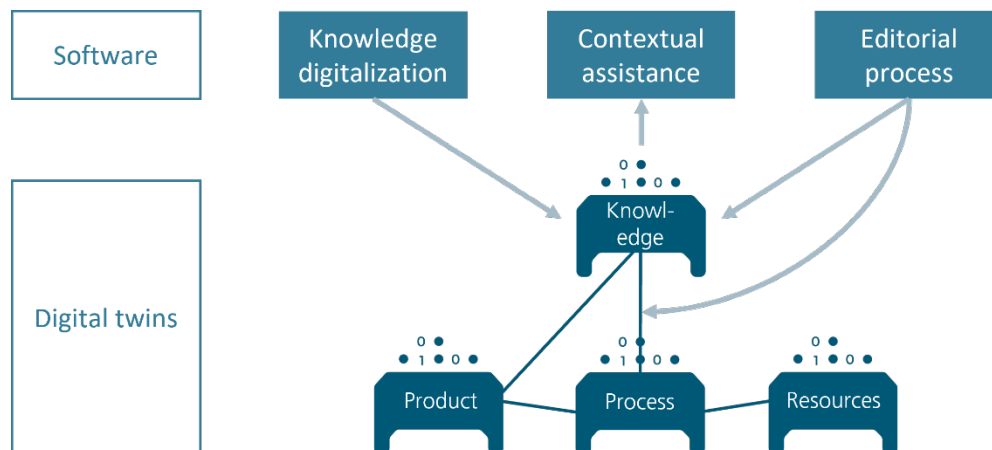
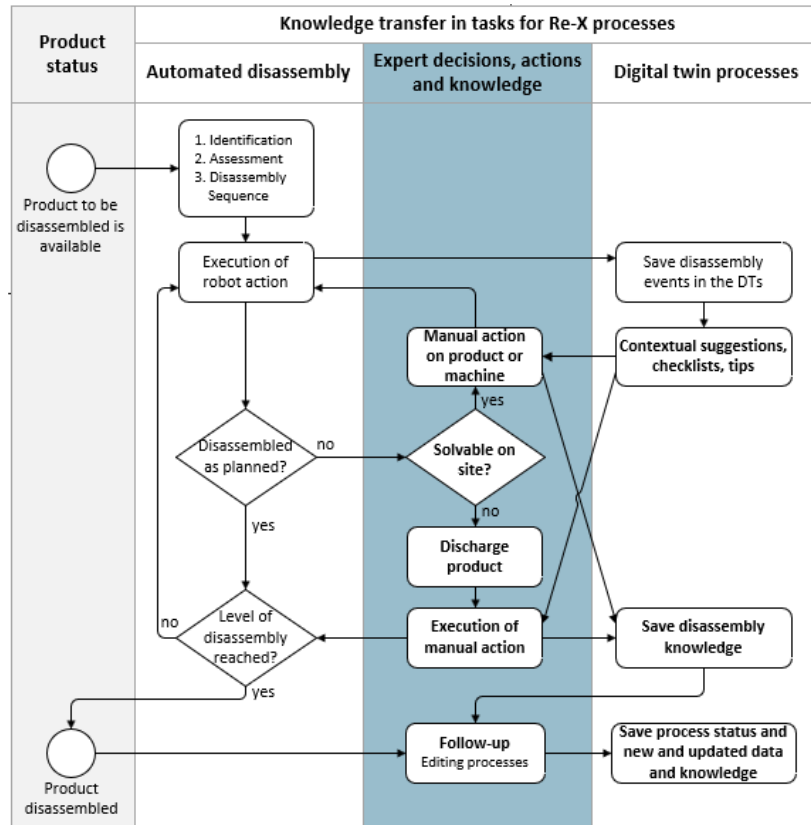


Figure 2: Software components and digital twins of the demonstrator (created by the author)

#### 3.2 Scenario Process Description

On-site problem resolution is employed when a quick solution will enable the system to resume operation. Two cases are considered: In the first case, the system requires an adjustment to resume operation (because of incorrect disassembly tooling). A worker selects the correct tool, enabling the system to resume operation. In the second case, the system cannot perform a specific disassembly step automatically (because of tool unavailability or limited robot capabilities). A worker performs the required manual action on the product, enabling the system to resume operation.



