INCLUDES NEW AFTERWORD
Updated for 2024

MIT Technology Review Insights

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SIEMENS

An interface between the real and digital worlds will transform how we work, live, and interact

The emergent industrial metaverse

Preface

"The emergent industrial metaverse" is an MIT Technology Review Insights report sponsored by Siemens. The report was produced through interviews with technologists, industry analysts, and academics worldwide, conducted in September and October 2022. It examines the emergence of the industrial metaverse, its use cases and future challenges and opportunities, and the impacts it will have on both businesses and everyday life. Cindy Waxer authored this report, Teresa Elsey edited it, and Nicola Crepaldi was the publisher. The research is editorially independent, and the views expressed are those of MIT Technology Review Insights.

The afterword, written by Siemens, was added in March 2024.

We would like to thank the following individuals for their time and insights:

Douglas Bellin, Global Lead of Business Development, Smart Factories, AWS

Veronika Bienert, Chief Executive Officer, Siemens Financial Services

Mike Campbell, Chief Product Officer, Bentley Systems

Ian Fisher, Head of Product Management Visualization, Siemens Digital Industries Software

Michael Grieves, Executive Director and Chief Scientist, Digital Twin Institute

Annika Hauptvogel, Head of Technology and Innovation Management, Siemens

Stefan Kögl, General Manager, Siemensstadt Square

Selim Köklü, Digitalization Lead, Siemens Mobility Turnkey

Peter Körte, Chief Technology and Strategy Officer, Siemens

Danny Lange, Senior Vice President, Artificial Intelligence, Unity Technologies

Rev Lebaredian, Vice President of Omniverse and Simulation Technology, NVIDIA

Kevin O'Donovan, Co-Chair, VR/AR Association, Industrial Metaverse & Digital Twin Committee

Hemdat Sagi, Chief Strategy and Business Development Officer, Konnect Volkswagen Group

Leslie Shannon, Head of Trend and Innovation Scouting, Nokia

Landry Signe, Executive Director and Professor, Thunderbird School of Global Management, and Senior Fellow, Brookings Institution

Marshall Van Alstyne, Digital Fellow, MIT Initiative on the Digital Economy, and Questrom Chair, Boston University

Matthias Ziegler, Managing Director, Technology Innovation, Accenture

CONTENTS

Foreword

Today, our lives and our future are being shaped by a few powerful megatrends. We need to protect the very foundations of our civilization, reduce emissions, and decrease the consumption of precious resources – while at the same time enabling new opportunities for a growing world population and a better life in ever-larger cities and metropolises. This creates a paradoxical challenge: We must literally create more, while using fewer resources. And we must do this while the political and economic world order is undergoing enormous change.

Luckily, another megatrend can help us meet and shape these challenges: digitalization. And with a view to the future of our economy and society, this means, above all, the industrial metaverse.

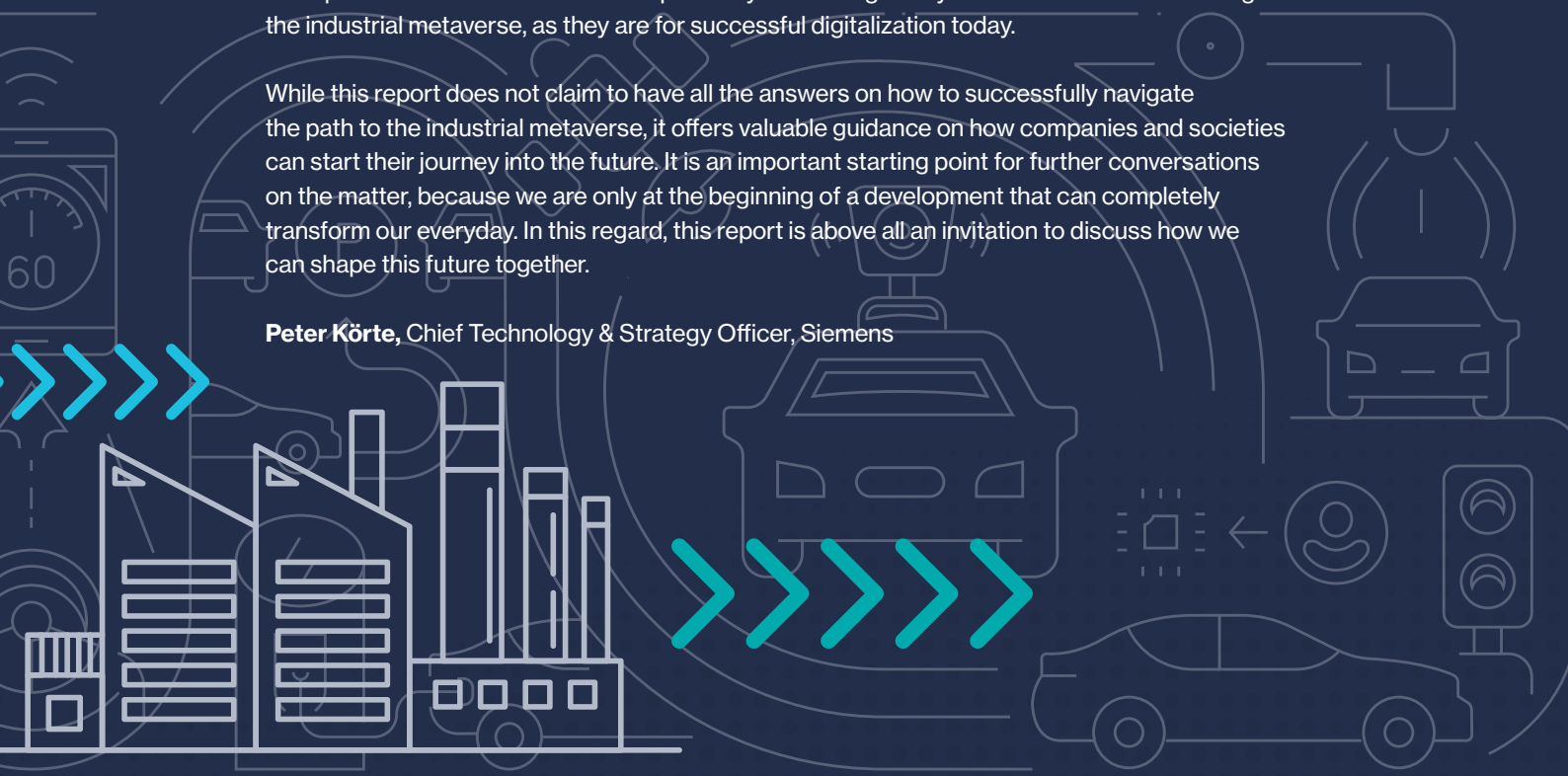
While many people associate the term "metaverse" with a colorful virtual world for entertainment and shopping, the industrial metaverse has the potential to revolutionize the real world in ways that few technologies can. In this digital world, machines, factories, buildings, cities, vehicles, and entire traffic systems can be mirrored and simulated, enabling virtual testing that conserves resources. The industrial metaverse will help develop sustainable products, as well as more efficient and sustainable factories, buildings, and cities. It will enable the democratization of engineering, allowing everyone to innovate without fearing risks or high additional costs.

By merging digital twins with their real-world counterparts, companies can optimize production and processes in a continuous feedback loop. This convergence of digital and real worlds will change the way we work and collaborate, enabling real-time interaction with other people and machines, just like in the real world.

This report provides an in-depth exploration of the industrial metaverse, explaining how it will emerge as an evolution and convergence of today's technologies, such as digital twins, artificial intelligence, and cloud and edge computing. It outlines the challenges and decisions societies and businesses face in making this vision a reality and creating a truly sustainable and open industrial metaverse. Interoperability and strong ecosystems are crucial for building the industrial metaverse, as they are for successful digitalization today.

While this report does not claim to have all the answers on how to successfully navigate the path to the industrial metaverse, it offers valuable guidance on how companies and societies can start their journey into the future. It is an important starting point for further conversations on the matter, because we are only at the beginning of a development that can completely transform our everyday. In this regard, this report is above all an invitation to discuss how we can shape this future together.

Peter Körte, Chief Technology & Strategy Officer, Siemens



01 Executive Summary

The industrial metaverse – a metaverse sector that mirrors and simulates real machines, factories, cities, transportation networks, and other highly complex systems – will offer to its participants fully immersive, real-time, interactive, persistent, and synchronous representations and simulations of the real world.

