



prostep ivip Association

ProductData Journal

2026-1

Magazine for members



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Artificial Intelligence in Product Development: A Systematic Path from Potential to Industrial Practice

Between Momentum and Reality

The debate around Artificial Intelligence has gained considerable momentum in recent years. What was long regarded as a promise for the future has now arrived in many areas of industrial value creation – albeit often in the form of numerous, only loosely connected individual initiatives. Product development, too, offers compelling applications, for instance in the analysis of complex test data or in requirements management. At the same time, the picture is a nuanced one: while individual initiatives are achieving remarkable progress, the systematic use of AI at scale remains the exception. Identifying the right path also remains challenging—encompassing both an understanding of what is genuinely fit for purpose and the practical questions of implementing individual tools and putting them to operational use.

This brings a central question into focus: how can existing potential be translated into scalable industrial practice? Unlike traditional process management, the challenge here extends beyond the use case or process step to include the question of data – and that of the best-suited models.

The need arises from the very nature of product development. Today's products are highly complex, interconnected systems whose development is shaped by growing variant diversity, shorter innovation cycles, and expanding volumes of data that are often poorly structured – or increasingly so. Classical engineering methods remain indispensable, yet they are increasingly reaching their limits. This is where Artificial Intelligence can act as both support and extension – unlocking large data spaces and enabling more well-founded decisions. At the same time, the question of how much structured data is still required is difficult to answer; the hope that the answer might be “none” is, in all likelihood, unfounded.

From Use Case to System

Across the product development process, there are numerous entry points for applying AI – from the concept phase and generative design through simulation and validation to the feedback of field data. And yet the industrial breakthrough has so far failed to materialize. The reason rarely lies in the models themselves, but rather in how they are embedded: AI is frequently piloted in isolated use cases, whereas genuine impact scales through better integration into processes, data (models), and the organization itself. While this is positive in that it generates progress, it is also, to some extent, driven by chance and isolated initiatives.

The decisive task, therefore, is to establish AI as an integral part of product development. This calls for end-to-end processes, consistent and interconnected data, and close integration with existing development environments. Equally essential are organizational structures that systematically foster collaboration between engineering and data science.

A Shared Responsibility of Industry and Research

Against this backdrop, my involvement in prostep ivip is, for me, far more than an organizational step – it is a matter of conviction. The prostep ivip association provides a forum and a community for working across industries on end-to-end solutions for digital product creation. I attended the symposia as a doctoral candidate and later during my time in industry, and I am delighted to be able to deepen that engagement once again.

It will be exciting to see how “we in academic research” can help to set the course for the future. Individual initiatives can – and indeed must – often move very quickly in industrial application, but a systematic, broad-based build-out with lasting, long-term impact frequently benefits from collaboration between industry and research. This is something I am keen to advance. Here, research can make a decisive contribution by laying the foundation for robust, industry-ready approaches.

Ultimately, the way we deal with AI in product development will prove to be not so much an optional competitive advantage as a fundamental capability. What matters is not whether companies adopt AI, but how consistently and systematically they do so. The conditions for this are something we must create together, today.

Prof. Dr.-Ing. Matthias Kreimeyer, Ingénieur ECP

University of Stuttgart
Institute for Engineering Design and Industrial Design (IKTD)
Member of prostep ivip Board

prostep ivip
Scientific Award -
for engineers focusing on
virtual product creation

**SCI
EN
TIF
IC**

AWARD
prostep ivip

Scientific Award

7

Are you a young engineer – and does your master/doctoral thesis focus on virtual product creation? Are you interested in introducing your ideas to representatives of leading manufactures and IT companies?

Here is your chance!

prostep ivip promotes tomorrow's PLM talents with €1,000 (master's thesis) or €4,000 (doctoral thesis) with the prostep ivip Scientific Award!

Who can apply for the award?

Any interested candidate who has submitted his/her diploma/master/doctoral thesis to a university by 31 January 2027 on a topic related to virtual product creation.

Theses written in German or English are eligible for submission, providing they do not fall under any conditions of non-disclosure. Please provide the graded thesis and the related opinion letter of the supervising professor.

The prostep ivip Scientific Award Jury will pick the winners from the submitted theses. The decision-makers include Dr. Henrik Weimer (AIRBUS), Prof. Dr. Matthias Kreimeyer (Universität Stuttgart), Thomas Kamla (Volkswagen), Tomohiko Adachi (Mazda Motor Corporation), Jens Poggenburg (AVL | Chairman of the Board) as well as Philipp Wibbing (UNITY).

In addition to the prize money (1,000 € master thesis or 4,000 € doctoral thesis), we offer the winner in the field of doctoral thesis the opportunity to become part of the prostep ivip symposium and to report on the results of their studies as part of the "Scientific Track". A unique chance to leave a lasting impression on an expert audience and thus potential future employers!

The closing date for applications for the Scientific Award 2027 is 31 January 2027!

Send us your graded work and the corresponding expert opinion:

Dr. Alain Pfouga, Managing Director prostep ivip Association
alain.pfouga@prostep.org

as well as

Nora Tazir, Technical Program Manager prostep ivip Association
nora.tazir@prostep.org.



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General Manager
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prostep ivip Association Elects New Board

At the General Assembly of prostep ivip e.V. in Frankfurt/Main on April 13, 2026 – the eve of this year's Symposium – the association held its regular board election. The assembly also marked a significant change in leadership.



From left to right:

Philipp Wibbing (Unity AG), Chairman of the Board Jens Poggenburg (AVL), Tomohiko Adachi (Mazda Motor Corporation), Thomas Kamla (Volkswagen AG), Prof. Dr. Matthias Kreimeyer (University of Stuttgart).

Not in the picture: Dr. Henrik Weimer (AIRBUS)

Transition in the Research and Universities Member Group

After 14 years of dedicated service as Board representative for Member Group 3 (Research and Universities), Prof. Dr. Rainer Stark (TU Berlin) passed his role to his successor, Prof. Dr. Matthias Kreimeyer of the University of Stuttgart. The prostep ivip Association extends its sincere gratitude to Prof. Dr. Stark for his long-standing commitment, scientific expertise, and invaluable contribution to the growth of the community. We are delighted to welcome Prof. Dr. Matthias Kreimeyer to the Board and are confident that his academic expertise and industrial experience will be a tremendous asset to the association. We wish him every success in his new role and look forward to a productive and forward-looking collaboration.

Existing Board Confirmed in Office

The remaining Board members were confirmed in their positions and will lead the association through the 2026-2028 term. The Board is composed of: Jens Poggenburg (AVL) as Chairman of the Board, Thomas Kamla (Volkswagen AG), Dr. Henrik Weimer (AIRBUS), Philipp Wibbing (Unity AG), Tomohiko Adachi (Mazda Motor Corporation), and newly elected Prof. Dr. Matthias Kreimeyer (University of Stuttgart). The Board will guide the association forward with drive, expertise, and a clear vision for the future.

Strategic Priorities 2026-2028

The Board has defined clear strategic priorities for the coming term: expanding membership in the MedTech and Defense sectors, and deepening the association's work on Artificial Intelligence – areas of central importance to the future of Systems Engineering.

Project HARMONIQ Launched!

Enabling flexible, automated and networked production systems – this is the focus of our new research project „HARMONIQ – Harmonising equipment behaviour representation enabling digital twins of production systems“. The research project, funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) under the WIPANO programme, commenced on 1 November 2025.

Together with our project partners CAIQ GmbH, the Institute of Production Systems at TU Dortmund University and RIF Engineering & Consulting GmbH (consortium lead), we are working to contribute to a complete and standardised description of production facilities and their components, with particular focus on the behaviour and status information of a facility's assets. This forms the basis for comprehensive data capture in production systems, real-time control of production processes and their flexible adaptability.

In addition to further developing and harmonising relevant standards such as the Equipment Behaviour Catalogue (EBC) or Asset Administration Shell (AAS), a central element of HARMONIQ will be the implementation of these standards in industrial practice. The focus is on capturing, prioritising and analysing industrial use cases to ensure that standardisation is consistently aligned with practical requirements.

A complementary project will be initiated as part of our Technical Programme – all members of the prostep ivip association are cordially invited to participate, contribute their own use cases, jointly advance interoperable standards for production, and exchange views on challenges in planning and operating digitalised production systems in a neutral, pre-competitive environment.

We look forward to your valuable ideas and input!
Would you like to participate or simply learn more?
Please contact Rachel Bauer!

Gefördert durch:



**Bundesministerium
für Wirtschaft
und Energie**

aufgrund eines Beschlusses
des Deutschen Bundestages



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The prostep ivip Media Library: A Treasure Trove of Knowledge for the Digital Age

Knowledge that drives progress – available for download at any time: the prostep ivip Media Library is one of the most comprehensive collections of practical working results, studies, and specialist publications on digital transformation, interoperability, and model-based engineering.

A broad selection of content is freely accessible to non-members – however, the full scope of the Media Library, including all documents and exclusive studies, is reserved for prostep ivip members. Following a one-time registration or log-in, the entire breadth of our association's work is at your fingertips. Register now: [prostep ivip: Registration](#)

What Awaits You

The Media Library consolidates the working results of more than 25 active project groups – from FAICE and LOTAR to CDT, HAIVISH, and CASCARA. These documents form the backbone of our association's work: methodically sound, industry-relevant, and immediately applicable.

For a full overview of all project groups and their respective focus areas, please visit: [prostep ivip: Projects](#)

Open to Dialogue

Would you like to explore specific project content in greater depth or engage in direct technical exchange? Our Technical Programme Manager Nora Tazir is happy to assist: nora.tazir@prostep.org

For any questions regarding access, registration, or log-in to the Media Library, please contact: fabienne.kreusch@prostep.org

We invite you to make full use of our Media Library – your direct gateway to the collective expertise of the prostep ivip community.



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Right Now

Two highlights in the prostep ivip events programme – both free of charge, both rich in content, and both featured with dedicated advertisements in this edition of the ProductData Journal. Here is a first overview:

Engineering Interoperability Day 2026

1 October 2026 | NH Frankfurt Airport West, Raunheim | Free Admission

For the first time, two well-established communities – the STEP AP242 Day and the JT Day – are joining forces under a single roof: the Engineering Interoperability Day 2026. The result is a focused, one-day event bringing together experts from engineering, IT, and production to exchange knowledge on standards, data models, and seamless engineering processes.



ENGINEERING
INTEROPERABILITY
DAY2026
JT & STEP FOR DIGITAL CONTINUITY

ENGINEERING INTEROPERABILITY DAY 2026

JT & STEP FOR DIGITAL CONTINUITY



1 October 2026
09:30 - 17:30



NH Frankfurt Airport West
Kelsterbacher Straße 19
65479 Raunheim

Where STEP and JT Communities Unite

For the first time, the STEP AP242 Day and the JT Day merge into one powerful event. The Engineering Interoperability Day brings together engineers, IT professionals, decision-makers and solution providers to drive industrial interoperability forward – in a single, focused and free-of-charge format built for real exchange and lasting impact.

The Engineering Interoperability Day is part of a full week of international expert meetings – making it the ideal opportunity to connect, collaborate and stay ahead in your field:

Sept 28–30
LOTAR & MBx Interoperability Forum

Oct 1
Engineering Interoperability Day

Oct 2
JT Workflow & Implementor Forum

Topics that move the industry:

From long-term data archiving to smart manufacturing – the 2026 programme covers the full spectrum of engineering data challenges. Expect in-depth sessions, real-world use cases and direct exchange with international experts on:

- Data Exchange & Long-Term Archiving (LOTAR)
- Smart Manufacturing Data
- Material Properties incl. Composites
- Product Data Traceability
- End-to-End Product Lifecycle Processes
- Classified Information Handling

Interested? Find out more at prostep.org



Questions? Contact:

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Tel.: +49 6151 9287 382
E-Mail: jochen.boy@prostep.com



**Secure your spot – admission is free,
registration is required.**

Register here!

Key topics include data exchange and long-term archiving (LOTAR), smart manufacturing data, material properties, product data traceability, and end-to-end product lifecycle processes – rounded off by extensive networking opportunities with international specialists.

The Engineering Interoperability Day is also embedded in a full week of specialist meetings (28 September – 2 October), encompassing the LOTAR & MBx Interoperability Forum, JT Workflow Forum, and JT Implementor Forum – maximum knowledge transfer with minimum travel effort.

Full information and registration:

[🔗 prostep ivip: Engineering Interoperability Day](#)



SYSTEMS
ENGINEERING
SUMMIT

2026

Tokyo Systems Engineering Summit 2026

27 November 2026 | Marunouchi Hall & Conference, Tokyo | Free Admission

Where global engineering meets Japanese precision: the Tokyo Systems Engineering Summit brings together practitioners from Japan and Europe who apply model-based, software-defined engineering in real-world projects every day – across industries, from two perspectives, in a format built for real depth.

The program features expert presentations from aerospace, automotive, shipbuilding and medical technology, complemented by scientific contributions and practical case studies on digital transformation. All presentations will be simultaneously translated English <–> Japanese.

Save the date now – further details to follow shortly.

A Platform for Visibility Where It Matters

The Tokyo Systems Engineering Summit is one of the rare international forums that brings together a highly qualified, cross-industry audience from both Japan and Europe in a single setting. For technology providers and solution partners, this represents a compelling opportunity to engage with decision-makers and technical experts in an environment where conversations lead to results.

Exhibition spaces and Premium Partnership packages are available for organisations wishing to make the most of this platform. As an exhibitor, your solutions are presented at the very heart of the event – integrated into the conference space, not placed on the periphery. As a Premium Partner, your brand gains full visibility across all Summit communication channels, from the event website and print materials through to pre- and post-event coverage.



Contact

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If you are interested in exploring exhibition or partnership opportunities, we would be delighted to hear from you:

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[🔗 prostep ivip: Tokyo Systems Engineering Summit 2026](#)



SYSTEMS
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Join the premier networking event that brings together 150+ engineering professionals from Japan, Korea, and Europe. Building on the remarkable success of previous years, the Tokyo Systems Engineering Summit has established itself as the essential platform for intercultural exchange and knowledge transfer.

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Call for Contributions - prostep ivip Symposium 2027

14 & 15 April 2027 | Düsseldorf

Mark your calendars: the prostep ivip Symposium 2027 takes place on 14 and 15 April in Düsseldorf. Those wishing to contribute actively should note the following key dates without delay.

Key Dates at a Glance

Mid-September 2026 - Call for Contributions opens

Submissions will be accepted from mid-September onwards. We strongly encourage early submission - in our experience, the number of contributions received consistently exceeds the available programme slots. All submissions are carefully evaluated by the Programme Committee; only the most compelling and high-quality contributions will be selected for the programme.

Mid-October 2026 - Exhibition spaces available

From mid-October, single and double exhibition stand spaces will be available for purchase. Full details will be published at www.symposium.de from the end of August.

Important Notes on Submissions

IT companies and consultancies may only submit contributions in conjunction with an end-user organisation. Please note: the end-user partner must be named at the time of submission - additions at a later stage will not be accepted.

End-user organisations are welcome to submit contributions independently, without a partner company.

Quality is key: Given the high volume of submissions and the limited number of programme slots, we strongly recommend paying close attention to the quality of your contribution and the choice of end-user partner. This is the most effective way to maximise your chances of being included in the programme.

For further information and regular updates, please visit:

www.symposium.de

We look forward to your submissions - and to a Symposium that once again sets the standard.

Questions about the Symposium? Get in touch:

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Welcome back, Sabrina!

We are delighted to welcome back a valued member of our team: Sabrina Reis, our experienced point of contact for membership and project controlling, returns to prostep ivip after her parental leave - bringing with her the expertise and in-depth knowledge our community has come to rely on. We are very glad to have her back!



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Book Recommendation: New Publication by prostep ivip Honorary Member Dr. Steven Vettermann

From Interoperability to Decision-Making Capability

The prostep ivip Association has long been dedicated to the question of how collaboration across organisational, system, and domain boundaries can be improved.

With the advancing digitisation of industry, the rise of software-defined products, and the growing role of artificial intelligence, a further question is increasingly coming to the fore: how do organisations make sound decisions when complexity intensifies and uncertainty can no longer be fully resolved?

This is precisely the question at the heart of *Kursänderung - Leadership zwischen Transformationsdruck und Orientierung* (Course Correction - Leadership between Transformation Pressure and Orientation).

Drawing on experience from industrial transformation, systems engineering, and organisational development, the book explores the significance of orientation, adaptability, and responsible action under uncertainty - particularly in contexts where decisions must be made before all the necessary information is available.

The first edition will be published on 24 June 2026, initially in German. Bibliographic information to follow.



ARRK Engineering

ARRK Engineering is a global development partner for the automotive and mobility industries, as well as for cross-sector, innovative product development. We support our customers from the initial idea through series production, implementing complex technologies in the fields of e-mobility, autonomous driving, software and system development, AI-supported methods, and digitally integrated, end-to-end engineering processes.

Our Digitalization & Software division is driving the transformation toward software-defined products, model-based development processes, and AI-based engineering solutions. We focus on scalability, data quality, cybersecurity, and holistic system architectures.

The expertise of our approximately 1,600 employees at locations around the world, as well as the strength of our shareholder, Mitsui Chemicals, form the foundation for quality, innovation, and long-term customer satisfaction.

As a member of prostep ivip, we actively contribute to the development of standards in digital product development and connect our approach to development and digitalization with the association's international engineering ecosystem.



Petrus Petrus
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Contact



CAIQ

CAIQ is a renowned provider of software and services for engineering processes. As an owner-managed medium-sized company (SME) headquartered in Munich, we develop standard software solutions based on an open and innovative component architecture.

Our customers value us as a trusted advisor and innovative integrator of IT systems concerning the optimization of process chains in the product life cycle, as we develop standard software solutions based on the CONTACT Elements platform. In this way, we support companies worldwide in optimizing process chains in the product lifecycle in many industrial applications.

Our offering includes standard software for simulation process and data management for CAE, data exchange, and enterprise and supplier integration. CAIQ products facilitate technical collaboration for product data management and enable technology data management for functional and parameter data.

CAIQ portfolio of virtual engineering services is committed to extensive expertise in leading solver technologies and intelligent automation concepts. This enables us to accelerate development processes, reduce costs, and ensure the highest quality standards—even before the first prototype is created. Our core competence is based on innovative engineering and methodological advancements in the field of functional validation, backed by high quality standards.

With over 160 employees at 5 locations in Germany, Poland, and Romania, CAIQ is a well-positioned company (SME) capable of offering and implementing innovative solutions for small and medium-sized businesses as well as large corporations

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Keysight

At Keysight (NYSE: KEYS), we inspire and empower innovators to bring world-changing technologies to life.

As an S&P 500 company, we are delivering market-leading design, emulation, and test solutions to help engineers develop and deploy faster, with less risk, throughout the entire product life cycle.

We're a global innovation partner enabling customers in communications, industrial automation, aerospace and defense, automotive, semiconductor, and general electronics markets to accelerate innovation to connect and secure the world.

Learn more at www.keysight.com



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qwitto

qwitto supports in the implementation of MBSE, from initial setup to ongoing, qualified operation. We offer a wide range of services, incl. our DevOps tool for MBSE: qAnalytics.

For our long-standing partners, we implement tool customizations, tool connections, and digital threads, including seamless data workflows. These improvements streamline processes, reduce errors, and significantly accelerate digital engineering.

Our proprietary tool, qAnalytics, realizes DevOps for MBSE. We speed up the systems engineering work-flow using triggered, configurable, and traceable model pipelines for continuous quality feedback. These pipelines combine automated validations, lifecycle-state monitoring, trend analysis, dashboarding, and change tracking with lightweight reviews.

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Contact



Royal Philips

Royal Philips is a leading health technology company focused on improving people's health and well-being, and enabling better outcomes across the health continuum - from healthy living and prevention to diagnosis, treatment and home care.

Philips leverages advanced technology and deep clinical and consumer insights to deliver integrated solutions. Headquartered in the Netherlands, the company is a leader in diagnostic imaging, image-guided therapy, patient monitoring and health informatics, as well as in consumer health and home care.

Philips generated 2025 sales of EUR 17.8 billion and employs approximately 65,000 employees with sales and services in more than 70 countries.



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Uncountable Inc.

Uncountable Inc. delivers an AI-powered Product Lifecycle Management (PLM) platform that centralizes formulations, BOMs, test data, process parameters, and documentation into a single searchable system of record. It provides full lifecycle visibility from concept through scale-up and manufacturing, aligning R&D, quality, and operations for traceability and faster innovation. Valued clients include Dow, DuPont, Sika, TotalEnergies, Repsol, Clariant, Mondelez, Beiersdorf, and 150+ more.

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Contact



Share PLM GmbH

Successful change begins with people, not technology. Founded in 2026, we guide organisations through complex digital transformation projects – covering the full scope of OCM, from strategy to implementation.

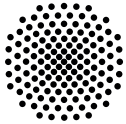
Our Transformation Management Framework aligns people, processes, and technology to drive sustainable adoption and create genuine added value. Drawing on our expertise in engineering, psychology, and design thinking, we offer tailored transformation support that empowers employees, optimises processes, and connects technology with organisational goals.

Whether introducing new software or leading broader transformation initiatives – we ensure that change is not merely possible, but lasting.



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**Universität Stuttgart**

Institute for Engineering Design and Industrial Design

Our research focus is the systematic investigation of design methods for complex technical systems. The emphasis is on models, methods, and tools for efficient, IT-supported development processes. The results of our research and projects form an integral part of teaching, doctoral training, and knowledge transfer in interdisciplinary industrial collaborations.

A particular focus of our current work is on the design of (modular) system architectures and their relationship with the design of IT systems. Artificial intelligence represents an important aspect in this context, as do sustainability aspects of systems and components.

In teaching, the lab is active as part of the Institute of Engineering Design and Technical Design (IKTD) in the bachelor's program in the areas of design methodology and machine elements, and in the master's program in the areas of methodology, systems engineering, FEM, gearbox design, and drive systems.

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**Contact**

Three Minutes. Main Stage. Real Impact.

Start-up Pitch at the prostep ivip Symposium 2026



For the fourth consecutive year, the prostep ivip Symposium provided young companies with one of the most valuable platforms the PLM and digital engineering sector has to offer: the Start-up Pitch – live, in front of more than 600 industry professionals, potential investors, partners and customers from precisely the environment these companies are built for.

The format is as straightforward as it is powerful: three minutes on the clock, a running countdown, the main stage of the plenary hall – and an audience that knows the field inside out. Immediately after the pitches, attendees cast their votes via live polling through the Symposium app, deciding on the spot who takes home the prize

Three start-ups took the stage in 2026:

- Circulonix
- Share PLM
- Connectorprise

Each brought a compelling vision rooted in the realities of digital transformation. The audience's verdict went to **Lucas Weyrich and his start-up Circulonix** – who left Frankfurt not only with the recognition of the plenary hall, but also with a prostep ivip association membership and **prize money of €2,500.**

Our warmest congratulations to Lucas and Circulonix – and our sincere thanks to all three participants for their courage, their energy and their willingness to put their ideas in front of this outstanding audience. In the pages that follow, we introduce Circulonix, Share PLM and Connectorprise in detail – because each of these companies deserves attention well beyond their three minutes on stage.

To all three: we wish you sharp ideas, sound decisions and the resilience that entrepreneurship demands.

Are you a founder working in the PLM or digital transformation space?

The Start-up Pitch at the prostep ivip Symposium could be your moment. Applications for 2027 open in September 2026, running alongside the Call for Contributions – submit yours at **www.symposium.de**.

The next Symposium takes place on **14 and 15 April 2027 in Düsseldorf.**

The stage is set. Make it yours.

Circulonix

Circulonix

1. The Elevator Pitch

Circulonix brings AI to project engineering and technical sales for tailored machinery and industrial equipment. Our system turns customer inquiries into custom engineering proposals automatically. We help **engineer-to-order companies use unstructured historical project data to create proposals faster while building more flexible and modular product structures** over time.

2. The "Why Now?" Moment

Engineer-to-order companies are under growing pressure to respond to complex customer inquiries, while experienced experts who know past projects and feasible solutions are leaving. Traditional automation in technical sales relies on rigid configurators, predefined rules and structured product data, which rarely fits customized industrial projects. Circulonix's AI system can now use existing unstructured documents, CAD models, BOMs and project folders to capture valuable knowledge and automate technical sales more flexibly.

3. Your Value to the Industry

Industrial companies receive hundreds of customer inquiries, ranging from small adaptations to complex machines, tailored lines or custom solutions. Today, project engineering and technical sales teams often work manually across Word, Excel and project folders, creating proposals from scratch even though similar solutions have already been developed before. Circulonix reduces the time needed to create solution proposals, makes expert knowledge accessible across teams and helps companies combine existing solutions into new proposals while developing a modular and flexible product structure over time.

4. The Technology Behind It

Traditional configurator systems require highly structured product data and rigid configuration logic before they create value. Simple LLM chatbots with RAG databases can search documents, but they cannot handle the complexity of project engineering and technical sales. Circulonix uses AI agents and a domain-specific knowledge graph to flexibly structure company knowledge from unstructured data such as documents, CAD models, BOMs and project folders. Unlike generic LLM-based systems, it connects and reasons across requirements, solution concepts, system components and interfaces, enabling companies to automatically generate proposals and run variant analysis.



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Share PLM GmbH

1. The Elevator Pitch

Share PLM is a boutique consulting company that bridges the critical gap between complex technology and the people who use it. We guide organizations through digital transformations by covering the entire Organizational Change Management (OCM) journey from strategy to execution. Our tailored approach ensures new PLM systems are fully embraced, turning resistance into adoption.

2. The "Why Now?"-Moment

The industrial landscape is evolving rapidly, yet an alarming 70% of digital transformations still fail. Why? Because PLM is historically treated as a mere IT implementation rather than a cultural business shift. Today, the complexities of connected ecosystems, powerful AI capabilities, and the pressing need for efficiency and sustainability demand a new approach. Companies increasingly recognize that even the best systems fail if users don't adopt them. This paradigm shift opened the window for our human-centric vision, proving that successful digital transformation begins with people.

3. Your Value to the Industry

Our solution makes lifecycle processes smarter by ensuring that complex PLM systems are actively utilized rather than just installed. By focusing on Organizational Change Management, we help companies significantly increase the success rate of their digital initiatives. We align technology with business objectives, combining engineering, psychology, and design thinking. Through tailored strategies, our customers can expect smoother transitions, higher user adoption rates, and streamlined workflows. Ultimately, we empower employees to embrace new, sustainable processes with confidence, enabling organizations to maximize their return on PLM investments and adapt faster to market changes.

4. The Technology Behind It

While we navigate leading PLM platforms, our true 'core technology' is our proven Organizational Change Management methodology and our unique 'House of Change' framework. Built on three pillars - experience, learning, and collaboration - and surrounded by a common transformation vision, this holistic approach ensures every transformation aspect is managed from strategy to execution. What makes us genuinely different is our system-agnostic, human-centric lens and our hands-on approach. This ensures complex PLM landscapes become accessible and intuitive, proactively managing risks and driving lasting behavioral change across the entire organization.



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Connecterprise



1. The Elevator Pitch

Founded in 2022, ConnectERPrise provides software solutions and services dedicated to industrial data exchange and technical data package interoperability. We help companies break silos by mastering CAD/PLM standards like STEP and JT. Our mission is to ensure that complex data remains fluid, accessible, and reliable throughout the entire product lifecycle from engineering to manufacturing, maintenance and circularity reuse.

2. The "Why Now?"-Moment

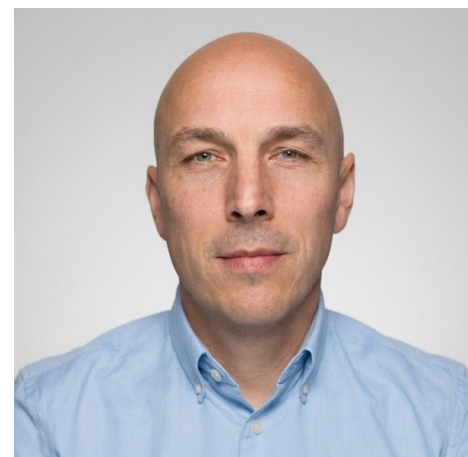
The European industry is at a strategic turning point. Facing fierce international competition and geopolitical shifts, we must accelerate our digital transformation. The emergence of AI, combined with the urgent need for industrial sovereignty, has opened a unique window. Now is the time to move away from proprietary locks and embrace open standards to build a resilient, fast, and independent industrial backbone for Europe.

3. Your Value to the Industry

Our approach aligns with the European DataSpace logic, promoting the transparency required for the upcoming Digital Product Passport (DPP). By ensuring deep interoperability, we make processes smarter and more sustainable, facilitating material and product end-to-end digital traceability. Customers can expect a streamlined "Digital Thread" that supports circular economy goals and long-term asset management.

4. The Technology Behind It

Following a successful R&D phase in 2024 focused on STEP AP242 real-time exchange, we are now entering a new stage. Our vision is to bring this 'Digital Twin' interoperability directly into the heart of industrial operations. By aligning our service layer with the Asset Administration Shell (AAS) standards, we facilitate the move from a prototype mindset to a large-scale, internal industrial reality.



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Symposium Review

At the annual prostep ivip Community Meeting, AI took centre stage.

Author: Daniela Hoffmann



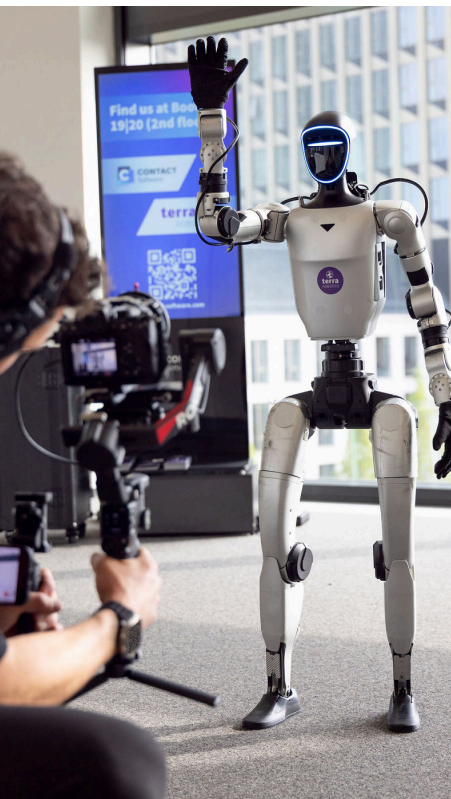
At the prostep ivip Symposium, participants explored the boundaries of what is achievable with AI today and exchanged real-world experience. With curiosity and passion, the international community debated which approaches are best suited to accelerating the development of software-defined products – and extended an open invitation to other industries to join the conversation.



Board member Philipp Wibbing (Unity) opened the event by presenting the prostep ivip community with a choice straight out of The Matrix: those who take the blue pill will spend two inspiring days at the Symposium – and then carry on exactly as before. Those who take the red pill make the bold decision not merely to leave with inspiration, but to bring tangible change back to their organisations. „We are living in challenging times, and you need to decide which pill you want to take,” said Wibbing. Thomas Kamla (Volkswagen) confirmed that the association’s board had itself opted for the red pill. The ambition is to push even further into deep tech, robotics, and physical AI – the game-changing themes of tomorrow. "The association has a strong legacy and deep expertise to build on," he noted.

"Driven by tech, united for impact" was the motto articulated by Chair Jens Poggenburg (AVL). "We have a very clear picture of how we can create value for the community, and we have sharpened our guiding principles," he stated. The goal is to support members in navigating disruption. "That is what we are passionate about, and it is precisely what our members and the board discuss with great intensity in order to find the best way forward," said Poggenburg. After 14 years of dedicated service to the association, Prof. Rainer Stark (TU Berlin) handed over his board seat to Prof. Matthias Kreimeyer of the University of Stuttgart. The fifth board member, Dr. Henrik Weimer (Airbus), was unfortunately unable to attend.



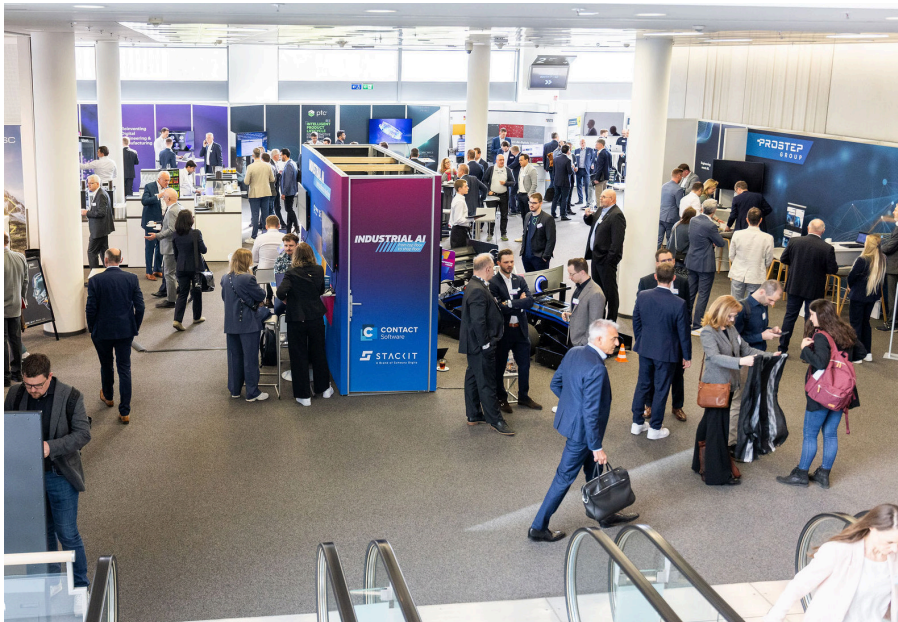


The next Frontier: AI

The pill analogy continued to resonate throughout both conference days, resurfacing repeatedly in conversations. For many, transformation is no longer a "nice to have" given the current economic and geopolitical dynamics – the overarching question of how to further shorten development cycles and reduce costs was front and centre. The gathering was accordingly dominated by the twin themes of AI and data, which are reshaping the engineering landscape as few trends have done before. AI – and agentic AI in particular – is here to stay, and will play a massive role especially in R&D. It profoundly touches the professional identity and working practices of engineers.



Wolfgang Puntigam, Vice President Software at AVL, painted a vision of the future in which AI evolves from assistant to team member and ultimately enables humans to "try out" a wide variety of designs in next to no time – much like Tony Stark in Iron Man. „AI transformation is always about people. There are many fears and narratives out there that may or may not be accurate. Will I still have a job in the future? Will AI do my job?" – Puntigam identified taking people along on this journey as the central challenge. He sees the advancement of open data standards for agentic AI as a key mission for the association – including open MCP services (Model Context Protocol), agent-to-agent protocols, and open APIs. At the same time, the data required for agentic AI in particular must urgently be made available and semantically interpretable – a point that was already clear at the previous Symposium, where ontologies and semantic layers were a major focus.



Factoring in Data Sovereignty

The dimension of data sovereignty has since gained considerably more weight. This was illustrated by a question from the audience: "If we try to use AI to support design, how do we protect our intellectual property?" The current attitude on this, it was acknowledged, is somewhat „schizophrenic": "On the one hand, we want to use AI for design proposals. On the other, we are not prepared to feed our ideas into the AI environment." The more engineering is done with AI, the more sensitive engineering knowledge inevitably flows into the algorithms.

"Digital sovereignty starts in your IT architecture and in the way you deploy AI. Before we can use AI comprehensively, we need to accelerate our digital transformation – because AI is entirely dependent on data," summarised Patrick Müller of Contact Software. Trust, he emphasised, is the central element in all of this – and a core theme of prostep ivip. "We observe that PLM data is increasingly being made available along the supply chain in order to regain greater transparency and control," said Müller, with reference to the particular difficulties that geopolitical shifts are creating for just-in-time supply chains today.

The insight that European sovereignty can only exist if companies actively work towards it has become increasingly established. European hyperscaler challengers such as Stackit play a central role here. Ghoutam Banerjee, VP at principal sponsor Stackit, explained that more and more industrial manufacturers are offering their solutions on the eponymous platform –



including the solutions of the other two premium partners, AVL and Contact Software. SAP is also set to become available on Stackit from September. The company belongs to the Schwarz Group and already supplies sovereign solutions to 600,000 employees across its portfolio, including Lidl. In Neckarsulm, Banerjee reported, the plan is to invest two billion euros in an AI Innovation Park serving OEMs and automotive suppliers in the region.

