Fraunhofer IPK

Industrial Metaverse

Strategic Foundations and Lifecycle Value for Industrial Transformation

Content

Executive Summary

Challenges and obstacles

Industrial value creation is continuously undergoing profound transformations. Global competition, supply-chain volatility, the accelerating shortage of skilled workers, and rising sustainability requirements are forcing companies to rethink how they develop products, operate factories, provide services, and collaborate with partners. At the same time, digitalization has matured to a point where companies operate complex IT landscapes, accumulate vast quantities of heterogeneous data, and increasingly rely on interconnected systems. Yet organizations still struggle to translate this potential into actionable value. Today, most workers and decision-makers interact with industrial data through fragmented systems, non-integrated interfaces, or isolated tools. Engineering simulations, IoT data, operational dashboards, and lifecycle documentation reside in separate environments that rarely communicate. As a result, collaboration is constrained, insights are lost, and decision-making remains slow or incomplete.

The industrial metaverse potential

The industrial metaverse addresses these challenges by creating a persistent, immersive, and data-rich environment in which digital twins, simulation models, real-time data, and human interaction converge. Current industrial applications primarily focus on internal use cases, where companies already achieve measurable improvements in efficiency, quality, and knowledge transfer. In the long term, however, the industrial metaverse extends far beyond internal optimization: its full value emerges when multiple companies can collaborate securely and sovereignly, sharing lifecycle data to enable new service offerings, accelerate innovation, and support circular-economy strategies.

The importance of strategy and collaboration

Realizing this potential requires not only technological maturity but also a clear strategic plan. Adopting the industrial metaverse is a long-term transformation that relies on robust data architectures, interoperable IT and OT systems, and new organizational capabilities. At the same time, companies must achieve tangible benefits early in the journey to justify investment and build internal momentum. Effective strategies therefore balance long-term architectural development with short- and mid-term use cases that deliver measurable value – such as XR-based training, immersive engineering reviews, virtual commissioning, among others.

Cross-company collaboration introduces additional challenges related to data sovereignty, identity management, and secure data exchange. Data spaces provide an emerging architectural foundation for addressing these requirements. They enable decentralized, policy-governed data sharing among partners while allowing each organization to retain full control over its own data. As industrial metaverse ecosystems evolve toward multi-stakeholder participation, data spaces offer the governance layer needed to ensure trust, interoperability, and scalability.

Fraunhofer IPK supporting this transformation

Fraunhofer IPK supports companies throughout this entire transformation. Using established technology roadmapping methods, Fraunhofer IPK helps define strategic goals, identify high-value use cases, and develop structured adoption pathways. Further support includes the conceptualization of industrial metaverse applications, the development of data-driven and service-oriented business models, the development of data-space architectures, prototypical realization of industrial metaverse applications, and systematic evaluation of their impact. Through this combination of systematic methods and technological expertise, Fraunhofer IPK enables companies to achieve the full potential of the industrial metaverse and build the foundation for resilient, future-oriented industrial ecosystems.

What the Industrial Metaverse Is

Evolution of an industrial paradigm

The concept of the metaverse gained popularity in consumer contexts, but the industrial metaverse emerges from different industrial needs: enabling more efficient and intuitive collaboration, closing the gap between planning and operation, responding to workforce shortages, and navigating increasingly complex supply chains. It would not have been able to emerge, however, if it weren't for many drivers: the growing availability of real-time data, the maturity of virtual and augmented reality, and the need for more flexible, sustainable industrial operations.

Over the past decade, companies have increasingly adopted digital twins, simulations, XR-based training, and IoT systems – but often as isolated solutions. The industrial metaverse integrates these technologies into a cohesive, persistent environment in which digital and physical realities converge. It provides a shared space for exploring, validating, and operating products, processes, and services, enriched by dynamic data and immersive interaction.

Core characteristics

Despite visionary depictions of fully interconnected industrial ecosystems, current industrial metaverse implementations are predominantly internal. Most companies begin with applications in training, engineering visualization, or production support, each operating within their own organizational boundaries. Even inside a single company, questions of data sovereignty, access control, and cross-department integration remain substantial challenges. Nevertheless, several characteristics define what the industrial metaverse is – and what it is evolving toward:

- **Immersive and persistent representations of industrial assets**: Organizations are building virtual replicas that respond to real-time data and support engineering reviews, operator assistance, or process analysis.

- **Convergence of data, models, and human interaction**: The industrial metaverse integrates operational data, simulation models, and intuitive interaction technologies such as XR. Achieving this requires substantial alignment across IT and OT systems, which many companies are still in the process of harmonizing.