Existing and developing technologies, including digital twins, artificial intelligence and machine learning, extended reality, blockchain, and cloud and edge computing, will be the building blocks of the industrial metaverse. These will converge to create a powerful interface between the real and the digital world that is greater than the sum of its individual parts.

Annika Hauptvogel, head of technology and innovation management at Siemens, describes the industrial metaverse as "immersive, making users feel as if they're in a real environment; collaborative in real-time; open enough for different applications to seamlessly interact; and trusted by the individuals and businesses that participate" – far more than simply a digital world.

The industrial metaverse will revolutionize the way work is done, but it will also unlock significant new value for business and societies. By allowing businesses to model, prototype, and test dozens, hundreds, or millions of design iterations in real time and in an immersive, physics-based environment before committing physical and human resources to a project, industrial metaverse tools will usher in a new era of solving real-world problems digitally.

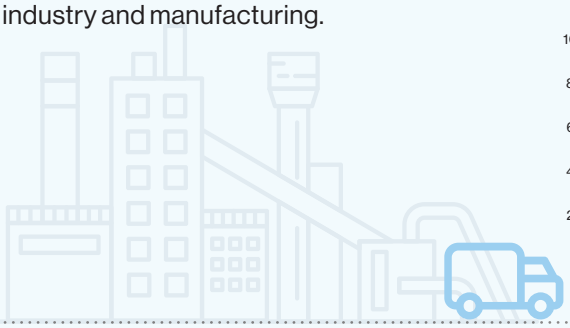
"The real world is very messy, noisy, and sometimes hard to really understand," says Danny Lange, senior vice president of artificial intelligence at Unity Technologies, a leading platform for creating and growing real-time 3-D content. "The idea of the industrial metaverse is to create a cleaner connection between the real world and the virtual world, because the virtual world is so much easier and cheaper to work with."

Metaverse sectors

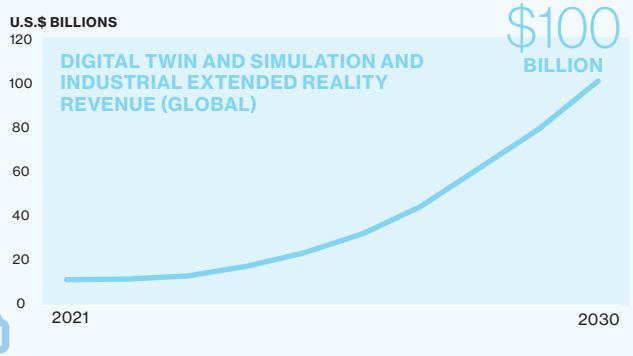
Although the metaverse is often represented as a single, all-encompassing digital world, it can be divided into three distinct sectors, the industrial metaverse, the enterprise metaverse, and the consumer metaverse. The pace at which each of these sectors will evolve is uncertain, but all analyses project rapid growth for the industrial metaverse and its enabling technologies in this decade.

Industrial

Simulated machines, factories, transport networks, and other complex systems, enabling real-world problem solving in industry and manufacturing.

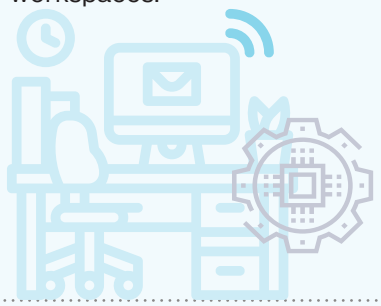


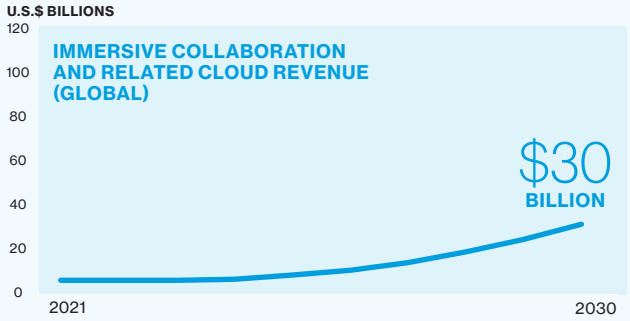
MARKET PROJECTIONS (ABI RESEARCH)



Enterprise

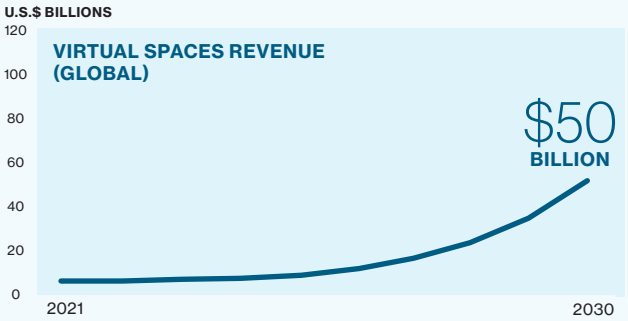
Technologies enabling immersive business collaboration, including productivity tools and virtual workspaces.





Consumer

Digital worlds and immersive spaces for shopping, gaming, socializing, and entertainment.



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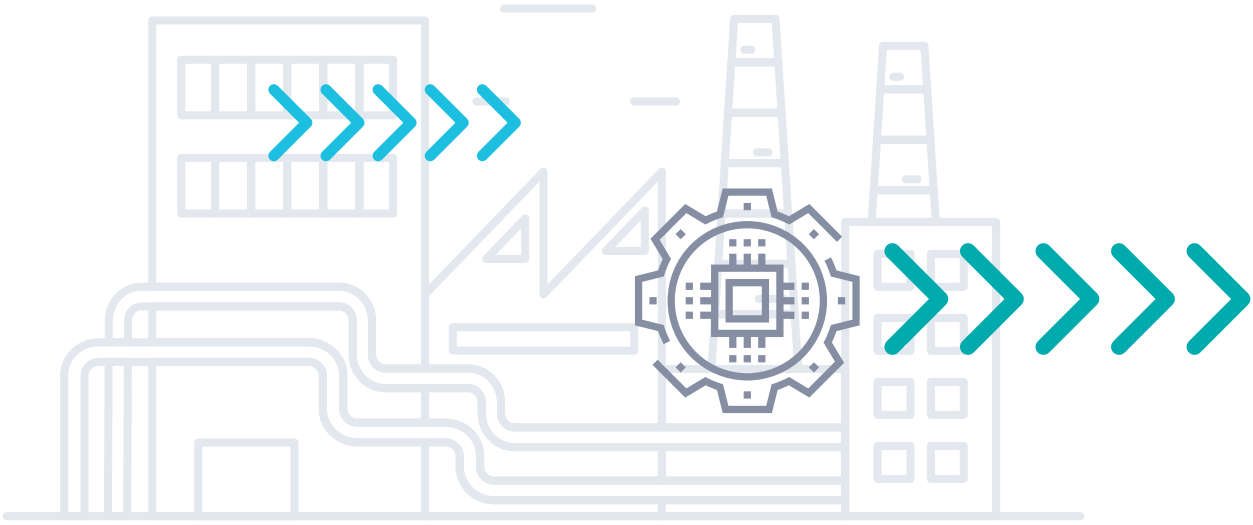


While real-life applications of the consumer metaverse are still developing, industrial metaverse use cases are purpose-driven, well aligned with real-world problems and business imperatives. The resource efficiencies enabled by industrial metaverse solutions may increase business competitiveness while also continually driving progress toward the sustainability, resilience, decarbonization, and dematerialization goals that are essential to human flourishing.

This report explores what it will take to create the industrial metaverse, its potential impacts on business and society, the challenges ahead, and innovative use cases that will shape the future. Its key findings are as follows:

- **The industrial metaverse will bring together the digital and real worlds.** It will enable a constant exchange of information, data, and decisions and empower industries to solve extraordinarily complex real-world problems digitally, changing how organizations operate and unlocking significant societal benefits.

- **The digital twin is a core metaverse building block.** These virtual models simulate real-world objects in detail. The next generation of digital twins will be photorealistic, physics-based, AI-enabled, and linked in metaverse ecosystems.

- **The industrial metaverse will transform every industry.** Currently existing digital twins illustrate the power and potential of the industrial metaverse to revolutionize design and engineering, testing, operations, and training.