Early Adopters Share Their Approaches

This year's Symposium once again embodied the – in many other contexts, by no means ordinary – spirit of peer-level knowledge exchange. Curiosity, openness, and a willingness to share in order to learn from one another were palpable in virtually every session. Several presenters shared a particular focus on how AI can accelerate the demanding processes of change management and requirements management. BMW, for example, presented jointly with partner Raiqon how it had already achieved enormous time savings in requirements management using CodeBeamer and the Raiqon AI platform. Around 120,000 entries are added to the system each month, reported Patrick Grüßenbeck from BMW. With integrated semantic search and automated data transfer – no copy-and-paste required – it is now possible to locate an entry in seconds that previously had sixty engineers occupied for an entire day.

AI also has a central role to play in sustainability – particularly when better information is available in the early stages of the design process and the right decisions for reducing the carbon footprint can be made in time. Stefan Gatersleben from Schaeffler demonstrated how a solution from Transition Technologies PSC significantly reduced the time required to compare material alternatives from a CO2 perspective.

The Software-Defined Product Is Transforming Many Industries

Matthias Kreimeyer reinforced this sentiment in his opening remarks: "This idea of 'united for impact' is something that genuinely works as a community – and the prostep ivip organisation functions the same way. We want to reach beyond our core industry – the automotive sector." The board has its sights set not only on aerospace, but also on sectors such as defence, medical technology, and mechanical and plant engineering. When it comes to the software-defined product, other industries can learn from the groundwork already laid within the association – and bring their own strengths to the table. Bernd Feldvoss from Airbus shared insights in a workshop from the prostep ivip project LOTAR (Long-Term Archiving and Retrieval across extended life cycles) that are of compelling relevance across industry sectors.

"Complexity is growing enormously: many product variants, long life cycles, increasingly stringent regulations. Legacy products must meet new requirements – and that is barely manageable with paper anymore," explained Thilo Jania from Japanese medical technology manufacturer Olympus in the Expert Corner session "Engineering at Digital Speed". At the same time, the strategic direction is towards ever-greater product individualisation within a tightly regulated industry.



Different Tasks, Similar Challenges

In many cases, the signed drawing is still the only single source of truth. "Regulatory bodies are evolving as well and are increasingly accepting digital evidence. We are standing at an inflection point," said Jania. At the same time, the challenge is to transfer domain expertise from people's heads into digital form – including to preserve the knowledge of those approaching retirement in the coming years, where AI tools are proving essential.

"We have trained our engineers to create models and conduct engineering in order to solve their respective engineering problems. And all the data has been structured for years – and continues to be structured today – in exactly that context. But now we want to flip the equation," summarised Kenneth Swope of The Boeing Company. The goal is to make data transparent, cross-domain relevant, and available to agents – even though the models were not originally built with that in mind. "That means we need to start modelling with precisely that requirement in view, so that the data is structured and provided in a way that is actually useful. This is a transformation of the workforce, and it is a transformation of organisations," Swope concluded.



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MBSE, Simulation and Virtual Validation Are the Future

In the defence sector, Jörg Wirtz from Airbus Defence and Space outlined the challenges posed by new defence systems such as the Multi-Domain Combat Cloud. "This is an extraordinarily complex system-of-systems. Development is further complicated by the fact that it is a multinational and cross-organisational project. The key to managing this complexity lies in model-based working and in the early verification of hypotheses through simulation of the operational environment and the overall system," reported Wirtz.

The greatest obstacle in simulation remains the question of credibility. Only when model-based systems engineering and simulation converge can virtual testing also inform hardware decisions. Hans-Martin Heinkel from Robert Bosch addressed what has already been achieved in this area through the prostep ivip project Smart Systems Engineering (SmartSE). This includes a now globally adopted standard for ECU modelling, as well as the experience that a technology base built on standards such as the Modelica Association, FMI (Functional Mock-up Interface), and SSP (System Structure and Parameterisation) is indeed fit for practical use. In the MBSE environment too, large language models can assist with translating SysML into SSP.

International Collaboration

In recent years, an increasing number of Asian manufacturers have become active contributors to the association. For many in the community, it is a sign of hope that trustworthy international collaboration continues to hold value. In Frankfurt, presentations by Japanese manufacturers sent a powerful signal to that effect. For the next Symposium, Mazda and Toshiba have already committed as premium partners.

Just as the 1990s were defined by learning from Japanese efficiency – with kaizen, kanban, and lean becoming the martial arts of engineering – the exchange today continues to yield fascinating cultural and technological insights. Takao Senko from Honda Motor spoke at length about the importance of the dream in Honda's engineering philosophy and about the path to the model-based enterprise: a company-wide approach in which the digital product model becomes the central and authoritative source of information across the entire product life cycle – elevating the MBSE concept to a higher plane. In the MBE maturity model, Honda is currently working to reach Level 4, at which digital product data is used directly and in a machine-readable form in downstream processes. Level 4, Senko noted, is the "starting point for the AI dream".

"The future is not AI replacing engineers, but a cross-human, cross-model way of working with AI – with models and structured knowledge as a common language," added Takao Nii from Dentsu Soken. "I currently have two dreams. The first is to realise MBE Levels 5 and 6, to enable AI-driven work with my colleagues. I want to pursue these activities under the concept of dreaming," said Takao Senko. His second dream: "To report progress on Levels 5 and 6 and on AI activities at next year's event."





New Ideas at the Start-Up Pitch Award

This year's Start-Up Pitch was won by Cyrcolonix, founded by Lucas Weyrich. The solution is an AI agent that automatically generates tailored system proposals for customer enquiries, designed for project engineering and technical sales with a focus on mechatronic systems in complex projects such as industrial machinery. "The engineering logic of which components work together currently resides in the heads of experts," explained Weyrich. That makes the process time-consuming and creates a high dependency on individual employees. In the second half of the year, the plan is to roll out the solution commercially and launch a pre-seed financing round.

The value of close dialogue between start-ups with disruptive ideas and established companies – for all parties involved – was further demonstrated by the keynote from Spread, winner of the 2023 Start-Up Award, which presented a software platform that retrieves engineering data from disparate systems and makes it available to both developers and AI agents. "Millions of iterations of engineering decisions have already taken place, and there are data traces behind every one of those decisions," observed Robert

Göbel from Spread. He elaborated on how decisive context is for enabling AI agents to help product developers find information or navigate the growing proliferation of tools. Without this foundation, even the most powerful AI models are of limited use. "This community – these 650 participants here today – are genuinely capable of making things happen," Göbel told the audience.



Contribution of the Scientific Award Winner in the Category Master's Thesis



My name is Gerolf Schalk, and I am affiliated with Siemens Digital Industries Software as a PhD researcher at Graz University of Technology. My research work, titled "Integrated Data Management for Multidisciplinary System Development - Framework Conception and Practical Application," was honored with the Scientific Award 2026 in the category Master's Thesis by the ProSTEP iViP Association - a recognition that fills me with immense pride.

The motivation for my work stems from my longstanding engagement with the fields of Systems Engineering, digital transformation, and interdisciplinary product development, which have always fascinated me as a contributor to the development of modern systems. Throughout my academic journey, I frequently encountered the projects, publications, and standards of the ProSTEP iViP Association, which proved to be valuable resources for my research. Through this connection, I came across the announcement of the Scientific Award. The thematic alignment with my master's thesis made submitting my work a natural decision. Although I initially did not anticipate winning, receiving the notification of the award was all the more exciting.

The focus of my master's thesis lies in the development of a practice-oriented framework that enhances collaboration and traceability in complex development processes. The goal of my research is to address the growing demands of modern mechatronic systems – from increasing technical complexity to fragmented software landscapes and the challenges of efficiently linking interdisciplinary teams. At the heart of my thesis is the design of specific data models for Product Lifecycle Management systems, which provide comprehensive transparency and structured organization of development data. These models enable engineers to concentrate more effectively on their core activities while fostering innovation across disciplinary boundaries.

I am particularly proud that my work bridges the gap between theory and practice: The developed concepts are successfully validated through a practical use case – the development process of a quadcopter drone. In this scenario, all digital models are created, structured according to the designed data models, and ultimately implemented as a fully functional prototype. This practical focus demonstrates how digital product development can make the creation of physical systems not only more efficient but also future-oriented.

My vision is to actively contribute to sustainable and future-ready engineering through my research. I strongly believe that technology should not only optimize development processes but also create trust, enrich lives, and deliver solutions for a better world. This conviction serves as my daily motivation and shapes both my academic and personal journey. To further share this conviction and the core concepts of my award-winning master's thesis, I have generated a summary to make the thesis more accessible within the engineering community.

In conclusion, I would like to sincerely thank the ProSTEP iViP Association for the professional organization and the exceptionally warm welcome – an experience that will remain unforgettable for me. I look forward to meeting the team again at future symposia and continuing to be part of this inspiring community.

Best regards,
Gerolf Schalk

Winner Scientific Award Master Thesis

Integrated Data Management for Multidisciplinary System Development - Framework Conception and Practical Application

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Interdisciplinary system development faces growing pressure from rising system complexity, fragmented software tool landscapes, and an increasing demand for seamless collaboration across engineering domains. Under these conditions, traditional development approaches often fall short in maintaining traceability and coherence of engineering data. These challenges call for a fundamental rethinking of existing methodologies and the introduction of new approaches that enable engineers to navigate complexity more effectively.

Building on established concepts for handling complexity, namely Systems Engineering, Model-Based Systems Engineering, and Product Lifecycle Management (PLM), this paper introduces a practical framework for managing interdisciplinary development data within PLM systems. The proposed approach offers an implementation-oriented and adaptable structure that supports the organization of engineering data, enables end-to-end traceability, and facilitates cross-disciplinary collaboration. To assess the framework's applicability, it is applied and evaluated in a development project involving digital engineering models and a physical prototype within a practice-oriented engineering environment. The results illustrate a best-practice approach for structuring development processes and engineering data and supporting digital transformation.

Introduction

Developing modern mechatronic systems poses significant challenges – including increasing system complexity, advancing digitalization, greater interdisciplinarity, growing demands for sustainability and traceability, as well as rising cost and time pressure. However, for companies to remain competitive and ensure engineering efficiency, the development phase plays a critical role, as key system characteristics – such as functionality, repairability, recyclability, and engineering data quality – are largely defined at this initial stage. Addressing these challenges requires a shift in engineering education, working habits, and the ability to collaborate across technical disciplines. Common issues in this context include a lack of shared understanding, the absence of a common engineering language, and limited interdisciplinary methodologies [1]. Effective cross-disciplinary communication, however, depends on a holistic system understanding, enabled by T-shaped knowledge, which combines deep expertise in an engineering discipline with broad interdisciplinary comprehension. This T-shaped profile enables engineers to understand each other's needs, identify shared information interfaces, and consider discipline-specific information throughout the development process [2].

This paper addresses the challenges described above by introducing a practical and adaptable framework for structuring interdisciplinary system development that enables engineers to focus on their core tasks by reducing coordination efforts, information search, and troubleshooting. From a technical perspective, the paper presents a concept for comprehensive interdisciplinary data structuring and process-wide traceability within a centralized data platform. The paper begins with a discussion of the state of the art, followed by a review of relevant engineering concepts, the presentation of a customized data structuring model, the scientific procedure, the development results, and the digital environment that enabled the implementation. Core elements of this work are derived from the first author's master's thesis, which provides additional implementation details and theoretical background [3].

State of the Art in Technology

As outlined in Section 1, the development of modern mechatronic systems is inherently interdisciplinary and highly complex. To address these challenges, Systems Engineering (SE) provides a foundational philosophy aimed at enabling the realization of successful systems through structured, cross-disciplinary development [4]. Model-Based Systems Engineering (MBSE) extends this scope by introducing system modeling as a semantic formalization that fosters discipline-neutral understanding of the system under development. Moreover, it relies on digital engineering models from different engineering disciplines as central artifacts to represent and support engineering activities. This approach facilitates the reuse of specifications and design artifacts, thereby improving common understanding and engineering traceability [5]. Product Lifecycle Management (PLM) complements SE and MBSE as it is the discipline of managing products throughout their lifecycles – from development to decommissioning [6]. While closely related to the fields of SE and MBSE, PLM places a stronger emphasis on implementing their methodologies through dedicated software solutions [7]. PLM systems offer shared data repositories for various engineering artifacts, thereby supporting traceability and improving interdisciplinary communication. In this context, data structuring is seen as a key strategy for addressing complexity and collaboration issues [8].

The structuring of development data is managed through so-called data models, which define how system artifacts – such as requirements, electronic components, system modeling functions, and simulation results – are organized and related across different levels of abstraction. However, PLM systems often do not come with predefined, comprehensive data models, and traditional ones lack the capability to integrate data from different authoring tools into the PLM system [9], required for efficient development processes. In practice, such data models must be tailored to organizational processes and system characteristics, which vary widely [10]. Still, there is broad agreement that standardized, lifecycle-integrated data structuring models would be beneficial as best-practice blueprints [11]. Although structured data is considered the backbone of system development, unified data structuring models are lacking, resulting in fragmented engineering data across various software tools, thereby hindering the realization of comprehensive, integrated data management platforms [12,13].

Several models for system data structuring have been established in the literature, including the Asset Administration Shell [7], the Core Product Model [14], and the Product Process Organization Model [15], which are discussed in detail in the underlying master's thesis. These data structuring models aim to standardize development data and consider process and organizational dimensions. However, they primarily address conceptual data organization and typically do not showcase practical engineering artifacts in interdisciplinary system development (see Figure 1) including their relationships. Therefore, few of the established models provide comprehensive support for the design of mechatronic systems [16]. In addition, many of the reviewed models are based on theoretical considerations, lack

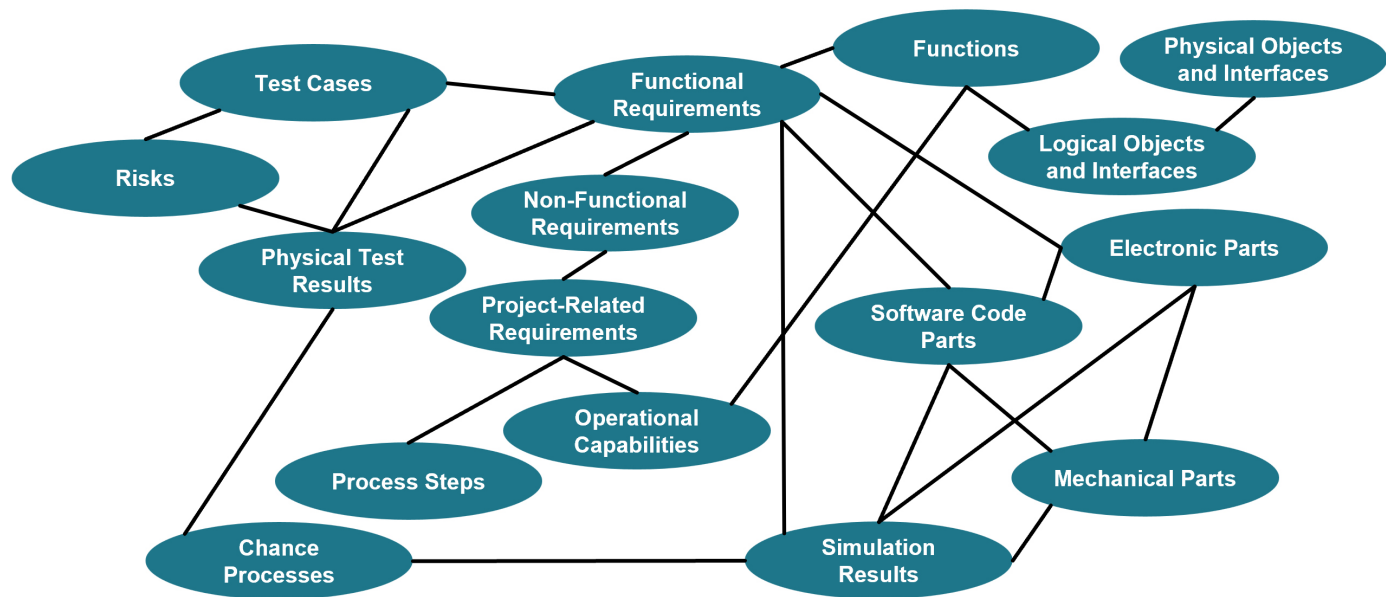


Figure 1: Overview of Engineering Artifacts in Interdisciplinary System Development

implementation guidance, and are only partially integrable into industrial PLM systems. This gap motivated the development of customized PLM data structuring models, with a strong emphasis on practical application, developed in the context of the author's master's thesis. One such model, referred to as the PLM Convergence Framework (PLM-CF), is proposed in this paper. Its aim is to achieve a high level of visual clarity and to bridge the gap between high-level and detailed data modeling, thereby offering a generic yet adaptable structure grounded in practical application.

In summary, there remains a significant lack of comprehensive data models for structuring development data within PLM systems. This is partly explained by the fragmentation of data across numerous software tools, the heterogeneity of data artifacts, and the lack of seamless interfaces to PLM systems, making unified repositories difficult to realize.

Scientific Procedure

The methodology for systematically structuring and tracing data within a unified data platform is based on the PLM-CF, which is developed from foundational principles in SE, MBSE, and PLM, as described in Section 4.1. To derive this framework, established methods for interdisciplinary system development were first analyzed, followed by a targeted literature review of existing data structuring models. These were examined for their suitability in supporting integrated and traceable system development. Building on these insights, a set of customized data models (PLM-CF) was developed,

emphasizing conceptual clarity, practical applicability, and adaptability to different systems and organizational contexts. To evaluate the applicability of the PLM-CF, it was implemented in a prototyping project involving the creation of digital engineering models – such as mechanical, electronic, software, simulation, and requirements models – alongside a corresponding mechatronic prototype. Within this setup, the PLM-CF functioned as a structural guideline for linking and organizing artifacts from the digital engineering models across disciplines and hierarchy levels. In addition, a representative engineering change scenario involving cross-disciplinary modifications was introduced to examine the capability of the PLM-CF to maintain traceability and structural integrity under dynamic conditions, as detailed in the author's master's thesis. Overall, this work follows a practice-oriented engineering perspective and presents a reference implementation within a lifecycle-oriented engineering environment.

Results

This section presents the theoretical background of the PLM-CF and discusses the results of the prototyping project, as well as the enabling environment. It begins with a theoretical outline of the PLM-CF's design and methodology, followed by an overview of the engineering environment that supported its practical implementation. Finally, the implementation results of the prototyping project are examined.

4.1 Development of a Customized Data Structuring Model

The PLM-CF builds on established principles, including the V-Model [17], the RFLP approach [18], Zigzagging [19], and the Four Interlocking Pillars [20]. It illustrates the logical flow and traceability relationships of development data along the engineering process, as shown in Figure 2. However, the figure does not directly represent the data organization within the PLM system, as the data within the PLM-CF is not separated by discipline. In addition, it must be noted that, unlike the traditional V-model, the verification and validation (V&V) activities are already shown on the left side of the V-shape to form a logical traceability via RFLP-V&V. This is because V&V must be interwoven early with development activities on all levels of the system architecture for quality control and test planning [21].

The PLM-CF offers a structured yet scalable framework for managing development artifacts and their traceability links – without introducing unnecessary complexity. It provides horizontal traceability via RFLP-V&V, vertical traceability through Zigzagging, and systematic decomposition across hierarchical levels. The depth of the hierarchical structure is expandable depending on system complexity and the scope of the engineering project. To support practical application and common understanding, the PLM-CF includes additional illustrations, as discussed in the author's master's thesis.

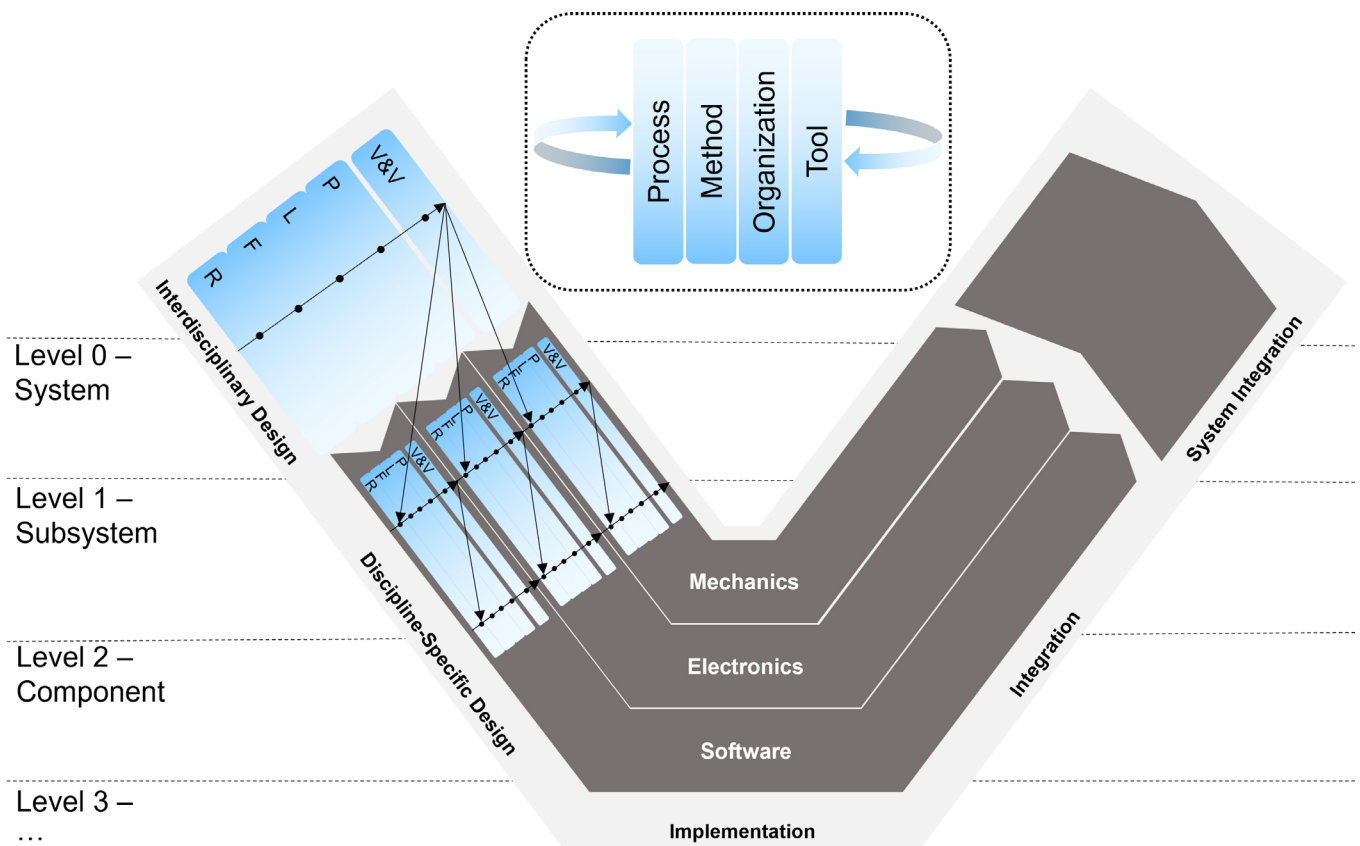


Figure 2: Overview of PLM-CF

A key advantage of the PLM-CF is its clear traceability structure, which allows for efficient modifications by engineers. By organizing data across disciplines rather than within isolated domains, the PLM-CF fosters interdisciplinary collaboration and prevents silo-thinking by design. However, it must be noted that the PLM-CF also does not necessarily mirror the chronological creation of artifacts from RFLP-V&V across disciplines in real-world engineering projects. In this context, trace links from RFLP-V&V would serve primarily for documentation purposes rather than actively supporting the development process. Moreover, it may not always be practical to model all RFLP-V&V artifacts at every hierarchy level, particularly when higher-level components are already well-understood by the organization or are off-the-shelf components that must not be developed themselves. In the context of the prototyping project presented in Section 4.3, the development followed a textbook approach, with all artifacts modeled comprehensively across several hierarchy levels to mitigate system failures and ensure robust system design.

4.2 Engineering Environment

The proposed PLM-CF was not evaluated in an isolated engineering context but was instead applied under realistic development conditions. Therefore, the corresponding prototyping project was executed in the Digital Lifecycle Lab (DLL), hosted by Antemia GmbH [22] at the Institute of Machine Components and Methods of Development. A top view of the lab setup is shown in Figure 3. The DLL serves as a practice-oriented, end-to-end engineering and management platform aligned with industrial needs for interdisciplinary system development. While it focuses on digital engineering through a seamlessly integrated industrial software toolchain, the DLL remains a physical environment, providing hands-on access to different workspaces representing typical roles of an interdisciplinary engineering team, including a project leader, systems engineer, process engineer, mechanical engineer, electrical engineer, software engineer, and testing engineer.

The comprehensive implementation of the PLM-CF in the prototyping project was enabled by the DLL's integrated digital infrastructure, which supported the modeling, management, and traceability of engineering artifacts across disciplines. In particular, the seamlessly connected toolchain from authoring tools to the PLM system, together with direct interfaces for artifact capturing and interactive visualization capabilities, served as key enablers for establishing the framework, generating comprehensive traceability, testing its implementation, and analyzing interdisciplinary dependencies.

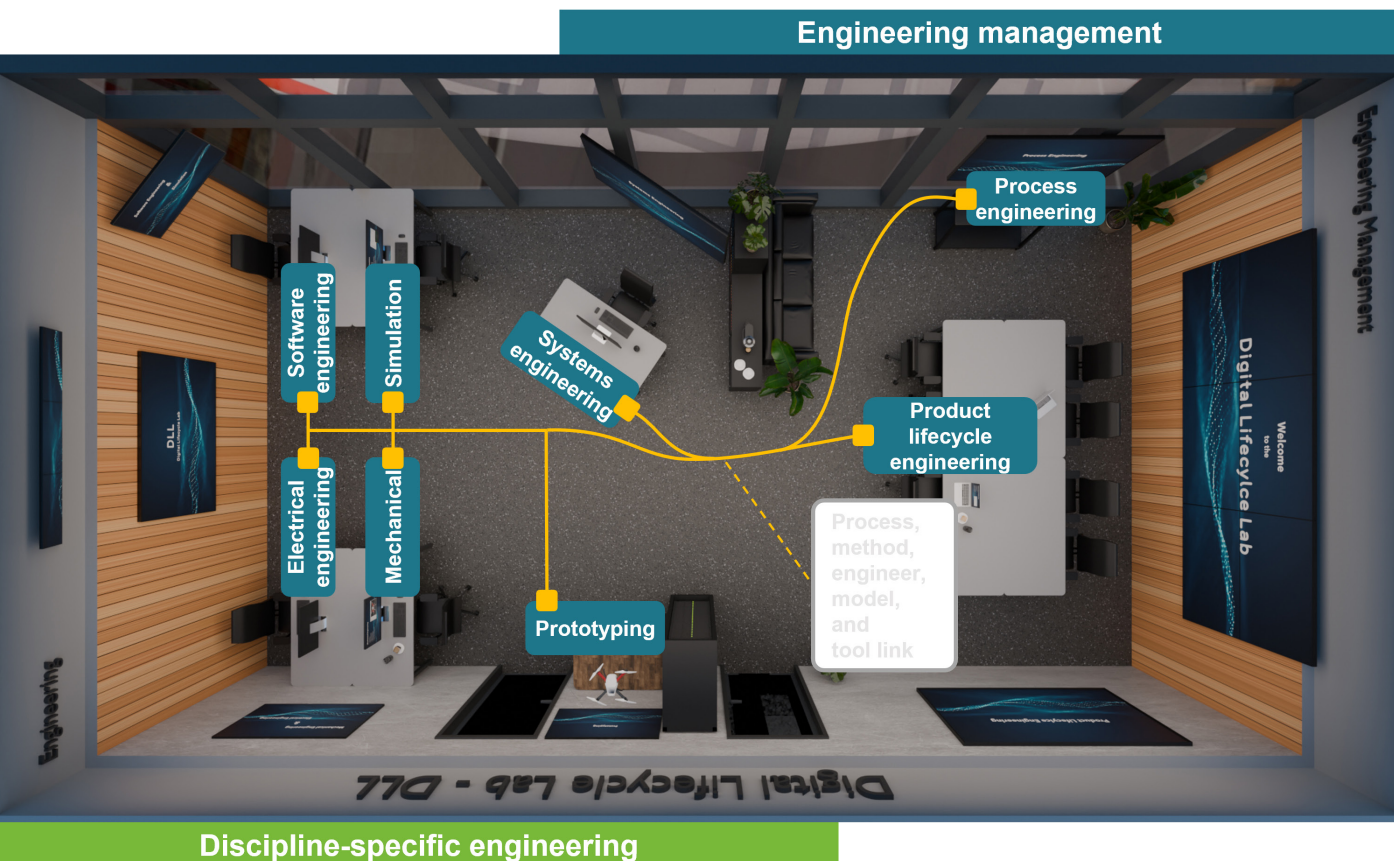


Figure 3: Top View of the Digital Lifecycle Lab © Antemia [22]

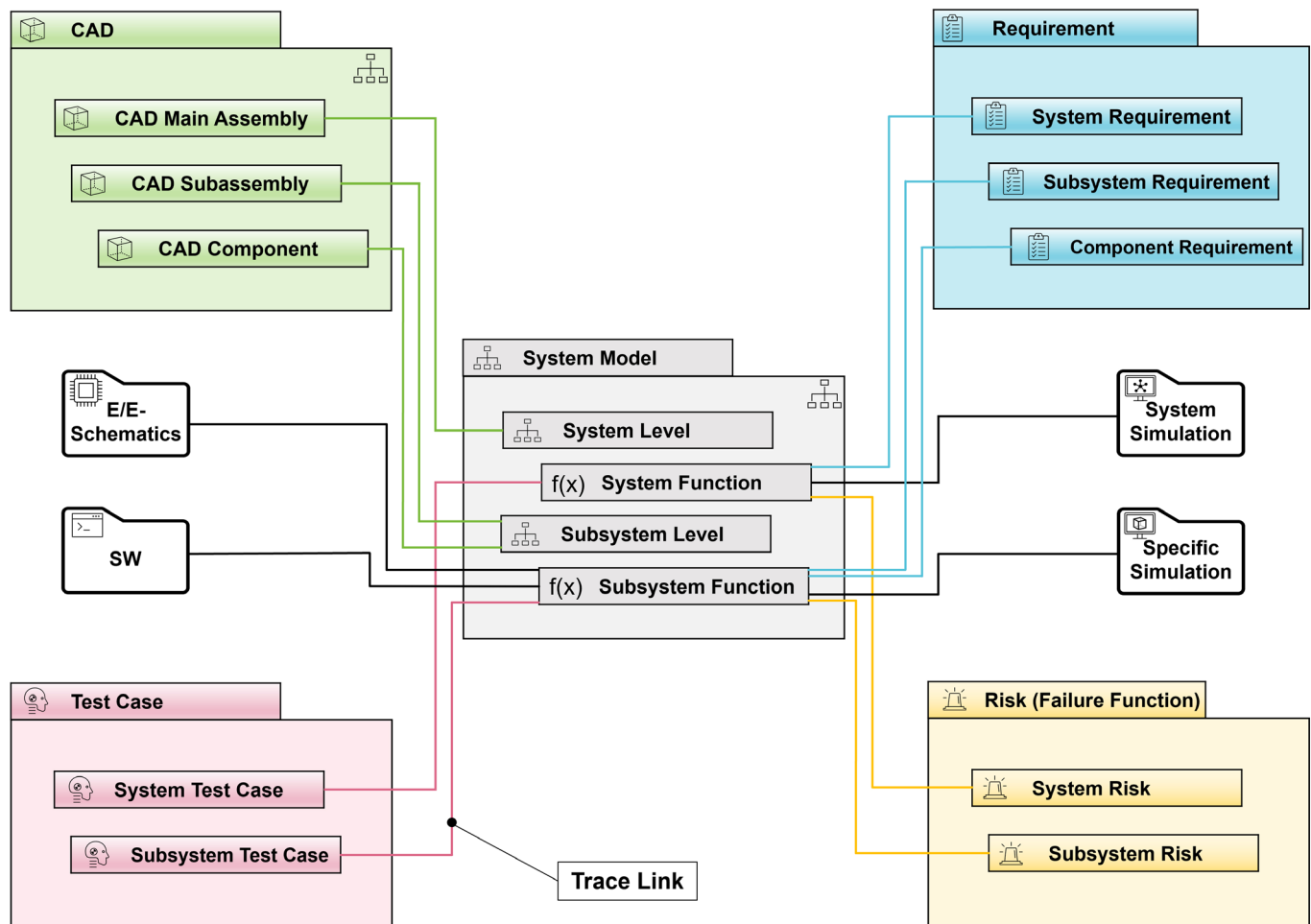


Figure 4: Tailored PLM-CF for Drone Development

4.3 Implementation Results

This section describes the tailored PLM-CF and the digital development of engineering models for the mechatronic system considered, namely a quadcopter drone. The drone was chosen as a representative system due to its multidisciplinary nature, widespread recognition, and high implementation flexibility, enabled by readily available base platforms, sensors, and programmable controllers. Building on the generic PLM-CF presented in Section 4.1, a tailored framework version was derived for the drone system, as illustrated in Figure 4. This included the concrete definition of required artifacts, the appropriate levels of detail for sufficiently specifying the system, and the adaptation of the logic for linking individual artifacts across disciplines.

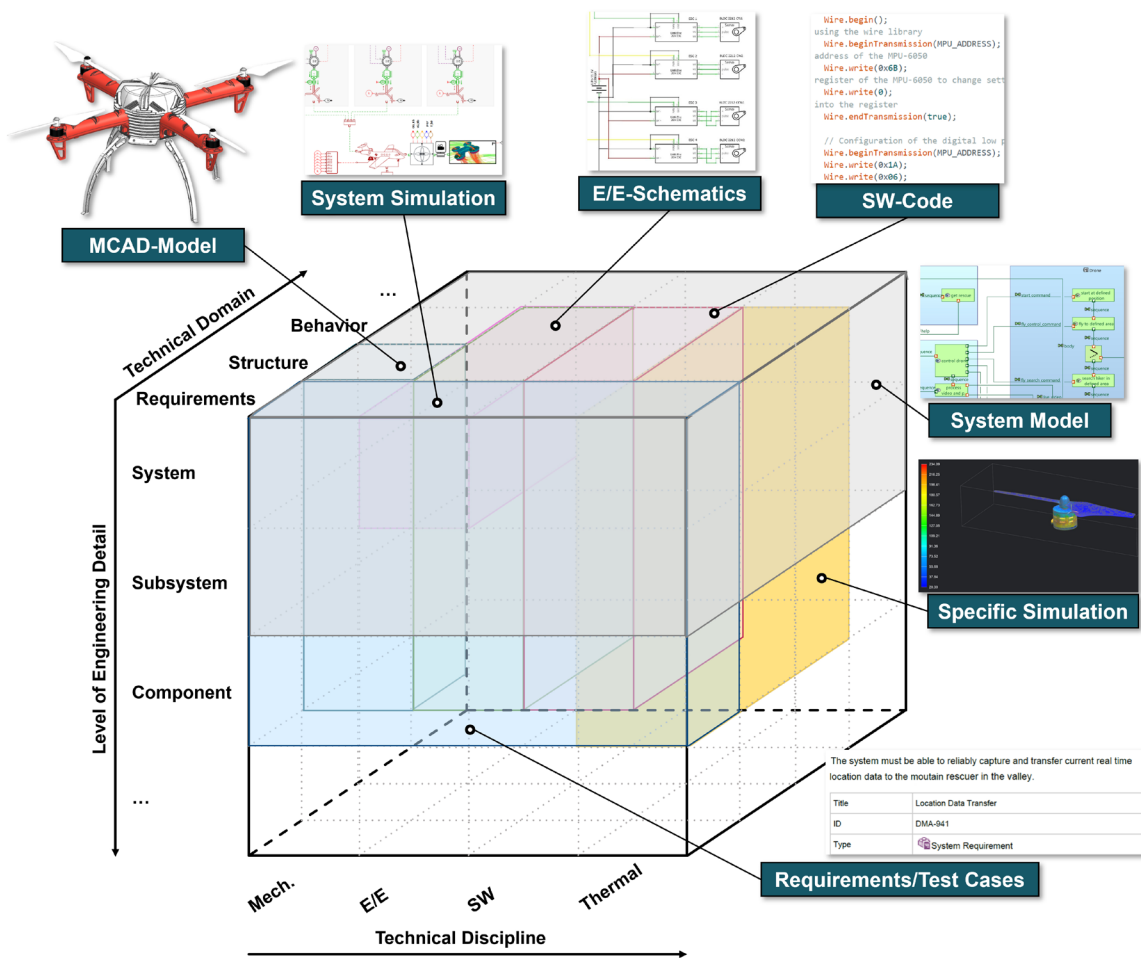


Figure 5: Digital Models for Drone Development within the Model Cube Visualization Method

Throughout development, multiple digital engineering models were created, ranging from the initial system requirements to detailed physical component designs, fully covering the RFLP-V&V approach. For clarity, these models are systematically structured across engineering disciplines, levels of detail, and technical domains, using the Model Cube Visualization Method [23], as depicted in Figure 5, which supports navigation across interfaces and provides an overview of missing or redundant information in the engineering project within the DLL.