- **Scalable integration with enterprise systems**: To become useful at scale, the industrial metaverse must interoperate with PLM, MES, ERP, and IoT platforms. This integration is a cornerstone of internal readiness and a prerequisite for any future cross-company collaboration.

- **Emerging frameworks for sovereignty and collaboration**: True multi-stakeholder industrial metaverse applications – where suppliers, OEMs, service providers, and recyclers collaborate in shared environments – are still rare. The architectural foundation for these future ecosystems lies in data spaces, which enable sovereign, controlled, and interoperable data exchange. These concepts are promising but not yet widely implemented, marking a transitional maturity level.

Most companies begin with applications in training, engineering visualization, or production support, each operating within their own organizational boundaries.

In this sense, the industrial metaverse is both a current set of technologies and a future vision: evolving from isolated implementations toward connected, data-sovereign ecosystems as organizational practices, technological infrastructures, and data-sharing frameworks mature.

Enabling technologies in context

The industrial metaverse is built on a multi-layer technological ecosystem: **Digital twins** form the dynamic core, synchronizing physical assets with their virtual counterparts. **Extended reality (VR/AR/MR)** establishes intuitive interfaces for immersive collaboration, training, and visualization. **Artificial intelligence** supports prediction, optimization, and automated decision-making. **IoT and cyber-physical systems** supply real-time operational data. Data spaces provide sovereign, decentralized mechanisms for sharing data among partners. Together, these technologies create a foundation for integrated, collaborative industrial value creation.

Value Creation Across the Product Lifecycle

The industrial metaverse generates value by connecting data, people, and processes across the entire lifecycle of a product – from development to production, through service, and ultimately into reuse or recycling.

Product development

In development, companies aim to accelerate innovation cycles, ensure manufacturability, and improve cross-functional collaboration. The industrial metaverse offers immersive environments in which digital twins become shared reference points for all stakeholders. Engineers evaluate product concepts in 3D, simulate feasibility, examine ergonomics, and anticipate integration challenges long before physical prototypes exist.

Through collaborative design reviews, for example, distributed teams can interact with the same digital model, enabling more alignment and faster decision-making. Early detection of design issues reduces rework and shortens time-to-market.

Production and manufacturing

Production environments benefit from virtual commissioning, immersive operator training, and continuous optimization. Entire production lines can be replicated virtually, enabling engineers to test control logic, simulate cycle times, and validate layout decisions before physical implementation.

Additionally, augmented reality assistance, for example, can provide operators with context-specific instructions, reducing errors and enhancing safety, while XR-based training environments help companies onboard new employees rapidly – a crucial advantage given widespread workforce shortages.

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Furthermore, integrating real-time data into digital twins allows for dynamic performance monitoring, supporting continuous improvement and bridging the gap between plan and operation.

Service and operation

In the operational phase, the industrial metaverse enhances asset management through predictive analytics, immersive diagnostics, and remote collaboration. Technicians can explore digital twins enriched with real-time sensor data, enabling more efficient troubleshooting. Service providers can guide field technicians remotely, overlaying instructions through AR to reduce travel time and improve problem resolution.

Customers may also have access to new insights through interactive performance dashboards, and companies can refine their service offerings based on real usage patterns, creating new opportunities for data-driven services and customer engagement.

End-of-life and circularity

As circular economy models gain importance, the industrial metaverse supports disassembly planning, material recovery, and decisions about reuse, refurbishment, or recycling. Through access to lifecycle data – ideally collected across organizations – stakeholders can evaluate material composition, component conditions, and safety considerations.

Digital transparency also enables second-life strategies, such as reuse of components or redeployment of partially consumed systems, reducing environmental impact and creating new value streams.

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Strategic Considerations for Industrial Adoption

Implementing the industrial metaverse is not a matter of acquiring a new technology – it represents a structural transformation in how companies design products, operate production systems, enable collaboration, and create value across the lifecycle. Such transformations naturally evolve over several years, touching multiple layers of an organization: data architectures, IT-OT-integration, process design, employee capabilities, and even the company's business logic. Because of this complexity, a clear strategic plan is indispensable. Without one, organizations risk investing in disconnected pilots that fail to scale or generate meaningful outcomes.

A clear strategic plan is essential to orchestrate data architectures, IT/OT integration, process design, workforce capabilities, and business logic.

A strategic plan must acknowledge that the journey toward the industrial metaverse has two distinct but interdependent horizons. The first horizon is long-term, where the company gradually builds an integrated ecosystem of digital twins, interoperable systems, sovereign data exchange, and immersive applications. These foundational changes take time, especially in organizations with heterogeneous systems and rigid processes.