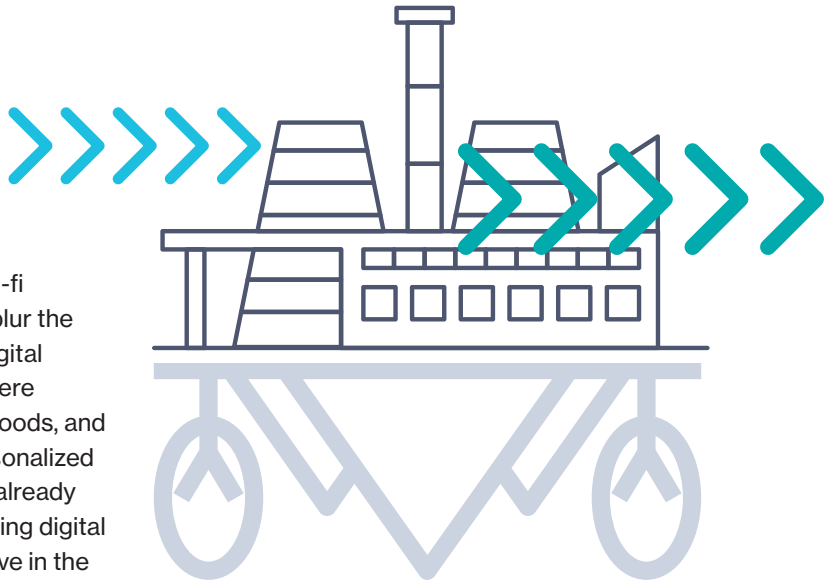
- **Everyday life will be radically changed.** The industrial metaverse will change how we can experience the physical environment and how we work, live, manufacture goods, and travel. It will help us solve real problems and make our world more sustainable.

- **Key capabilities and ecosystems that will enable the metaverse are still emerging.** These include connectivity, computational power, digital twin fidelity, interoperability, and privacy and security. Marketplaces, payment systems, and regulatory frameworks for metaverse tools and applications will have to be designed and built.

- **Partnerships will be essential.** Bringing the industrial metaverse to life will require substantial cross-industry collaborations on standards and infrastructure. Organizations may partner with suppliers, competitors, or customers to assemble the complex technology stacks undergirding metaverse participation. Metaverse players ranging from established companies to startups and from governments to individual enthusiasts will bring new ideas and voices into the industrial metaverse.

02

Industry's next chapter: The metaverse



As if plucked from the pages of a sci-fi novel, the metaverse promises to blur the boundary between physical and digital spaces, creating a digital world where people can meet up, buy and sell goods, and attend events in a hyper-immersive, hyper-personalized environment. Some aspects of this metaverse already exist – think of the legions of teenagers traversing digital worlds in the video game Fortnite. Others still live in the province of imagination – Landry Signe, executive director and professor at the Thunderbird School of Global Management and a senior fellow at the Brookings Institution, invokes "a network of interconnected virtual worlds using a three-dimensional platform. Humans will interact with digital content and with each other to form an ecosystem, in a fusion of technology that blurs the frontier between the physical, the biological, and the digital world."

But the arguably greatest potential for these immersive, interactive spaces lies in the industrial metaverse. An integration of existing technologies – including high-fidelity simulations, extended reality, artificial intelligence, machine learning, the Internet of Things, blockchain, cloud, and 5G/6G – with those being further developed, the industrial metaverse will offer fully immersive real-time and synchronous representations of the real world.

> "Humans will interact with digital content and with each other to form an ecosystem, in a fusion of technology that blurs the frontier between the physical, the biological, and the digital world."
>
> Landry Signe, Executive Director, Thunderbird School of Global Management

"In the same way the mobile phone revolution changed how we consume media, the metaverse will change how we interact with the real and virtual world."

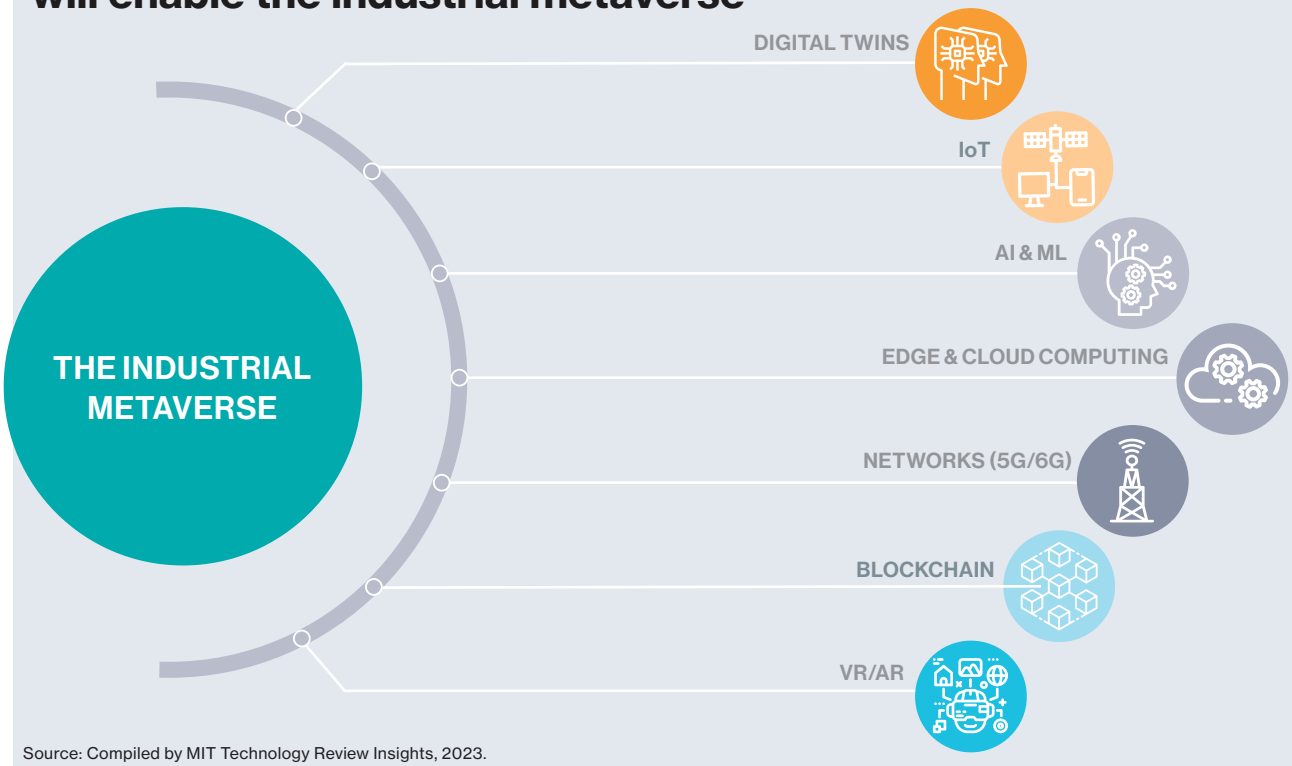
Hemdat Sagi, Chief Strategy and Business Development Officer, Konnect Volkswagen Group Innovation Hub

Analysts define the scope of this emerging market differently, but they all project rapidly growing investment in digital twin technology, a key metaverse building block. The global digital twin market was estimated at $6.5 billion in 2021 and is expected to reach $125.7 billion by 2030, according to Allied Market Research.[1] Gartner offers a similar projection, expecting the digital twin market to grow to $183 billion by 2031,[2] and notes that VC investment in digital twin startups increased 20% from 2020 to 2021.[3]

In many ways, the industrial metaverse heralds the next step in a decades-long journey toward industrial digitalization, or Industry 4.0 – the fourth industrial revolution, in which physics-based, data-driven, and autonomous systems are integrated throughout production facilities and embedded in key processes, for greater speed and agility.

"In the same way the mobile phone revolution changed how we consume media, the metaverse will change how we interact with the real and virtual world," says Hemdat Sagi, chief strategy and business development officer at Konnect Volkswagen Group Innovation Hub in Tel Aviv. "On an industrial level, this will allow for more flexibility to integrate new technologies and innovation."

Evolution and convergence of key technologies will enable the industrial metaverse



Source: Compiled by MIT Technology Review Insights, 2023.

03 The industrial metaverse in action: Use cases

The industrial metaverse will significantly transform today's highly competitive marketplace. By mirroring and simulating real machines, factories, cities, and other complex systems in the digital world, it will empower industries, from automotive to health care, to solve extraordinarily complex real-world problems digitally.