To integrate the generated models and artifacts, all artifacts were transferred from their respective authoring tools into the PLM system, enabled by the seamless interfaces of DLL's PLM system. To recreate a realistic engineering setup, roles and accounts reflecting typical interdisciplinary team structures were defined within the PLM system. These roles were assigned responsibility for uploading and managing their respective artifacts and models, thereby representing the cross-disciplinary flow of information and enabling the analysis of interdependencies between roles and required information.

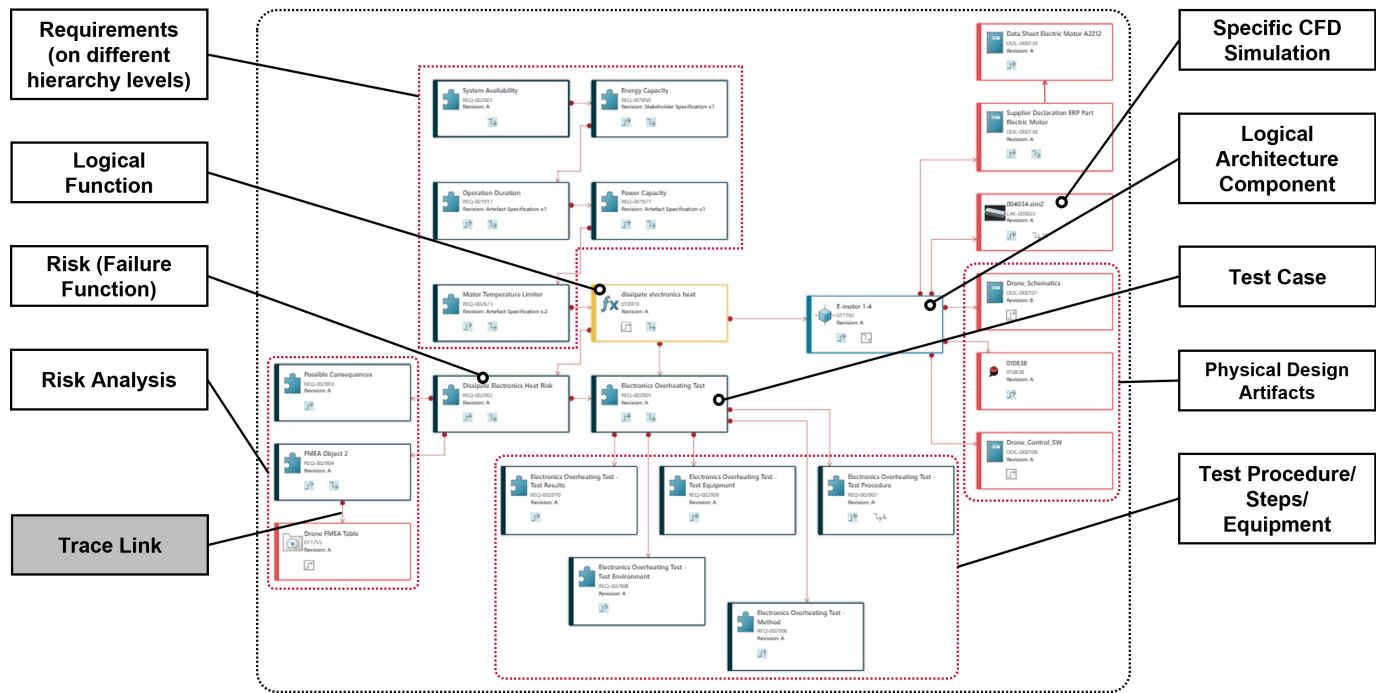


Figure 6: Excerpt of the PLM-CF within the PLM System

Figure 6 shows the implemented PLM-CF within the PLM system Siemens Teamcenter. It illustrates individual artifacts and the traceability structure, spanning multiple hierarchy levels of requirements through to the physical design artifacts for simulation, mechanical, electronic, and software disciplines of the drone. As the full traceability network is significantly larger and more interconnected, only a selected detail, starting from a single requirement, is shown. To support navigation and reduce complexity within large traceability structures, the PLM system provides targeted search functionalities for artifact relationships and interfaces.

Discussion

The results of the prototyping project demonstrate the applicability and adaptability of the PLM-CF in enabling structured and traceable management of development data within a multidisciplinary engineering process. By tailoring the PLM-CF to the quadcopter drone system, a centralized, process-wide data structure was established that supports artifact traceability and interdisciplinary collaboration and serves as a best-practice example for other use cases. Compared to existing data structuring models, the PLM-CF offers a more visually guided, coherent, and implementation-oriented approach. While many models emphasize data standardization or high-level data integration, the PLM-CF bridges the gap between high-level and detailed data modeling, offering a generic yet adaptable structure. Beyond

theoretical design, it demonstrates practical applicability through its implementation in a PLM system within the context of a mechatronic development project. This positions the PLM-CF as a relevant contribution to ongoing discussions in SE, MBSE, and PLM, particularly regarding collaboration and data traceability in complex development settings.

However, several limitations must also be acknowledged. Integrating and configuring all the software tools involved for multidisciplinary system development requires significant effort and may pose a barrier to adoption in industrial environments. Additionally, the evaluation was limited to a single use case – the quadcopter drone system – which restricts the generalizability of the findings. Therefore, the applicability of the PLM-CF to more complex or different kinds of systems remains to be verified. Furthermore, the PLM-CF focuses primarily on the development phase, and its applicability to downstream lifecycle phases requires further investigation.

Summary and Outlook

This work introduced a novel approach for organizing and managing interdisciplinary system development by combining established engineering methodologies with the capabilities of seamlessly connected software tools. Central to this approach is a customized data structuring model – the PLM-CF – which was applied to the digital development of a mechatronic system and verified through the implementation of a corresponding physical prototype.

Several promising directions exist for further advancing the PLM-CF. One key area is the integration of Artificial Intelligence (AI) into SE, MBSE, and PLM, as traditional PLM systems often lack the capabilities required for engineering automation. Leveraging structured development data – as enabled by the PLM-CF – AI applications could be trained to support workflow automation, enhance search and reuse, assist design processes, and improve quality assurance [24]. In this context, the drone project serves as a practical blueprint for AI-enabled engineering. In addition, advancements of the PLM-CF could focus on engineering change processes and variant management through deeper integration of workflows and processes, offering enhanced traceability throughout development. The framework may also be extended to cover downstream lifecycle phases such as operation and decommissioning. Continued research should explore these directions and further evaluate the scalability, adaptability, and applicability of the PLM-CF. Despite these limitations, the PLM-CF presents a robust yet adaptable framework with the potential to enhance both theoretical understanding and the practical execution of traceable, model-based development.

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Scientific Award Winner Doctoral Thesis 2026

Systems Engineering Frameworks for AI-Integrated Autonomy: A Synthesis of Research in Virtual Product Creation

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Note: This article is based on the author's doctoral thesis, „Towards Intelligent, Safe, and Scalable Autonomy: A Study Driven by Trajectory Planning for Automated Vehicles“ [P1], completed at the Chair of Automatic Control at Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). The research was awarded the 2026 prostep ivip Scientific Award [1] and is consolidated here to provide an industrial and systems engineering perspective for the prostep ivip community.



Figure 1: Award ceremony of the prostep ivip Scientific Award at the prostep ivip Symposium 2026 in Kap Europa, Frankfurt am Main. The award honored Lars Ullrich for his doctoral thesis on intelligent, safe, and scalable autonomy for automated vehicles.

The integration of artificial intelligence (AI) and machine learning (ML) into cognitive cyber-physical systems is driving a fundamental paradigm shift in virtual product creation. Within the automotive sector, this transition challenges classical Systems Engineering (SE) methodologies, which are designed for deterministic, mathematically explicit “white-box” models. When confronted with data-driven, implicit “black-box” AI systems, traditional linear development processes struggle to provide safety assurance and scalable validation. This article synthesizes a comprehensive framework spanning process modeling, control-theoretic safety assurance, and decentralized product data management (PDM) to bridge the gap between academic autonomy and industrial systems engineering. By introducing the “Iterative Data-Based V-Model,” we outline how data must transition from a passive operational input into a version-controlled, cryptographically verified, and first-class engineering artifact within the product lifecycle.

Introduction: The Technological Ceiling of Software-Defined Vehicles

Modern product development is undergoing a transformation driven by digital continuity, Industry 4.0, and the embedding of machine learning into safety-critical, closed-loop applications. In highly automated and fully autonomous driving (AD), systems must navigate in open, dynamic, and ever-changing real-world environments [P11]. To date, the automotive industry's response to this complexity has centered on the "Software-Defined Vehicle" (SDV), wherein hardware configurations are decoupled from software-driven features. However, as autonomy levels increase, SDV architectures face a technological ceiling.

Traditional modular, service-oriented software architectures segment the autonomous stack into discrete, sequential modules: perception, prediction, planning, and control [P4]. While this structural modularity facilitates isolated verification, it introduces compounding measurement errors and significant semantic information loss across intermediate boundaries. Specifically, representing complex real-world dynamics via simplified geometric abstractions, such as 3D bounding boxes, strips away crucial contextual information. To achieve robust autonomy, the system must maintain multi-level Situation Awareness (SA) [2]. This includes not only raw perception (Level 1 SA) but also situational comprehension (Level 2 SA) and future state projection (Level 3 SA). For example, a system must distinguish between an open drivable shoulder and a physically unobstructed but hazardous non-drivable zone, a task that purely geometric models struggle to resolve without dense semantic context.

To overcome these limitations, recent research has explored differentiable, modular end-to-end learning paradigms.¹⁶ In frameworks like Unified Autonomous Driving (UniAD), a single neural network natively integrates tracking, mapping, occupancy prediction, and motion planning [3]. By enabling the downstream motion planner to backpropagate errors directly to upstream perception layers, these architectures maximize joint performance. Yet, this shift from mathematically explicit code to data-driven, implicit software introduces a core systems engineering conflict [P2]. When the system's behavior is learned implicitly from data rather than designed explicitly via code, traditional, linear verification and validation (V&V) methodologies fail. Proving the safety of a non-deterministic AI system operating in an open world requires a fundamental restructuring of the systems engineering lifecycle.

The Iterative Data-Based V-Model: Structuring the Data Lifecycle

The classical V-model [4], long established as the standard reference for complex mechatronic lifecycles, assumes that a system can be decomposed top-down into deterministic specifications, verified in isolation, and integrated bottom-up. This linear structure assumes a closed-world operational envelope. To accommodate the implicit, data-dependent nature of AI, we proposed the “Iterative Data-Based V-Model” [P3]. This process reference model formalizes the iterative transitions between the real-world operational space, virtual simulation environments, and continuous deployment loops.

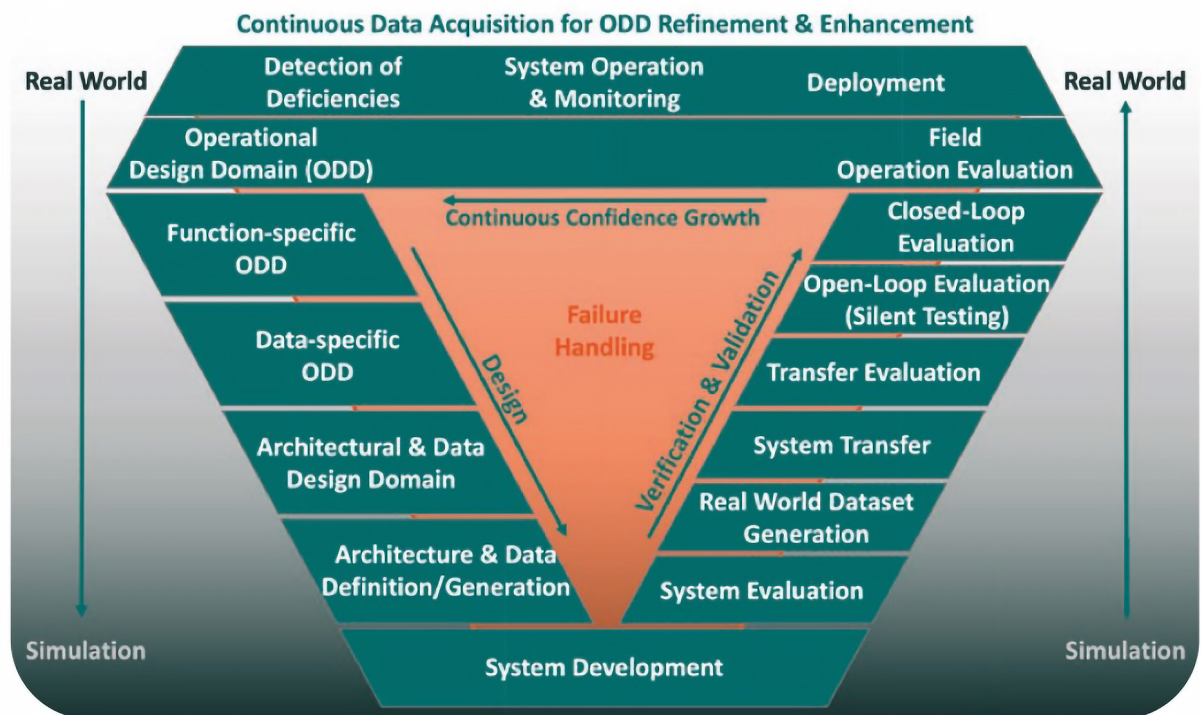


Figure 2: Iterative data-based V-model for the development and safety assurance of AI-enabled systems. Starting from the definition of the Operational Design Domain (ODD), the framework formalizes the closed-loop process between real-world operation and simulation, integrating data-driven development, verification, and validation. The iterative structure supports continuous system improvement and confidence building while addressing the challenges posed by complex AI-based systems operating in open-world environments.

A cornerstone of this model is the hierarchical decomposition of the Operational Design Domain (ODD) into three distinct, version-controlled specification layers:

- **System ODD:** The macro-level tier that defines the physical, environmental, and socio-political boundaries within which the automated vehicle is legally and functionally designed to operate. This serves as the top-level requirements specification. [P3]
- **Function-Specific ODD:** A top-down decomposition of the System ODD into localized requirements for specific subsystems. For example, the camera-based object detection subsystem is assigned a dedicated functional boundary that directly aligns with and inherits constraints from the overall System ODD, thereby minimizing functional specification uncertainties. [P3]
- **Data-Specific ODD:** This layer translates the function-specific requirements into concrete, quantifiable data specifications. It formally defines the volume, diversity, quality, and statistical distribution of the real-world and synthetic datasets required to train, verify, and validate the underlying machine learning models. [P3]

By making this translation explicit, the model establishes a continuous validation loop. When out-of-distribution (OOD) scenarios or edge cases are encountered during real-world operation, they are monitored, captured, and systematically fed back into the data-specific ODD. This triggers targeted synthetic data generation, virtual regression testing, and localized model fine-tuning. [P3]

Unlike conventional iterative methods that lack systems-engineering rigor, or highly empirical fleet-driven data loops that lack formal requirements tracking, the Iterative Data-Based V-Model bridges the gap. It harmonizes the structured, scenario-based virtual testing of initiatives like the German Verification Validation Methods (VVM) project [5] with the scalability of active continuous integration (CI) frameworks, along credibility building and safety determination of Waymo's Safety Framework [6], creating a traceable, engineering-grade data loop.

The AI Safety Assurance Triad and the "Data Control" Paradigm

Ensuring the safety of AI-integrated mechatronic systems requires proving that machine learning outputs remain valid, trustworthy, and explainable throughout the entire product lifecycle [P8]. In our work, we mapped this domain along a triad composed of technical research, industrial standardization, and legal regulation, emphasizing that these three pillars must evolve in parallel to prevent technological and regulatory fragmentation. [P2]

Our analysis [P2] further highlights the growing need for data-driven approaches to AI safety assurance that account for the inherent challenges of empirical AI systems, support lifecycle-wide safety assessment, and remain sufficiently technology-agnostic to accommodate future innovations. At the same time, it underscores the importance of open innovation, collaborative standardization efforts, and adaptive regulatory frameworks that facilitate continuous improvement while enabling safe technological progress. The study also identifies a fundamental paradigm shift from mathematically explicit systems toward data-driven, implicitly specified systems, requiring a corresponding evolution of system analysis and safety assurance methodologies.

To ground the safety analysis of these empirical systems in classical systems theory, we introduced the interdisciplinary “Data Control” paradigm [P5]. Rather than treating deep neural networks as isolated, static “black boxes,” Data Control interprets the underlying data-generating process (DGP) and its abstraction by AI systems through a system-theoretic and system-analysis-driven lens. This paradigm seeks to bridge the gap between performance-oriented, data-driven AI development and system-theoretic analysis focused on behavior, stability, and robustness.

A central focus of the Data Control paradigm [P5] is analyzing an AI system’s vulnerability to violations of the independent and identically distributed (i.i.d.) assumption under dataset shifts. By linking statistical dependencies to underlying causal relationships via Reichenbach’s Common Cause Principle, we demonstrate that causal structures, such as cause-effect relationships, yield conditional probabilities that remain invariant to input distribution shifts, such as covariate shift. This causal-graphical perspective provides a solid mathematical foundation for evaluating how well a learned model generalizes beyond its training distribution. [P5]

To formalize the analysis and evaluation of data-based AI signals and systems, we defined three central system properties:

- **AI Circumstance Robustness (AIC Robustness):** This property evaluates whether the statistical input-output relationship of the model remains invariant across different environmental or internal circumstances, such as sensor tolerances, noise, or weather conditions. It directly links the model’s robustness to a pre-specified set and range of operational conditions. [P5]
- **AI Circumstance Sensitivity (AIC Sensitivity):** This property captures the required responsiveness of non-stationary and dynamic AI systems. It defines how the statistical relationship changes in a pre-specified, controlled manner, measured by Kullback-Leibler divergence, when designated sensitivity factors vary beyond a specified threshold. [P5]
- **AI Dynamics Stability (AID Stability):** For dynamic AI systems, this property analyzes how the statistical relationship changes over time. Inspired by discrete-time Lyapunov stability, it uses the Kullback-Leibler divergence between consecutive time steps as a Lyapunov function candidate. This allows systems engineers to prove that the time-varying statistical divergence does not increase after a specific circumstance occurs, ensuring the system remains stable over its operational lifecycle. [P5]

By forcing the explicit documentation of assumptions, the Data Control paradigm provides a generic, application-agnostic framework for the formalized analysis, monitoring, and regulation of AI systems, enabling targeted diagnostics and continuous maintenance.

Control-Theoretic Trajectory Planning and Regional Scalability

At the physical execution layer, the core of our research focuses on trajectory planning and control optimization under strict physical and environmental constraints. Safe motion planning requires solving non-linear, non-convex optimization problems in fractions of a second. To resolve this, my thesis introduced three major control-theoretic advancements:

Robust Meta-Learning of Vehicle Dynamics

Vehicle parameters, such as tire-road friction, change dynamically due to weather, payload, or surface degradation. Traditional Model Predictive Control (MPC) relies on static physical parameters, which can lead to instability during sudden transitions. We developed an online adaptation method using Conditional Neural Processes (CNPs) [P9] that marries a nominal physical vehicle model with a data-driven error model. This hybrid formulation models the vehicle's dynamic state as a combination of a nominal physical model and a data-driven yaw rate dynamics component. The yaw rate dynamics is determined online by the Conditional Neural Process using a rolling window of recent state-action context history. This formulation allows the vehicle to safely adapt to highly hazardous surface conditions, such as black ice, within milliseconds, preventing loss of control while maintaining nominal actuator limits.

Stochastic Normalizing Flows for MPC Sampling

In highly complex, multi-modal environments, such as busy urban intersections, numerical optimization algorithms frequently become trapped in local minima. To guarantee path feasibility, we integrated Stochastic Normalizing Flows [7] into sampling-based model predictive trajectory planning. Normalizing Flows map a tractable, simple probability distributions, such as an isotropic Gaussian, to a complex, multi-modal trajectory distribution through a sequence of invertible, differentiable transformations. This process mathematically maps the simple probability density of the base distribution to a complex, multi-modal target trajectory space by scaling it with the absolute determinants of the Jacobians of the inverse transformations. By sampling directly from this learned, highly realistic flow, the trajectory planner can generate multiple distinct, collision-free path alternatives [P10], e.g., passing a stalled vehicle on the left versus waiting on the right, in under 20 milliseconds, which are subsequently refined by a low-level MPC optimization step.

Motion Transformer Transfer Learning

Predicting the future trajectories of surrounding traffic participants is crucial for proactive path planning. While deep-learning-based Motion Transformers [8] achieve high predictive accuracy, they are notoriously data-hungry and costly to train. We conducted a comprehensive transfer learning study demonstrating that a transformer model pre-trained on massive, generalized public datasets can be successfully adapted to highly specific local operational domains using minimal localized data [P7]. This transferability drastically reduces the data collection and computational overhead required to scale predictive models to new urban deployment areas across the globe.

Managing Regional Scalability

Even with robust physical control and predictive capabilities, deploying autonomous vehicles globally introduces socio-political, legal, and ethical challenges. Driving cultures, legal right-of-way interpretations, and ethical norms differ vastly across international boundaries.

To manage these regional variances, we proposed a two-stage scalability framework [P6]. In the first stage (Global Technical Stabilization), a high-performance, standardized baseline model is trained on global datasets to manage physical vehicle control, standard perception, and hard safety envelopes. In the second stage (Local Socio-Political Fine-Tuning), the baseline model's decision boundaries are adjusted using country-specific reward models [P6]. These reward models act as a digital configuration interface. Moreover, by altering the cost functions within the trajectory optimizer, the vehicle's driving style can be adapted, e.g., from an assertive, tight-merging style suited for dense Mediterranean traffic to a highly defensive, large-distance style required in northern Europe. Thus, to comply with local legal frameworks and cultural expectations without altering the underlying safety-critical software stack.

Industrial Systems Engineering: Interoperability and the Digital Thread

For the virtual product creation and PDM communities, transitioning these academic frameworks into industrial practice requires aligning them with open standards and configuration management (CM) guidelines [9]. Under the prostep ivip Smart Systems Engineering (SmartSE) guidelines, collaborative co-simulations between OEMs and suppliers should evaluate simulation credibility. This requires a clear separation of IP within shared models.

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Using the Functional Mock-up Interface (FMI 3.0) and System Structure and Parameterization (SSP) standards, the physical, deterministic aspects of the vehicle can be packaged as model parameters, while the data-driven, neural components are isolated as model functions. This structural separation allows partners to exchange behavior models as Functional Mock-up Units (FMUs), protecting internal algorithmic IP while ensuring functional interoperability within the virtual testbench.

Furthermore, as the industry transitions from document-centric exchange to linked data spaces (e.g., Gaia-X), semantic interoperability becomes paramount. Standards like the Vehicle Electric Container (VEC) are being evolved into RDF-based ontologies. Unlike raw XML schemas that define only syntax, ontologies define both syntax and semantics, ensuring that downstream AI perception models can natively parse a vehicle's electrical and physical architecture without manual, error-prone translation.

To secure the digital thread of these complex configurations, product data management should implement robust, cryptographic traceability [10]. In highly regulated industries, virtual verification and validation cannot rely on siloed databases. By leveraging Public Key Infrastructure (X.509-PKI), digital signatures can be embedded directly into product data packages.

Within our proposed release workflow, each major milestone, such as the definition of a new Data-Specific ODD, the release of a synthetic validation dataset, or the approval of a neural trajectory planner, is cryptographically signed by the responsible engineering role. The Configuration Management (CM) system then cross-signs these packages, vouching for the entire multi-stage engineering review chain. This cryptographic chain of trust ensures that when an autonomous vehicle is deployed, downstream consumers and regulatory authorities can verify that the onboard software matches the certified simulation loop and is fully authorized for its operational domain [10].

Outlook: From Software-Defined Vehicles to Data-Defined Autonomy

As we look to the future of autonomous systems, the traditional software-centric paradigm must evolve. We must transition from Software-Defined Vehicles to Data-Defined Autonomy. In this new paradigm, the driving capabilities, safety profiles, and regional adaptability of an autonomous system are not determined by the complexity of its hand-written code, but by the completeness, quality, and structure of the data that shapes its implicit models.

Achieving this transition requires establishing data as a first-class engineering artifact through the Interactive Data-Based V-Model [P3]. This means that data can no longer be treated as a transient, operational input. Instead, datasets, training distributions, and ODD boundary definitions should be managed with the same structural rigor, version control, change-management loops, and cryptographic traceability as physical hardware components.

By embedding these data specifications natively into PLM and configuration management systems, linked via open standards like STEP AP242, ReqIF, and FMI 3.0, the systems engineering community can build a secure, continuous, and scalable digital thread. The 2026 prostep ivip Scientific Award underscores the vital importance of this intersection between control theory, machine learning, and systems engineering. Through these unified frameworks, we pave the way for a future of intelligent, safe, and truly scalable autonomy.

Own Publications

- [P1] Ullrich, L.: Towards Intelligent, Safe, and Scalable Autonomy: A Study Driven by Trajectory Planning for Automated Vehicles. Doctoral dissertation, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany. DOI : 10.25593/open-fau-2326 (2025).
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Live Collaboration in Engineering (LCE): The Evolution of Cross-Organizational Collaboration in Engineering

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Peter Gerber (Schaeffler Technologies AG & Co. KG)

Today, cross-organizational information exchange in engineering is often asynchronous, file-based, and lacks sufficient transparency regarding maturity level, responsibilities, or context. Over the past three years, the Collaborative Digital Twins (CDT) project group has established important methodological and technical foundations for cross-organizational, synchronous collaboration in engineering, ranging from user journeys, glossaries, and ontologies to a sandbox implementation of a data space in which a proof of concept (PoC) for exchanging requirements information was successfully implemented.

With the conclusion of the CDT project at the end of 2025, the groundwork was laid for the new Live Collaboration in Engineering (LCE) project group, which began its work in early 2026. LCE not only builds on the results of CDT but also further develops them to enable cross-organizational synchronous collaboration throughout the entire product development cycle. Instead of exchanging documents asynchronously, relevant data will be synchronously connected in the future. LCE's goal is thus to make end-to-end connected engineering a reality, from early requirements definition through system architecture and simulation to integration and testing and beyond.

From Collaborative Digital Twins to Real-Time Collaboration in Engineering

The new Live Collaboration in Engineering (LCE) initiative continues the vision developed in CDT. LCE aims to lay the groundwork for synchronized and federated real-time collaboration across the entire V-model. The focus is on further developing the CDT results into a concept for networked engineering processes.

As part of the CDT project, key methodological and technical foundations for cross-organizational, synchronous collaboration were developed between 2023 and 2025. Among the most important results are a comprehensive, harmonized glossary with over 130 terms, coordinated ontologies for various engineering domains, and detailed user journeys describing practical collaboration scenarios. These concepts were supplemented by a generic, DT-ready IT architecture compatible with Dataspace technologies.



Figure 1: prostep ivip Symposium presentation „Collaborative Digital Twins - Enabling Live Collaboration in Engineering: Project Results, Collaboration with Catena-X & Way Forward“.

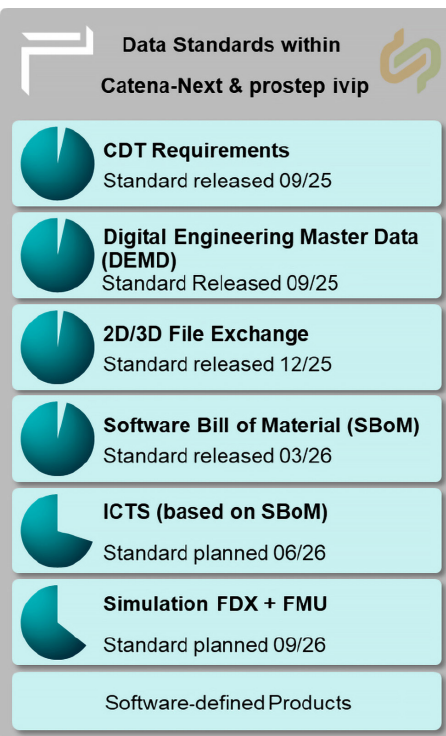


Figure 2: Published Standards

Building on these foundations, a demonstrator was implemented that shows how requirements data can be exchanged synchronously, securely, and without file-based exchange between multiple partners. This enables individual requirements to be exchanged on a point-by-point basis between different, heterogeneous IT landscapes.

These results were presented at the prostep ivip Symposium 2026 by project leaders Dr. Sebastian Handschuh (Mercedes-Benz AG) and Peter Gerber (Schaeffler AG). Using the CDT demonstrator, it was shown how the developed framework can reduce the time required for requirements exchange from several days to just a few seconds. This highlighted the added value of semantically harmonized data models and federated IT architectures. Not only can development time be significantly reduced, but data quality, availability, and security are also improved.

The accompanying CDT project video (https://www.youtube.com/watch?v=LvFL_-XKhqM) also offers an in-depth look at the results of the CDT project, clearly illustrating the objectives, architecture, and implementation of the demonstrator.

The LCE project group builds on these results. A key enabler for this is the availability of uniform and interoperable data standards. Building on the results of the CDT project group and in coordination with Catena X, several relevant standards have been published or prepared in recent months (Figure 2: Published Standards).

With CDT Requirements, Digital Engineering Master Data (DEMD), 2D/3D File Exchange, and the Software Bill of Materials (SBOM), key standards for the cross-organizational exchange of engineering information are already available. They address essential data types throughout the product life-cycle, from requirements to geometry and master data, all the way to software-related information.

In addition, further standards are currently being developed and are scheduled for release in 2026. This will lay the groundwork for gradually expanding live collaboration to additional engineering disciplines and providing comprehensive support for software-defined products.

Launch of the “Live Collaboration in Engineering” (LCE) Project Group

In early March 2026, the new project group held its first onsite workshop in Darmstadt (Figure 3: First onsite workshop of the Live Collaboration in Engineering (LCE) project group in late March 2026 in Darmstadt). Twenty-two representatives from 14 companies and organizations worked on three key focus areas during interactive sessions:



Figure 3: First onsite workshop of the Live Collaboration in Engineering (LCE) project group in late March 2026 in Darmstadt

1. Refining the vision and mission

In the first step, the shared objectives of LCE were further refined. The group discussed what “Live Collaboration” specifically means in industrial engineering and what forms of synchronous collaboration are necessary for this. The discussion focused on appropriate levels of real-time capability, data quality requirements, and clear responsibilities for shared information.

2. Collection and Prioritization of Use Cases

Subsequently, a wide range of use cases from various other project groups and initiatives were presented along the V-model. On this basis, the project group agreed to initially prioritize those processes that promise the greatest technical benefit and the strongest leverage in particular, Collaborative Simulation, Integration & Test, and System Engineering.

3. Working Method and Interfaces

Finally, the project group’s planned working method and the structure of the work packages were defined in detail. The teams presented their roadmaps and expected deliverables. In addition, relevant interfaces were identified to ensure the exchange of results and requirements between the work packages.

The LCE project group is divided into four work packages that together establish the methodological, organizational, and technical framework:

Work Package 0: Organization & Strategic Networking

This work package is responsible for overall coordination, harmonizing the vision, and formulating the business value of LCE. It also organizes exchanges with other prostep ivip projects and external initiatives such as Catena-X, DDP, SmartSE, FAICE, and HAIViSH. Its tasks also include producing publications and preparing contributions for events such as the prostep ivip Symposium.

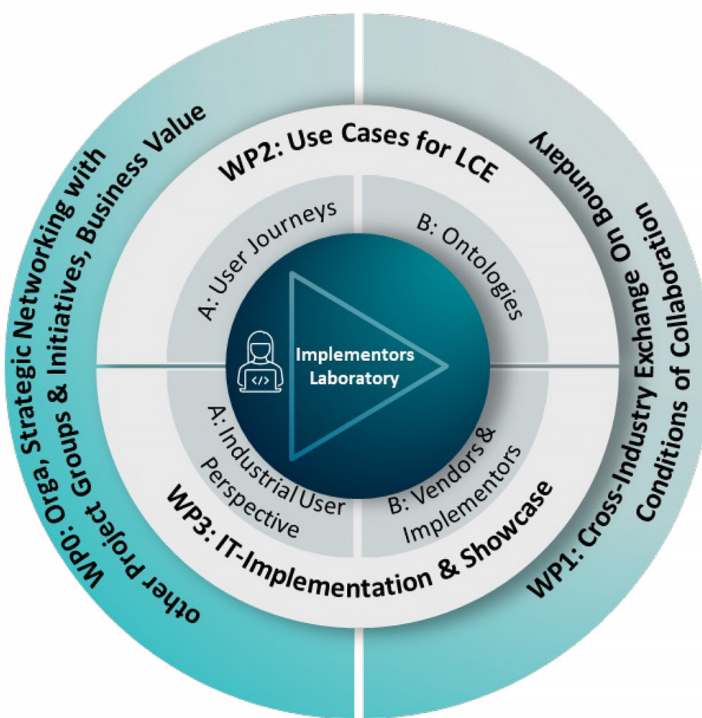


Figure 4: LCE Workpackage structure

Work Package 1: Cross-Industry Exchange on Boundary Conditions

This work package addresses legal, organizational, and procedural framework conditions across industries. This includes issues related to data sovereignty, governance models, and supply chain integration. Through regular “walk-in sessions,” questions from the technical work packages are collected, discussed, and translated into recommendations.

Work Package 2: Use Cases for LCE

This work package forms the technical core of LCE. Through a combination of the user journey perspective (A) and the ontology perspective (B), use cases are harmonized, prioritized, and redesigned with a focus on live collaboration. Existing ontologies from DDP, Catena-X, and other sources are analyzed to determine LCE requirements, gaps are identified, and proposals for further development are created. Cross-organizational co-simulation was selected as the first use case.

Work Package 3: IT-Implementation & Showcase

This work package is responsible for the technical requirements and implementation. The goal is to develop an LCE demonstrator that illustrates the added value of synchronous collaboration using a prioritized use case. The technical architecture describes both implementation options and recommendations for interoperable deployment in real-world enterprise environments.

Outlook

The next milestones are the finalization of the roadmaps and the development of concrete implementation requirements for the LCE demonstrator. In summary, the results to date show that virtual data spaces enable true synchronous cross-organizational collaboration in engineering. The transition from file-based exchange to collaboration on semantically described, unambiguous data lays the foundation for efficiency, quality, and security.

LCE is establishing a project group that paves the way for dynamic, interoperable, and at the same time sovereign engineering collaboration, thereby laying a central building block for the next generation of digital product development.

Interested companies and organizations are cordially invited to actively participate in the Live Collaboration in Engineering (LCE) project group. If you would like to join the initiative and help shape the next steps toward synchronous, cross-organizational engineering collaboration, please fill out the LCE Member Survey (<https://forms.office.com/e/0swuGG8qJA>), or contact us directly.