**Figure 3: Swimlane flowchart of knowledge transfer in disassembly processes, based on Saenz et al, 2024 with boldface additions by the author. The automated disassembly process has been condensed**

Components are removed from the automated process whenever on-site diagnostics require shutting down the system for an extended period. In such a case, staff perform the necessary manual disassembly steps at a separate work cell. Once they have finished, the PC is either returned to the automated disassembly system or the disassembly process ends at that point.

In both cases, an expert makes decisions based on their own tacit knowledge and the system's contextual suggestions and checklists (Figure 3). The expert performs manual disassembly steps and records new knowledge. This new knowledge is stored as raw data and is immediately available for future disassembly tasks (live documentation). An editing process follows to enhance the knowledge's value and ensure its quality. Experts edit the content and compile adapted disassembly sequences, checklists and notes (feedback loops), which are then integrated into the proper digital twins.

## 4. Technological Implementation

This section outlines the planned technological implementation of the demonstrator described in section 3. The following sections present the central elements of the implementation plan, beginning with the determination of an appropriate disassembly depth, continuing through the integration of TK into digital submodels and concluding with the planned implementation of the complete system with software support.

### 4.1 Determining the Depth of Automated PC Disassembly

An interdisciplinary workshop was conducted in the iDeaR project to determine the depth of automated disassembly of a DELL i5 OptiPlex 3010 PC as a case study. The objective was to capture explicit and implicit knowledge systematically and to assess the automation capability of individual disassembly steps.

The workshop centered on the structured documentation of each disassembly task, such as rear cover removal, graphics card extraction and cable detachment, factoring in time requirements, component weights and manipulation techniques. The analysis combined domain expertise with practical knowledge. Particular emphasis was placed on component accessibility and fasteners. Plug-in, screw and tool-free fasteners were determined to be well-suited for robotic systems, whereas glued or highly stressed parts require manual action. Only four screws secure the SSD, for instance, making it an ideal candidate for automation. Conversely, cable

removal remains a largely manual activity because it is difficult for robotic manipulation but trivial for human workers.

Altogether five out of ten standardizable disassembly substeps were classified as highly automatable. These results were included in a criteria package intended to serve as the basis for the evaluation of future disassembly processes. Explicit knowledge assets, such as CAD models and digital process models, were incorporated as well. The workshop additionally targeted unskilled operators: The documented tasks were worded to be easily understood and safe to perform with the aid of digital assistance systems.

**Table 1: Core workshop results**

| Core Result                                                       | Description                                                                                    |
|-------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Documentation of individual disassembly steps                     | All disassembly substeps were documented using explicit and implicit knowledge                 |
| Assessment of individual disassembly steps' automation capability | Automatable disassembly steps were identified based on manipulation, variability and fasteners |
| Consideration of target user group                                | Disassembly steps were worded to be easily performed by unskilled operators                    |

The workshop results are the basis for model-based implementation in the digital twin (section 4.2) and provide essential information for the software architecture (section 4.3).

#### **4.2 Digital Twin Submodels**

As explained in section 3.1, one goal is to transfer tacit knowledge to an Asset Administration Shell. A specific submodel for TK must be developed to do this. Our approach for the submodel is based on a structure proposed by Mittelmann et al (2023), comprising context, task description, solution approach, conflicts, pitfalls and references. These elements are present in the submodel as follows:

- Situation: Description of the situational context in which the problem occurred (e.g., product configuration, process status, resource status)
- Background: Contextual information such as technical dependencies or previous experiential data
- Problem: Description of the disruption or problem encountered in the process
- Solution: Documentation of the measure taken to resolve the problem
- Guidance: Step-by-step instructions for implementing the solution
- Benefit: Indication of the value added by the solution (e.g., time savings, error prevention)

Digital twins that utilize this submodel are linked with other digital twins in the system, such as those for products, processes, or resources (Figure 2). This enables targeted contextualization and reuse of TK across different application scenarios, covering access and disassembly sequences, status and process data, notes, checklists and training content.