This new phase of digitalization will enable virtual sensors that predict equipment failures, autonomous trucks that improve logistics, collaborative robots that boost productivity, and sophisticated supply chain optimizations. Its reach will extend far beyond the development of products and the maintenance of machinery to facilitating collaboration of stakeholders from anywhere and creating new insights for product design and manufacturing. "You can find a use case anywhere in the industrial life cycle and make it better with industrial metaverse," says Ian Fisher, head of product management visualization for Siemens Digital Industries Software.

An impressive array of application areas for the industrial metaverse are emerging. Many of the new capabilities enabled will be relevant for a wide variety of industries, from manufacturing and transportation to utilities and urban development. Here are just a few examples of metaverse use cases for industry:

Improved design and engineering: Team members from disparate departments, locations, and even industries will be able to interface with clients, design new products, and gain real-time insight in a collaborative setting, without the need for time-consuming, costly, and resource-intensive travel or multiple physical prototype developments. Moreover, the industrial metaverse levels the playing field by allowing distributed teams across disciplines to contribute equally to a project, enabling everyone to become an innovator without the risks and costs associated with real-world mishaps.

More extensive testing and validation: By combining photorealistic environments with multi-physics simulations, industries can test a wide range and number

"You can find a use case anywhere in the industrial life cycle and make it better with industrial metaverse."

Ian Fisher, Head of Product Management Visualization, Siemens Digital Industries Software

of scenarios while training and enabling autonomous systems through machine learning and synthetic data. This might result in faster development of a new product, a more efficient design of new facilities, or an early integration of circular economy principles into designs.

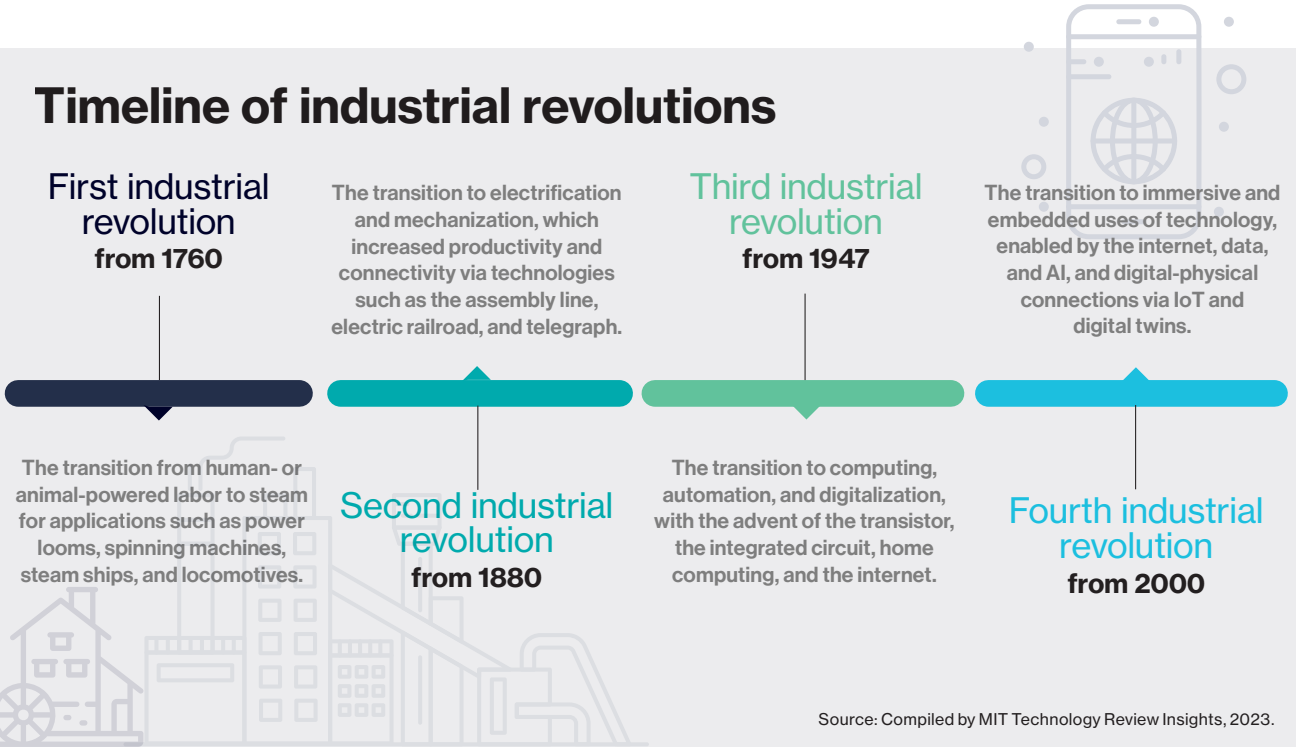
Virtual commissioning: Using a virtual model of a manufacturing system can build resiliency, helping to detect and correct early errors in the design and software without disrupting ongoing production lines or wasting physical resources.

Enhanced operations: By simulating a factory or other workplace, team members can collect data in a digital world – information that can be used to support a wide range of AI-enabled use cases, such as virtual factory planning, autonomous robots, predictive maintenance, and big data analytics. Furthermore, immersive real-time representations will support frontline workers and improve the efficiency of their real-world operations.

Access to talent and training: In today's tight labor market, organizations can't afford to lose talent due to a lack of access to training and career development. The good news is that "the opportunities offered by the metaverse to uplift skills and to provide training are quite unique," says Signe. That's because the metaverse can offer employees remote access to expert skills and virtual training modules regardless of their physical locale. In the future, these technologies may help ease labor shortages in an aging society.

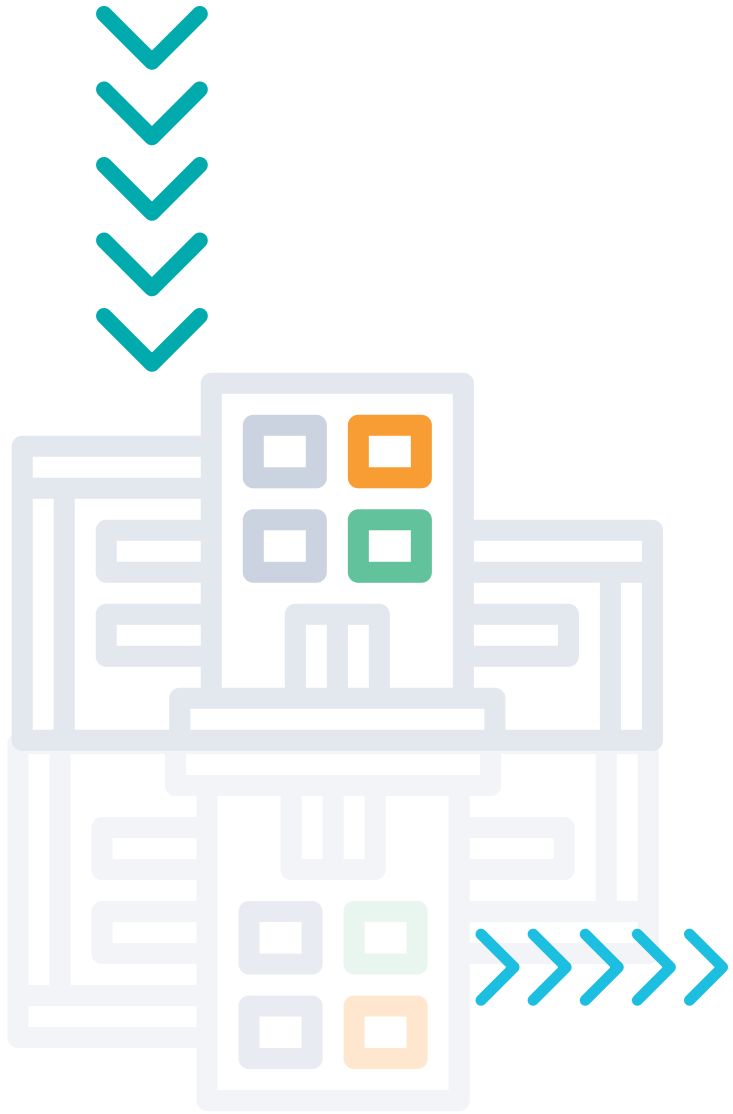
In the industrial metaverse, next-generation digital twins will represent everything from whole manufacturing plants and transportation networks to growing cities and highly complex human systems. By interconnecting the physical and digital worlds, the industrial metaverse will not only change how organizations operate and employees work but will also unlock significant benefits for society in ways that drive sustainability and enhance human life.