Further information about the Live Collaboration in Engineering (LCE) project group is available on the official project page of the prostep ivip Association:

<https://www.prostep.org/projekte/live-collaboration-in-engineering-lce>



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Sewing the Digital Thread Together via Standards

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The CAX Interoperability Forum (CAX-IF)

Within the larger Model-Based “x” Interoperability Forum (MBx-IF) framework, jointly hosted by PDES, Inc. in the US, AFNeT in France, and the prostep ivip association, the CAX-IF supports the deployment of STEP AP242 [1] and focuses on 3D geometry enriched with semantic properties such as Product & Manufacturing Information (PMI). Its user group and implementor group count a dozen member companies each, including Aerospace and Automotive manufacturers and suppliers on the one hand side, and CAD system vendors as well as CAD translation and validation software providers on the other. The team can already look back on a successful history, reaching back to 1999 when PDES, Inc. and prostep ivip combined their respective efforts and conducted the first joint test round, or “Round 1J” for short. The 57th joint round of testing (R57J) was concluded in March 2026 with a meeting in Charleston, SC, USA.

The main goal of the forum is to collect industry requirements, develop and document approaches to map the desired information onto the STEP standard in so-called “Recommended Practices”, coordinate with the standards developers at ISO in case changes to the data model are needed, and finally validate the data model, agreed approaches, and vendor implementations in its test rounds. In the end, the users benefit from a validated standard upon release, and robust, interoperable software products built on it. For software vendors, the group serves as an incubator that significantly accelerates implementation efforts while increasing product quality through thorough pre-release testing.

Why Persistent IDs in STEP?

A robust digital thread requires that every feature, tolerance, datum, and operational element introduced in design retain its identity as it moves through manufacturing, inspection, and in-service support. When that identity survives every translation and round-trip, organizations gain faster time-to-market, less rework on the production floor, and the ability to perform forensic analysis when in-service failures occur. Aerospace, defense, and automotive sectors are leading the push, but the requirement is universal: a single authoritative identifier per element, persistent across tools, releases, and decades of product life.

Several communities are tackling this challenge from different angles – MBSE, MTConnect, PDM-IF, and the CAX-IF, among others. This article focuses on the work underway within PDES, Inc.’s Persistent ID (PID) Project, which is tightly integrated with the CAX-IF and targets STEP AP242 as the authoritative carrier of those identifiers. We outline what has been delivered, the gaps that remain, and what is planned for the next 12 to 18 months. The foundational research underpinning this work is documented in NIST AMS 300-12 [2].

Cross-Domain Exchange with Downstream Systems

In January 2026, the CAX-IF and the Digital Metrology Standards Consortium (DMSC) released the “Recommended Practices for Cross-Domain Exchange for Downstream Uses”, Release 1.0 [3]. The practice establishes how UUIDs originating in STEP AP242 are carried into the Quality Information Framework (QIF) so that geometry, PMI, and measurement results remain linked across the design → plan → measure → results chain. STEP exports use V5_UUID_ATTRIBUTE; QIF preserves the same identity through EntityExternalIds. The result is a bidirectional trace that supports both forward verification of design coverage and backward root-cause analysis when a measurement fails.

Between testing within the CAX-IF and in the PID project, full backtraces from measured characteristics in QIF results to STEP features with their design characteristics (PMI) have been proven. This means automated data linking across domains can be shared between users quickly and efficiently, allowing clear and unambiguous identification of manufacturing defects due to tool wear or identification of required design changes to facilitate production process flow. The goal is to extend this capability to include, for example, linking requirements from model-based system engineering at the front end and linking targeted observations from in-service failure analyses to the digital thread. It should be noted that the current effort is limited to exchanges within the mechanical engineering domain.

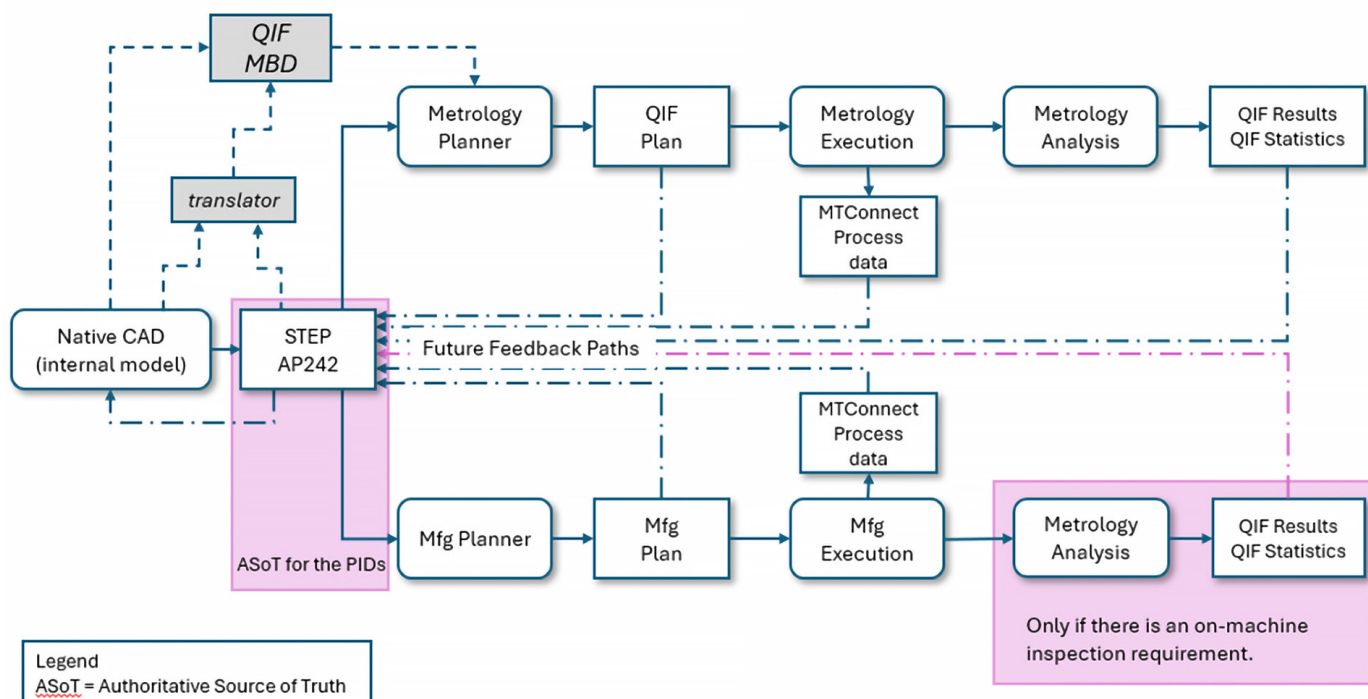


Figure 1: Design to Downstream Workflows (from [3]).

Cross-domain exchange, as described in this article, is still contained within the sub-domains of mechanical engineering, as the mechanical engineering handbook is understood (more or less) by all practitioners. Because the base engineering knowledge is there, we can deal with different representations of the same underlying data. We are not trying to communicate between Electrical and Mechanical. Though this should be possible, future research would be required to understand the feasibility and efficacy of such transfers.

CAx-IF Progress

Steady progress has been demonstrated across recent CAx-IF test rounds. The PID v1.8 Recommended Practice [4] codifies how identifiers are produced and consumed for design iteration (PDI) and downstream consumption (PDC). The Cross Domain Exchange (CDE) practice [3] covers cross-domain exchange between STEP and QIF. R55J established baseline capability and R56J extended coverage. The most recent test round, R57J (Sep 2025 – Mar 2026), confirmed bidirectional traceability through both PMI and their associated features and geometry in STEP and characteristic results and their associated features in QIF.

In R57J, PDI exchanges achieved a 97% overall success rate across 75 files and 160 results submitted by six vendors; PDC exchanges reached 76% across 14 files and 18 results from five vendors; and CDE exchanges – the first systematic STEP-to-QIF round-trip – reached 77% across 7 files and 7 results from four vendors. Across test rounds, results show a clear upward tendency as vendor implementations mature against the Recommended Practices. Growing participation demonstrates strong interest in Persistent ID exchange, while the trends indicate vendors are actively collaborating, engaging with STEP and QIF experts, and improving their capabilities. Overall, these statistics highlight the CAx IF's effectiveness as an incubator for new STEP capabilities.

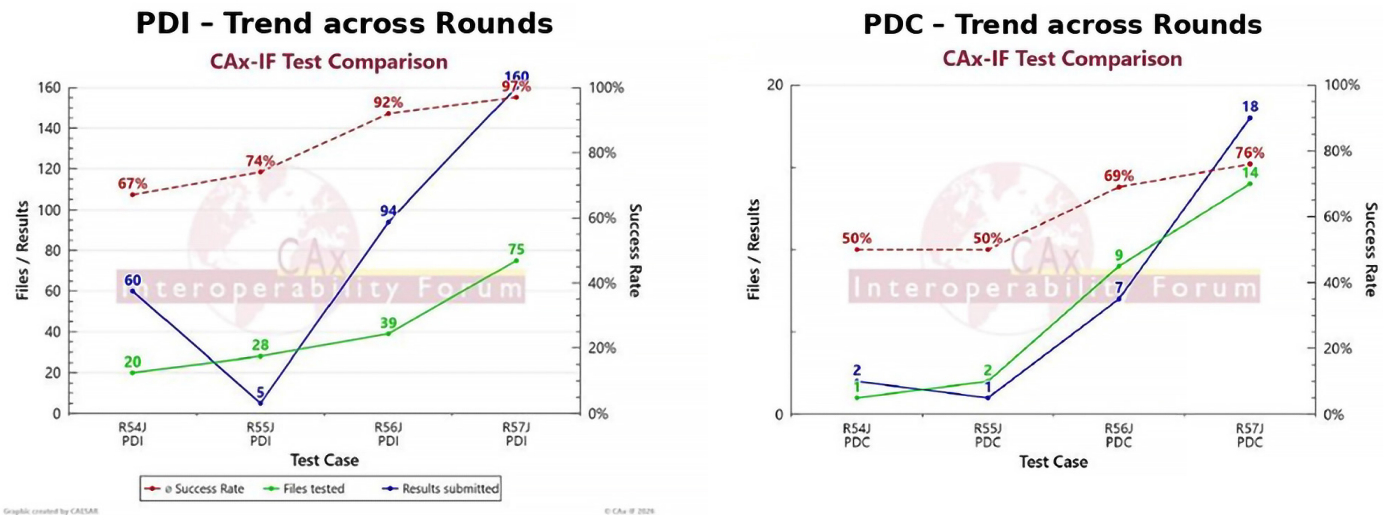


Figure 2: CAX-IF R57J results: trend plots across R54J-R57J for PDI and PDC test cases.

What is Next?

Momentum is real, but gaps remain. Most will be addressed as part of AP242 Edition 5 development and the parallel CAX-IF testing program [6]:

- Bill of Operational Features (BOF) [5] – a planning view of the product, with detailed properties for each operational feature and UUID links back to the design view.
- Model-based Notes – embedded document, attribute and PMI references; embedded compliance specification, all in a structured model.
- Parametric PMI templates – first-class representation of screw threads, welds, and balloons.
- Feedback from Metrology to Design – use of the Observation entity to surface design-relevant findings discovered during inspection (for example, an unexpected burr).

CAX-IF Plans for the next test rounds include (final scope to be negotiated between stakeholders and vendors):

- The introduction of BOF collection concepts in Part 21 files via the Draft Recommended Practices.
- Introduction of Model-based Notes and Parametric PMI templates via the trial Edition 5 schema and a new Recommended Practices; introduction of feedback from metrology results to design.
- Continued testing of BOF, Model-based notes and parametric PMI templates and Feedback.
- Integrated PID testing between Domain Model XML and Part 21 files
- Integrated PID testing between MBSE models and Part 21 files.

Together, these steps move the digital thread from a design-to-inspection demonstration to a fully integrated, multi-domain capability – sewn together by persistent identifiers and the standards that carry them. These automated links between product data in different domains will enable clear, unambiguous communication between stakeholders in the digital thread. This capability is expected to accelerate delivery of quality products, reduce rework, and support targeted feedback to stakeholders about forensic analysis of in-service anomalies.

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Cloud-Native DevOps in Automotive Engineering: **How cloud infrastructures and Security-by-Design are transforming Software-Defined Vehicle development**

Michele Del Mondo, PTC

Cloud-native DevOps platforms are becoming a key enabler for Software-Defined Vehicle development. As vehicles evolve into complex digital platforms, OEMs and Tier 1 suppliers need scalable, secure and traceable engineering environments that support continuous integration, compliance and Security-by-Design. The article explains how cloud infrastructures, Application Lifecycle Management and automated validation help accelerate development cycles, manage regulatory requirements and build trust in safety-critical automotive software.



Figure 1: Cloud-native infrastructures provide the foundation for scalable and connected development environments in Software-Defined Vehicle engineering. © PTC

Software-Defined Vehicles require new development principles. Cloud-native DevOps platforms and integrated security strategies do more than increase speed. They also create trust in safety-critical environments.

Modern vehicles are no longer just machines. They are digital platforms on wheels. With many millions of lines of code, software has become the new differentiator. This creates fundamental challenges for OEMs and Tier 1 suppliers. Instead of rigid development cycles and local toolchains, they need flexible, scalable and secure cloud-native environments. The ability to safely operate, maintain and update complex systems with a high pace of change is increasingly becoming a decisive factor for market success.

New architecture, new requirements

Software-Defined Vehicles are based on centralized E/E architectures with powerful central computing units. This increases the need for dynamic updates, functional decoupling and systematic reuse. At the same time, regulations and standards such as ISO/SAE 21434, Automotive SPICE and UNECE R155 require end-to-end documentation, secure development processes and comprehensive risk management.



Figure 2: Software-Defined Vehicles enhance safety and user control through intelligent, data-driven assistance systems. © PTC

These regulatory requirements make it essential to consider security aspects from the earliest phases of the development process. If security requirements are not integrated during the architecture phase, the result can be costly rework, delays in certification or even product recalls. Supply chain security is also becoming a growing priority. Every component must be traceable, verifiable and securely integrable.

Cloud-native DevOps as a response to complexity and speed

Cloud-based DevOps platforms provide the methodological backbone for Software-Defined Vehicle development. Continuous Integration and Continuous Delivery with integrated security scans, automated compliance checks and scalable test environments all contribute to efficiency, security and transparency. Providers such as PTC support these processes with solutions tailored to the specific requirements of the automotive industry. The cloud enables faster development cycles as well as a smoother transition between development, testing and deployment.

For example, instead of building and validating long release cycles locally, global teams can develop, test and deploy in a unified environment. This significantly reduces time to market, lowers error rates and improves software quality over the long term. CI/CD pipelines ensure that every code change can be tested, validated and, where necessary, delivered in near real time. The integration of feature toggles also enables rolling updates, allowing new functions to be deployed gradually and rolled back when needed.

Security-by-Design: security starts with the architecture

With UNECE Regulation R155, ISO/SAE 21434 has become a regulatory reality. In practice, this means security must be considered early and systematically embedded in the development process. Cloud-native Application Lifecycle Management platforms support this with integrated requirements management, automated risk assessments and audit trails. This allows security requirements to be managed, monitored and documented in a model-based way.

Security-by-Design means integrating mechanisms such as secure boot, encryption, network segmentation and anomaly detection at the architecture level. Combined with automated test coverage and model-based threat analysis, cloud-native platforms provide the transparency and security required for complex automotive software. The integration of threat models and attack scenarios in the early stages of system design helps identify and address vulnerabilities proactively.

Scalability meets compliance

The cloud does not only offer speed. It also provides traceability. Every change, every feature and every release is documented. This is essential for certification processes, approval procedures and legal requirements. At the same time, cloud resources allow test and simulation environments to be scaled flexibly, whether for hardware-in-the-loop, software-in-the-loop or model-based testing. The integration of AI-supported test management and predictive quality monitoring is also significantly simplified by cloud platforms.



Figure 3: Connected data flows link engineering and production, enabling end-to-end digital development processes. © PTC



Figure 4: Modern automotive engineering combines simulation, automation and software development within integrated platforms. © PTC

Standardized APIs and microservice architectures make it possible to integrate new features into existing systems without disrupting the overall context. A strong ALM system centrally manages these changes, documents version histories and enables targeted rollback in the event of problems. This flexibility is particularly important for OEMs managing multiple model variants across different markets. At the same time, the system supports close integration with production and aftermarket services, creating the basis for consistent, maintainable and scalable system landscapes.

Best practices: what the industry is already implementing

Automotive companies are already using cloud-based engineering environments to bring together mechanical, electronic and software requirements. Centralized management of security requirements helps address regulatory differences between markets more efficiently. ALM systems also support end-to-end safety certification for critical systems, including versioning and audit trails.

In parallel, OEMs are increasingly connecting Model-Based Systems Engineering with DevOps to manage compliance, variant diversity and security architectures within a unified process. By combining model-based engineering with automated pipelines, they create digital development paths that are not only efficient, but also traceable and auditable.

Digital twin strategies are also gaining importance, especially for the early simulation of safety-critical functions. This real-time validation, combined with cloud-native infrastructures, accelerates innovation cycles and reduces the number of physical prototypes required. Cloud-based software-in-the-loop environments also make it easier to validate complex control algorithms automatically and optimize them continuously.

Conclusion: **Software-Defined Vehicles require cloud and trust**

The shift to the Software-Defined Vehicle is not only a technological transformation. It is also a cultural transformation in engineering. Cloud-native DevOps platforms create the foundation for developing complex software products securely, efficiently and traceably. They provide scalability, security and compliance with a level of integration that was previously difficult to achieve.

Only those who think about architecture, security and variant management in an integrated way will remain competitive over the long term. Applying proven IT principles to Software-Defined Vehicle development is critical for future viability and scalability. Companies that see security not as a barrier, but as a differentiator, create trust in digital mobility and remain competitive in the cloud era.



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R&D Reinvention with AI: **Why Product Data, Context and the Underlying Development Logic Matter**

Dr. Alexander Albers, Mario Mikuschek, Daniel Spiess, Accenture

AI is moving rapidly onto the R&D agenda as companies seek structural cost take out and higher development speed. But real impact will not come from more use cases alone. It will depend on whether organizations can combine strong product data foundations, meaningful context, and a new underlying development logic.



Figure 1: AI in engineering depends on the interaction of product data, context, and development logic.

Industrial R&D organizations are under growing pressure to reduce cost, increase engineering productivity, and accelerate development despite rising product complexity. AI is therefore becoming a major topic across software, systems engineering, MBSE, simulation, testing, documentation, and mechanical development. Yet many initiatives remain stuck at proof of concept level or confined to isolated use cases. The reason is often not a lack of ideas, but a lack of scale-ready conditions. AI can create local efficiency gains, but broader performance gains require more: reliable product data foundations, context that makes engineering information usable across tasks and domains, and an underlying development logic that can absorb and scale AI's potential. R&D reinvention with AI is not about adding more use cases. It is about unlocking structural cost take out and speed through AI, enabled by strong product data foundations, meaningful context, and a new underlying development logic.

Cost take out and speed have become the real R&D agenda

R&D is under pressure to become faster and more efficient. In many industrial companies, that has become the defining condition of product development.

The challenge is no longer only innovation or product differentiation. It is increasingly also about structural cost take out and higher development speed. Engineering organizations are expected to deliver more output, shorten development cycles, and manage rising cross domain complexity under tighter economic pressure than before.

In many sectors, this pressure is amplified by global competition, rising regulatory demands, and growing scrutiny of R&D budgets. At the same time, products are becoming harder to develop. Hardware, software, electronics, systems logic, and data driven functions are more tightly interdependent. Product variants increase, update cycles accelerate, and dependencies across domains grow.

This is pushing many organizations toward the limits of traditional improvement logic in R&D. Incremental optimization is often no longer enough. The old assumption that complexity can be managed mainly through more specialization, more documentation, and more sequential coordination is becoming less reliable.

This is why AI is moving rapidly onto the R&D agenda. For many R&D leaders, it is linked to a clear economic ambition: reduce engineering effort, accelerate throughput, and improve responsiveness without sacrificing technical rigor.

That makes the current discussion highly relevant. But it also creates a risk. If AI is approached mainly as a growing portfolio of use cases, companies may generate local improvements without changing the overall performance profile of R&D.

AI clearly has value in engineering, but that is no longer the main question

There is little doubt that AI can create value across large parts of the engineering value chain. In software related development, it can support coding, testing, debugging, and documentation. In systems engineering and requirements work, it can help structure information, identify inconsistencies, and improve access to distributed knowledge. In MBSE related contexts, it can assist with model navigation, consistency checks, and the handling of complex system artifacts.

The same applies to simulation, testing, and mechanical development. AI can accelerate synthesis and analysis, support design iteration, and reduce manual effort in documentation, search, and knowledge reuse.

This creates more than incremental convenience. In selected activities, AI can act as a form of virtual capacity by taking over repetitive preparation tasks and supporting knowledge intensive work. Human in the Lead remains essential.

The more important question, however, is why so much of this value remains local. Why do promising applications emerge, while broad performance gains in cost and speed often remain limited?

That is where the debate has to move next. The issue is no longer whether AI can help engineering. The issue is what keeps that help from translating into system level R&D performance.

The real bottleneck is not use case discovery, but scale readiness

Many organizations have already made progress in identifying AI opportunities in R&D. They build proofs of concept, validate technical feasibility, and demonstrate local benefits. Yet broad performance effects across the development system often remain limited.

The reason is that many companies have progressed further in identifying vertical use cases than in building horizontal readiness. They know where AI could be applied, but not yet what kind of environment is required to scale it across functions, domains, and workflows. This creates a gap between local feasibility and enterprise level value realization.

Many initiatives are still framed around isolated AI use cases rather than embedded in the broader product development process. As a result, local feasibility is demonstrated, but system level value remains hard to realize.

That gap is particularly visible in engineering. R&D performance does not depend only on the productivity of isolated roles. It depends on the quality, speed, and coherence of the full development system.

In many engineering environments, requirements, system architectures, product structures, CAD models, simulation results, software artifacts, and test evidence still do not interact in a sufficiently connected way. Information is transferred manually, context gets lost across system boundaries, and traceability weakens exactly where AI would need it most.

This is why many initiatives remain trapped at POC level. A solution works in one department, within one specific tool environment, or in one carefully prepared process step. But scaling beyond that point proves difficult. Interfaces break. Context is missing. Data is inconsistent. Outputs are hard to reuse across adjacent functions.

The main bottleneck is often no longer the lack of promising AI applications. It is the lack of scale ready development environments.

Three technical conditions determine whether AI can scale

If organizations want to translate AI into structural cost take out and speed, three technical conditions become critical: product data foundations, interoperability, and context.

Product data foundations determine whether engineering information is reliable. AI can only create dependable value if underlying data is robust, structured, and usable. That includes clear objects, sound metadata, consistent semantics, version awareness, and traceable relationships across engineering artifacts.

Interoperability determines whether engineering information can move. Requirements, architectures, bills of material, software artifacts, simulation results, test evidence, and change information need to interact across tools and domains. If tools remain weakly connected or information flows are broken across system boundaries, AI can only optimize within partial contexts.

Context determines whether engineering information becomes relevant in use. Access to data alone is not enough. AI needs the right situational and functional context. A requirement only becomes actionable when understood in relation to architecture, variant, release status, validation logic, and downstream implications.

These are familiar themes. In the context of AI, however, they become direct preconditions for scaling value in product development.

What AI increasingly requires is not just accessible data, but a harmonized and machine-readable engineering environment.

Still, that is only half of the story. Better data foundations, better connectivity, and better context are essential enablers. But on their own, they do not turn AI into structural value.

The overlooked lever is the underlying development logic

The most underexplored issue in the current AI debate is not technical enablement. It is the underlying development logic itself.

By the underlying development logic, we do not mean the governance of AI initiatives or the management of AI use cases. We mean the structural choices that shape how product development is run: how work is divided, how information moves between domains, when learning occurs, and how decisions are made, independently of any specific tool or AI application.

Figure 2. Product data foundations, interoperability, context, and development logic must evolve together for AI to create structural value in R&D.

In many industrial companies, AI is introduced into a development system that still follows assumptions shaped by an earlier engineering era. Work is organized through sequential handovers, domain based silos, slow coordination loops, and relatively late learning cycles. Integration and validation often happen late. This model may still provide control, but it limits the ability to absorb the full value of AI.

That matters because AI does not only accelerate isolated tasks. Its deeper potential lies in compressing iteration loops, connecting knowledge across boundaries, and supporting faster synthesis, analysis, and decision preparation. AI changes what is technically possible in product development, but organizational reality often lags behind.

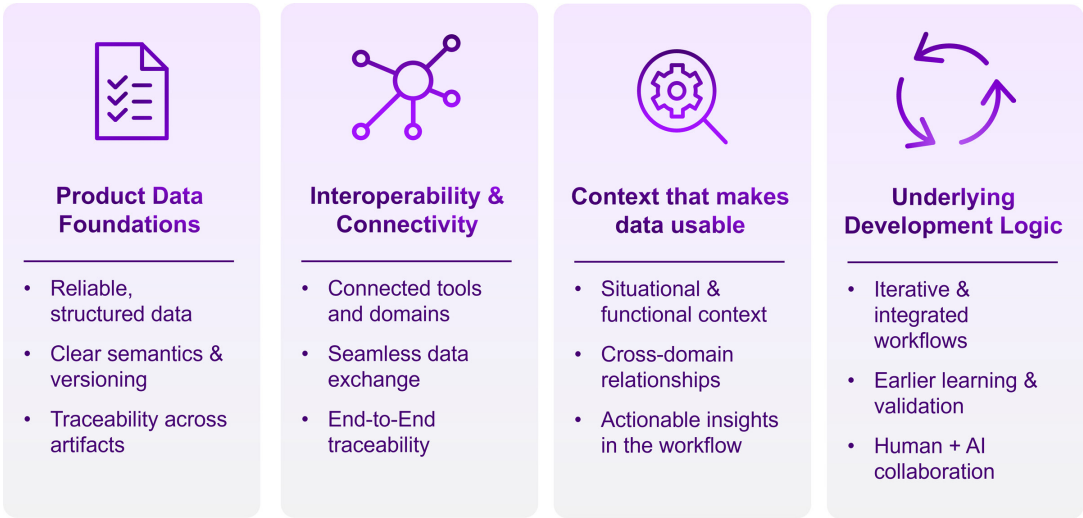


Figure 2: Product data foundations, interoperability, context, and development logic must evolve together for AI to create structural value in R&D.

If the surrounding development logic remains unchanged, AI is pushed back into local productivity gains rather than system level performance improvement. The result is a familiar mismatch: technical potential rises, but structural performance barely moves.

This is the core tension in many R&D organizations today. Technically, they can augment engineering work with AI. Structurally, they still operate through slower transitions, stronger separation between domains, and delayed feedback. R&D reinvention with AI therefore cannot be reduced to a tooling agenda. It requires product development to become more iterative, more architecture aware, more capable of handling different domain speeds, and more integrated across functions.

This also has direct implications for cost take out. In engineering, late corrections are almost always more expensive than early learning. If AI is used to support earlier synthesis, faster evaluation, and quicker feedback across domains, its value lies not only in local efficiency, but in shifting effort away from late integration and rework.

None of this means abandoning rigor, safety, or engineering discipline. Industrial product development will continue to require traceability, control, and human judgment. Human in the Lead remains the right principle in most industrial contexts.

This is the real meaning of R&D reinvention with AI. It is not simply the digital enhancement of established processes. It is the redesign of product development so that AI can contribute not only to isolated productivity gains, but to broader gains in cost, speed, and throughput.

What R&D reinvention with AI requires now

If this view is correct, the implication is clear. The next step for industrial companies is not to stop experimenting with AI. It is to reposition those experiments within a broader R&D transformation logic.

First, shift the unit of ambition. Use cases matter, but they are not the right unit of ambition. The real question is whether AI contributes to broader performance improvement in R&D.

Second, strengthen the technical scaling conditions. AI can only scale on top of stronger product data foundations, better interoperability, and more meaningful context.

Third, make the underlying development logic a design topic. The question is no longer only where AI can be inserted. It is where the logic of product development itself must change so that AI can become structurally valuable.

Fourth, treat AI as a catalyst for R&D redesign, not as an add on. The winners will not be the companies with the most pilots or visible demos. They will be the ones that use AI to rethink how product development actually works.

R&D reinvention with AI is not about adding more use cases. It is about unlocking structural cost take out and speed through AI, enabled by strong product data foundations, meaningful context, and a new underlying development logic.

That is the difference between local AI assistance and structural R&D performance. For R&D leaders and engineering IT architects, the practical question is not whether to invest in AI, but whether the development environment is ready to absorb it.

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Human-AI Dialogue at the Heart of MBSE: **An AI Companion for Systems Engineering**

Vincent Hummel, Jean-Sébastien Gros, Felix von Pechmann, Mews
Project context: Project carried out on behalf of the French Defence Procurement
Agency, DGA

Model-Based Systems Engineering (MBSE) promises better control of complex systems through traceability, consistency, and multidisciplinary collaboration. In practice, however, adoption remains limited by tool complexity, long learning curves and the effort required to build and maintain models. This project contribution presents SyneSys, an AI-based companion developed by Mews Partners with CIL4SYS and Deepika for the French Defence Procurement Agency. The solution enables systems engineers and project stakeholders to interact with engineering models through natural language, while preserving methodological rigour and traceability to source documents.

A surveillance drone case study shows how a technical specification can be analysed, transformed into model artefacts and checked for consistency. Initial measurements indicate a reduction in modelling time from approximately 15 hours to 1 hour on this case, and from 40 hours to 12 hours on a more complex forklift truck case. The article discusses benefits, limitations and adoption conditions for Alaugmented MBSE.

Why Complex Projects Need Systems Engineering

Consider a mini-drone surveillance system for internal security forces. At first sight, the requirements seem compact enough to fit into a few pages. Yet the system quickly reveals the typical characteristics of complex engineering.

The system is not limited to the drone itself. It includes an aerial vehicle with six motors, an electrical power supply, three battery sets, a removable payload, high-definition and thermal cameras, a gyro-stabilised gimbal, data and video links, primary and secondary ground stations, spare parts, tooling, technical documentation, and storage and transport equipment. Functionally, it must support manual and automatic flight, flight plans with multiple waypoints, deployment in less than five minutes, thirty minutes of endurance with a one-kilogram payload, automatic return in case of link loss or low battery, degraded modes, geolocated metadata and day and night observation.

Behind a “small” system, one therefore finds several interacting subsystems, requirements from different disciplines, cross-cutting performance constraints, and the need to connect operational needs with design choices. This is precisely where systems engineering brings value: it structures the problem, organises requirements, defines architecture, supports integration, verification and validation, and enables disciplines to collaborate across the life cycle.

Model-Based Systems Engineering, MBSE, goes further by replacing isolated documents with a formal shared model. Each requirement can be linked to the functions that satisfy it, each function to the components that realise it, and each interface to the flows that pass through it. Traceability becomes native. Consistency can be checked. Change impact analysis becomes faster and more reliable.

In the drone example, increasing a communication range requirement from one to two kilometres affects the transmitter, receiver, power consumption, battery sizing and flight endurance. Without a model, such cascades are often discovered late, typically during integration. The promise of MBSE is to make these dependencies visible earlier and to turn engineering knowledge into a shared asset.

The MBSE Adoption Paradox

Despite more than twenty years of advocacy, MBSE adoption remains slower than expected, even in defence, space, transport, and energy programmes, where managing complexity is becoming increasingly critical. Three barriers recur.

The first one is the learning curve. Mastering a modelling environment, its meta-models, UML or SysML profiles and architecture frameworks can take many months before an engineer becomes truly productive. Even after learning the tool, teams often face the “empty model syndrome”: where to begin when the modelling environment contains no initial structure?

The second barrier is the effort required to build the model. Creating a usable model still involves a large amount of manual work: blocks, ports, relationships, diagrams and traceability links must be entered and maintained. The engineer spends too much time operating the tool and not enough time reasoning about the architecture. In the surveillance drone case, manually constructing a model covering logical architecture, requirements, and operational scenarios takes an experienced engineer approximately 15 hours – simply to convert a textual specification into a model.

The third barrier is accessibility. Models often remain black boxes for non-specialists. Project managers, customers and domain experts, although they would benefit from the model, often continue to rely on documents, spreadsheets and presentations. As a result, the model coexists with traditional documentation instead of replacing it as the authoritative engineering reference.

Current responses are mainly methodological: simplified meta-models, best-practice guides, training programmes and deployment coaching. They are useful, but they do not fully solve the problem. Simplifying the method can reduce the value of the model, while training remains long and costly. Above all, the model remains a technical artefact used by a limited circle of specialists.

AI as a Companion for Systems Engineers

Our approach is to avoid simplifying MBSE to the point of losing its richness, but to augment engineers so that they can use the full power of modelling without suffering its complexity. To this end, Mews

Partners, with CIL4SYS and Deepika, developed SyneSys, an AI-based companion for systems engineering. The solution integrates with existing modelling environments and enables natural language dialogue with the system model.

The vision is structured around three roles.

First, the AI acts as a guide. It helps the engineer plan and organise the work, then start and structure the model. It extracts requirements from source documents, proposes model skeletons, generates diagrams, and automates repetitive tasks. It can also suggest architectural patterns and detect methodological deviations during modelling.

Second, the AI acts as a guardian. It strengthens traceability and model quality by linking model objects to their documentary sources, checking compliance with the target meta-model, and identifying gaps or inconsistencies. It can help perform impact analyses when new needs or change requests arise. Above all, it ensures that the model provides a reliable foundation for all engineers.

Third, the AI acts as a translator. It makes the model accessible beyond the circle of modelling experts, both for improvement and exploitation. A project manager may ask about schedule or risk impacts, a customer may express needs in operational language, and an engineer may describe technical changes. The companion translates these interactions into formal model operations or model queries.

For systems engineers, the value lies in refocusing on architectural decisions rather than tool mechanics. For other stakeholders, the value lies in accessing the model through natural language, without having to master the modelling tool. The model becomes easier to query, explain, and enrich.

Application to a Surveillance Drone Case

The project was applied to a 12-page technical specification for professional mini-drones. The objective was to analyse the document, identify relevant engineering artefacts and generate a structured model according to the target meta-model, here at the logical level of the NATO Architecture Framework.

The process begins with document exploration. The AI companion ingests the specification, segments it into semantic chunks and indexes the content relevant for modelling. This allows the user to navigate the source, verify that the full scope is covered and understand where each extracted element originates.

The second step is model construction. From the analysed document, the companion generates a logical model including system nodes such as aerial vehicle, payload, HD camera, thermal camera, gyro-stabilised gimbal, ground stations, data link and battery. It also identifies capabilities, performance measures, operational scenarios such as deployment and day or night surveillance, and logical activities such as image acquisition or endurance monitoring.

Each model element is linked back to its documentary source. This traceability is essential not only for verification, but also for user confidence. The engineer can check why an element exists, which requirement justifies it and whether the interpretation is correct.

The third step is consistency analysis. Once the model is built, the user can ask questions such as: "Are there inconsistencies between the model and the source document?" In the drone case, the companion identified several points requiring engineering judgement. For example, the gyrostabilised gimbal had been modelled as a subclass of payload, while the source suggested that it should rather be a component of the payload. The battery was listed as an independent node, although it is physically embedded in the aerial vehicle. Some degraded modes were also incomplete. At the same time, the companion confirmed that the main node hierarchy, capabilities, scenarios and activity diagrams were largely consistent.

The resulting model was not considered final without human review. However, it provided a solid and traced foundation. The engineer's work shifted from entering data to validating, correcting and enriching the architecture.

Initial Results

We measured the modelling process from an input document through three steps: document analysis, identification of engineering artefacts and model construction. Two cases were assessed.

On the surveillance drone case, which represents moderate complexity, the full process required approximately 15 hours without the AI companion and approximately 1 hour with it. This corresponds to a time reduction of about 93%.

AI as a Companion — Neither Master, Nor Slave, Nor Substitute

The three roles of SyneSys in Model-Based Systems Engineering



Figure 1: The three roles of the AI companion: guide, guardian, translator.

On a second case concerning a forklift truck system, with higher complexity, the process required approximately 40 hours without the AI companion and approximately 12 hours with it. This corresponds to a time reduction of about 70%.

The gain is strongest when the scope is well defined. On the drone case, the companion handled most of the process. On the more complex case, human guidance remained more significant, but the acceleration was still substantial.

These figures cover the core modelling process. They do not include all complementary activities, such as detailed quality-rule verification, full meta-model compliance checks or fine-grained traceability validation. These activities still require engineering control and represent further automation potential.

Lessons Learned

The use of natural language creates immediate engagement, including among audiences that are usually reluctant to adopt MBSE. Instead of approaching modelling through tool commands and diagrams, users can start with questions, needs and engineering intent.