#### **4.3 Software**

To actually transfer knowledge, an employee interacts with software that uses the structures and data of the Asset Administration Shell in the background. The modular software architecture comprises multiple applications customized for specific workflow steps and user groups. Established software platforms, such as Eclipse BaSyx (BaSyx, 2025) and KIWI's Artificial Intelligence Framework (KIWI, 2022) are employed to enable seamless integration of the AAS. These applications facilitate end-to-end linkage of tacit knowledge with components' digital twins, ensuring targeted delivery of information in the appropriate context. The underlying architecture is built around three functional areas, presented in Figure 2:

- Knowledge digitization: This module systematically captures TK. Data is entered in user- and context-specific forms, such as standardized input fields for problem statements, solution approaches, action steps and benefit evaluations. Unique assignment of these data to components, process steps or resources is essential for subsequent reuse in the complete system.
- Contextual assistance: This module provides specific guidance and recommendations. A user-friendly interface automatically displays content based on documented TK contextually. Automatic linking of these instructions to the proper digital twins (product, process, resource) directly supports practical implementation.

- Editing process: This module is used to edit and release captured knowledge. An expert validates, contextualizes and approves content on disassembly. The goal is to use AI methods to automate validation and contextualization further, thus reducing manual editing.

The prototype software is currently focused on efficiently representing, structuring and transferring knowledge to digital twins. The user-friendliness of the input interfaces is critical to acceptance and sustained use of the solution. Emphasis is additionally being placed on smooth integration of the modules into existing IT architectures to ensure practical utility and industrial applicability.

## 5. Conclusion and Outlook

This paper outlined key features of a demonstrator that uses feedback loops and live documentation to digitize and leverage tacit knowledge in industrial settings. It described the role that digital twins play and provided an overview of a possible technical implementation. Studies demonstrate that a structured knowledge management approach employing digital twins can document TK and make it available for future processes in the form of operational guidance, tips and tricks. Continually upgrading the digital twins during use optimizes the automation process in the long term and gradually reduces manual actions. Editing preserves and makes existing TK accessible. The prototype demonstrator designed has already yielded valuable insights into the automation capability of disassembly steps.

Refinement of the prototype for AI-assisted storytelling and the integration of related methods into a software solution such as EverAssist (Keller et al, 2022) are promising next steps AI-assisted storytelling would take interaction with a system that digitizes TK to a new, more intuitive level. Moreover, AI methods could be used to generate proposed instructions and actions automatically during editing. Further of sensing technology and intelligent systems to record live data more accurately and further enhance the quality of feedback loops is also conceivable.

The approach presented allows directly linking tacit knowledge with the proper digital twins, facilitating the creation and refinement of disassembly sequences (Poenicke et al, 2025). Experiences from disassembly enter directly into the adaptation and refinement of disassembly sequences.

These developments are intended to contribute in the next steps of the iDeaR and other Fraunhofer IFF projects to making the entire process of capturing, linking and applying knowledge possible in automated systems, based on standards such as the Asset Administration Shell. In the long term, this will reduce both workers' error rates and manual labor.

**Ethics declaration:** No ethical clearance was required for the research presented in this paper. Since the study did not involve human or animal subjects or the collection of sensitive or personal data, approval from an ethics committee was needed.

**AI declaration:** An AI tool (Fraunhofer Gesellschaft's FhGenie) was used during the development of this paper for minor tasks related to structure and translation. Specifically, the tool helped the author rephrase and organize certain sections more clearly and translate select passages from German to English. All content generated or revised with the help of the AI was carefully reviewed and edited by the author to ensure accuracy, coherence and academic integrity.

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