Timeline of industrial revolutions



Source: Compiled by MIT Technology Review Insights, 2023.

04 Industrial metaverse building blocks: The digital twin



At the core of the industrial metaverse will be the digital twin – a virtual model designed to accurately reflect a real-world object. A digital twin integrates all the data about a physical object across that object's entire life cycle. In fact, digital twins can simulate objects in such accurate detail that they mimic every aspect of an object as if it were real.

And while the foundations of the industrial metaverse are still being laid, digital twins are already changing how work is done. Siemens, for example, used digital twin technology to plan and simulate the construction of a 73,000-square-meter factory in Nanjing, China. By combining factory data, production line data, performance data, and building information, Siemens was able to test and validate the facility's performance and efficiency before laying a single brick. The digital twin is now used to optimize factory output: The new factory boasts productivity up to 20% higher than

"Building a digital version of a physical object is actually just the beginning."

Danny Lange, Senior Vice President of Artificial Intelligence, Unity Technologies

conventional factories, manufacturing volume flexibility up to 30% higher, and space efficiency up to 40% higher.

NASA's Mars rover, *Perseverance*, is another product of digital twin technology. Before launching the space-exploration vehicle into the Martian atmosphere at more than 12,000 miles per hour, NASA created a digital twin vehicle and used it to detect any problems with its concept design and anticipate issues that might prevent the rover from safely landing on Mars.

For all the advantages of building a digital twin that behaves exactly like the physical object, however, there is still room for innovation. "Building a digital version of a physical object is actually just the beginning," says Lange.

Digital twins will allow teams to examine what-if scenarios and run simulations to generate richer and more granular insights for more sophisticated business cases. Autonomous vehicles could be trained in simulated photorealistic environments, and then, during operation, collect real-world data to improve their initial training model.

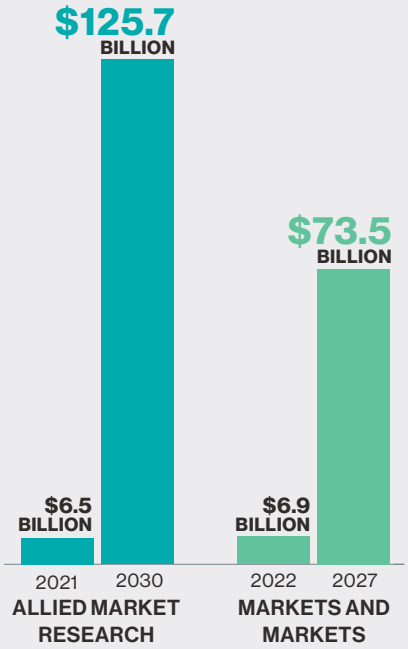
Lange offers the hypothetical example of an autonomous vehicle that "continuously feeds sensor data back to a digital twin, while the digital twin constantly analyzes, learns, and improves from that data, and feeds updates back to the physical world."

Another advance in digital twin technology will be creating fast, photorealistic, physics-based digital twins. This will provide a more immersive experience for participants and give them real-time feedback in their interactions with digital assets or other participants. When working in a digital world that feels just like the real thing, participants will have the necessary confidence to make quick decisions.

And finally, by linking multiple digital twins in a single environment, companies will build the backbone of the industrial metaverse. Capgemini has dubbed this next phase, featuring collaboration between people, digital twins, and simulated environments, the "Internet of Twins."[4] This interconnecting of dozens of digital twins will allow companies to simulate the complex relationships among different objects, thereby bridging a gap between the digital and physical – and creating the industrial metaverse in the process.

Global digital twin market set to boom

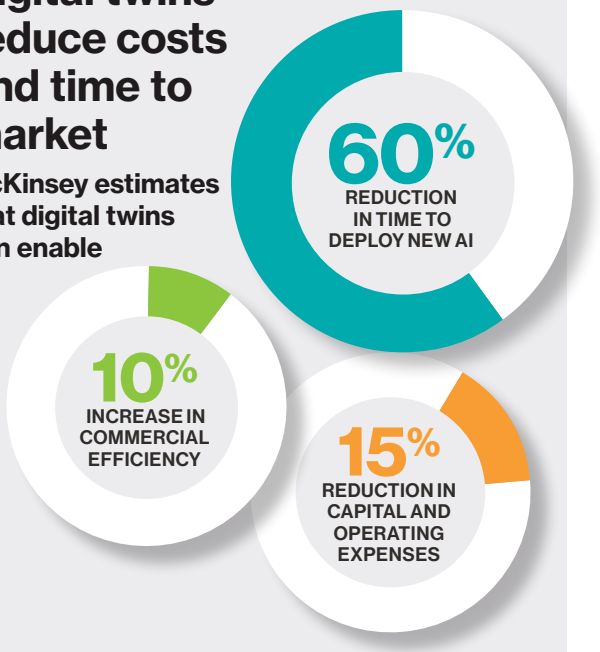
Two research firms project massive growth in the digital twin market this decade.



Source: Compiled by MIT Technology Review Insights, based on data from Allied Market Research and Markets and Markets, 2022.

Digital twins reduce costs and time to market

McKinsey estimates that digital twins can enable



Source: Compiled by MIT Technology Review Insights, based on data from "Digital twins: The foundation of the enterprise metaverse," McKinsey, 2022.

Digital twin applications

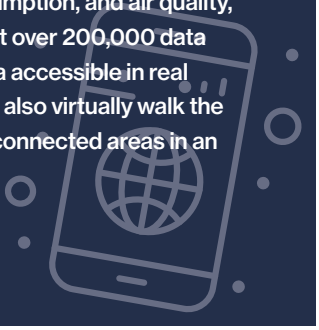
Siemens' case studies of digital twins in use demonstrate the potential of combining the real and the digital.

THE MACHINE Heller is a leading CNC machine producer that turned to executable digital twin technology to further improve efficiency in its machines. "They needed a solution to identify possible misalignments of the tooling that was compatible with their existing sites," explains Hauptvogel, "and the Siemens Executable Digital Twin could deliver that." With this solution, Heller was able to detect as few as 20 microns of misalignment in less than 400 milliseconds, without the need for additional hardware. This allows Heller to drastically improve the efficiency of its automatic tool changer and limit vibrations on the machine.

THE RAILWAY Siemens Mobility is creating a digital twin for the construction of a 2000-kilometer high-speed network in Egypt, enabled by end-to-end data integration across the entire project. Up to 300 project staff will use this digital twin. "It will guide them, for instance, to identify and track the impact of technical changes, monitor the implementation, and automate reports, which will help reveal errors before they have an impact on the project," says Selim Köklü, digitalization lead for Siemens Mobility Turnkey. In the future, AI-supported forecasts simulated in the digital twin may provide additional perspectives for project control.

THE PRODUCTION LINE Unilever, a global manufacturer of personal care products, frequently needs to test and produce new bottles for new or updated products – often with varying designs for different markets. Changing production lines to accommodate these new designs, however, is time-consuming and costly, especially when testing small lots. By employing digital twins of the new products and machinery, Unilever can quickly identify necessary modifications to parts and manufacture them via 3-D printing within a few hours. This has significantly expedited the process, reducing product launch time from nine months to five months, while also lowering capital expenditures by 70%.

THE CITYSCAPE Developed with Siemens for the Expo 2020 in Dubai, the Smart City app was designed to monitor and operate the networked and digitized Dubai Expo site, which encompassed more than 130 buildings. The app is based on a digital twin fed with real-time data. The Smart City app collected, monitored, correlated, and analyzed data on energy, water consumption, and air quality, for example, from sensors at over 200,000 data points while making the data accessible in real time. Users of the app could also virtually walk the Expo grounds and visit the connected areas in an AR/VR experience.



05

Transforming experience: Metaverse impact and value

It is clear that the industrial metaverse will reshape the economy. Just as the internet has, it will also fundamentally transform the day-to-day experience of people all over the world. Expect the industrial metaverse to significantly impact how we experience the physical environment, how we work, and how our activities impact the planet.