The project also shows that AI does not replace methodological rigour. On the contrary, the quality of the results strongly depends on the quality of the meta-model and of the engineering framework. AI performs better when the modelling rules are clear. It does not compensate for a lack of systems engineering discipline.

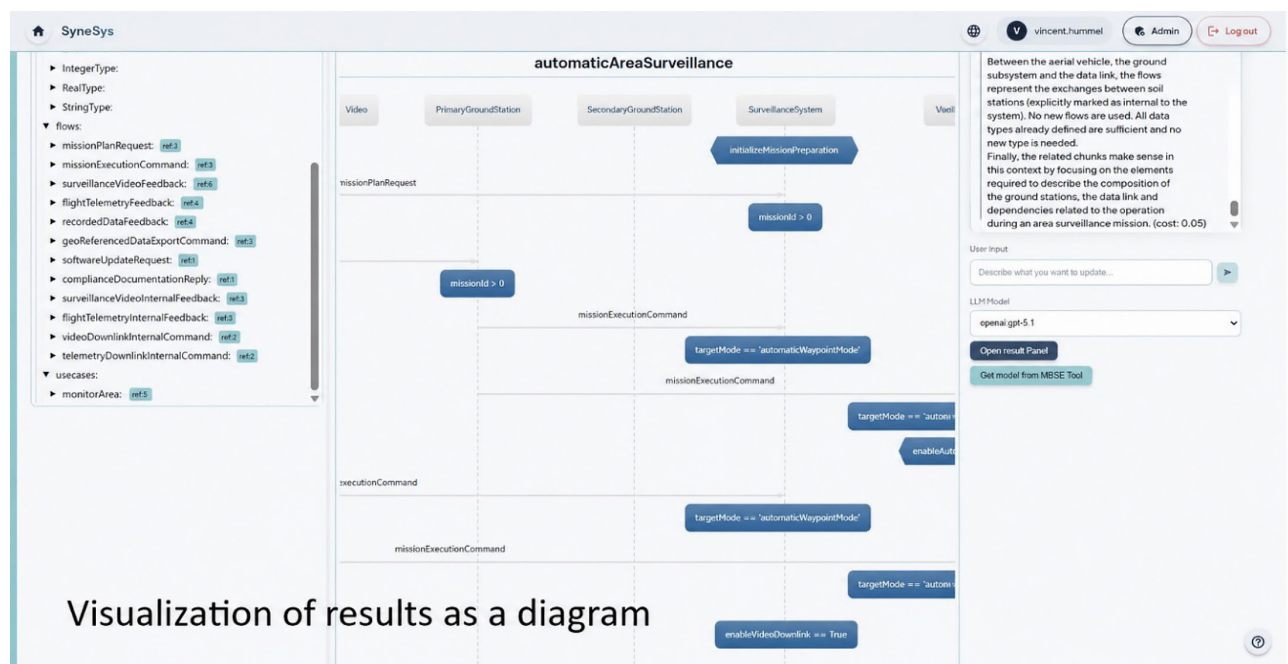


Figure 2: Model construction: capabilities and operational process diagram.

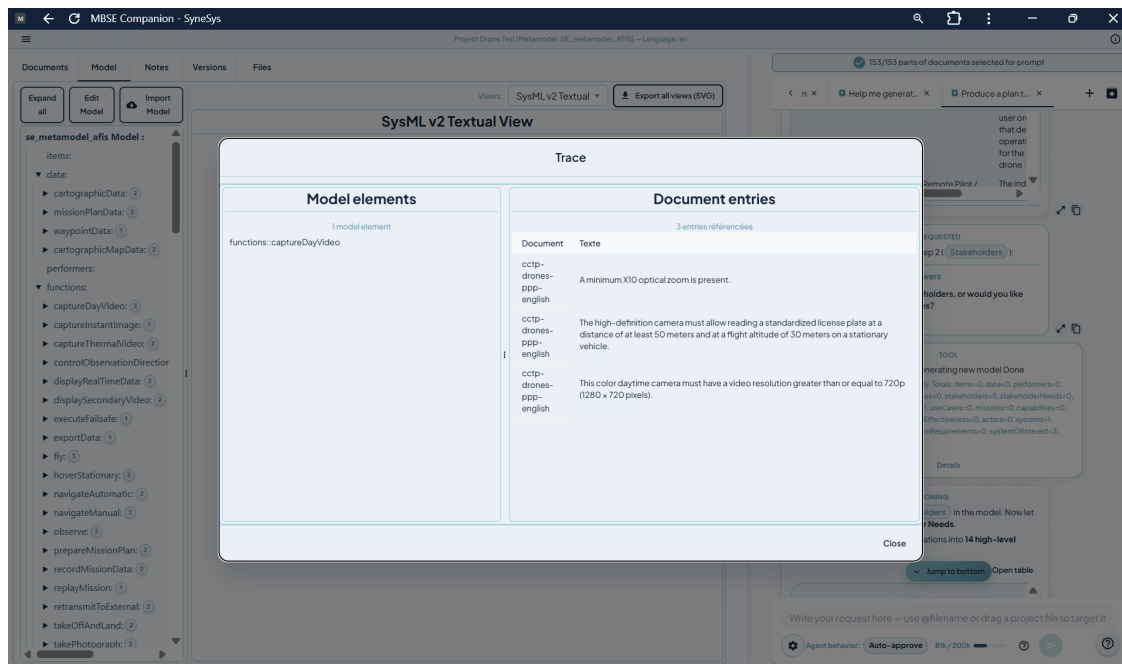


Figure 3: Traceability of model elements to the source document.

Human supervision remains essential. Successive iterations with the companion must be controlled so that the engineer keeps ownership of the content. The objective is not autonomous model generation without review, but an efficient dialogue between engineer and AI.

Change management is also critical. A natural language interface can make the solution attractive, but adoption must be supported to avoid replacing today's "click factory" with a future "prompt factory". The value comes from combining AI assistance, engineering method and human judgement.

Outlook

AI will not replace the systems engineer or the architect. It will free them from low added-value tasks to focus on understanding, arbitrating and deciding. Repetitive modelling operations, low-level consistency checks and document-to-model transformations can increasingly be delegated to AI, while engineering responsibility remains human.

This evolution may also change roles in engineering organisations. Domain experts could become owners of the system view for their scope, supported by AI as a tutor and assistant. Systems engineers could move further towards cross-functional architecture, trade-off analysis and coordination.

Several challenges remain open. Interoperability with requirements management, ALM and PLM environments is a key topic. Organisations must also learn how to right-size their meta-models to optimise the balance between methodological effort and AI-generated value. They will also need to adapt the management of skills, competencies and knowledge to ensure a proper human-machine teaming.

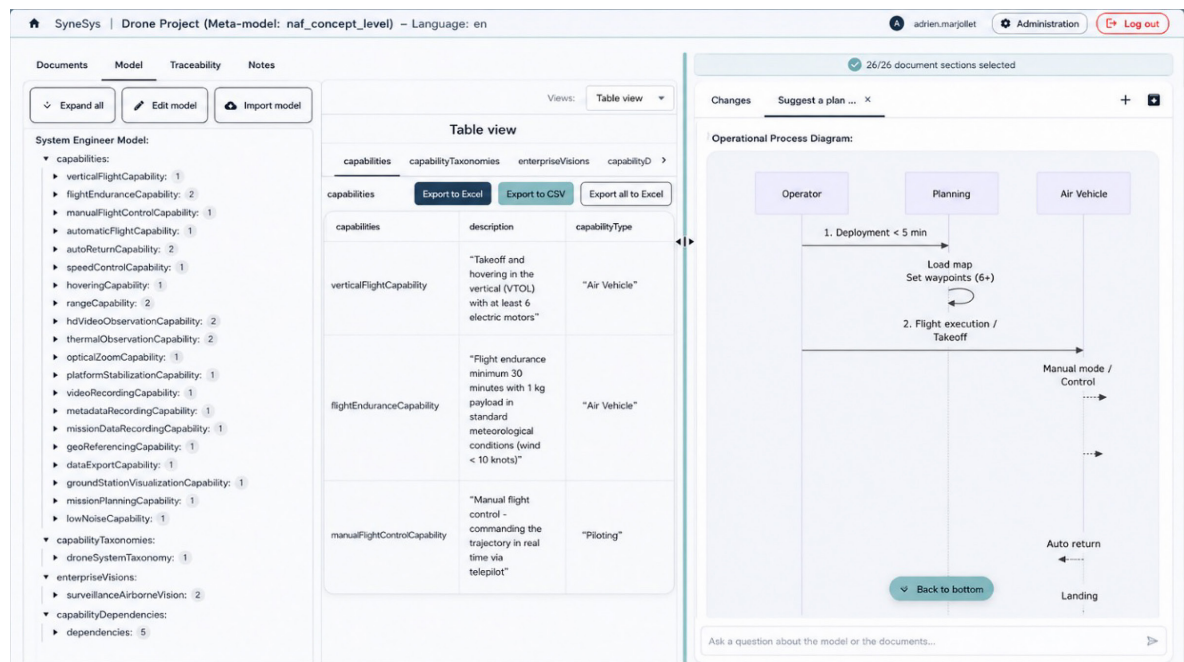


Figure 4: Exploration of model elements in different formats

The conclusion is simple: AI can act as a skills amplifier and a consistency revealer. It helps engineers understand the impact of their choices, while leaving them responsible for decisions. Used correctly, it can make MBSE more accessible, more useful and more widely adopted.



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Knowledge B-Rep Graph: Enabling Collaborative Digital Engineering with STEP and Knowledge Graphs in the Age of Software-Centric Product Development

Julian Gebhard, David Pfister, Yuebo Wang, Katrin Brudny, Steffen Staab

Knowledge graphs have shown potential for engineering applications for several years and are emerging in productive use in large manufacturing enterprises. Yet, there is a lack of transformation from traditional solutions to knowledge graph infrastructure.

Mercedes-Benz and the Analytic Computing group at the University of Stuttgart are conducting active research into delivering tangible value with the tools already available in the semantic web ecosystem, adapting them for industrial planning, assembly, and engineering workflows. This paper presents a proof of concept for applying knowledge graphs to analyse the topology and geometry of CAD models and automate model validation. The additional semantic context that knowledge graphs provide, in contrast to traditional CAD exchange formats, enables targeted information extraction without the need to write bespoke code. We further present a workbench for constructing queries and constraints against CAD models and visualising the results, bringing semantic web operations closer to experts of the engineering domain.

Introduction

The future of product development depends on the right data structures and the right use of AI agents [Kolossvary2023, 6]. Software will be at the centre of our processes. If products are validated so thoroughly in the digital realm that there is no longer any need to build physical prototypes, a car can be developed entirely in a digital environment, twinned across all its facets, and, after safety, quality, and stress testing conducted purely digitally, released directly to production [21]. One hundred percent digitally engineered, designed by agents, ready for release. Today, however, digital product development looks quite different. It remains grounded in proprietary solutions, file exchange, and manual model supervision and validation. There are handbooks of general CAD rules, industry standards, and OEM-specific guidelines for designing CAD parts, yet validation of these rules is still largely manual [16]. Extracting 2D drawings from 3D models to check annotations is daily business in European companies. Manual change documentation with typos and incorrectly referenced serial numbers remains commonplace. It is difficult to see how the automotive industry can achieve real automation while relying on such error-prone, manual tasks. At the same time, processes are shifting towards simultaneous engineering, accelerating development timelines before the underlying processes have been stabilised [23]. What is needed is fast change propagation through synchronisation [6], semantic enrichment for data comprehension [7], and automation of CAD model analysis and validation. We argue that knowledge graphs for B-Rep data, used alongside existing systems, can address these challenges. The declarative nature of knowledge graphs makes them an 1 extensible data structure, capable of storing additional information and providing participants with the semantic context needed to understand it. Ontologies, which describe the concepts and relationships of a domain, provide the skeleton for a stable semantic infrastructure. They break down data silos, expose every part of a CAD model through a standard API, and bring native tooling for automated information validation within

the graph. Currently, knowledge graph technologies lack native handling of CAD models. While some research exists, the field remains open, with limited work on 3D reasoning, semantic rules, and production-ready use cases. This work aims to demonstrate that, even while the area is still maturing, it already has the potential for productive use and is capable of performing geometric reasoning and validation on CAD models. To this end, we implemented a SPARQL extension for three-dimensional B-Rep data and a user interface for visualising the results, enhancing communication of knowledge graph potential within the engineering sector. In the following, we first present an exemplary use case of geometry validation. We then provide background information on data structures and knowledge graphs, followed by an overview of related work. Next, we explain the proof of concept and its validation, before concluding with a feasibility study.

Use Case

In industry, CAD models are subject to a wide range of quality and compositional requirements. We identify four distinct categories: (1) general model integrity constraints, such as the requirement that every solid has a closed shell; (2) norms defined by standards bodies or industry initiatives, such as ISO 1101, which specifies rules and symbols for geometric tolerances [13]; (3) expert or company guidelines focused on design for manufacture, for example minimum wall thickness requirements for 3D-printed parts; and (4) company-specific rules governing aspects such as safety classifications, colour coding, or font usage. These requirements may further depend on material, part function, and industry sector. We chose the minimum permissible distance from a hole to a part edge (see Figure 1) as our exemplary use case because it is representative of a class of geometric design rules that are currently validated manually or by purpose-built, hard-coded scripts [16].

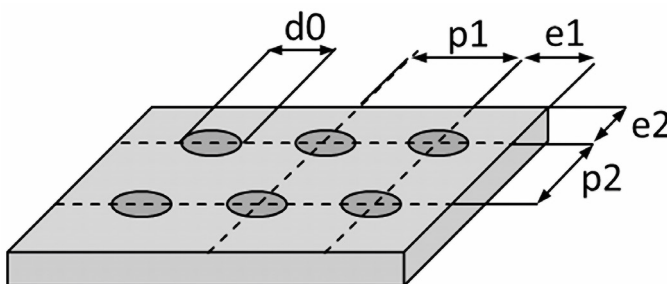


Figure 1: Hole-to-edge distance rule: $d0$ denotes the hole diameter, $p1$ and $p2$ are the hole centres, and $e1$, $e2$ are the part edges. The minimum permissible distance from the hole wall to the nearest edge is a function of $d0$ and the part material.

Checking this rule requires inferring several pieces of implicit information from the graph:

1. **Hole detection.** A hole is inferred from the B-Rep graph by identifying an advanced face that has a cylindrical surface with negative orientation and whose outer face bound contains only closed circles (i.e., circles whose start point equals their end point).
2. **Distance computation.** The distance from the hole face to any other face of the same solid must be computed geometrically using our custom SPARQL function `brepf:distance`.
3. **Solid connectivity check.** A naive distance check can produce false positives: two faces of a U-shaped clip may be geometrically close but separated by air rather than solid material. To exclude such cases, we defined a boolean function `brepf:connected(face1, face2)` that uses ray-casting to verify that solid material exists between the two faces along the connecting path.

Solving this use case requires three distinct forms of reasoning: topological reasoning to identify holes from their structural graph pattern, dimensional reasoning to measure distances between faces, and geometric reasoning to determine whether two faces are connected through solid material. Together, these demands make it a representative and challenging proof of concept for the automated validation of CAD models against design rules.

Background

1. RDF Graph

The Resource Description Framework (RDF) is defined by the World Wide Web Consortium (W3C) as a standard for representing information on the Semantic Web as a directed, labelled graph [24]. Data is expressed as triples of the form (subject, predicate, object), where each element is identified by a URI or, in the case of objects, optionally by a literal value. Figure 2 shows a triple consisting of a circle instance connected by the predicate `hasRadius` to the literal `3^^xsd:float`, representing a floating-point value. A collection of triples forms an RDF graph, which can be stored in a triple store and queried using SPARQL. OWL (Web Ontology Language) extends RDF with formal semantics, allowing the definition of classes, properties, and axioms that support automated reasoning via description logic.



Figure 2: An RDF triple consisting of the subject `www.example.org/circle#170`, the predicate `www.example.org/hasRadius`, and the literal object `„3“^^xsd:float`. This triple asserts that the circle instance has a radius of 3.

2. SPARQL

SPARQL (SPARQL Protocol and RDF Query Language) is the standard query language for RDF data. A SPARQL SELECT query specifies graph patterns using triple patterns and optional expressions to bind additional variables or within filter operations [9]. Named graphs allow multiple RDF datasets to coexist in the same store and be addressed individually within a single query. SPARQL can be extended with custom functions registered in the query engine; such functions receive RDF literals as arguments and return computed values, enabling non-native operations such as geometric distance calculations [5]. Listing 1 shows a minimal example: it retrieves every circle in the graph together with its radius, filtering to return only those with a radius greater than 2.

```
PREFIX brep: <http://www.example.org/brep#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

SELECT ?circle ?radius
WHERE {
  ?circle a brep:Circle ;
          brep:hasRadius ?radius .
  FILTER(xsd:double(?radius) > 2)
}
```

Listing 1: A simple SPARQL query retrieving all circles with a radius greater than 2.

3. SHACL

The Shapes Constraint Language (SHACL) is a W3C standard for validating RDF graphs against a set of conditions [8]. Where SPARQL is designed to query and extract information from a graph, SHACL is designed to validate it: a SHACL processor evaluates a set of shapes against a data graph and produces a validation report indicating which nodes conform and which do not. SHACL operates under the closed-world assumption, meaning that the absence of a required statement is treated as a violation rather than as unknown information. SHACL distinguishes between two types of shapes. A node shape targets a set of nodes in the graph and applies constraints to them directly. A property shape targets the values of a specific property on those nodes, expressing constraints such as datatype requirements, cardinality bounds, or value ranges. Shapes are themselves represented as RDF, which allows them to be stored alongside the data they constrain and queried like any other graph content. For cases where the built-in constraint vocabulary is insufficient, SHACL-SPARQL allows a full SPARQL query to be embedded within a shape as a constraint. The shape is violated whenever the embedded query returns a non-empty result set. This extension makes it possible to express complex, graph-traversal-based validation rules, such as geometric design checks, within the same declarative framework used for simpler structural constraints.

4. Boundary Representation (B-Rep)

Boundary Representation is a technique for storing geometric models by representing their boundaries as parametric mathematical equations for two-dimensional geometric entities [25]. These 2D geometries are then projected onto 3D surfaces, thereby bounding a face. The set of faces bounds a region in Euclidean space, forming a manifold that represents a solid. A B-Rep model consists of a hierarchy of topological entities that describe the structure of the model, for example, vertices, edges, and faces. These are connected as follows: an edge may reference two vertices, and a face may reference multiple edges. This alone does not convey the actual geometry of the object; however, geometry is also attached to the topology. Every vertex is associated with a Cartesian point, an edge can be associated with a line, a circle, or a spline, and a face references a surface such as a cylinder or plane, as shown in Figure 3. B-Rep is widely adopted in CAD systems because it preserves geometric information exactly. It is therefore superior to tessellated representations, which share similar topological elements but lack geometric variety, excluding splines, circles, and analytic surfaces, whereas tessellated representations excel in rendering performance. B-Rep is limited in that it cannot store or export the modelling operations from the engineering history within the tool; Boolean operations such as subtraction and addition between solids are therefore not reconstructable from the exported data.

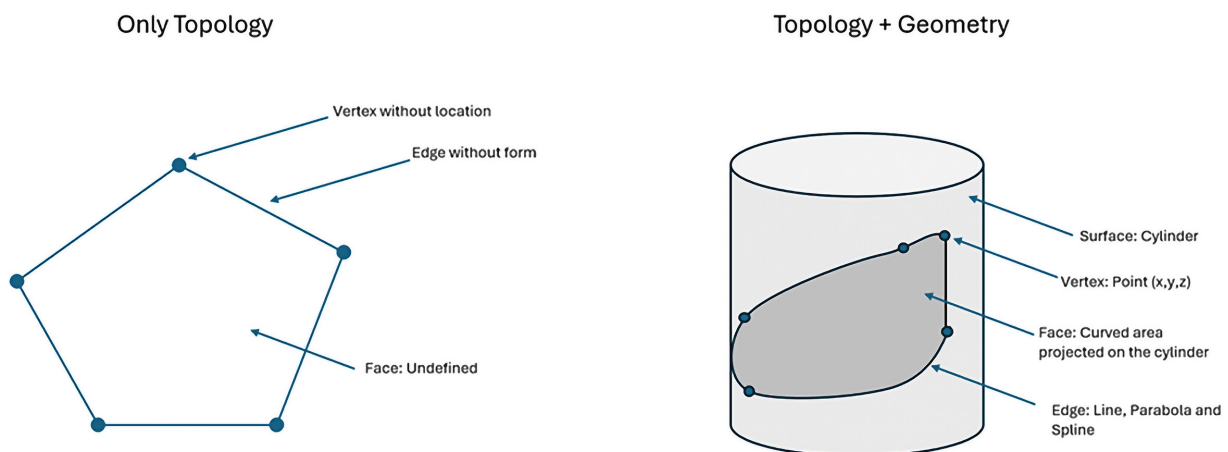


Figure 3: Comparison of topology alone (left) and topology combined with geometry (right). Without geometry, a B-Rep graph contains only unlabelled vertices, edges, and faces with no spatial meaning. Adding geometry attaches a Cartesian point to each vertex, a curve type (line, parabola, or spline) to each edge, and a surface type (e.g. cylinder) to each face, fully defining the solid in Euclidean space.

Related Work

1. Ontologies and Graph Data for Product Geometry

Geometry. Research into ontologies for product geometry and their representation in RDF has been active for over a decade. A prominent direction is grounding ontologies in existing industry standards, directly addressing the interoperability problem. In 2009, Krüger et al. published *OntoStep*, which translates the logic of the STEP AP 203 (ISO 10303-203) EXPRESS schema to OWL DL, enabling the representation of B-Rep in knowledge graphs [14]. Alongside the language, they developed the parser *STP2OWL*, which converts STEP EXPRESS schemas and Part 21 instance files to OWL [15]. Both tools served as a reference for the ontology design in this work. However, a key limitation of *OntoStep* and *STP2OWL* is their translation strategy: both primarily perform a low-level parsing of STEP EXPRESS schemas into OWL, yielding a structurally faithful but semantically shallow representation. The resulting graphs lack higher-level semantic extensions required for advanced reasoning tasks such as change traceability, parametric constraint interpretation, and design-rule validation. Later, in 2015, Perzylo et al. defined the *OntoBREP* ontology, which also targets B-Rep but without depending on the STEP standard, adding explicit constraints for assemblies [20]. They used the combination of topology, geometry and constraints to define semantic robot tasks. *OntoBREP* is not grounded in an existing standard, however, which complicates integration into established engineering workflows. In the AEC sector, *ifcOWL*, based on ISO 16739 (IFC), structures building elements and spaces to support architectural modelling and BIM coordination, with geometry support covering CSG, tessellated, and B-Rep representations [1]. Current languages provide limited support for PMI, material data, and rules for inferring semantic features such as holes or walls.

Product structure. Complex engineering products, such as an automobile, may consist of up to 5,000 individual parts, each with multiple revisions differing in geometry, weight, or name. Although data schemas exist that can represent a complete assembly, engineering practice typically uses separate files per part. When applying semantic web technologies to such assemblies, the individual part graphs must be linked and annotated with semantic information to enable conjunctive queries across the full assembly, for example, retrieving all parts above a given weight that share a specific material, or identifying components whose geometry violates a design norm. The role of product-structure ontologies is therefore to bridge geometry, functional description, and metadata. Open-source ontologies addressing product structure include the Basic Product Ontology (BPO) [26] and the Assembly Hierarchy Subgraph proposed by Bharadwaj et al. [2]. More broadly, recent work has used ontologies to model product structures in a queryable format [12]. Rongen et al. [22] propose a Semantic AAS that maps Asset Administration Shell (AAS) data to RDF, reflecting an industry-wide shift towards intelligent, interoperable knowledge graphs. Building on

these foundations, Gebhard et al. [6] introduced a multi-layered product ontology covering structure, geometry, and behavior, and demonstrated its application in a value-level synchronization framework for simultaneous engineering at Mercedes-Benz. At a broader system level, Hofmann et al. [10] propose an ontology-based knowledge backbone for circular factories, tackling the challenges of semantic representation of products and uncertainties, leveraging of experience, system interoperability, and data management. Their ontology captures the product, resources, and the environment, as well as supervision, planning, and execution processes. The resulting platform is able to support decision making in processes such as inspection, disassembly, manufacturing, testing, and assembly by reasoning about the state of the product from its historical context to its future condition.

2. SPARQL Extensions for Geometry

Geometric relationships such as parallelism, coincidence, distance, and angle are typically not stored explicitly in geometric models but are implied by the underlying mathematical representations. SPARQL's native functionality provides no built-in support for such geometry-specific operations, motivating several extension frameworks. In the architecture domain, GeoSPARQL is the established standard, published by the Open Geospatial Consortium in 2012 [19]. It defines spatial datatypes, operators, and filter functions that extend SPARQL's syntax and semantics for 2D geospatial data. Homburg et al. [11] extended GeoSPARQL in 2020 to support reasoning over raster data, by defining new literal datatypes and recursively define the additional expressions to operator on them and how to evaluate them. BIM-SparQL [27] is enabling queries over threedimensional BIM data through a classified set of spatial functions, though it remains limited to the IFC standard. They used it for the validation of BIM models for different criterias, as every building element should be associated with a building storey. Most recently, Elshani et al. [5] defined a comprehensive set of 3D geometric functions with explicit signatures and provided a framework for implementing them using CAD libraries integrated with an RDF4J triple store, work that directly informs the approach taken here.

Proof of Concept

We conducted both theoretical and practical research into the application of knowledge graph technologies to CAD models. In contrast to the architecture domain, the application of semantic web technologies to mechanical CAD models is relatively nascent and lacks practical implementations that would allow industry to assess its benefits. Our proof of concept comprises three main components: (1) a mechanism for generating RDF graphs from STEP data, (2) SPARQL function 6 extensions for geometric reasoning over B-Rep data, which can be used either as a standalone query language or embedded within SHACL-SPARQL constraints, and (3) a web-based user interface that integrates the full workflow of loading, querying, and validating CAD models.

1. System Architecture

RDF-graph data is stored in an RDF4J triple store, chosen for being open-source and for its support for custom function registration [3]. RDF4J runs with Apache Tomcat on a Debian/Ubuntu server. The overall architecture is illustrated in Figure 4. Graph generation is implemented in Java as an RDF4J extension that automatically converts uploaded STEP models into named graphs. For geometric analysis, we use the OpenCascade Technology (OCC) C++ library [18], identified by Elshani et al. [4] as the most capable library for geometric operations on engineering models. Because OCC is a C++ library, we developed a custom Java Native Interface (JNI) wrapper to integrate it into the Java-based RDF4J environment. The user interface is implemented in Node.js and React; it communicates with RDF4J via its REST API and with OCC indirectly through the custom function layer to visualise CAD models and B-Rep graphs and to execute SPARQL queries and SHACL validations interactively.

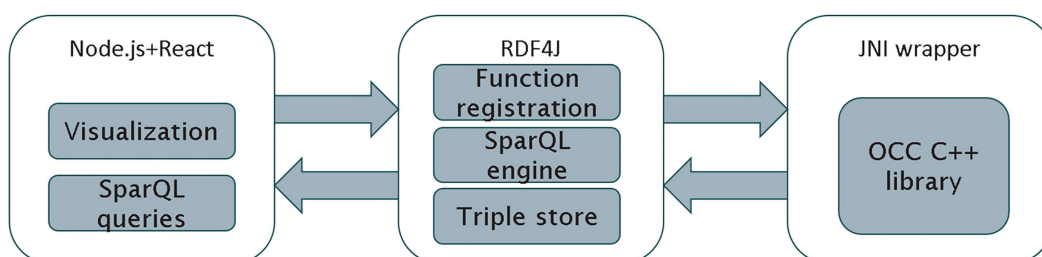


Figure 4: System architecture: the Node.js/React front end communicates with RDF4J, which registers custom SPARQL functions that delegate geometric computations to the OCC C++ library via a JNI wrapper.

2. Graph Generation

We defined a custom B-Rep ontology aligned with the STEP 242 standard. Geometric and topological feature types, their properties, and their inter-relationships were derived from the STEP 242 EXPRESS schema and expressed in RDF/OWL. For this proof of concept, the ontology covers geometric and topological features only; kinematics and PMI (Product and Manufacturing Information) are excluded. The ontology class hierarchy is shown in Figure 5.

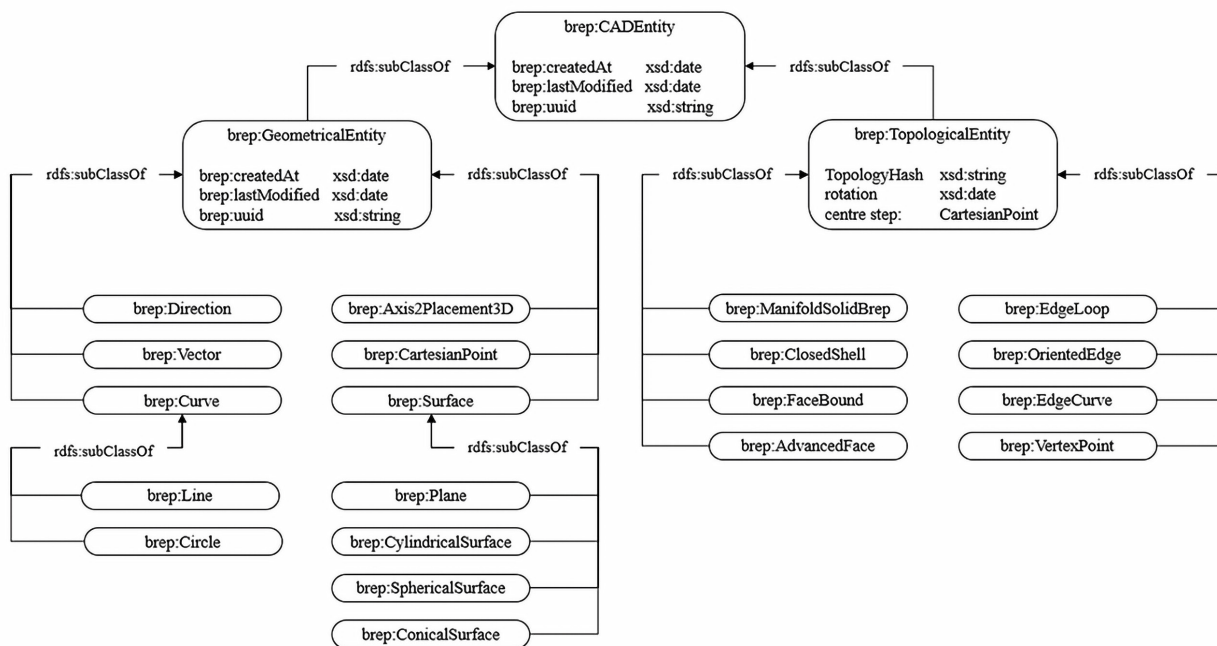


Figure 5: B-Rep ontology class hierarchy, structured around two top-level branches: *brep:GeometricalEntity* (surfaces, curves, points, axes) and *brep:Topological Entity* (manifold solid, closed shell, advanced face, edge loop, oriented edge, edge curve, vertex point).

We then developed an algorithm to convert STEP Part 21 instance files into RDF graph instances according to this ontology. The algorithm uses string parsing to build a hash map keyed by STEP entity type, then creates RDF nodes and edges from each entry. Two semantic enhancements were applied during conversion. First, relationships were made explicit: instead of the syntax-level STEP reference #x references #y, the graph records a named predicate, for example *brep:hasOuterFaceBound*, making the relationship type queryable without knowledge of the STEP schema. Second, geometric duplicates were eliminated: when two faces share an edge, that edge is represented by a single node in the graph, so shared topology can be detected by a simple node-identity check rather than a geometric comparison.

3. SPARQL Extensions for B-Rep Geometry

We extended SPARQL with a new literal datatype for B-Rep geometry and a set of custom functions registered in RDF4J. The functions operate on the topological entities defined in our ontology: `brep:Vertex`, `brep:EdgeCurve`, `brep:AdvancedFace`, and `brep:ClosedShell`. Following the classification approach of prior work [5, 27], we grouped the functions into four categories:

- **Algebraic relationship functions:** compute scalar quantities between entities, such as the minimum distance between two faces, edges, or vertices.
- **Geometric relationship functions:** evaluate geometric predicates, such as whether two faces are parallel or whether two solids intersect.
- **Boolean operation functions:** compute set-theoretic combinations of solids, such as union or intersection.
- **Analytic functions:** compute intrinsic properties of entities, such as face area or shell volume.

A significant implementation challenge arises from the cost of initialising OCC solid objects, which requires parsing and constructing the full B-Rep data structure from the graph geometry literal. The challenge is compounded by the fact that individual primitives such as faces or surfaces often require information about the overall solid to which they belong, for example, when checking whether two faces are connected through the solid, or when determining whether a face is a wall, a notion that only makes sense in a broader context. Constructing a complete CAD model object on every function call is therefore computationally expensive.

To address this, all custom functions are implemented in a shared Java class that acts as a cache, realised as the CAD Model Object. On the first call involving a given closed shell, the corresponding OCC object is constructed from the geometry literal and stored in a hash map keyed by the shell's graph identifier; its sub-entities (faces, edges, vertices) are indexed at the same time. Subsequent function calls retrieve the cached objects rather than re-initialising them, meaning that evaluating a function over hundreds of faces of a single solid requires only one OCC initialisation. To make the solid context available to each function, we augment every function signature with the overall solid identifier.

For example, the abstract function

$$\text{minDistance} : \text{face} \times \text{face} \rightarrow \mathbb{R}$$

becomes the custom SPARQL function

$$\text{brepf:minDistance} : \text{faceID} \times \text{faceID} \times \text{solidID} \rightarrow \mathbb{R}.$$

The architecture of the CAD Model Object is described below.

CAD MODEL OBJECT
— Geometrie-Instanzen — + <code>cad_objects</code> = { <code>solidID</code> : { <code>object</code> : <code>solid_object</code>, <code>AdvancedFace</code> : { <code>advID</code> : <code>adv_object</code>, <code>advID</code> : ... }, <code>Surface</code> : { <code>surfID</code> : <code>surf_object</code>, <code>surfID</code> : ... }, ... } } — Funktionen — 1: + <code>brepf:minDistance</code>(<code>faceID</code>₁, <code>faceID</code>₂, <code>solidID</code>) → ℝ 2: + <code>brepf:connected</code>(<code>faceID</code>₁, <code>faceID</code>₂, <code>solidID</code>) → {<i>true</i>, <i>false</i>} 3: + <code>brepf:volume</code>(<code>solidID</code>) → ℝ 4: ...

When a `brepf:` function is called, it first checks whether all required objects are already cached. If not, it initialises them. If they are found, it executes the operation using the OpenCascade CAD libraries.

4. User Interface

We implemented a web application to demonstrate the value of knowledge graphs and SPARQL extensions for CAD model analysis. As a benchmark dataset, we used the CAD models of a SCARA robot published by HowToMechatronics [17]. The interface is divided into three sections, as shown in Figure 6.

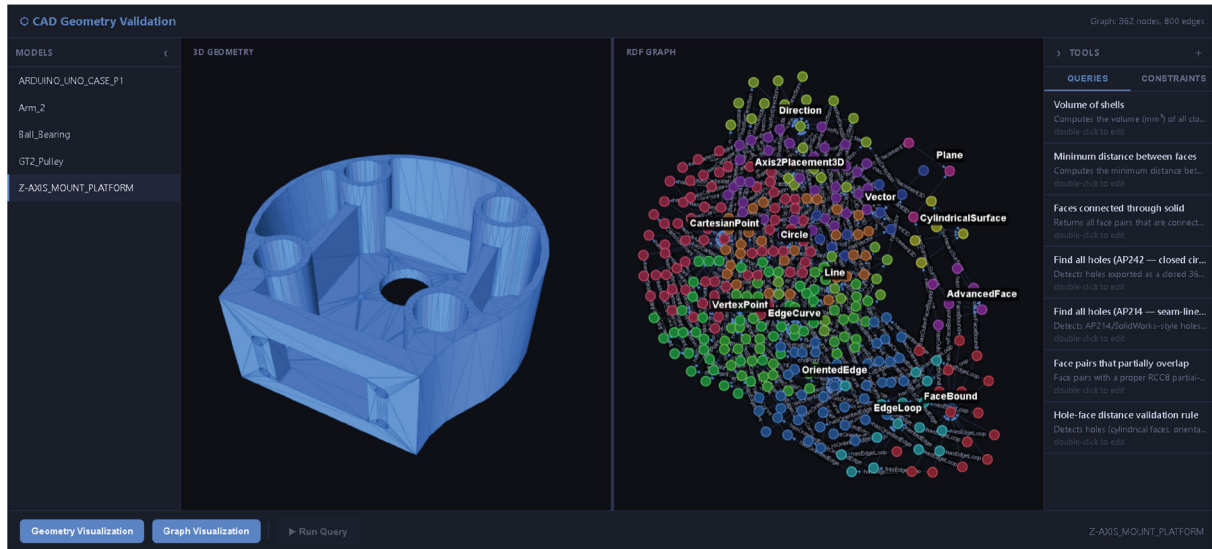


Figure 6: User interface: (left) model browser, (centre) geometry and RDF graph visualisation windows, (right) toolbox with SPARQL queries and SHACL constraints.