However, the second horizon is short- and mid-term, and it is equally crucial. Companies cannot wait years before seeing results. A well-designed strategy ensures that the organization continuously realizes value along the way. This means identifying use cases that can deliver measurable impact early – such as XR-based training to address workforce shortages, virtual commissioning to reduce ramp-up time, or immersive engineering reviews that shorten development cycles. These initiatives provide »quick wins« that build trust, demonstrate tangible value, and create internal momentum for the transformation. In a mature strategy, these short-term applications are not isolated experiments; they are aligned with the long-term architecture, ensuring that every early step contributes to the final vision rather than becoming a silo.

Financial and organizational readiness also play a central role. The industrial metaverse requires investment in device infrastructure, data integration, secure networking, and high-fidelity digital models. It also requires alignment across departments that may have conflicting data-ownership rules or incompatible systems. Without a strategic approach that includes phased investments, ROI analysis, and shared objectives, companies risk inefficiencies, duplicated efforts, or underutilized technologies. A coherent roadmap mitigates these risks by determining where immersive interaction brings immediate efficiency, where data integration gradually offers benefits, and which areas require parallel modernization before more advanced applications can be developed.

One point that should be highlighted is that the industrial metaverse is not only about operational efficiency but also about new business opportunities. Organizations increasingly explore data-driven business models, such as predictive maintenance services, usage-based billing, or outcome-based contracts. In these contexts, the industrial metaverse acts as a unifying platform for customer collaboration, asset transparency, and shared decision-making. Furthermore, the industrial metaverse can generate opportunities for completely disruptive new business models.

A good strategy recognizes, integrates and potentializes new business models opportunities that use the industrial metaverse as their technological backbone.

A strong example is the development of innovative product-service systems (PSS), in which companies integrate products and services (or even offer products as a service) to deliver continuous, performance-based value. The industrial metaverse provides the technological backbone for enabling such models: digital twins enriched with operational data, immersive environments for customer engagement, predictive algorithms for service optimization, and augmented reality for efficient remote maintenance. When multiple stakeholders must exchange data, data spaces ensure sovereign and controlled collaboration, enabling PSS models to operate reliably.

In summary, a successful industrial metaverse strategy balances vision with pragmatism. It recognizes the scope of long-term transformation while ensuring that the company generates value throughout the journey. By defining a roadmap that integrates quick wins, mid-term expansions, and long-term architectural development, companies can evolve steadily toward a future of interconnected, data-driven, and immersive industrial ecosystems while continuously improving their operations and strengthening their market position.

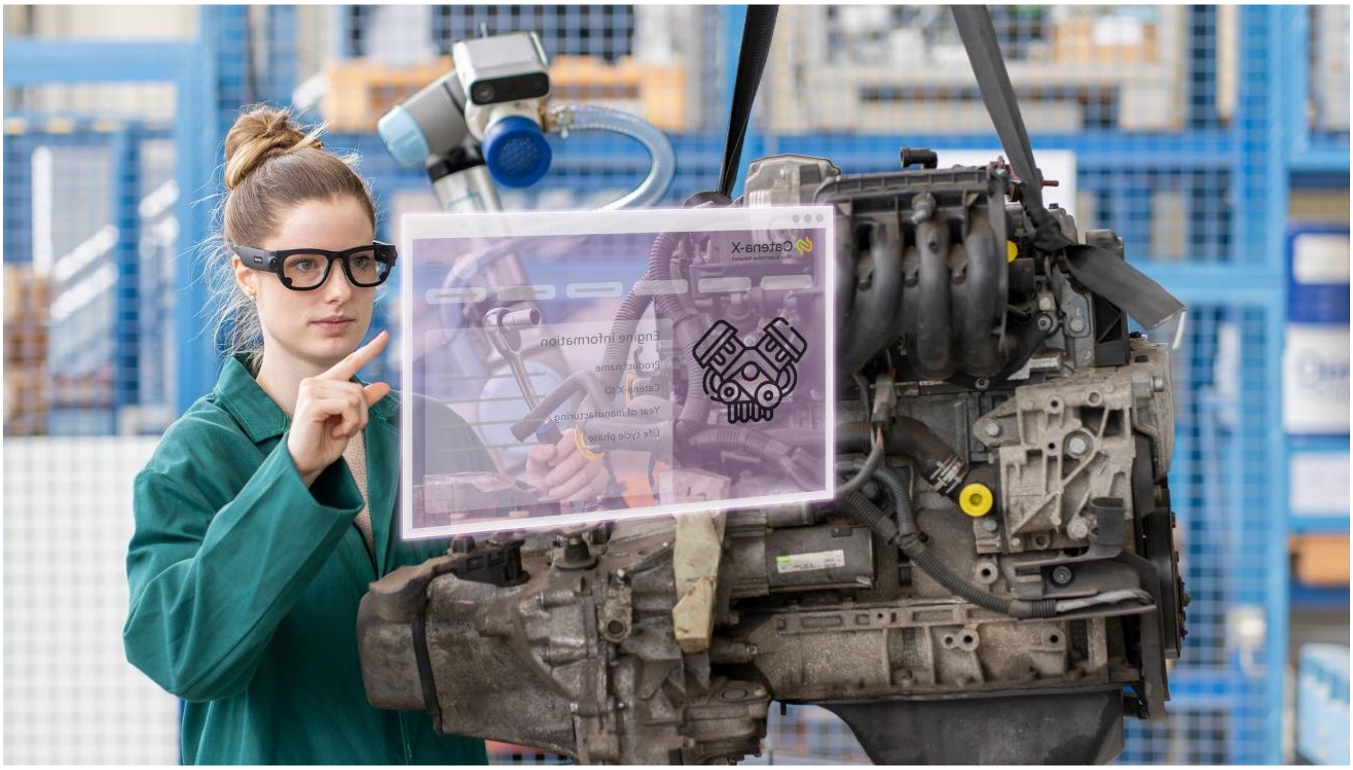
Furthermore, a good strategy recognizes, integrates and potentializes new business models opportunities and strategies that use the industrial metaverse as their technological backbone, ensuring return on investment and new revenue sources.