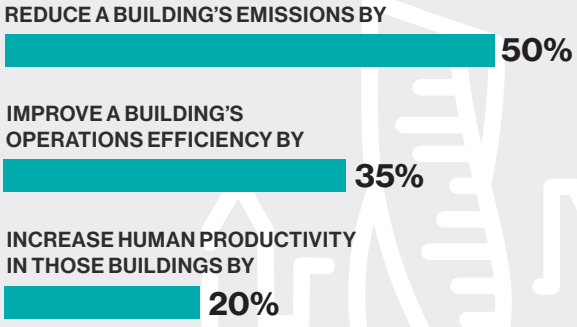
Experiencing and improving the human environment

In 2022, Google Maps introduced Immersive View, a feature that integrates billions of Street Views and aerial images to create a visual digital twin of the world. Using advances in computer vision and artificial intelligence, Immersive View provides users with a multi-dimensional view of an area, such as a city or popular landmark, along with critical details, including weather and traffic updates, altering users' experience of the physical world.

Advances in the industrial metaverse will affect even the streets we walk on and the public services we depend on. The Siemensstadt Square development project in Berlin, for example, aspires to convert a closed 76-hectare industrial area into a futuristic and carbon-neutral urban district by 2030. To monitor and optimize its development and operations, a unique ecosystem of digital twins collects and combines static and dynamic data on its open spaces, buildings, infrastructure, energy, and transportation.

Building sustainability

Digital twins can be used to...



Source: Compiled by MIT Technology Review Insights, based on data from "Metaverse: Could creating a virtual world build a more sustainable one?" EY, 2022.

Further integrating the district's digital twins into an immersive metaverse will make this data more intuitively accessible for users, creating a collaborative environment that extends the physical space as we know it. "Data models are the necessary foundation to address the ecological and economic challenges of cities both now and in the future," says Stefan Kögl, general manager of Siemensstadt Square. "Digital twins are the backbone to achieve this, while the metaverse will make this multitude of overlapping data transparent and usable in real time. This will offer us an extended collaboration beyond spatial boundaries that we cannot even imagine today."

Enabling the workplace of the future

Future metaverse use cases may transform customer experience. Sagi describes a time when "customers will be able to choose and purchase a car by visiting a virtual showroom," completing their shopping, test driving, feature selection, and financing without leaving their homes.

But beyond virtual car dealerships, the workplace will also be transformed by the metaverse. The covid-19 pandemic precipitated a major shift in how employees work by popularizing web conferencing and converting office cubicle-dwellers into remote workers. Yet, Fisher says, the question remains: "How do you get people to work together virtually so that they can have real immersive experiences without having to travel?" He notes, "That will be one of the key changes we see with the metaverse – people working much more closely together, but without having to necessarily travel."

What's more, the industrial metaverse will increase the types of work that can be done from anywhere, further decoupling employment from geography and creating the possibility of "working from home" for occupations that currently require in-person interaction or physical infrastructure. At the same time, the industrial metaverse will change the calculus for companies deciding where to build new facilities.

Workplace safety will also be fundamentally changed: Imagine training engineers on how to maintain dangerous machinery or helping a field team troubleshoot potentially life-threatening issues in a safe and immersive digital world. Detecting potential hazards, for fire or injury, for example, is also more intuitive when you can really see and experience the environment.

The metaverse will be a proving ground for experimentation, as well: "Companies need to show that they can actually do something safely before they put that forklift in the warehouse or put that autonomous vehicle on the roadway," says Lange. "Can you actually do it in the metaverse? There are multiple users in that space that are playing out these scenarios and trying to see if they can actually accomplish their work in a digital world."

> "Information is a replacement for wasting physical resources."
>
> Michael Grieves, Executive Director and Chief Scientist, Digital Twin Institute

Matthias Ziegler, managing director of technology innovation at Accenture, says the ability of these digital worlds to capture the personal nature of physical interactions will have a great impact. "If you're moving in a room and you can hear a person close to you and hear if they're behind you or in front of you, that creates a much more immersive experience that gives humans the clues they need to develop trust and more naturally interact with each other in a virtual environment," he says.

Pursuing sustainability

An energy-efficient metaverse powered by renewable sources will have the potential to help accelerate the transition towards sustainability, by empowering companies to harness the power of data.

Digital twins can make construction projects far more resource efficient, both during the building process and throughout the building's life. By gathering data generated in a digital world and making structural changes to a factory's digital twin based on this information, for example, an organization can save resources and materials, minimizing a site's environmental impact even before construction begins. As well, manufacturers can integrate data between engineering, manufacturing, and services in real time to make operations run more efficiently and sustainably.

"Information is a replacement for wasting physical resources," says Michael Grieves, executive director and chief scientist at the Digital Twin Institute. Digital worlds can guide people in using physical resources optimally, and also catalyze additional shifts toward dematerialization, replacing formerly physical products with digital objects or services.

Consumers can increase their own sustainability contributions by testing and validating the products and services they wish to purchase in a digital world – if not by fully replacing them with digital equivalents. "Before they buy something, they can check it out and see if it's actually going to work for them," says Lange. "As a society, we're going to be much more efficient, and there will be less waste."

A key impact: enabling sustainability

The statistics are startling: The world population is expected to increase from 8 billion today to more than 9 billion in 2050, with attendant increasing demands for energy, clean water, and other resources.[5] To promote human flourishing into the future, the way we live will have to change.

Industry is a major contributor to our current production of carbon emissions and waste, and by making industrial processes more efficient, the metaverse can play a role in creating a more sustainable world. Relying on infinitely available data rather than fossil fuels and natural resources, the industrial metaverse can also help accelerate the transition to net-zero and greater resource efficiency.

The computing power that fuels metaverse technologies, however, itself requires significant amounts of energy. Ensuring that we meet this demand in a sustainable manner is a challenge that cannot be ignored or underestimated, and ecosystem participants will have to be fully transparent about their energy accounting to prove their impact.

Here are some ways the industrial metaverse can support sustainability:

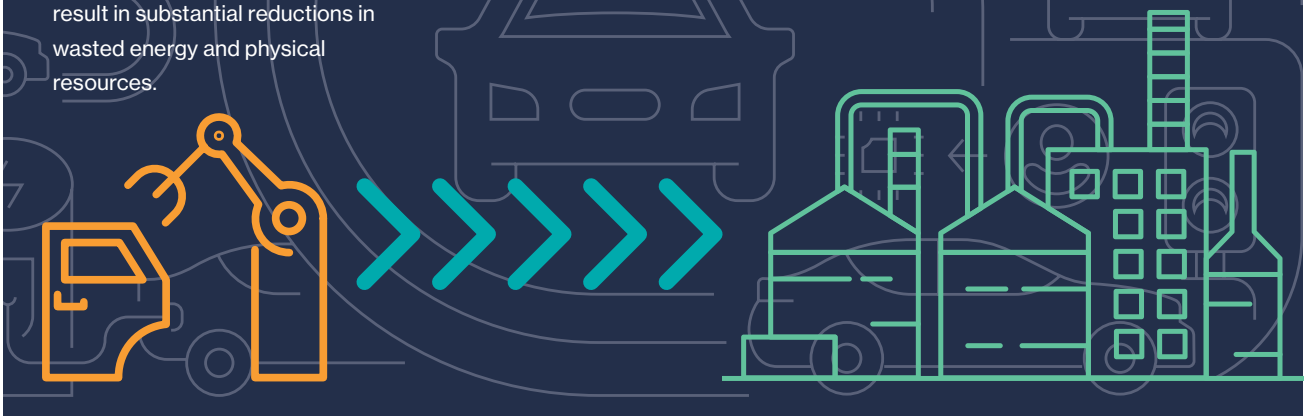
- The industrial metaverse **could assist the transition toward less use of environmentally harmful and nonrecyclable materials** by reducing physical waste in construction and industrial production. It also has the potential to encourage a substantial shift toward business models that replace the production and life cycle management of physical objects with digital services and assets.

- Digital twins **could support smarter and faster decision-making in real life,** allowing the optimization of processes to reduce costs. These streamlined processes—and the ability to continually adjust them based on real-time feedback—will result in substantial reductions in wasted energy and physical resources.

- Experimentation is a precursor to innovation, but it can be costly and wasteful. In a digital world, however, **organizations can experiment with new materials and processes without using any physical resources.** This can be applied to sustainability itself, with new ideas for biomaterials, more efficient wind turbines, and electric vehicles brought to market with more speed and ease for greater sustainability. New products can also be developed from the start in a way that considers their entire life cycle and incentivizes reuse and repurposing.

- It is imperative to shift our energy sources from fossil fuels to green electricity. The industrial metaverse **could be a key enabler to reduce demand for some of the most GHG-heavy energy uses**, such as transportation and heating and cooling, by more efficiently organizing transportation, increasing the energy efficiency of buildings, and optimizing industrial processes.