The left panel provides a model browser; selecting a model activates the visualisation controls. The central area contains two side-by-side visualisation windows. The geometry window renders the selected CAD model: an OCC object is constructed from the SPARQL query result, tessellated, and rendered in the browser using WebGL. The graph window displays the corresponding RDF graph: nodes are coloured by ontology class (e.g., EdgeLoop, Circle) and edges are labelled with their predicate names; node labels are suppressed for clarity. The right panel is the toolbox, which contains predefined SPARQL queries and SHACL shape constraints. SPARQL queries can be executed on demand against the active model; SHACL constraints are evaluated automatically whenever a model is parsed into the graph store.

Validation

To address the use case defined in Section 2, we combined the implemented SPARQL functions with validation logic to cover all three aspects: hole detection, distance computation, and solid connectivity checking. To this end, we combined SPARQL reasoning with SHACL shapes.

1. Reasoning

The complete validation query is shown in Listing 2. The inner SELECT block identifies candidate hole-face pairs by matching the B-Rep pattern for holes within the part graph and retrieving the applicable minimum-distance norm from a separate named graph `hole_norms`, which stores material-dependent distance factors. The outer BIND and FILTER expressions then compute the geometric distance, compare it against the norm, and retain only the pairs that violate the rule.


```

PREFIX brep: <http://www.example.org/brep#>
PREFIX brepf: <http://www.example.org/brepf#>
PREFIX norm: <http://example.com/norm#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

SELECT DISTINCT ?hole ?distance ?min_distance
FROM NAMED <http://www.example.org/testdata/part21#Z-AXIS_MOUNT_PLATFORM>
FROM NAMED <http://www.example.org/hole_norms>
WHERE {
  {
    SELECT DISTINCT ?shell ?geo ?hole ?face ?diameter ?factor
    WHERE {
      GRAPH <http://www.example.org/testdata/part21#Z-AXIS_MOUNT_PLATFORM> {
        ?shell brep:hasAdvFace ?hole ;
          brep:hasGeometry ?geo ;
          brep:hasMaterial ?material1 .
        ?hole brep:hasSurface ?surface ;
          brep:orientation "False" ;
          brep:hasOuterFaceBound ?fb .
        ?surface a brep:CylindricalSurface ;
          brep:RADIUS ?radius .
        ?fb brep:hasEdgeLoop ?loop .
        ?loop brep:hasOrientedEdge ?oe .
        ?oe brep:hasEdgeCurve ?edge .
        ?edge brep:endPoint ?ep ;
          brep:startPoint ?sp ;
          brep:hasCurve ?curve .
        ?curve a brep:Circle .
        FILTER(?ep = ?sp)
        ?shell brep:hasAdvFace ?face .
        FILTER(?hole != ?face)
        FILTER NOT EXISTS {
          ?hole (brep:hasOuterFaceBound|brep:hasFaceBound)
            /brep:hasEdgeLoop/brep:hasOrientedEdge/brep:hasEdgeCurve ?shared .
          ?face (brep:hasOuterFaceBound|brep:hasFaceBound)
            /brep:hasEdgeLoop/brep:hasOrientedEdge/brep:hasEdgeCurve ?shared .
        }
      }
    }
    GRAPH <http://www.example.org/hole_norms> {
      ?norm a norm:hole_norm ;
        norm:material ?material2 ;
        norm:edgeFactor ?factor ;
        norm:max_size ?max_size ;
        norm:min_size ?min_size .
    }
    FILTER(?material1 = ?material2)
    FILTER(datatype(?min_size) IN (xsd:decimal, xsd:double, xsd:integer))
    FILTER(datatype(?max_size) IN (xsd:decimal, xsd:double, xsd:integer))
    BIND(xsd:double(?radius) * 2 AS ?diameter)
    FILTER(?diameter > xsd:double(?min_size) &&
      ?diameter < xsd:double(?max_size))
  }
  BIND(?diameter * xsd:double(?factor) AS ?min_distance)
  BIND(brepf:distance(?geo, ?hole, ?face) AS ?distance)
  FILTER(?distance > 0 && ?distance < ?min_distance)
  BIND(brepf:connected(?geo, ?shell, ?hole, ?face) AS ?connected)
  FILTER(?connected)
}

```

Listing 2: SPARQL query for hole-to-edge distance validation.

After execution, the interface generates a tabular report listing every violating hole-face pair with the measured distance and the required minimum distance (Figure 7). Applied to the Z-axis mount platform of the SCARA robot, the query identified 8 holes with distances to nearby faces that fall below the material-specific norm.

Hole-face distance validation rule — Z-AXIS_MOUNT_PLATFORM18.88s

24 row(s)

HOLE	DISTANCE	MIN_DISTANCE
1842	2.2817279836452946	3.2
1842	1.431727983645295	3.2
1867	2.2817279836452955	3.2
1867	1.4317279836452954	3.2
1909	2.281727983645293	3.2
1909	1.431727983645294	3.2
2273	2.2817279836452955	3.2
2273	1.4317279836452943	3.2
2439	1.9499999999999993	5.1
2439	2.9499999999999993	5.1
2439	3.864847884329831	5.1
2457	1.9499999999999993	5.1

Figure 7: Query result table for the Z-AXIS_MOUNT_PLATFORM part: each row reports a violating hole identifier, the measured distance to the nearest non-adjacent face, and the required minimum distance derived from the applicable norm.

The violating faces are also highlighted directly in the 3D geometry view, providing immediate visual feedback to the designer (Figure 8).

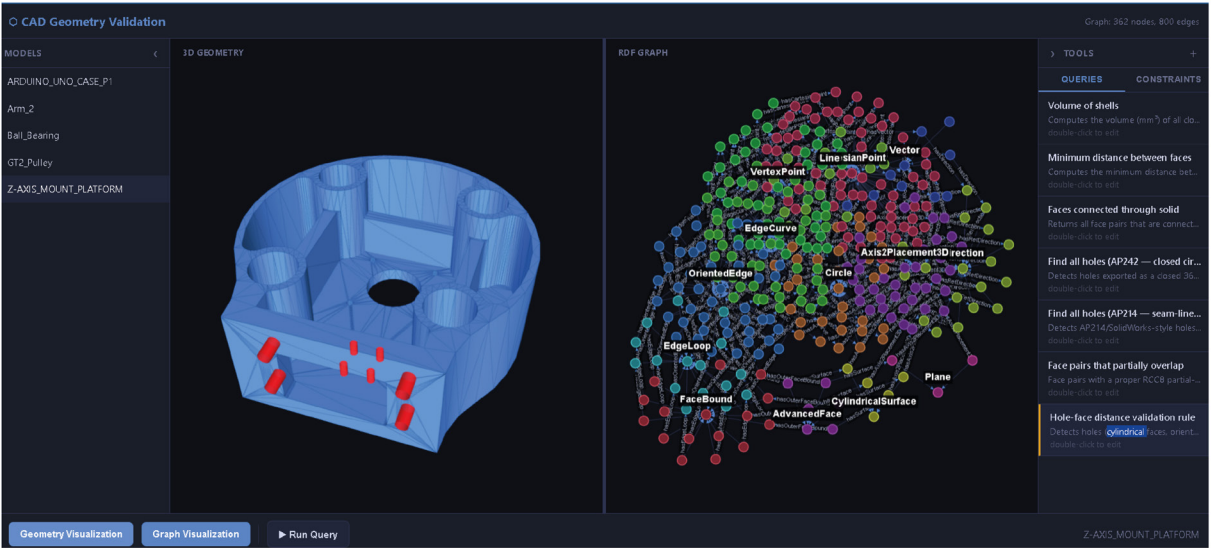


Figure 8: Visualisation of query results: faces that violate the hole-to-edge distance rule are highlighted in the 3D geometry view.

2. Constraints

While SPARQL is well suited for reasoning over RDF data and for extracting or generating information, it is not optimal for validation. SHACL shapes are preferable in this context because constraints can be embedded directly in the graph. The SHACL extension SHACL-SPARQL enables the integration of SPARQL queries into shapes. Because shapes operate under the closed-world assumption, validation fails when the SPARQL query returns a result. In our use case, this means that if a hole is found to be closer to an edge than permitted, a violation is reported. In our application, the constraints are displayed in the second tab on the right side of the UI. They are evaluated automatically on server startup, once all geometry has been converted into knowledge graphs. This represents the final combination of reasoning logic and automated CAD model validation, and can serve as a gatekeeping layer between models received from suppliers and the productive systems of large manufacturing companies. Furthermore, it can provide semantically enriched diagnostics indicating what is wrong and potentially guide resolution.

Listing 3 shows an excerpt of the validation report produced by the SHACL engine for a part in which a hole violates the minimum distance rule. The report is structured around the standard SHACL validation vocabulary. The top-level node carries `sh:conforms` false, indicating that at least one constraint was violated. Each child `sh:ValidationResult` node identifies the shape that triggered the violation via `sh:sourceShape`, the solid being validated via `sh:focusNode`, and the specific offending face via `sh:value`. The `sh:sourceConstraintComponent` is set to `sh:SPARQLConstraintComponent`, reflecting that the constraint was expressed as an embedded SPARQL query. The `sh:resultMessage` provides a human-readable diagnostic containing the hole face identifier, the neighbouring face it is too close to, the measured distance, and the material-specific minimum distance derived from the norm graph. Three representative results are shown, each corresponding to a different hole diameter class and therefore a different minimum distance threshold; the full report for this part contains 86 violations in total.

```
[ a sh:ValidationReport ;
  sh:conforms false ;
  sh:result
    [ a sh:ValidationResult ;
      sh:resultSeverity sh:Violation ;
      sh:sourceConstraintComponent sh:SPARQLConstraintComponent ;
      sh:sourceShape <http://example.com/cad#HoleDistanceConstraintShape> ;
      sh:focusNode <http://www.example.org/ex/Z-AXIS_MOUNT_PLATFORM#2996> ;
      sh:value <http://www.example.org/ex/Z-AXIS_MOUNT_PLATFORM#1842> ;
      sh:resultMessage 'Hole face ...#1842 is too close to face ...#754:
distance 2.28 mm < minimum 3.2 mm.' ] ,
    [ a sh:ValidationResult ;
      sh:resultSeverity sh:Violation ;
      sh:sourceConstraintComponent sh:SPARQLConstraintComponent ;
      sh:sourceShape <http://example.com/cad#HoleDistanceConstraintShape> ;
      sh:focusNode <http://www.example.org/ex/Z-AXIS_MOUNT_PLATFORM#2996> ;
      sh:value <http://www.example.org/ex/Z-AXIS_MOUNT_PLATFORM#2439> ;
      sh:resultMessage 'Hole face ...#2439 is too close to face ...#817:
distance 1.95 mm < minimum 5.1 mm.' ] ,
    [ a sh:ValidationResult ;
      sh:resultSeverity sh:Violation ;
      sh:sourceConstraintComponent sh:SPARQLConstraintComponent ;
      sh:sourceShape <http://example.com/cad#HoleDistanceConstraintShape> ;
      sh:focusNode <http://www.example.org/ex/Z-AXIS_MOUNT_PLATFORM#2996> ;
      sh:value <http://www.example.org/ex/Z-AXIS_MOUNT_PLATFORM#2895> ;
      sh:resultMessage 'Hole face ...#2895 is too close to face ...#529:
distance 2.0 mm < minimum 2.4 mm.' ]
    # ... 86 weitere Verletzungen ausgelassen
  ] .
```

Listing 3: Excerpt of the SHACL validation report for the Z-AXIS_MOUNT_PLATFORM part (blank node identifiers shortened for clarity).

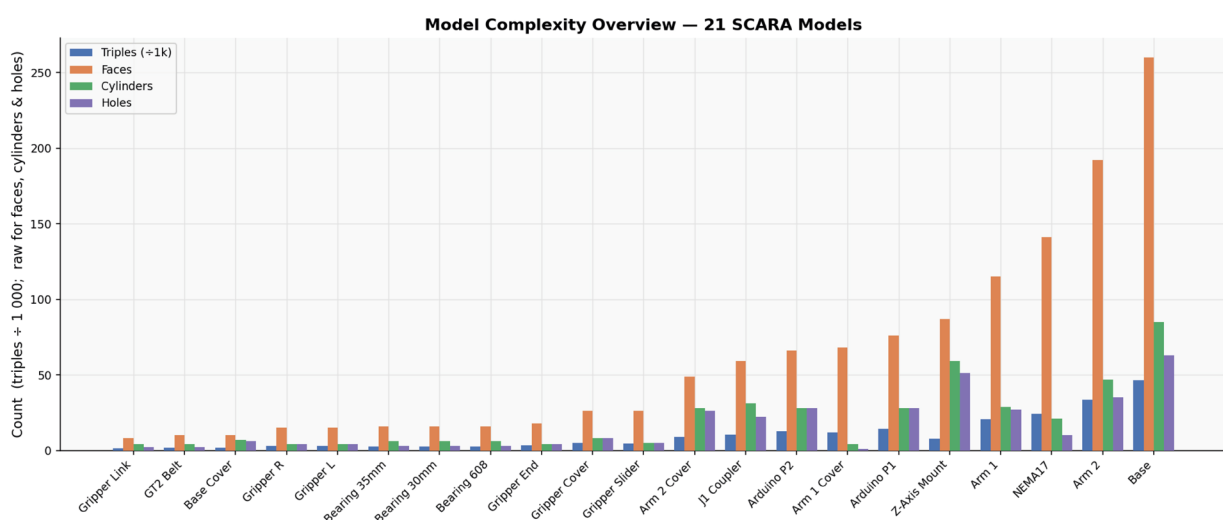


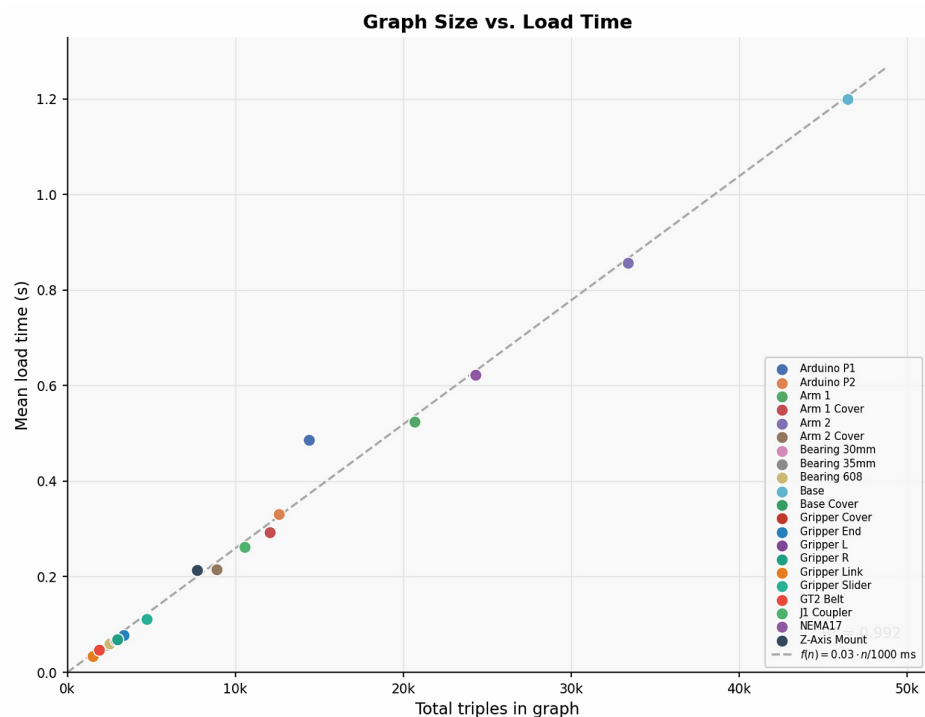
Figure 9: Model complexity overview for the 21 SCARA robot parts used in the benchmark, showing the number of triples (scaled by $\div 1,000$), faces, cylindrical surfaces, and holes per part. Parts are ordered by increasing overall complexity from left to right; the largest part (Base) has 46,448 triples, 260 faces, 85 cylindrical surfaces, and 63 holes.

Feasibility Study

To assess the viability of deploying these technologies in practice, we conducted a feasibility study evaluating both functional correctness and performance. We executed the query from our use case, which combines graph traversal with geometric computation. Additionally, we used a topology-only hole-identification query, without any external library calls or custom SPARQL functions, as a baseline for comparison. Model complexity is characterised by the total number of triples, faces, cylindrical surfaces, and holes. The benchmark dataset consists of models of a SCARA robot designed for home construction, created by Dejan Nedelkovski on his platform HowToMechatronics [17]. We selected 21 parts of varying size and complexity to assess the scalability of our approach; the distribution of model sizes is illustrated in Figure 9. The largest model is the base of the SCARA robot, with 46,448 triples, 260 faces, 85 cylindrical surfaces, and 63 holes.

We analysed performance in four areas: graph materialisation from STEP files, query execution time, query execution time with and without our caching mechanism, and SHACL-based validation. To analyse and discuss the scalability we used least-squares regression to fit a function to the distribution using scikit-learn.

Figure 10: Graph size vs. mean load time for the 21 SCARA robot parts. Loading time grows linearly with the number of triples ($R^2 = 0.992$), fitted by $f(n) = 25.95 \cdot n/1,000$ ms.



We start with the graph materialisation, which exhibits linear growth in loading time relative to the number of triples; with a regression coefficient of $R^2 = 0.992$,

$$f(n) = 25,95 \cdot \frac{n}{1000} \quad [\text{ms}],$$

we obtain the fit

where n is the number of triples, describing loading time growth in our system.

To analyse query time, we plot execution time for the topology-only hole-identification query and for the query with distance computation. All queries completed successfully. The distance query for the largest model, which required computing the distance from 63 holes to 260 faces (including the holes themselves), a total of 14,364 distance calculations, completed in approximately 13.5 seconds. Query time showed a strong dependence on the number of holes rather than on the total number of triples, which is expected, since the number of calculations depends directly on the number of holes. The relationship between query time and hole count for the topology-only query is shown in Figure 11, and for the distance query in Figure 12. The topology-only query exhibits a linear trend:

$$f_{\text{holes}}(h) = 0,225 \cdot h + 17,1 \quad [\text{ms}], \quad R^2 = 0,775,$$

where the constant 17 ms is the fixed SPARQL execution overhead regardless of model size, and the 0.225 ms/hole term is the marginal cost per hole found. The distance query exhibits quadratic growth:

$$f_{\text{dist}}(n, h) = 7,87 \times 10^{-5} \cdot n + 3,73 \times 10^{-3} \cdot \frac{h(h-1)}{2} \quad [\text{s}], \quad R^2 = 0,796,$$

where n is the number of triples and h is the number of holes. This causes query time to grow rapidly for parts with many holes.

SHACL validation, as expected given that the underlying query is identical, shows a similar distribution to the distance query, but requires substantially more time. Validation of the base model takes almost 20 minutes. In Figure 13 we compare the performance of SHACL-SPARQL and plain SPARQL on a logarithmic scale. SHACL validation requires approximately 120 times the execution time of the equivalent plain SPARQL query.

Our caching approach dramatically improved SPARQL query performance, particularly for models where the solid is large but the number of holes is small, since constructing the CAD model object is expensive while individual distance calculations are comparatively cheap. These models achieved a performance improvement of up to 92.5 times. The improvement is illustrated in Figure 14. While the relative speedup is more pronounced for smaller models, it converges as model size grows, remaining highly beneficial for large models with many distance calculations.

Figure 11: Topology-only hole-identification query time vs. hole count across the 21 benchmark parts. The relationship is approximately linear ($R^2 = 0.775$), with a fixed overhead of 17 ms and a marginal cost of 0.225 ms per hole.

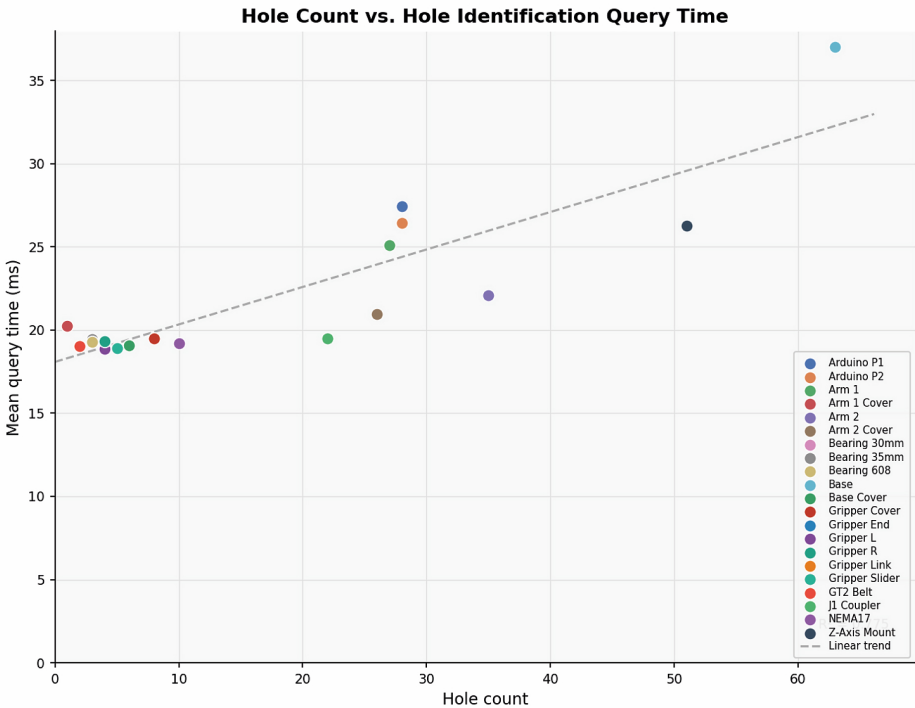
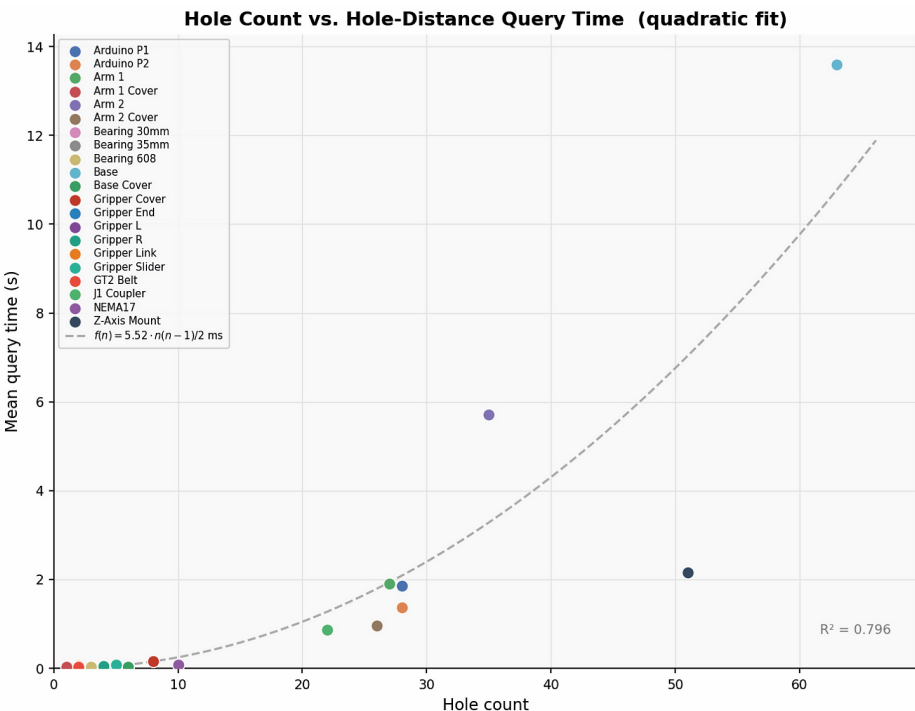


Figure 12: Hole-to-face distance query time vs. hole count. Growth is quadratic in the number of holes ($R^2 = 0.796$), as each hole must be compared with every other face, causing execution time to rise steeply for parts with many holes.



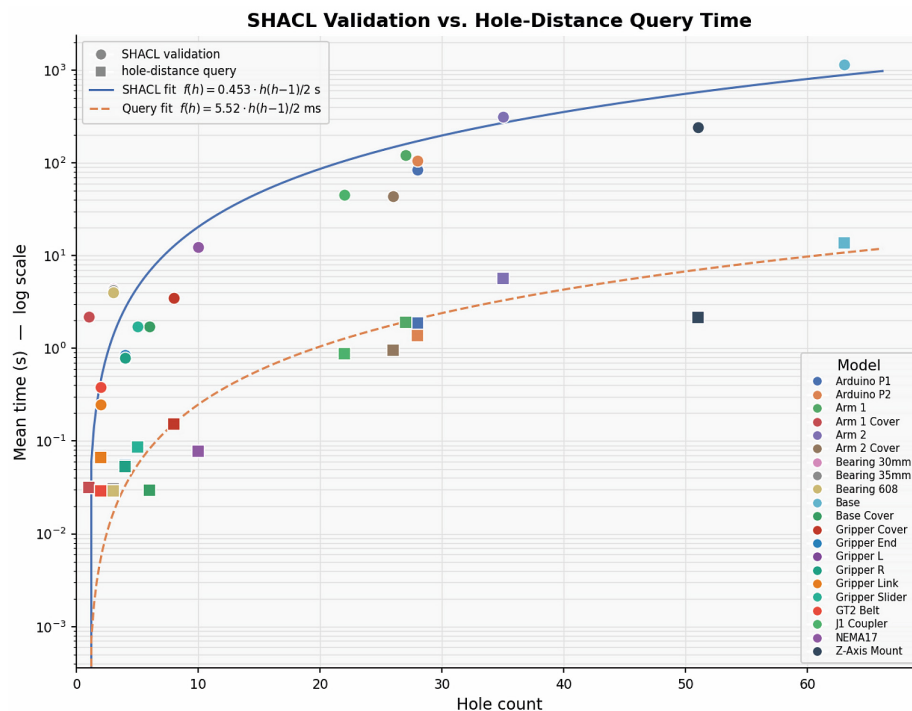


Figure 13: SHACL validation time vs. plain SPARQL distance query time on a logarithmic scale, plotted against hole count. SHACL-SPARQL consistently requires approximately two orders of magnitude more time than the equivalent plain SPARQL query; validation of the largest part (Base, 63 holes) takes close to 20 minutes.

Discussion

The combination of B-Rep and knowledge graph technologies into Knowledge B-Rep Graphs has demonstrated its potential for analysing and validating geometric models. We implemented a proof of concept with several analysis functions and evaluated it against a benchmark dataset. Our study showed that the integration of CAD libraries for the analysis of B-Rep primitives, which is an area that has so far received little research attention, is in fact feasible and can be computed in seconds for simple CAD models.

We first consider scalability. Graph materialisation scales linearly; extrapolating from our regression model, our system would load one billion triples in approximately 16.5 minutes. This may be acceptable for moderate-scale deployments but could become a bottleneck in large automotive contexts. A car consists of about 30,000 parts, each with many revisions, and many of these parts are more complex than the SCARA robot components used in this study. This is particularly problematic for geometric queries whose computational cost grows quadratic with model complexity. Deploying SHACL shapes across the many parts found in the automotive industry therefore seems difficult to realise in the near term. The best path forward is to begin with graph infrastructure that is already performant and to perform simple operations without external library calls, before integrating automated validation. Performance of SPARQL with CAD operations will require further improvement before it can be integrated into shapes for daily production use. Functions that do not depend on the number of primitives, such as part-intersection checks or metadata queries for volume and centre of gravity,

represent a quick win in this regard. Our caching model yielded excellent results, addressing the challenge of the high number of primitives in B-Rep and the need for contextual knowledge. A remaining limitation is that the brepf functions introduce additional complexity into queries, which may hinder intuitive use and integration with LLM-based agents.

Finally, we consider usability. No user study has yet been conducted, but our user interface is designed to help students and engineers understand the mechanisms of knowledge graphs. It also provides a workbench for

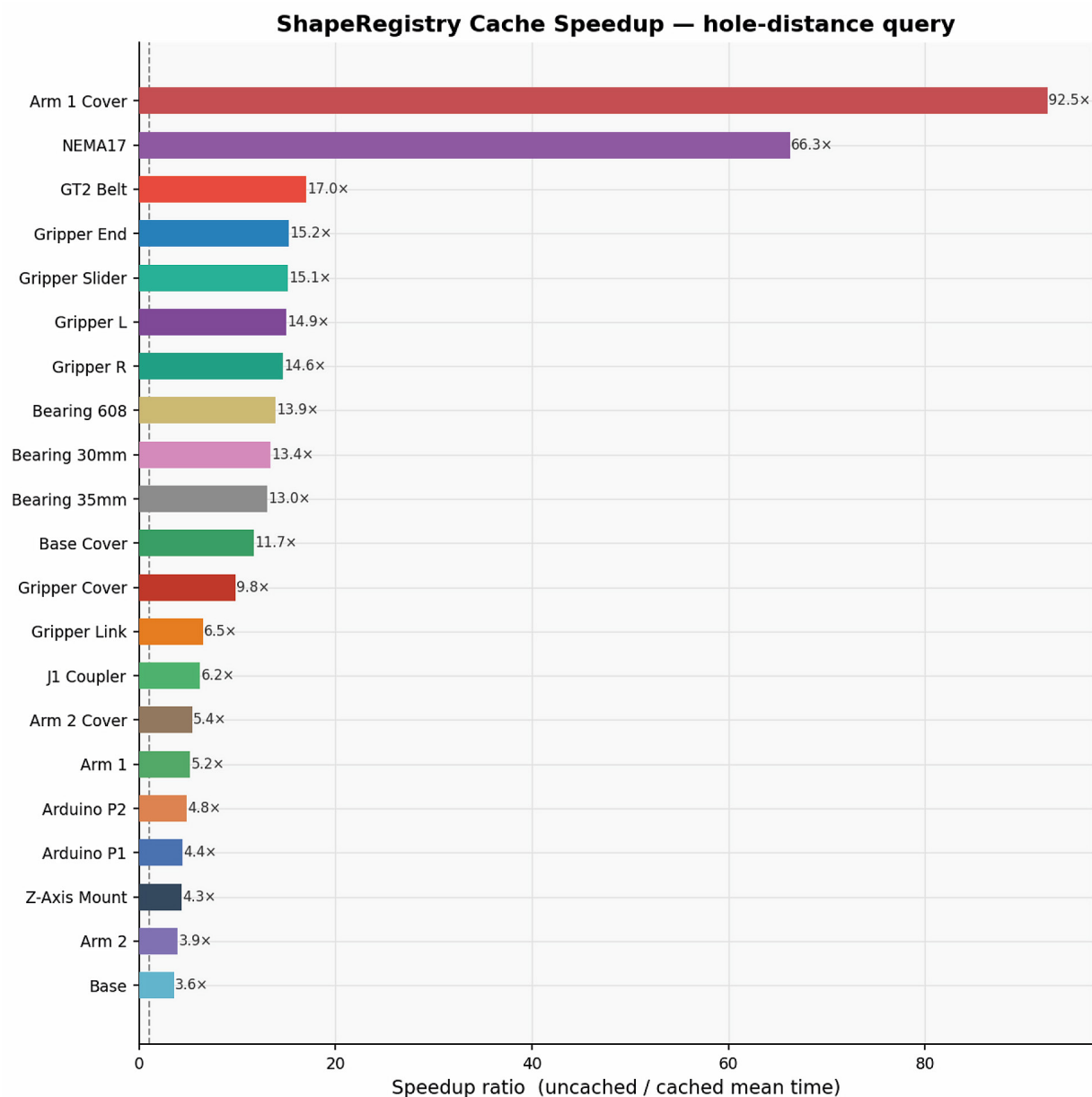


Figure 14: Cache speedup ratio (uncached mean time / cached mean time) for the hole-distance query across all 21 benchmark parts. Parts with a high solid-complexity-to-hole-count ratio benefit most, with speedups of up to 92.5x (Arm 1 Cover). Speedup converges towards lower values for larger, hole-dense models such as the Base, where repeated distance calculations dominate over initialisation cost.

easily integrating CAD models and developing custom queries and SHACL shapes with visual output, which should lower the learning curve. As more companies adopt this new approach to storing engineering data, it will become possible to leverage the full potential of graphs by performing conjunctive queries and connecting data from different sources. In summary, we show that the combination of knowledge graphs and B-Rep models is a valuable technology that deserves greater attention both in academia and in industry; the current state of the art lacks both theoretical foundations and practical implementations.

Future Work

We plan to extend the theoretical foundations of knowledge graph application to CAD models, including the expressiveness of current languages, the formal extension of the SPARQL algebra to 3D operations, and the integration of CAD knowledge into SHACL shapes. In current languages, much of the relevant information is absent from existing ontologies or is distributed across separate languages. As a result, no existing language combines geometry and PMI. Furthermore, there are no rules that can be used to ensure data integrity for SHACL shapes, which operate under the closed-world assumption, while graphs may be incomplete. For example, a SHACL shape might validate a CAD model of a pool table with the aim of ensuring there is a total of six holes. If none are found, not because the holes are absent, but because the model lacks an explicit hole attribute and instead contains a set of information from which holes could be derived, the shape would incorrectly report a violation. This is why such information must be encoded as rules within the ontologies before automated SHACL validation can be reliably applied. Next, the reasoning framework should be extended through



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a formal augmentation of the SPARQL algebra, to establish a standard and lay a foundation for future research. Finally, we plan to conduct a comprehensive industrial study with Mercedes-Benz and the University of Stuttgart to demonstrate the potential of knowledge graphs in engineering in a real-world case study.

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Twin Transformation:

The Digital Product Passport as Enabler for Digitalization and Sustainability

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The Digital Product Passport (DPP) is emerging as a key tool to ensure transparency, traceability, and sustainability throughout the entire product lifecycle. As part of the European Green Deal, it will become mandatory for most companies. However, these companies face challenges such as heterogeneous data landscapes, a lack of standards, and significant effort required to integrate the DPP into existing IT ecosystems.

To address these challenges, this article presents practical solutions, including the use of the Asset Administration Shell (AAS), modular data architectures, and Free and Open-Source Software (FOSS) such as Eclipse BaSyx. Furthermore, the article highlights how the DPP, as a strategic enabler for digital and ecological transformation (Twin Transformation), lays the foundation for new, data-driven business models and serves as the starting point for further use cases for digital twins.

The Impact of the Digital Product Passport on Industry

The Digital Product Passport (DPP) is coming. The question is no longer if, but when. Its scope covers all physical goods placed on the market or put into service within the EU. This explicitly includes individual components and intermediate products.

The framework for the DPP is provided by the EU's "Green Deal," which aims to make Europe the first climate-neutral continent. To achieve this goal by 2050, legally binding requirements are being established, and targeted investments in innovation, green technologies, and infrastructure are being promoted.

While the Ecodesign Directive [1] previously served as the basis for sustainable products, the Ecodesign for Sustainable Products Regulation (ESPR) [2] significantly expands the scope of application. The ESPR serves as a kind of empty shell. Specific requirements for products are set out through defined product groups and specified in delegated acts, e.g., for iron and steel, or batteries [3] (see Figure 1).

But what specific implications does this have for companies? As a general rule, every department within a company can be affected by the DPP.