Data Sharing and the Role of Data Spaces

Although current industrial metaverse implementations concentrate primarily on internal applications, the most transformative potential arises when data flows across organizational boundaries. Industrial value creation is inherently distributed: suppliers possess component information, OEMs hold engineering and manufacturing expertise, operators generate real-time usage data, and recyclers understand material composition and end-of-life conditions. No single organization sees the entire lifecycle. As a result, even highly advanced digital twins remain partial and limited if built exclusively on internal data.

Yet enabling cross-company data sharing is significantly more complex than extending existing internal IT systems. Each participating organization must protect intellectual property, ensure compliance with industry regulations, and maintain control over sensitive information. Even inside a single company, issues such as inconsistent governance practices, unclear data ownership, and incompatible system architectures create friction. When collaboration extends beyond company walls, these challenges become magnified. Identity management becomes more complex. Data sovereignty becomes a central requirement, ensuring that partners can define and enforce how their data may be accessed, processed, or combined. Safe data exchange – protected against misuse, unauthorized replication, or unintended inferences – becomes not just a technical challenge but a prerequisite for trust.

This is why decentralized data spaces may be an architectural foundation for the future industrial metaverse. While not yet widely deployed or mandatory, data spaces offer the strongest available approach for enabling secure, sovereign, and scalable data collaboration among multiple organizations. Instead of centralizing data in a single repository, data spaces allow each



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participant to retain control, storing information within their own infrastructure while exposing only the portions necessary for specific use cases. Policies governing usage rights are embedded directly into the data-exchange mechanisms, ensuring compliance and transparency. Identity and access management systems incorporated into data spaces provide a robust security layer that verifies actors, enforces permissions, and prevents unauthorized access.

As industrial organizations mature in their internal digital capabilities – connecting digital twins with real-time operational data, deploying immersive training, or enabling collaborative engineering – the limitations of isolated environments become increasingly evident. The industrial metaverse, when confined to a single enterprise, can optimize internal operations but cannot fully support lifecycle transparency, cross-company innovation, or new service-oriented business models. Data spaces fill this gap. They allow digital twins to incorporate multi-source data, enable service ecosystems that depend on shared operational insights, and support collaborative simulations across suppliers, OEMs, partners, and customers.

In this sense, data spaces form the governance and security backbone of future industrial metaverse ecosystems. They address not only interoperability but also the heightened security needs that arise when collaboration extends beyond organizational boundaries. Although still in an early stage of adoption, data spaces represent the most robust pathway for enabling trustworthy, sovereign collaboration at scale. Companies that prepare for this architectural shift today will be positioned to participate confidently in the next generation of networked industrial value creation – where secure data exchange and cross-company visibility enable innovation, sustainability, and competitiveness.

The most transformative potential (of the industrial metaverse) arises when data flows across organizational boundaries.

Industrial Metaverse with Fraunhofer IPK

For successfully implementing the industrial metaverse, companies should align technological possibilities, organizational structures, business priorities, and long-term strategic ambitions. Fraunhofer IPK supports companies through this entire journey, providing not only technical expertise but also methodological guidance, practical experience, and a deep understanding of industrial processes. Our support spans from the early clarification of strategic goals to the implementation of solutions and the evaluation of their impact in real environments.