The potential of the industrial metaverse to help humanity solve the sustainability problem is great. An Accenture study found that, at their current technological sophistication, digital twins could save 7.5 gigatons of CO_2 worldwide over about 10 years.[6]



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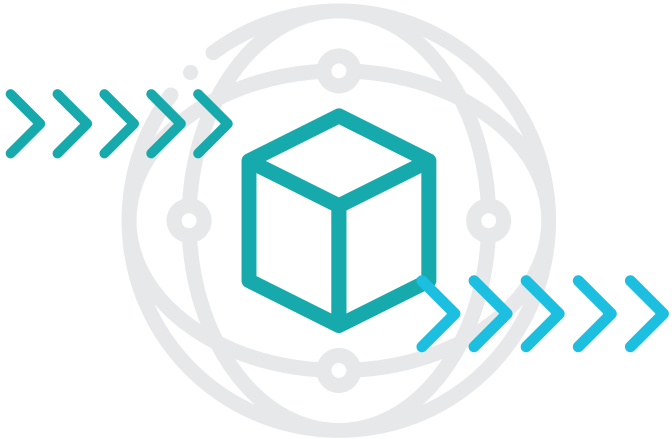
Enabling the emerging industrial metaverse



While the building blocks are evident, and already proving their value, the key capabilities needed to make the industrial metaverse truly immersive, persistent, and capable of providing real-time feedback are still emerging.

Connectivity: Hauptvogel says that, to become a coherent entity that takes Internet of Things interaction and collaboration to the next level, the industrial metaverse needs not only the proper hardware and software, but also the right connective tissue.

Hauptvogel says that key metaverse components include "a digital twin, artificial intelligence, and real data to transfer into a virtual application." She adds, "You also need connectivity solutions, such as 5G or 6G. Edge computing is also necessary, as well as blockchain, because it needs to be a secure environment. All of these technologies exist – the tricky part is actually bringing them all together and connecting them."

Computational power: Another challenge is acquiring the computation infrastructure required to power real-time, immersive experiences. "You need a massive amount of computational capability" to support the industrial metaverse, says Grieves. Fortunately, he notes, "huge increases in capabilities are coming along that will allow us to have tremendous computing power. When I worked on the first supercomputer, it had 25 megaflops of capability. Oak Ridge National Lab recently installed a supercomputer with 40 billion times that processing capability – the world is changing pretty dramatically."

Digital twin fidelity: Industries must also find ways to create and validate extremely high-fidelity models. In order to have reliable predictive capabilities, digital twins must behave exactly as their real-world counterparts would: "Getting all of our physics right is a big deal," says Grieves. Organizations also must fully capture the data surrounding the physical counterpart to their digital twin, incorporating real-time, real-world information. Köklü adds, "A 3-D model that just looks really good and comprehensive is not a digital twin. It's about the data behind it – if there is a piece of infrastructure equipment, you want to know, what is the serial number? What is the function of it? How is it connected to other assets? Which processes depend on it? Because otherwise, it's just marketing renderings for a catalog."

"All of these technologies exist – the tricky part is actually bringing them all together and connecting them."

Annika Hauptvogel, Head of Technology and Innovation Management, Siemens

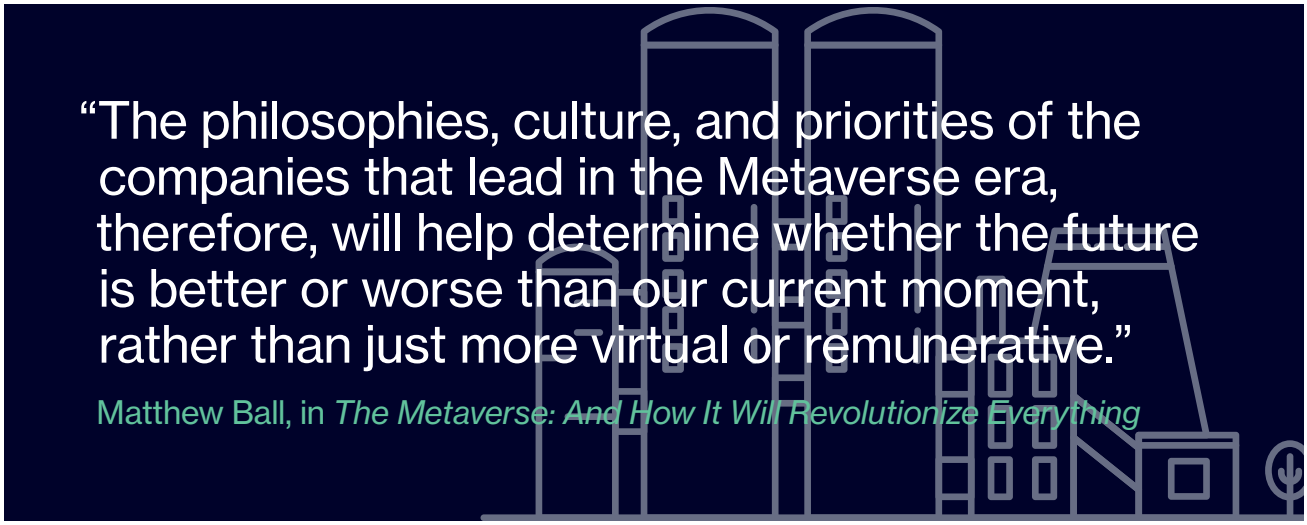
Interoperability: For companies to build and cultivate the industrial metaverse, they will need open and interoperable solutions that allow seamless, real-time, and concurrent collaboration. This requires, among other things, open APIs, compatible data formats, and protocols, like today's internet protocol suite. The goal is to integrate the industrial metaverse using a common language. Doing so allows users to connect their digital twins to dozens of others, if not hundreds, with nothing more than a drag-and-drop process.

That's not easy when most digital twins are currently custom-made, via a long and complicated design and development process. However, with interoperable, open systems and standard platforms, industries will be able to connect their digital twins with the digital twins of their partners and suppliers, creating larger ecosystems that produce deeper insights. Small and medium-sized businesses will also benefit from interoperability and standardization, as it will spark development of less expensive plug-and-play solutions that can accelerate their metaverse participation.

The next economy: The industrial metaverse will also require and create new ways of doing business. "One of the most important pieces of the industrial metaverse is that it's trusted by individuals and the businesses that participate in the metaverse," says Hauptvogel. Appropriate regulation needs to ensure and encourage collaboration and interoperability, while at the same time addressing privacy and security concerns and protecting intellectual property in digital assets. As a result, Signe warns that "both policymakers and business leaders should be very intentional about the future that they want to create with the metaverse."

Blockchain may be a key metaverse ingredient to ensure greater security and privacy. According to Ziegler, blockchain digital identity technologies can help industries better understand "with whom they are interacting, either as a company that wants to sell its services and products to a human, or in the interactions between different machines and digital components." Furthermore, non-fungible tokens (NFTs) based on blockchain technology may provide a way to prove the existence, authenticity, and ownership of content and assets in the industrial metaverse. This will enable value creation throughout the digital asset life cycle and allow for new business models, such as digital twin trading.

A key enabling element will be digital platforms and marketplaces that give companies of all sizes access to comprehensive, open, and flexible metaverse solutions. The development of new financing tools designed specifically for the digital world will be equally important. "Many times, we find that technology isn't what's preventing businesses from transforming fast enough," says Veronika Bienert, CEO of Siemens Financial Services. "It's often financial barriers that greatly impede progress." Providing the requisite financing products, at scale, will require a blend of financial and technology know-how, as well as cooperation between financial institutions, machine builders, end customers, and technology and service partners across the ecosystem.



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Conclusion: Cultivating virtual futures

Despite these challenges, there's no disputing that the industrial metaverse is about to emerge. "It's about time for the metaverse to lift off and really have the breakthrough that we have been working for over the past few years," says Ziegler.

"The industrial metaverse is simply the consequence of our next phase of digitalization," says Kevin O'Donovan, co-chair of the Industrial Metaverse and Digital Twin Committee of the VR/AR Association. "Do not ignore it as just the latest hype," he says. "You need to have a plan." As organizations react to the challenge, a few recommendations will help early adopters reap the benefits.