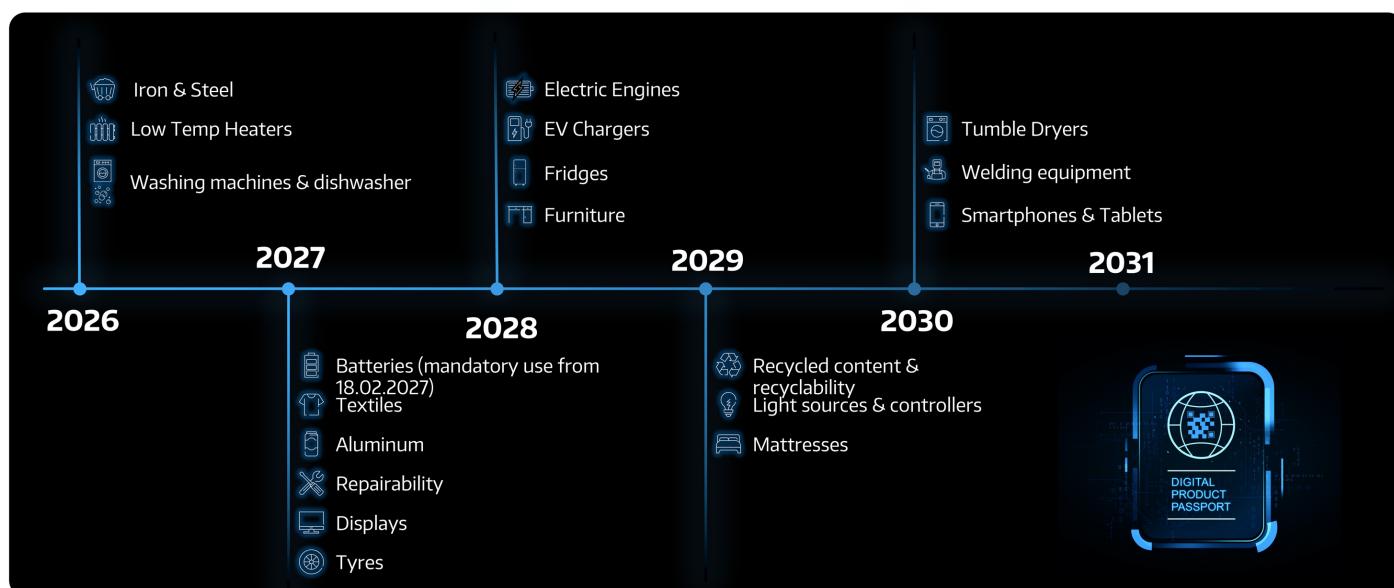


Figure 1: Expected timeline for delegated acts under the Ecodesign Regulation

Furthermore, due to the performance and information requirements set forth (see ESPR, Articles 6 and 7), supply chain information is becoming increasingly relevant, e.g., for calculating a company's carbon footprint.

The actual impact is divided into direct and indirect impacts [4]:

- **Direct Impact:** The company is placing a regulated product on the market. This product must have a DPP issued by the company.
- **Indirect Impact:** The company incorporates a regulated component from a supplier into its non-regulated product. The company must make the DPP for the supplier component available to its customers.

Due to the large number of additional regulations, the direct impact on businesses is becoming increasingly apparent. Companies should therefore prepare themselves.

Many challenges to the implementation of the DPP

Many companies are struggling to implement the DPP. In these economically challenging times, the regulation is primarily seen as an additional burden in terms of both cost and time. The key challenges are considered to be:

- **Unclear DPP requirements:** Unclear requirements, differing timelines, additional EU regulations, and unresolved questions regarding processes, systems, and penalties are causing uncertainty and delaying decision-making within companies. For example, the rules governing interaction between economic actors, as well as the specifics of individual processes and necessary system components, have not been clarified yet – such as those regarding the DPP system, the EU DPP Registry, or backup providers. The same applies to the consequences of non-compliance. This leads to hesitation on the part of companies and delays in decision-making and implementation of measures.
- **Insufficient data availability:** The availability, quality, and reliability of DPP-relevant data are critical. In addition to gaps in supply chain data, much of the existing data is based on assumptions or rough estimates. To validate and improve the reliability of data, there is often a lack of appropriate roles and responsibilities within companies. When integrating external data from the supply chain, clear processes, standards, and technologies are lacking. All of this leads to non-value-adding activities involving high manual effort and additional communication.
- **Document-based way of working:** Much of the DPP-relevant data is stored in documents outside of PLM and ERP systems. Data is exchanged between companies in text format, and media breaks also occur within companies due to a lack of IT interfaces. Often, a sprawling spreadsheet serves as a repository for DPP data that can only be edited by a few individuals within the company. Ultimately, this approach represents a dead end that results in a high level of manual effort.
- **Insufficient IT interoperability:** Data for the DPP is typically scattered across various IT systems. On the one hand, accessing the relevant data points requires appropriate IT interfaces, on the other hand, automated

mechanisms are needed to transform and harmonize the data so it can be made available to the DPP. In heterogeneous IT environments, existing IT systems provide only individual functionalities, and there is a lack of end-to-end integration for DPP data. Cleaning up and further developing the IT landscape requires companies to invest in capabilities for IT and its personnel.

- **Lack of reuse:** The vast majority of companies are already addressing issues of sustainability and product-related environmental impacts, for example through life cycle assessment (LCA) or environmental product declarations (EPD). Still, relevant DPP data as well as existing calculations and sustainability data are rarely reused. As a result, significant opportunities for efficiency gains and cost savings remain untapped.

The IT infrastructure must be made DPP-ready.

The implementation of the DPP must be seen as an integral part of a comprehensive, cross-functional data and IT strategy. Starting point for implementing the DPP should therefore be a strategy that defines the value the DPP is intended to deliver, its relationship to digital twins, and how these initiatives can generate additional revenue.

Building on this, relevant data points, sources, and a suitable data standard - such as from the Industrial Digital Twin Association (IDTA) [5] - as well as requirements from data spaces like Catena-X or Manufacturing-X, must be defined to address uncertain regulatory requirements. EAM-based approaches such as MBITA® (Model-Based IT Architectures) [6] can support data modeling.

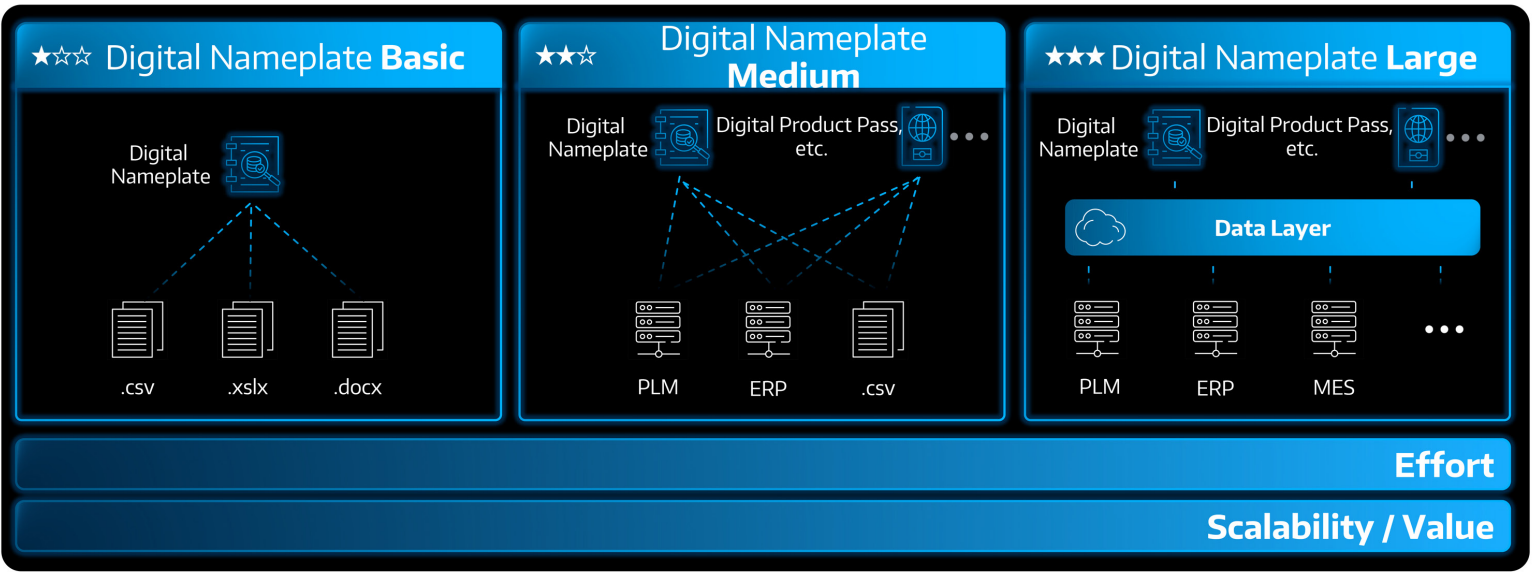


Figure 2: Different implementation levels of IT architectures for the digital nameplate.

The selected ontology is used to create semantic data models, ideally in a modular form. The starting point for the DPP within the AAS framework is the digital nameplate [7]. This lists basic product-specific data such as manufacturer information and markings. By adding further submodels, like the “Handover Documentation,” the DPP can grow incrementally [5].

This approach enables a pragmatic procedure. The greatest effort lies in data provision. Depending on the size of the company and the progress of digitization, different expansion options are available (see Figure 2). Small companies that work primarily with documents can use custom parsers to automatically transfer their data into a management shell. However, since this concept does not scale, accessing source systems via APIs is preferable. The DPP should not be viewed as a monolith, but rather as a collection of individual puzzle pieces. In particular, when additional use cases that go beyond the DPP itself – such as for the digital twin – arise, a data layer is worthwhile. In this layer, data is harmonized and semantically described and can be efficiently made available for any application via standardized interfaces.

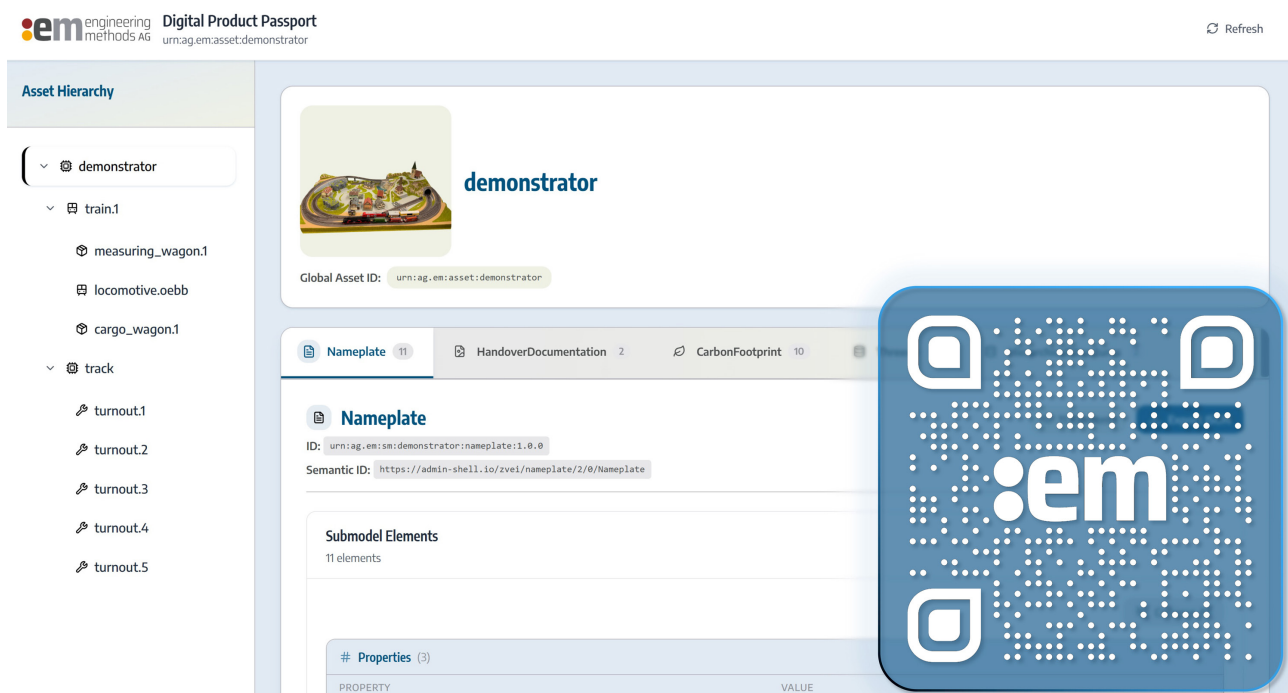


Figure 3: The Digital Product Pass as demonstrated in the :em Digital Twin Showcase

Free and Open-Source Software provides support during implementation

Free and Open-Source Software (FOSS) enables efficient system integration and IT interoperability within the DPP framework based on the vendor-neutral AAS. With Eclipse BaSyx as a modular reference implementation, existing IT landscapes can be quickly expanded, barriers to entry lowered, and in-house development as well as vendor lock-in avoided.

The open development model and associated communities ensure the continued development of standards and facilitate the integration of regulatory requirements. In this way, FOSS enables small and medium-sized enterprises in particular to participate in a decentralized DPP ecosystem in compliance with cross-industry standards [8], [9], [10].

Based on an H0 model railroad, the :em DT Showcase has been developed to demonstrate the potential of digital twins and the AAS [11]. For this use case, a DPP was implemented according to IDTA specifications (see Figure 3). A combination of commercial tools (Bosch Semantic Stack) and FOSS components (Eclipse BaSyx) have been used for the implementation. This demonstrates the integration of DPPs from multiple subsystems into a single overall system. The DPP is publicly available at: :em DT Showcase

The DPP as Enabler for Digital Transformation

The true value of the DPP extends far beyond mere compliance. When implemented correctly, the DPP serves as a key enabler for the Twin Transformation [12] (see Figure 4).

At the heart of the DPP is the provision of machine-readable lifecycle data at the instance level. Every manufactured product receives a digital twin that is kept up to date throughout its lifecycle. This creates a digital shadow of the physical product [13], which makes relevant information consistently available across development, manufacturing, use, and disposal, thereby creating digital end-to-end traceability. Once the DPP has been implemented, many indirect benefits, such as improved data availability and faster decision-making, can be realized. At the same time, the DPP supports increased circularity and improves customer communication. The structured and seamless integration of supplier data is also significantly facilitated, enabling synchronous, cross-organizational collaboration in data spaces such as Catena-X or Manufacturing-X¹.

¹) The prostep ivip project group “Live Collaboration in Engineering” is one of the groups investigating how data spaces can be used to enable real-time, cross-organizational collaboration based on semantic data.

Legal Framework



The EU regulation for sustainable, recyclable products. It lays the foundation for the Digital Product Passport and defines requirements for transparency, resource efficiency and recyclability.

Digital Product Passport

A central, structured data set with all relevant product information – from production to use and maintenance to recycling.

-  Material composition
-  Repairability
-  Energy consumption
-  CO₂ footprint
-  Recyclability

Benefits

The Digital Product Passports delivers benefits far beyond mere compliance.

-  Improved Traceability & Interoperability
-  Improved availability & quality of data
-  Monetization of data and Digital Business Models
-  Basis for digital twin models

The digital product passport will come – the question is not if, but when.

Figure 4: Overview Digital Product Passport

Furthermore, the DPP creates the technological foundation for advanced, value-adding use cases that deliver immediate economic benefits. For example, product and usage data can be monetized via the DPP platform and offered to customers “as-a-service.” The availability of up-to-date, structured, and reliable instance data enables data analytics use cases. It also enhances the quality of AI applications, such as through AI agents for circular economy scenarios like buyback prices or targeted recalls. At the same time, the DPP serves as a digital shadow, forming the foundation for digital twins.

Once established, the semantically described database can be reused throughout the entire value stream—from engineering through production to maintenance. Thus, submodels such as Asset Interfaces Description (AID) and Asset Control enable cross-vendor connectivity of assets and lay the groundwork for asset orchestration platforms or AI-agent-based matrix production, thereby also becoming the foundation for end-to-end digitized and scalable value creation in the context of smart manufacturing.

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Key Takeaways

The DPP is neither an end in itself nor an isolated exercise. It serves as the strategic starting point for sustainable, data-driven product development and use, provided it is understood as an integral part of a comprehensive strategy for PLM and the digital twin:



The DPP is coming. Initial insights can be gained from batteries.



The DPP is a key driver of the Twin Transformation toward greater digitalization and sustainability in the supply chain.



Efficient data integration and the consistent implementation of scalable IT solutions are crucial.



The technological foundation for the DPP is the digital twin, with AAS as the standard.



The DPP serves as a starting point for many other use cases and for establishing new digital business models and services.

Now is the time for companies to take action and prepare for the DPP.



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How VDA Volume 2 and VDA 231-301
pave the way from document-based
approvals to digitally controlled
evidence processes

Agentic AI in the Risk-Based Evidence Process

Bernd Löhle, material.one AG

In many approval processes, digitalization is still seen as nothing more than exchanging PDFs. True progress occurs when evidence is risk-based, clearly defined, and often equated with exchanging PDFs. However, real progress only begins when evidence is risk-based, semantically clearly described, and machine-processable. This is exactly where three developments: the risk-based approach of the new VDA Volume 2 (Production Process and Product Release/PPF Procedure), the data-oriented semantics of VDA 231-301, and agentic AI as an operational layer in the evidence process.

From document to decision

In industrial approval and evidence processes, the main challenge is often not the availability of data, but its form. Inspection reports, certificates, control plans, capability evidence, and approval documents are available, but they are still exchanged as files (mainly PDF and Excel) rather than processed as structured evidence. This creates media discontinuities, redundant data entry, ambiguity, and significant manual coordination effort. The result is a process that may look digital but remains operationally document centric.

This situation is not limited to individual companies. It is also clearly reflected in the product approval domain in Catena-X: today, approval-relevant documents are often uploaded manually as PDFs into customer-specific portals – with considerable effort, inconsistent data structures, and limited transparency.

The new VDA Volume 2 shifts the PPA logic

This is precisely why the new VDA Volume 2 is so relevant. The 7th edition places a stronger focus on the risk-based approach. The scope of the PPA procedure is no longer determined by a fixed set of evidence requirements, but by the risk associated with the product or modification to be approved. Existing evidence can be referenced more specifically. Deviations can be assessed in a more differentiated way. Documentation effort can be reduced, and explicit referencing of existing evidence becomes possible. At the same time, VDA 231-300/301 supports digital data exchange in material sample inspection. The foreword refers to an online tool that will replace the previous Excel templates.

This is more than methodological fine-tuning; it changes the logic of the process. If artifacts are no longer treated in the same way, and risk-based decisions are made about which evidence is needed, in what form, and how deviations are managed, the process requires more than documents – it requires decision logic. This is where agentic AI becomes industrially relevant: not as a general text assistant, but as an operational layer that helps orchestrate, prioritize, complete, and prepare evidence processes for decision-making. This is consistent with the risk-based structure of the new VDA Volume 2.

Agentic AI in the Risk-Based Evidence Process

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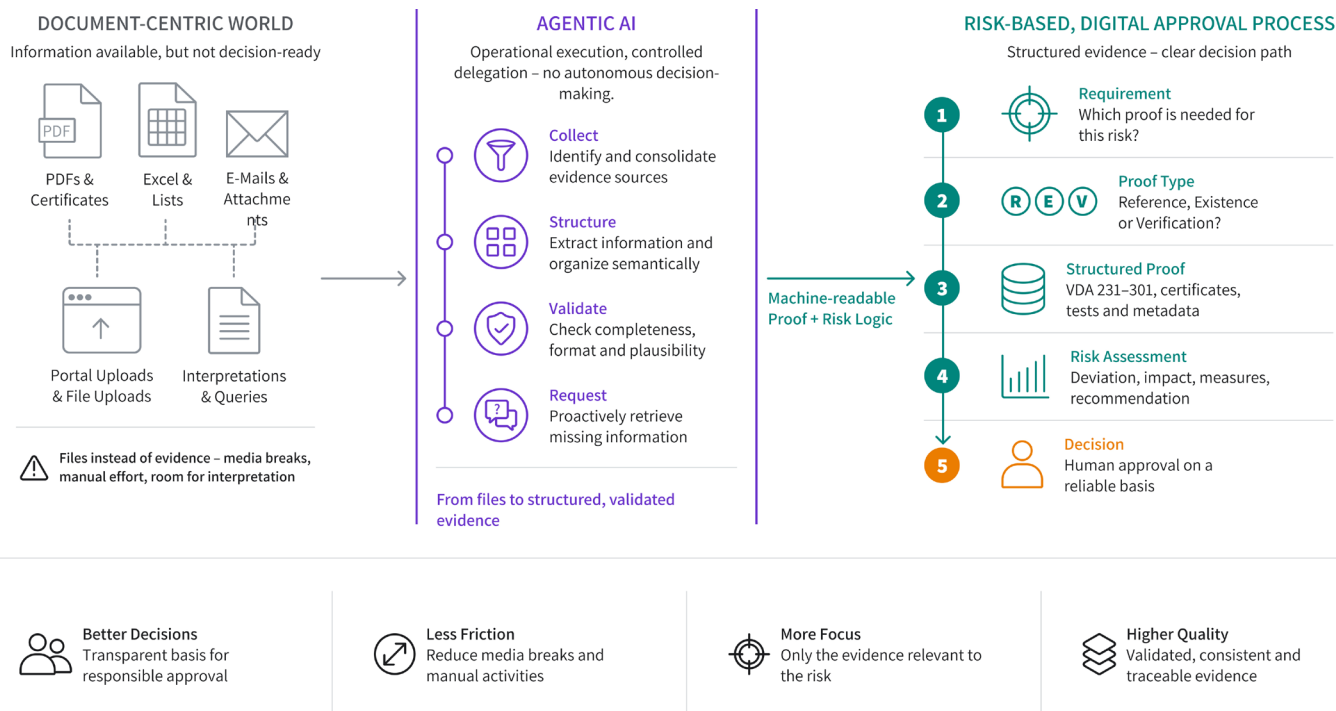


Figure 1: Product Approval Process – “Document Centric World” versus “risk based and digital verification process”

What Agentic AI Actually Does in the Evidence Process

First, what is agentic AI? In this context, agentic AI does not refer to freely deciding autonomous systems, but to specialized digital agents that take over tasks in the evidence process within defined roles, rules, and approval boundaries: collecting information, identifying check statuses, requesting missing evidence, structuring deviations, and preparing decision templates.

The new VDA Volume 2 distinguishes between three types of evidence checking: reference, existence, and verification. Reference evidence refers to documented information without requiring it to be submitted. Existence evidence confirms the availability of documented information. Verification evidence enables a target-actual comparison with regard to completeness, accuracy, sequence, and consistency. This three-part structure is highly relevant for agentic AI, because it means that agents do not process “arbitrary documents”, but operate in a clearly defined check mode. An agent can determine which type of evidence is required, collect suitable evidence, request missing information, resolve references, and prepare verification objects for the customer decision.

This becomes particularly evident in cases of deviation. The new VDA Volume 2 explicitly anchors risk assessment in the PPF process. If requirements are not fully met, the organization must conduct a documented risk assessment; this is part of the PPF documentation and is to be submitted to the customer. The risk assessment must be carried out by an interdisciplinary team, documented in a comprehensible manner, and include, among other things, the deviation, cause, potential failure effects, risk evaluation, risk-reduction measures, and an internal decision proposal. The customer then decides, based on this risk assessment, whether deviations are permanently accepted, temporarily accepted, or not accepted.

This is exactly where the natural role of agentic AI lies: not in autonomous approval, but in the reliable delegation of routine work within a controlled process. Agents can structure deviations, identify missing evidence, consolidate causes and measures from existing evidence, check references to previous approvals, consider variant and stage logic, and prepare the documentation for human, accountable review. The decision remains with humans; however, the workload involved in evidence management and preparation can be significantly reduced. From an industrial governance perspective, this is the key difference between “AI over documents” and “AI in the evidence process.”

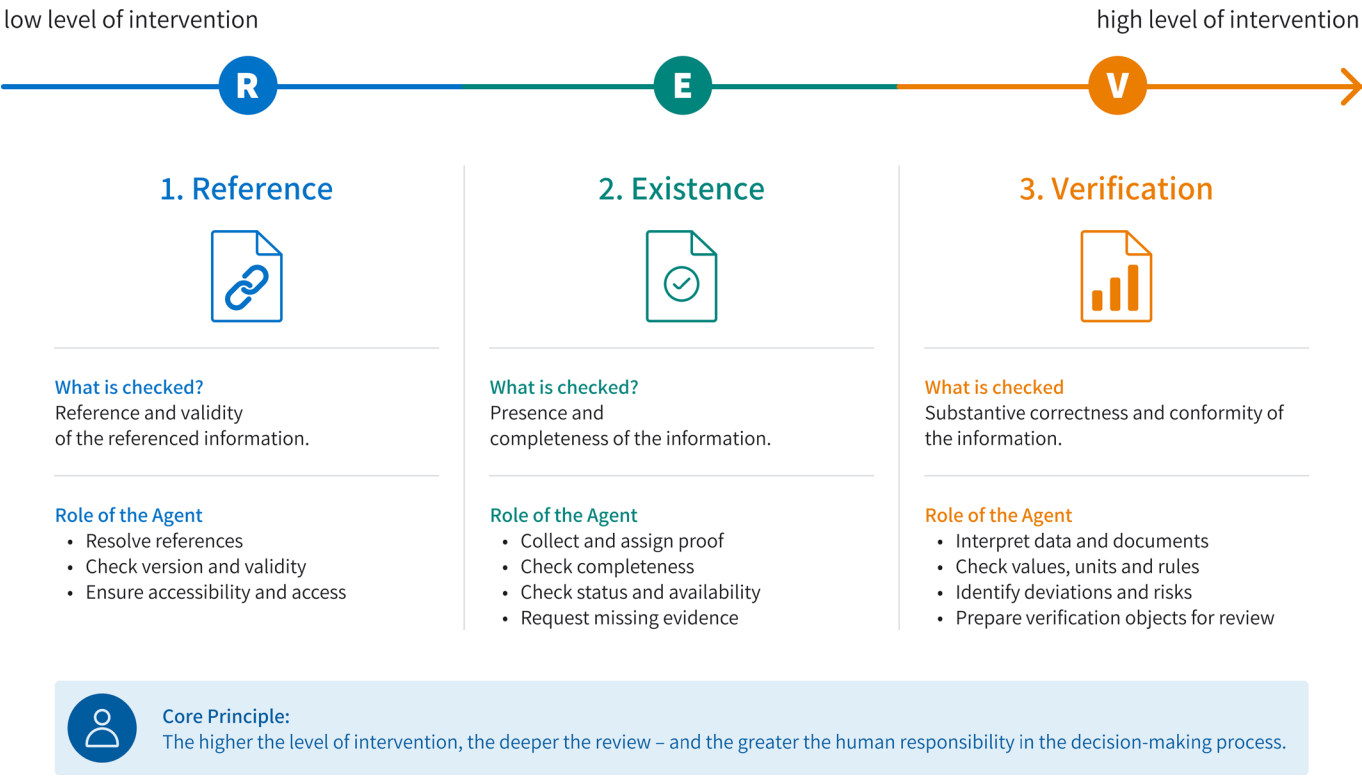


Figure 2: Three types of evidence review and the role of agentic AI in the PPA evidence process

VDA 231-301 Makes Document-Based Evidence Digitally Processable

For agentic AI to work reliably in this context, it needs semantically clear data structures. This is precisely where VDA 231-301 comes in. The official schema ecosystem describes released JSON schemas for the digital exchange of material-related test and approval data. The repository is explicitly intended for productive IT systems, validation, interfaces, converters, and automated tools, and addresses interoperability, automation, and consistent interpretation across system and organizational boundaries.

For the evidence process, it is particularly relevant that an EN 10204 subschema already exists within the VDA 231-301 ecosystem, including Inspection Certificate 3.1. This subschema describes, in machine-readable form, how the contents of such inspection certificates can be represented digitally: from material and batch identification to chemical and mechanical values, metadata, signatures, and references to standards and test methods. It supports automated processing, improved traceability, and integration into material data and quality systems.

This example clearly shows what agentic AI can practically achieve. For 3.1 inspection certificates, recognizing text alone is not enough. A robust system must also understand table logic, recognize cross-language field names, assign units correctly, account for exponents in headers, and place values in the correct technical context. Only then does a document become a verifiable evidence object. VDA 231-301 does not provide the AI itself; it provides the necessary semantic target structure. The combination of a standardized schema and agentic process logic is therefore stronger than any purely document-centric automation. This conclusion follows directly from the function of the schemas as a productive, validatable exchange structure.

Implementation Beyond Automotive

Although PPF and Catena-X originate from the automotive context, the underlying logic is applicable across a much broader industrial landscape. The EN 10204 subschema is explicitly described as relevant for sectors beyond automotive, including steel and metal production, mechanical and plant engineering, construction products, and industrial equipment.

In any supply chain where inspection certificates, specifications, test results, and approvals are exchanged, the same key questions arise: Which evidence is relevant? Which deviation is acceptable? Which information must be referenced, proven, or verified? This is why the risk-based, data-driven evidence process is not an automotive-specific use case, but a robust pattern for distributed quality and approval processes across industries.

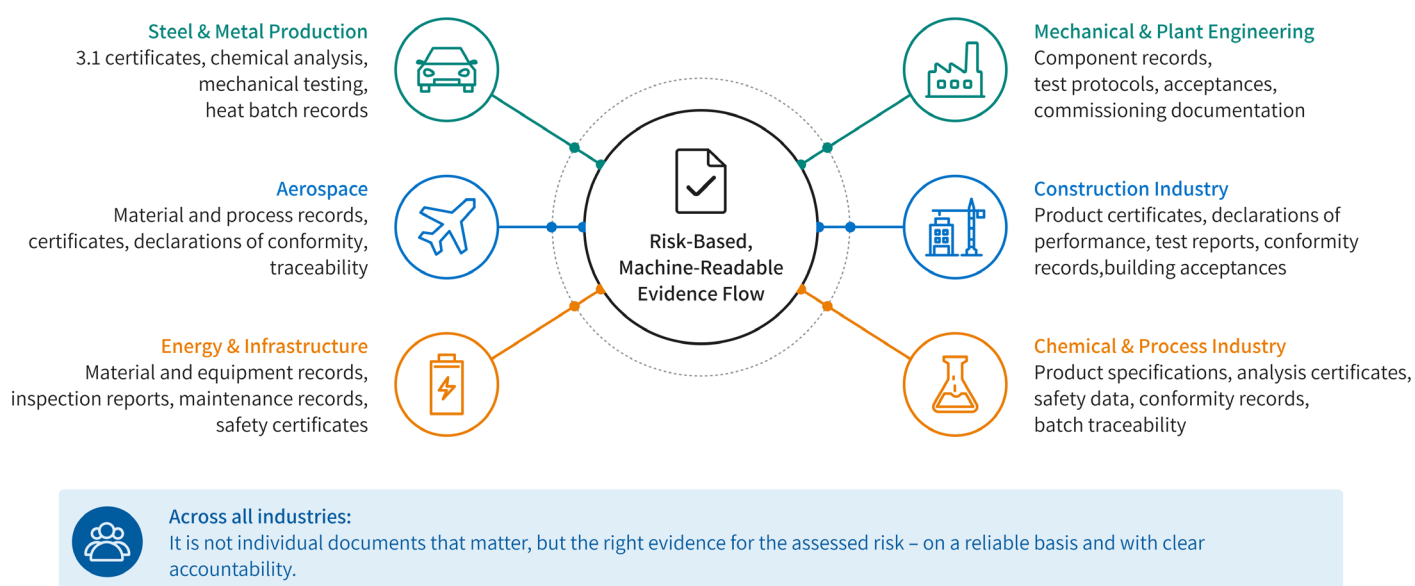


Figure 3: Implementation Beyond Automotive: Cross-Industry Evidence and Approval Processes

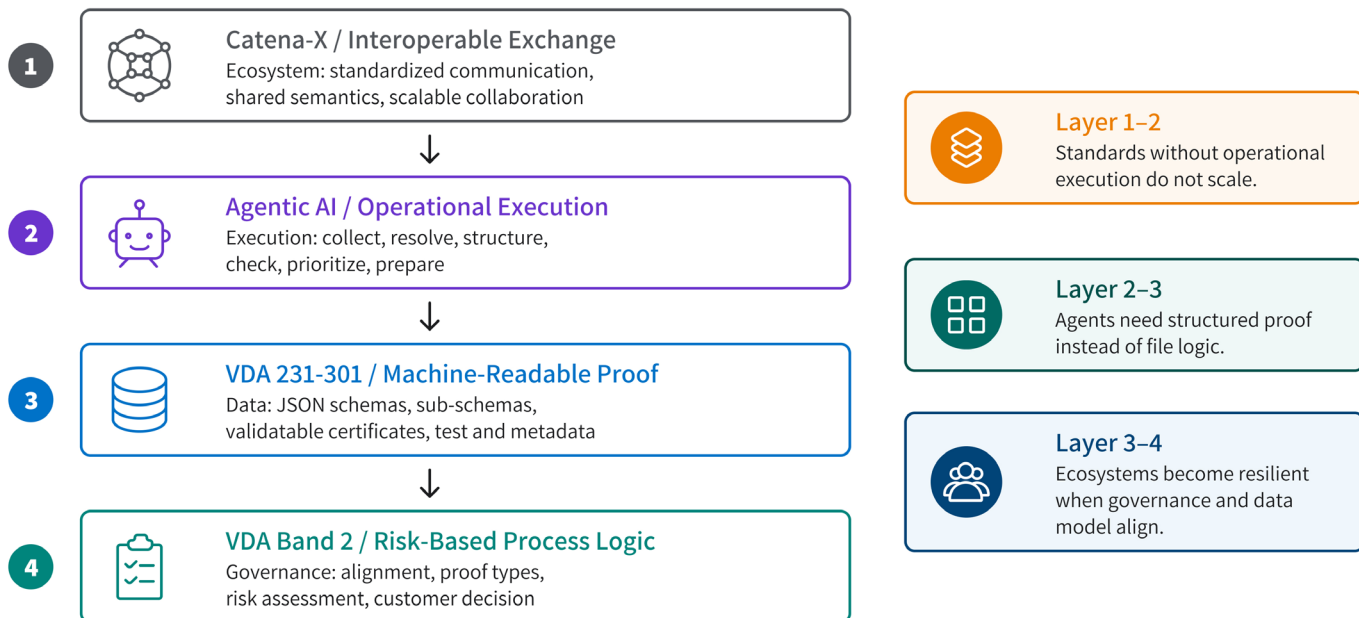


Figure 4: Product Approval Evolution: The Four Levels of Evidence Management with Agentic AI

Catena-X: Product Approval as the Next Eco-System Step

Catena-X shows that this issue is now also being addressed at the ecosystem level. With the new Expert Group "Product Approval", Catena-X is targeting precisely those complex data exchange processes in product and production process approvals that are still largely document-based and manual today. The aim is to increase transparency and traceability for approved products and the associated evidence, reduce manual uploads to customer-specific portals, and enable faster and more reliable approvals. According to the Expert Group profile, a Catena-X standard based on VDA 231-300/-301 is to be developed for this purpose. In addition, Aspect Models and a Tractus-X KIT with reference implementations, sample payloads, APIs, and test artifacts are planned. According to the current planning status, "26.09" is intended as the Catena-X release identifier.

This is an important development. It demonstrates that the evidence process is evolving from file-based exchange to a standardized, machine-readable, and increasingly executable data process. VDA Volume 2 defines the risk-based logic of PPF, VDA 231-301 provides the semantic data structure, and Catena-X translates this logic into an interoperable ecosystem. In this context, agentic AI is not merely a hype-driven add-on, but the operational layer that turns structured evidence into an actionable process.

Conclusion

The next level of digitalization in approval and evidence processes is not about managing even more documents electronically. It is about steering evidence in a risk-based way, modeling it with semantic clarity, and making it executable at process level. The new VDA Volume 2 provides the procedural logic for this. VDA 231-301 provides the semantic data foundation. With the Product Approval Expert Group, Catena-X signals that this direction is now also being substantiated at the network level. Agentic AI thus evolves from a general assistant into a specialized operational instrument in approval and evidence processes – controlled, secure, traceable, and scalable.