A central component of our approach is the **development of strategic roadmaps**, which defines the step-to-step approach that the company should follow for adopting the industrial metaverse. These roadmaps are built using Fraunhofer's technology roadmap methodology, ensuring that technological decisions, organizational change, and long-term architectural goals evolve coherently. Our strategic focus aims at laying the foundations for a robust, integrated industrial metaverse in the future, while simultaneously identifying early use cases that deliver tangible value. This balance allows companies to achieve measurable benefits at every stage of the journey, creating continuous justification for investment and building the basis for broader transformation. By ensuring that short- and mid-term initiatives contribute directly to the long-term vision, the roadmap avoids fragmented pilots and enables a controlled, scalable evolution.

Equally important is the **conceptualization of industrial metaverse applications** that address real operational challenges and deliver tangible value. Fraunhofer IPK works closely with industrial partners to analyze the company's context, identify bottlenecks, and translate them into solution concepts combining immersive technologies, digital twins, real-time data, and advanced interaction methods. These concepts are always tailored to the company's specific context – whether in engineering, production, service, or end-of-life processes – and are designed to integrate seamlessly into existing systems and future architectures.

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Beyond technology, Fraunhofer IPK also supports companies in **shaping the business models that the industrial metaverse enables**. The evolution from traditional product sales to data-driven or performance-based offerings requires new ways of thinking about value creation, customer engagement, and lifecycle management. We assist organizations in identifying opportunities for product-service systems that can be enabled by the industrial metaverse, defining value propositions based on digital transparency, and exploring how continuous data exchange can enable new revenue streams. In many cases, this involves not only rethinking services but also establishing the mechanisms that allow them to operate reliably across organizational boundaries.

If the company aims at exploring the full potential of industrial metaverse by working collaboratively beyond its walls, Fraunhofer IPK's expertise in the **conceptualization and creation of data spaces** can provide the architectural foundation for sovereign and secure cross-company data collaboration. Fraunhofer supports the development of semantic models, and the integration of connectors and identity-management solutions. This ensures that the resulting architecture is robust, scalable, and aligned with the company's strategic and operational needs.

Once strategic foundations and conceptual designs are in place, Fraunhofer IPK accompanies companies in the **prototypical implementation of industrial metaverse solutions**. This may include developing immersive training applications, collaborative engineering environments, digital twins with real-time data integration, tools for supporting the end-of-life, among others. These prototypes allow companies to validate concepts quickly, generate early value, and prepare the organization for broader adoption, while providing a practical environment in which technical challenges, user expectations, and operational constraints can be identified and addressed early.

Finally, Fraunhofer IPK provides **structured impact evaluation**, helping companies measure the effectiveness of their initiatives using clear KPIs. This includes assessing productivity improvements, analyzing return on investment, evaluating scalability, and identifying conditions for successful rollout.

The evolution from traditional product sales to data-driven or performance-based offerings requires new ways of thinking about value creation, customer engagement, and lifecycle management.

Through this systematic evaluation, companies gain the confidence needed to expand successful prototypes into full-scale solutions and ensure that their industrial metaverse transformation generates sustained benefits.

In all these areas, Fraunhofer IPK acts as a trusted partner – combining methodological rigor, technological excellence, and a deep understanding of industrial practice. By aligning organizational strategy, technological development, and measurable outcomes, we help companies achieve the full potential of the industrial metaverse and build the foundations for future-ready, interconnected industrial ecosystems.

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Fraunhofer Institute for Production Systems and Design Technology IPK

Authors
Kutay Yinanc
Dr. Maiara Rosa Cencic
Dr. Kai Lindow

Publisher
Dr. Kai Lindow

Fraunhofer Institute for Production Systems
and Design Technology IPK
Pascalstraße 8–9
10587 Berlin

Tel: +49 30 39006-0
Fax: +49 30 39110-37

info@ipk.fraunhofer.de
www.ipk.fraunhofer.de

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Contact

Kutay Yinanc
Virtual Product Creation division
Tel. +49 30 39006-298
kutay.yinanc@ipk.fraunhofer.de

Dr. Maiara Rosa Cencic
Virtual Product Creation division
Tel. +49 30 39006-417
maiara.rosa.cencic@ipk.fraunhofer.de

Dr. Kai Lindow
Virtual Product Creation division
Tel. +49 30 39006-214
kai.lindow@ipk.fraunhofer.de

Fraunhofer Institute for Production Systems
and Design Technology IPK
Pascalstr. 8–9
10587 Berlin
www.ipk.fraunhofer.de