What begins as an automotive standard becomes a transferable model for industrial evidence management across industries.



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The Answer Is Not AI

Dr. Steven Vettermann

Artificial intelligence (AI) is currently reshaping the agenda of nearly every company. But the real challenge lies not solely in the technology. AI is increasingly acting as a stress test for organizations' ability to operate effectively in an environment of uncertainty, accelerating change, and constantly shifting demands. This article explores why past success strategies alone are no longer sufficient, which organizational capabilities will determine competitiveness in the future, and what opportunities this presents for both member companies and prostep ivip as a shared learning and development platform.

The allure of the next big solution

Hardly any other topic is currently occupying companies as much as AI. Senior executives are discussing AI strategies. Business units are identifying use cases. Software providers are integrating AI features into nearly every product. Anyone attending industry conferences these days could easily get the impression that the future has already been decided. Expectations are correspondingly high.

According to McKinsey, 88 percent of the companies surveyed now regularly use generative AI in at least one business area [1]. At the same time, nearly all companies are investing in AI, while only about one percent describe themselves as truly "AI-mature."

This tension is striking. On the one hand, no one wants to fall behind. On the other hand, uncertainty is growing. Which use cases actually create value? What skills are needed? Which platforms will establish themselves in the long term?

The World Economic Forum describes this situation as part of a broader trend. Technological change, geopolitical tensions, economic uncertainty, and new regulatory requirements are simultaneously altering the operating environment for many companies [2].

The real challenge, therefore, does not seem to be access to the technology. Rather, the current debate on AI highlights how difficult it is for organizations to remain capable of responding effectively when the operating environment changes faster than their planning and adaptation cycles.

Therefore, the crucial question may not be how to implement AI, but how to develop one's own organization so that it can cope with a world in which technological change and disruption have become the norm.

Why yesterday's success formula is no longer enough

The industrial success story of the past decades is based on capabilities that continue to make companies strong today: standardization, planning, process control, specialization, and scaling. Global value-chain networks, highly complex products, and international collaborations would be virtually unthinkable without these capabilities.

The challenge, therefore, does not lie in a lack of competence. The challenge lies in an environment that – unlike in the 20th century and before – is constantly changing, sometimes radically.

Many challenges in the past were complicated, not complex. With sufficient knowledge, they could be analyzed, planned, and solved. Current challenges such as AI, cybersecurity, sustainability, and software-defined products often behave differently. Technologies continue to evolve, regulatory requirements change, and new areas of application often emerge faster than traditional planning cycles.

Planning remains important. However, it is no longer sufficient on its own. Decades ago, Nobel laureate Herbert Simon described how organizations must make decisions under conditions of bounded rationality. Information remains incomplete, and the future is only partially predictable [3]. It is precisely this situation that is becoming the norm for many companies today.

The key challenge, therefore, is not to eliminate uncertainty entirely. It is to be able to make effective decisions and take effective action despite uncertainty.

This also means that a different form of leadership is necessary – not leadership as control, not leadership as expertise, but leadership as the ability to provide direction, facilitate decision-making, and accelerate learning.

The real challenge: Acting without certainty

The discussion about AI is often framed as a discussion about technology. In reality, however, it concerns the very foundations of organizations themselves. Most companies have long been aware of which technologies are relevant. Information, studies, and examples are plentiful (e.g., [4]). The real challenge lies in turning opportunities into effective action. And this is precisely where a new competitive factor is currently emerging.

For many years, companies were able to build competitive advantages primarily through knowledge, experience, process mastery, and scale. These factors remain important. At the same time, however, skills that received less attention in comparatively stable environments are gaining in importance:

- Learning quickly.
- Making decisions under uncertainty.
- Taking responsibility before all the answers are in.
- Bringing together different perspectives.
- Remaining capable of responding together.

This trend has now been confirmed by international studies as well. The World Economic Forum identifies analytical thinking, the ability to learn, resilience, and leadership as key competencies for the future [2]. The OECD emphasizes the ability of organizations to absorb knowledge, adapt it, and translate it into decisions [5].

The question thus shifts from “Do we have enough information?” to “Do we have enough orientation to take the next sensible step?”

Organizational effectiveness means being able to make decisions, learn, and take action even when certainty is not available. Technologies can be purchased. Organizational adaptability cannot.

If the answer isn't AI, then what is it?

If the real challenge does not lie in technology, the next question inevitably arises: What should companies do instead?

The answer is not to invest less in AI. On the contrary. Technological capabilities remain crucial. Data, models, platforms, and digital tools will continue to be key success factors. At the same time, however, it is becoming clear that technological investments alone are not enough.

When organizational adaptability becomes a competitive factor, the next question is how it can be developed in a targeted manner. The following four areas of action are particularly relevant in this regard.

■ Providing Direction

The more dynamic the environment becomes, the more important clear direction becomes. Direction does not mean predicting the future. It means making priorities visible and aligning decisions around a shared purpose. The benefits: faster decisions, less friction, and faster implementation.

■ Strengthening Decision-Making Capabilities

Many companies have sufficient expertise. Nevertheless, decisions are delayed because responsibilities are unclear or because companies are waiting for additional information. Decision-making capabilities mean making decisions where knowledge is generated, clearly defining responsibilities, and consciously incorporating learning loops into the process. This leads to shorter response times and lower opportunity costs.

■ Accelerating Organizational Learning

In dynamic environments, learning itself becomes part of the implementation process. Successful organizations deliberately create opportunities to test assumptions, evaluate insights, and quickly feed experiences back into the organization. The benefit lies in faster adaptations to constantly changing conditions.

■ Empowering People

Not every employee needs to develop AI. But more and more people need to cope with uncertainty, take on responsibility, and use technology effectively. Organizations that empower their employees to do so increase their adaptability far beyond the current wave of AI.

The combined impact of these four areas of action extends far beyond the use of AI. They strengthen an organization's ability to remain capable of acting even under uncertain conditions. And it is precisely this ability that is increasingly becoming a decisive competitive factor.

After all, the question is not whether the next technological change is coming. The question is how well companies are prepared for it.

Organizations that provide guidance, facilitate decision-making, accelerate learning, and empower people will not only adopt new technologies more quickly. They will also recognize their benefits sooner, address risks earlier, and translate change into economic success more effectively.

The real competitive advantage, therefore, does not lie in the technology itself. It lies in the ability to use it successfully.

What does this mean for prostep ivip?

Virtually every organization grapples with similar questions: How do we identify meaningful use cases? How do we build acceptance? How do we define responsibilities? How do we integrate new technologies into existing processes?

The answers to these questions rarely emerge in isolation. This has always been one of prostep ivip's particular strengths. The association was founded to address challenges that individual companies find difficult to solve on their own. Over the decades, this has led to the development of standards, methods, reference models, and collaborative approaches that are now taken for granted in many companies.

The underlying idea has always been the same: Learning together drives progress that individual organizations would achieve much more slowly on their own.

This idea may be more relevant today than ever. For, in my view, the real challenge of the coming years may not lie in understanding the next technology. The real challenge lies in developing new organizational capabilities.

For many of the relevant issues, there are currently no generally accepted standards or established best practices. This makes it all the more important to have spaces where experiences can be shared, assumptions can be questioned, and new approaches can be developed collaboratively. This is precisely where an additional pillar - the next stage of development for the community - could be created.

In addition to discussions about technologies, architectures, standards, and processes, another perspective may be gaining importance: the question of how organizations can strengthen their ability to learn, make decisions, and act effectively in the face of uncertainty. Not as a substitute for technical work, but as a necessary complement.

After all, a company's future viability will not depend solely on which technologies are available. It will increasingly depend on how quickly organizations can identify and evaluate new opportunities and translate them into effective action.

Perhaps this is where the real opportunity in the current AI debate lies. It not only forces us to think about new technologies; it also forces us to think about the way we develop organizations and work within them.

And this is precisely the discussion we should be having together.

The real leverage

The debate over AI will be with us for a long time to come. New models will emerge. New technologies will hit the market. Many of today's use cases will disappear and be replaced by new ones. That is precisely why it would be a mistake to view current developments solely as a technological issue.

In many ways, AI is not just another technology wave. It is a stress test of an organization's ability to learn, decide, and adapt under uncertainty.

The real question, therefore, is not who uses the best AI. The real question is which organizations can learn the fastest, make decisions, and translate new opportunities into value creation. That is where the real leverage lies.

After all, the next wave of technology is coming. Whether it's called AI, quantum computing, or something else is of secondary importance.

Companies that provide direction, facilitate decision-making, accelerate learning, and empower people will also be able to successfully navigate the changes that follow.

That's why the answer isn't "AI." The answer is an organization's ability to learn, make decisions, and take action in the face of uncertainty. AI simply reveals how well it can already do that.

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This article is based on ideas from his book "Kursänderung (Changing Course: Leadership Between Transformation Pressure and Orientation)" (2026).

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From Strategy to Implementation – **A Role-Specific Training Program on Digital Twins**

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Development Approach

In recent years, digital twins have evolved into a central concept of industrial digitalization (Deuter/Pethig 2019). Their fields of application span numerous industrial sectors: For example, digital twins are used in power generation to support maintenance planning for gas turbines and diesel generators. In the manufacturing industry, they track products throughout their entire lifecycle, from design to final assembly, and the technology is also applied in the automotive sector, for instance in vehicle design, where complex, networked systems are to be optimized (IBM 2021).

In practice, however, the successful implementation of digital twins poses a significant challenge for many companies. A key aspect is the acceptance of the technology: Since the daily work of end users will be affected by the accompanying changes in the long term, success depends largely on their willingness to actually use the technology. Apitzsch et al. therefore emphasize the importance of comprehensive training measures that go beyond purely technical qualifications and address the changes in employees' daily work routines (Apitzsch et al. 2020). Fett and Breimann also emphasize that a lack of knowledge not only complicates technical implementation but also leads to skepticism and unrealistic expectations regarding the technology (Fett/Breimann 2026).

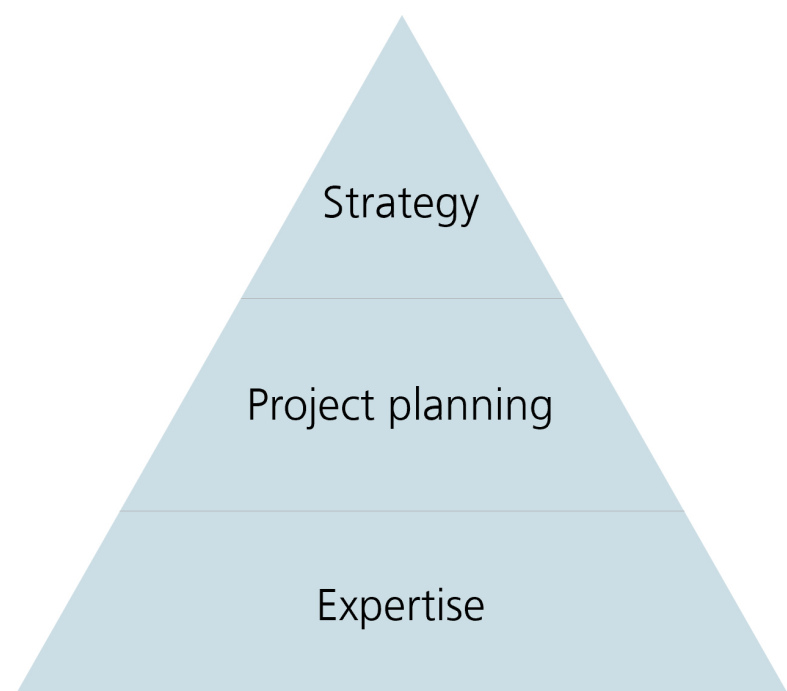


Figure 1: Competence Pyramid

Fraunhofer IPK's many years of project experience in supporting industrial digitalization initiatives show that the required knowledge varies considerably depending on the role and area of responsibility of those involved: While strategic decision-makers must primarily understand the business value a digital twin can generate, system architects need knowledge of how such a project is implemented conceptually and organizationally. Developers and IT specialists, on the other hand, face the task of technically implementing the twin and integrating it into existing infrastructures. A standardized training format cannot accommodate this heterogeneity.

Against this backdrop, Fraunhofer IPK developed a training concept that structures and specifically imparts role-specific knowledge on digital twins. This article describes the development process, the content and didactic design, as well as the key decisions that shaped the program.

Program Design: Three Perspectives on Digital Twins

To counteract the described knowledge gap and specifically empower different roles in the implementation of digital twins, the developed training program distinguishes three perspectives: the strategic, the architectural, and the technological dimensions. Since a standardized course format would not accommodate the heterogeneity of the target groups, each perspective was transformed into a standalone, role-specific course. The corresponding qualification profiles are presented below.

Digital Twins Business Consultant - Strategic Perspective

The strategic perspective aims to identify and realize the added value of digital twins for the company from a business perspective.

The course provides strategic knowledge on the implementation and design of digital twins within the company. It is aimed at individuals who have assumed technical or strategic responsibility for digital twins or plan to do so in the future. Business developers, decision-makers, and consultants who wish to acquire fundamental knowledge about the business potential and strategic approaches to implementation will benefit particularly. The content covers the strategic development and embedding of the digital twin concept within the company's value chain, as well as the creation of the necessary organizational and technical framework and the acceleration of the change process.

Upon completion of the course, the Digital Twins Business Consultant will be able to

- manage digital twin projects efficiently and in a future-proof manner,
- identify the value-creation potential of digital twins,
- understand the impacts and interactions on business models, product development, and services,
- systematically apply methods to identify business opportunities,
- assess technical and financial feasibility,
- establish a connection between different levels and business areas.

Digital Twins Solutions Architect - Architectural Perspective

The architectural perspective focuses on the concrete design: It translates strategic goals into a viable twin concept and its implementation, for example by defining use cases, value chains, governance structures, and the use of appropriate technologies and system architectures.

The course imparts architectural knowledge for the design and implementation of digital twins. It is aimed at operational managers and team leaders who wish to familiarize themselves with technologies and applications and gain a comprehensive overview of processes, methods, and tools for implementation. The content covers the architectural design of digital twin solutions, as well as the conception and evaluation of alternative solutions for digital assets in collaboration with top management and subject matter experts; the support and management of digital twin project implementation; and the integration of these solutions into the company's overall product or business context.

Upon completion of the course, the Digital Twin Solutions Architect will be able to

- manage digital twin projects efficiently and in a future-proof manner,
- to identify the value-creation potential of digital twins,
- plan and support the creation, integration, and operation of products and systems,
- systematically apply methods for describing and analyzing use cases in terms of architectural and technical implications,
- assess technical and financial feasibility,
- identify and quantify the necessary project prerequisites in terms of skills, personnel, technologies, and finances,
- establish a connection between different levels and business areas.

Digital Twins Technical Developer - Technological Perspective

The technological perspective focuses on the detailed design and implementation of the digital twin at the IT level. This includes designing the system and interface landscape, selecting and implementing databases, ensuring information security and data protection, and implementing interaction with other systems and users.

Digital Twin Technical Developers are product development engineers specializing in IT or IT professionals with a technical background. Compared to traditional, sometimes isolated software development projects, digital twin implementation projects involve extensive technical interactions with other disciplines (e.g., engineering, production, service), functional areas (e.g., control engineering, product data management), and competencies (human-machine interaction, digital factory, data science). In this context, Technical Developers design, implement, and develop holistic solutions. The course is aimed at technology specialists who wish to master the technological approach to create or integrate a digital twin solution tailored to their company's needs.

Upon completion of the course, the Digital Twin Technical Developer will be able to

- identify the underlying technologies and IT standards of Industry 4.0,
- identify the IT architectures, systems, and integration approaches used in product development, production, and service,
- take responsibility for the creation, integration, or operation of these systems and their interfaces,
- apply methods of industrial data science and simulation as well as underlying technologies,
- identify security requirements for digital twin IT solutions.

All three courses are specifically aimed at professionals in the fields of mechanical engineering, mobility solutions, computer and electronics manufacturing, medical technology, software development, IT system houses, as well as IT service and consulting firms. The common content structure of the courses is presented below.

A Role-Specific Training Program on Digital Twins

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Content Structure

All three courses are based on a similar content structure consisting of three module groups:

	Digital Twins Business Consultant	Digital Twins Solutions Architect	Digital Twins Technical Developer
Basics	Definitions, life cycle of products and digital twins		
	Application examples for digital twins		
	Overview of methodical twin development		
	Overview of capabilities for digital twins		
	Digital twins – Expert insights and industry perspectives		
Strategic Knowledge	Added value and different types of digital twins		
	Challenges and requirements when adopting digital twins		
	Methodic development of digital twins		
	Essential support technologies for enabling digital twins		
	Digital twins for sustainability		
Specific Knowledge	Change management at the organization level	Managing digital twin projects	Engineering IT and APIs
	Competencies and capabilities	Defining digital twin use cases	Clouds and edges
	Designing business models	Detailed consideration of the technologies	Data security and secure architectures
	Digital twins as part of smart products	Digital twin administration	Data analytics and AI
	Leading and measuring digital twin projects	IT-Systems and architecture	Databases
	Proof methods and progress	Data security and secure architectures	Semantics and ontologies
		Twin modeling and testing	Digital Factory
			Simulation and automation
			Extended Reality

Figure 2: Contents of the training program

The **basics** are intended to serve as the common starting point for all three courses. They provide a shared understanding of digital twins and establish the conceptual foundation for the subsequent in-depth modules. The integration of industry perspectives in this part of the program serves to link the foundational understanding with practical contexts from the very beginning. The fundamentals modules are part of every course, as they form the foundation for further learning and ensure that all participants have the necessary basic knowledge.

Strategic knowledge builds on the fundamentals and is an integral part of the Digital Twins Business Consultant and Digital Twins Solutions Architect tracks. Both roles require the ability to place digital twins within strategic, organizational, or architectural contexts. The modules cover the benefits, challenges, and prerequisites for implementing digital twins, as well as the necessary responsibilities and methods for managing digital twins throughout their entire lifecycle. This content is essential for making informed strategic decisions and successfully managing digital twin projects.

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The **specific knowledge** is what distinguishes the three courses from one another in terms of content. In the Business Consultant course, participants learn to apply management methods and tools for the strategic implementation of digital twins within the company. They gain insights into a model that examines both visible and invisible factors within the company and engage intensively with change management as the connecting element between technology and corporate culture.

The Architecture track teaches methods and technologies for planning and implementing digital twin projects. Participants learn how to integrate digital twins into existing system landscapes, design interfaces, and coordinate collaboration between different departments.

The technical track focuses on practical implementation. The course covers technological fundamentals, IT standards, security aspects, and innovative technologies such as artificial intelligence and the digital factory. Participants develop practical solutions for creating, implementing, and operating digital twins.

The content was developed by experts from Fraunhofer IPK who have many years of research and application experience in the field of digital twins. Industry experts were also consulted, contributing practical insights into selected topics and issues. The courses are deliberately designed as independent offerings – participants can enroll directly in the course relevant to their role.

This structure reflects the program's core principle: a shared conceptual foundation, supplemented by role-specific in-depth modules tailored to the specific tasks and responsibilities of the respective target group.

Didactic Concept

The courses are designed as online self-study modules and are provided in English on the ILIAS learning platform. Each course takes 5-8 hours to complete. Participants can work through the content flexibly in terms of time and location and tailor their learning progress to their individual needs. This makes it possible to integrate the training into their daily work routine without a fixed time commitment.

To ensure the quality of the self-study learning process and avoid a purely passive reception of the content, a varied mix of methods is employed. Key components include explanatory texts supplemented by interactive graphics. These are used particularly for complex topics and enable participants to actively explore the content and grasp it at their own pace. Instructional videos featuring experts from Fraunhofer IPK and industry delve deeper into selected topics, explain key concepts firsthand, and highlight different perspectives from research and practice. Quiz formats help learners assess their understanding after each section, identify knowledge gaps, and immediately reflect on their learning progress.

A formal certification exam has been deliberately omitted. Such an exam would entail structural requirements – such as standardized exam formats, defined evaluation criteria, and regulations for exam supervision – that are difficult to reconcile with the nature of a flexible self-study program. The program is aimed at experienced professionals for whom the acquisition of knowledge itself and its immediate applicability are the primary focus. The integrated quiz formats fulfill the function of monitoring learning progress in a manner appropriate to the format: they continuously accompany the learning process without overshadowing it with a final exam situation.

Outlook

This article has demonstrated how the observation of heterogeneous knowledge needs led to the development of a structured training program that specifically addresses strategic, architectural, and technological perspectives on digital twins through three role-specific courses. A shared conceptual foundation, supplemented by differentiated in-depth modules and a flexible self-study format, forms the basis for practical qualification.

At the same time, the program is intended as a starting point, not as a finished solution. Given the rapidly evolving nature of the digital twins field, the program is continuously reviewed and refined. Feedback from participants and new technical developments are systematically incorporated into future revisions. In this way, a training program is created that grows over the long term and supports companies in using digital twins effectively and in a value-adding manner in the future as well.



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Data-Driven Rotor Design – **Multi-Domain Decision Support for the Design of Electrical Machines**

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Increasing electrification in the automotive sector is driving a growing demand for compact, highly efficient electric motors. Achieving ambitious targets for power density, efficiency and installation space requires the optimization of both electrical and mechanical aspects of the motor. While electromagnetic performance is strongly influenced by the design of the rotor core, the mechanical performance of the rotor is primarily determined by the shaft-hub connection (see Figure 1) between the rotor shaft and laminated core.

For economic reasons, shaft-hub connections in electric motors are commonly realized as press-fit joints. Advances in electromagnetic performance and new operating conditions, such as regenerative braking, subject these connections to increasingly high mechanical loads. To ensure reliable torque transmission under such conditions, press-fit connections with larger interference are required. As a consequence, local plastic deformation may occur within the contact zone, necessitating a more complex elastic-plastic design approach. The design and verification of press-fit joints subjected to elastoplastic stresses are typically performed using numerical simulations based on the finite element method (FEM). Achieving an optimal balance between lightweight construction and structural integrity requires the evaluation of numerous design variants through an iterative simulation process.

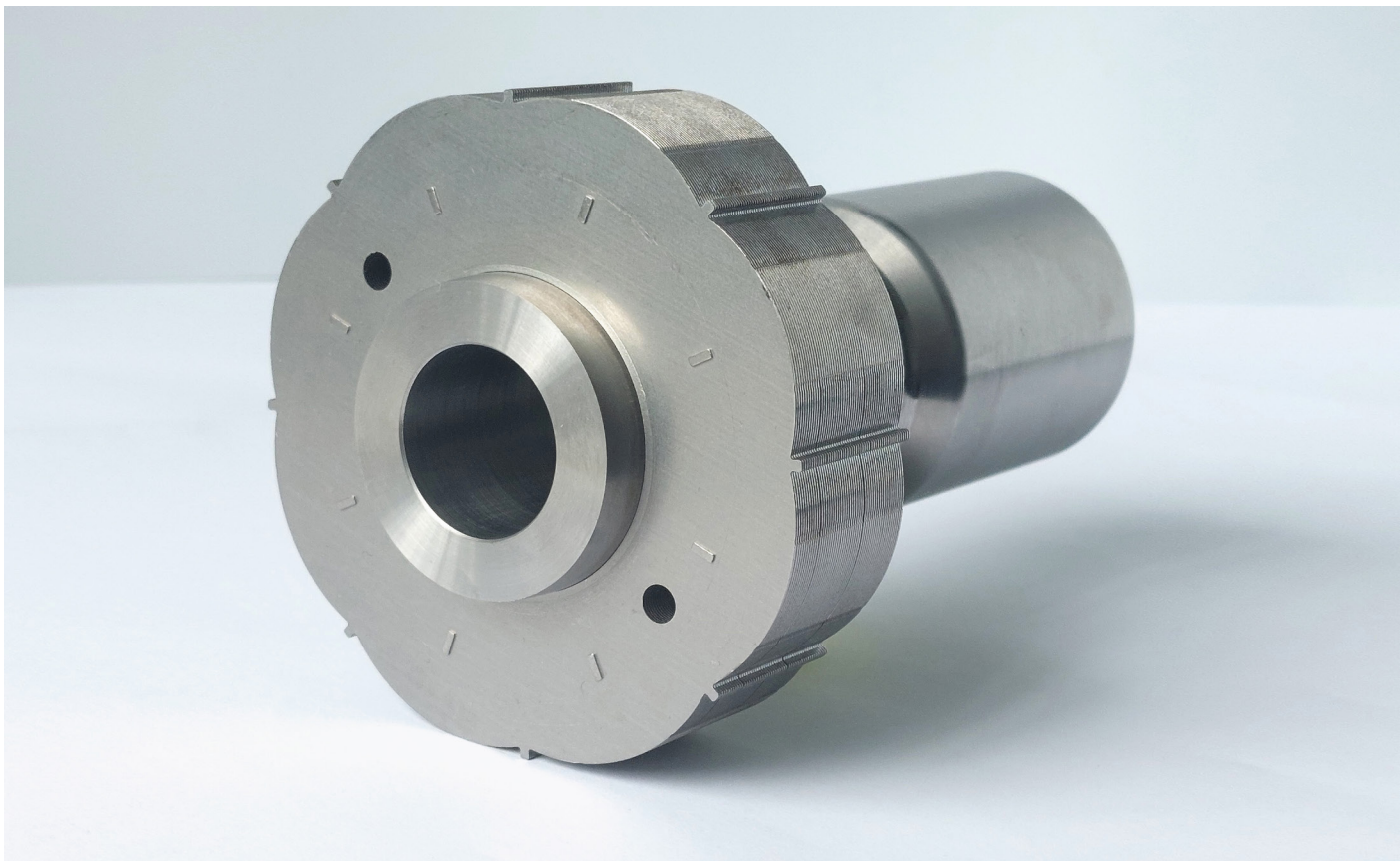


Figure 1: Press-fit as a shaft-hub connection between the rotor shaft and the laminated core

A larger interference fit results in increased contact pressure between the rotor shaft and the laminated core. While this contact pressure is required to ensure reliable torque transmission, it can adversely affect the electromagnetic properties of the laminated core. To date, the effects of mechanical stresses within the laminated core have been largely neglected or only considered to a limited extent in the design of electric machines. At the same time electromagnetic optimization measures influence the mechanical design of the press-fit joint. In particular, geometric features such as flux barriers in the electrical steel laminations affect the contact pressure distribution within the connection. Furthermore, optimizing the operating point of the electric motor toward higher rotational speeds while maintaining or increasing torque can lead to a reduction in contact pressure due to increased centrifugal forces. Both the design of the flux barriers and the assessment of the speed-dependent contact pressure losses require a large number of numerical simulations.

The design of electric motors is currently largely based on separate simulation workflows, in which the mechanical and the electromagnetic properties are independently optimized within their respective engineering domains. Due to the strong interdependencies between input parameters and performance objectives of both disciplines, numerous iterations between the involved engineering teams are required. So far, developers have limited systematic support for evaluating design alternatives and making informed decisions across domain boundaries. At the same time, the large volumes of data generated by numerous simulation iterations, combined with competing objectives, hinder efficient and robust decision-making. As a result, development costs increase, decision processes become less transparent and existing innovation potential may remain underutilized.

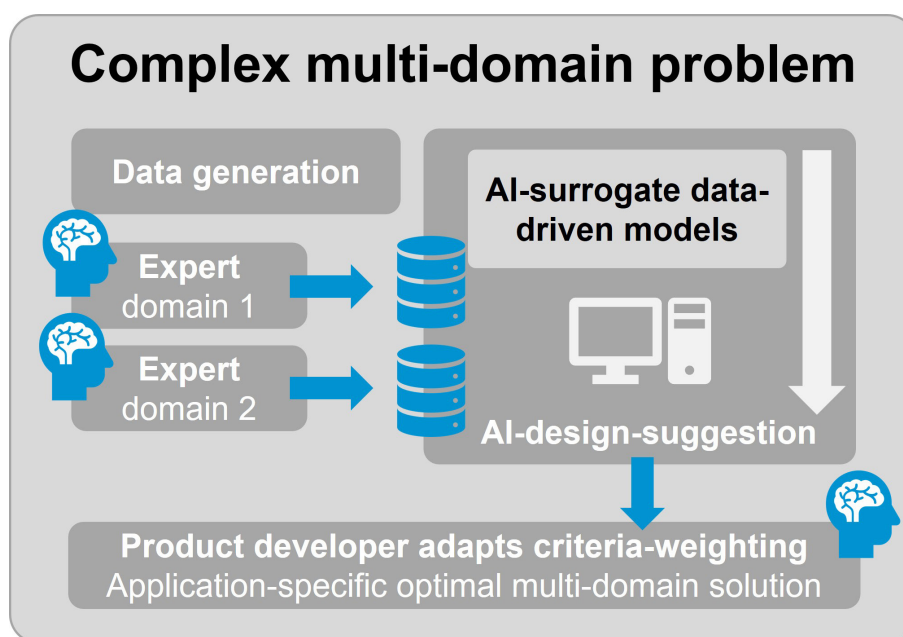


Figure 2: Schematic representation of the cross-domain, AI-driven product development process.

This is why at the University of Stuttgart the Institute for Engineering Design and Industrial Design, in collaboration with the Institute of Electrical Energy Conversion (iew), is conducting research on the multidisciplinary design of rotors for electrical machines. The long-term objective of the research project is to combine established engineering design methodologies, such as VDI 2221 and VDI 2225, with data-driven approaches of machine learning and artificial intelligence. The focus is on developing a holistic design methodology that simultaneously considers mechanical and electromagnetic design criteria and supports developers in their decision-making (see Figure 2). Initial cross-domain studies, in which the effects of various geometric parameters of the rotor shaft and laminated core on both mechanical and electromagnetic performance were analyzed using AI-based surrogate models, have yielded promising results. These findings highlight the potential of an integrated, data-driven design approach to reduce development effort and identify rotor designs that are optimized across multiple engineering disciplines.



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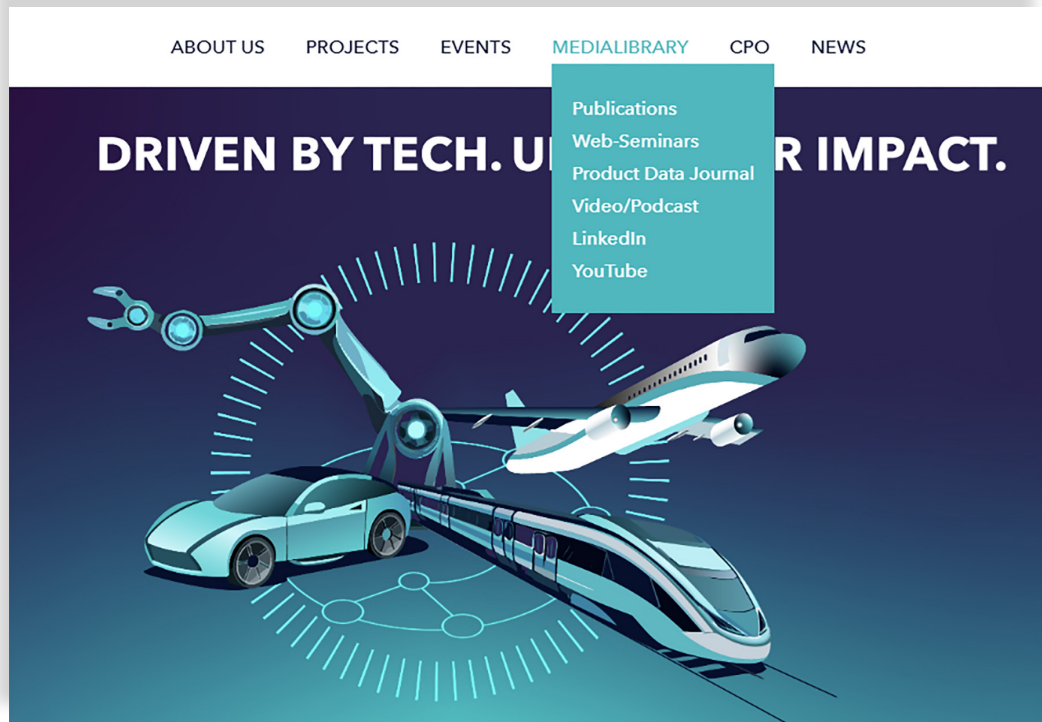
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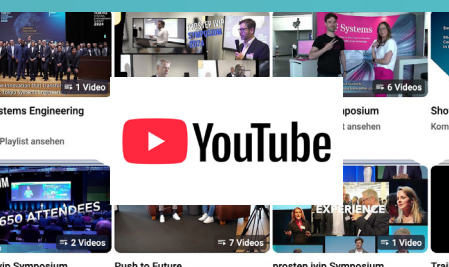
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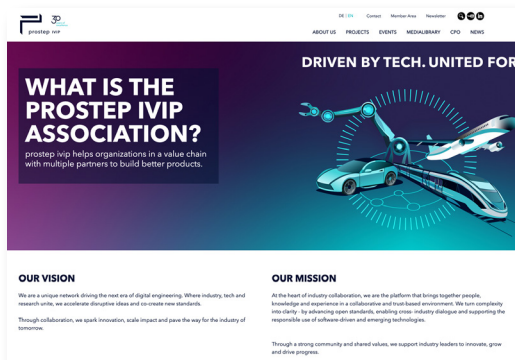
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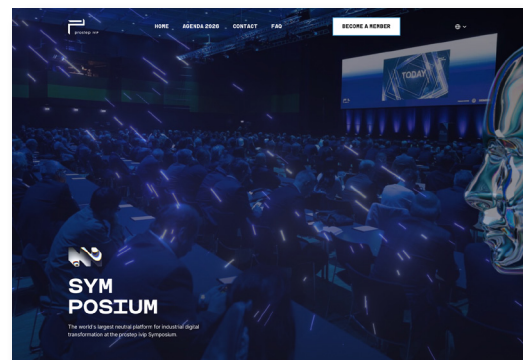
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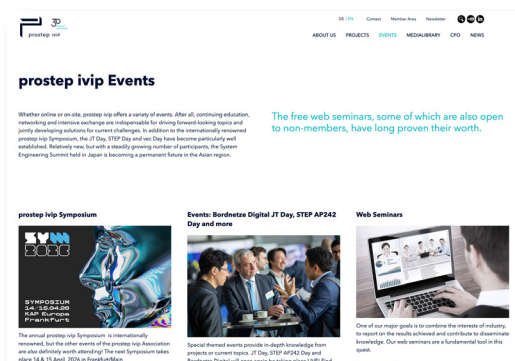
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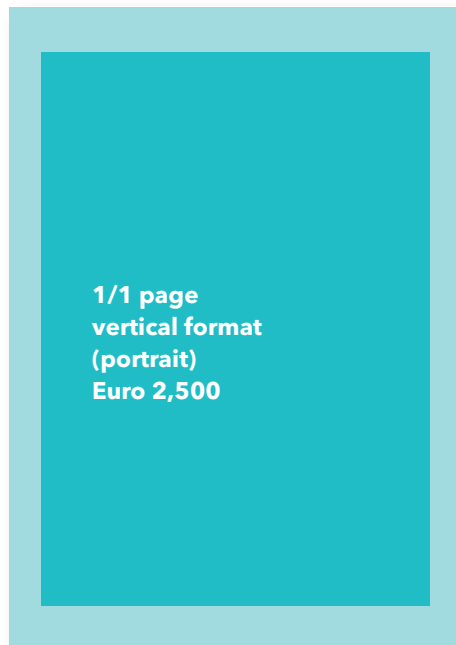
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General Information for Authors

To begin with...

Please submit an abstract of the article beforehand

Text/Article

- Reference value per page: 2,900 characters* + 1 graph
- Contact person's photograph
- Section New Members: 1,000 characters* + 1 graph
- Project Contributions: 12,000 characters* + 4 graphs
- Science & Research: 17,500 characters* + 5 graphs
- Industry expert articles: 12,000 characters* + 4 graphs
- Avoid product names in article titles and headlines
- Text formatting should be limited to title, introduction, subtitles, and enumerations
- Please include name of author, company/organization, title, phone and/or email address as contact information, gladly with a photo
- Please be sure to include an English version of the text right away
- Layout: proof-reading and editing possible for German as well as English version

*incl. blanks

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- Save text and photos/graphics separately
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For editorial reasons we reserve the right to publish your article in a later edition/issue.

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Do you have questions about prostep ivip? We're here to help!



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