> "It's about time for the metaverse to lift off and really have the breakthrough that we have been working for over the past few years."
>
> Matthias Ziegler, Managing Director, Technology Innovation, Accenture

Don't lock yourself in

Interoperability and openness of digital solutions are the basic prerequisites for building and participating in the industrial metaverse, but also for successful digitalization in the present. When companies try to lock others out, they will only lock themselves in. Nevertheless, Ziegler says, "we still see a lot of siloed landscapes and approaches. There's a lack of interfaces and interoperability, even a lack of standards."

Fortunately, some entities are taking significant steps toward establishing universal standards and protocols for participating in the metaverse. The Metaverse Standards Forum, for example, aims to "foster interoperability standards for an open metaverse" by encouraging collaboration among standards organizations and companies. The World Economic Forum is also working to foster collaboration among key stakeholders to "build the metaverse in an integrated and open way."

Although challenging, establishing open standards and ensuring interoperability for the metaverse presents organizations with a prime opportunity to bring about meaningful technological and societal changes. "Policymakers have the unique opportunity to learn from previous technological developments and disruptive innovation to create a better world, a better metaverse, to create the world we want," says Signe.

Define clear objectives

Even in the current absence of universal standards, though, organizations must decide how to develop and implement a clear industrial metaverse strategy. This includes, for example, investing in the underlying technology, including edge hardware, industrial 5G networks, digital twin technologies, and artificial intelligence and machine learning, or partnering with a provider of metaverse services or applications.

Organizations must also determine a value proposition or use case for their industrial metaverse initiatives. As with any emerging technology, there is plenty of buzz surrounding the metaverse and its potential to revolutionize the way businesses operate and people live. By working within the confines of a clear objective – such as minimizing waste or accelerating product development cycles – Grieves says organizations can build "an understanding of what's real, what's not real, and what's hype" when it comes to the industrial metaverse.

Empower people to build the industrial metaverse

Organizations must also consider their people's reactions to their metaverse strategy. For example, Sagi warns, "people may fear that their job will be taken away by the technologies or solutions that the metaverse offers." In response, organizations can emphasize how the industrial metaverse creates new opportunities: People don't have to be engineers to work on highly complicated machinery, for example, and mixed-reality technology and live feeds from experts can guide them in servicing complex systems. Better yet, training and up-skilling employees can prepare them to take on new tasks and pursue new career paths in the metaverse sector.

Another strategy for driving acceptance of the industrial metaverse is addressing employees' fears of the unknown. "This is new technology, so there's a natural skepticism," says Lange. "Is this really going to work? You have to convince people to do things in a new way."

Finding talent for metaverse projects also entails tapping into new sources of skilled workers. "Companies must really dig into the game development crowd to get help with the industrial metaverse," says Lange. "They've already been creating 3-D content for gaming. The expertise built up by the game development community can be applied to these industrial cases as well. If I want to animate a robot within the metaverse, for example, game developers are already used to doing this type of work." Team members will also have to pool their knowledge and expertise to succeed in this new space.

"To create meaningful digital twins you need the power of data and domain knowledge," Köklü says. "Data engineers sitting next to domain experts is essential, so that they can learn from each other and create insights with business impact."

Build partnerships and strong ecosystems

Similarly, organizations will increasingly look to external partners to drive innovation in the metaverse. Konnect Volkswagen Group in Tel Aviv, for example, helps the German automotive giant collaborate with Israeli entrepreneurs and startups to develop autonomous vehicles, electrification, decarbonization, and Industry 4.0 technologies. "Startups know how to adapt solutions to customers' needs," says Sagi. "That's a key to success." Case in point: The Konnect Volkswagen Group has been exploring how mixed-reality technology might be used for applications including manufacturing, training, and designing parts in a virtual environment.

Leslie Shannon, head of trend and innovation scouting at Nokia, says, "We're looking at multi-player partnerships going forward, which means that one of the most important elements for participating in the industrial metaverse is business agility." She adds,

"Collaboration and openness are essential for every digitalization strategy going forward."

Annika Hauptvogel, Head of Technology and Innovation Management, Siemens

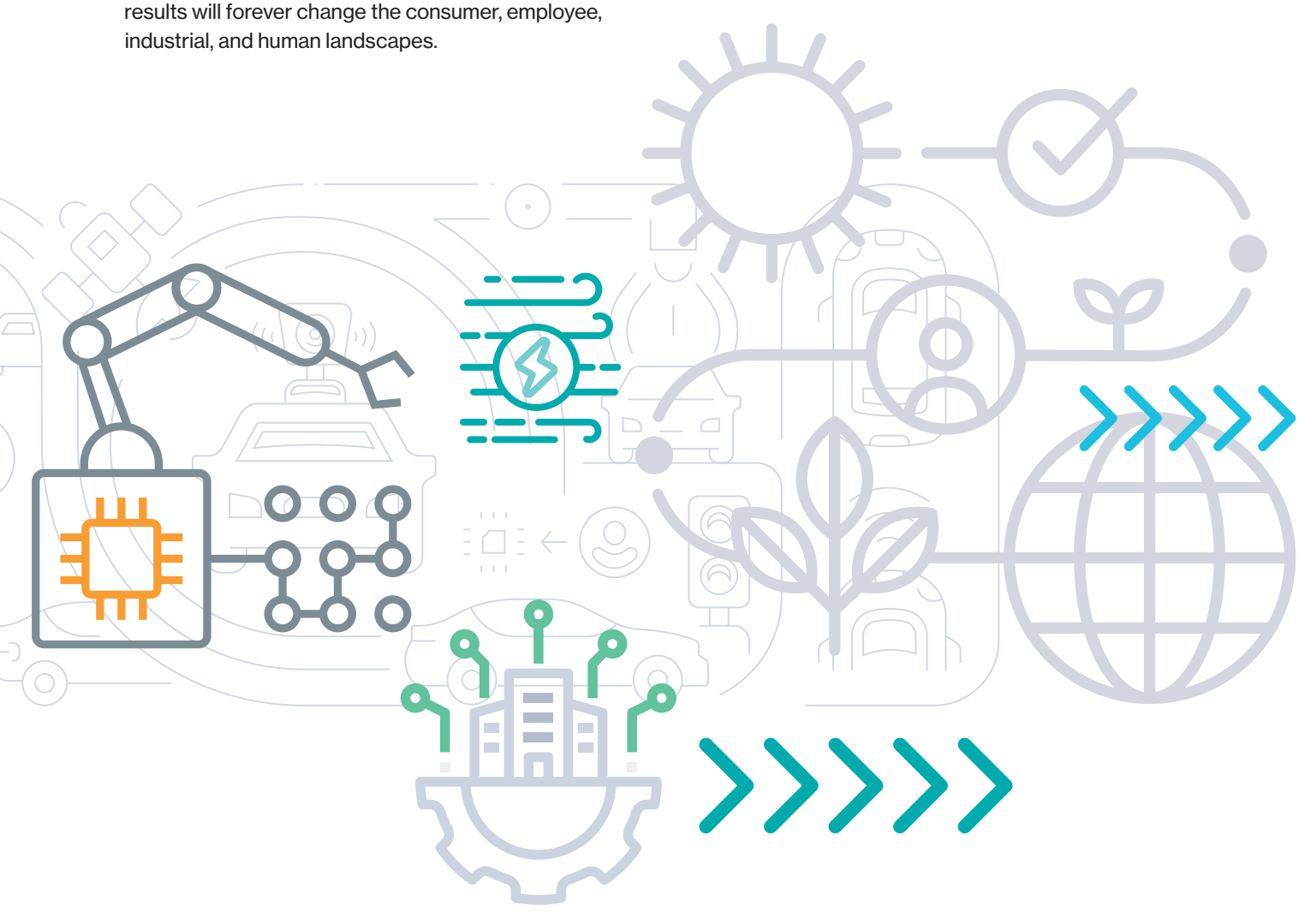
"Unless large companies become more agile, they won't be able to participate effectively in these partnership ecosystems that can create really powerful solutions."

Siemens also sees partnership as an essential element in building a strong metaverse ecosystem. "No one can do this alone," says Hauptvogel. "Collaboration and openness are essential for every digitalization strategy going forward." Beyond the individual project, Siemens is looking to build partnerships and ecosystems at a platform level. The Siemens Xcelerator digital business platform, announced in July 2022, aims to aid other companies in accessing the industrial metaverse by connecting customers, developers, and service providers, and providing solutions from various partners that are open, interoperable, flexible, and easier to scale.

For now, though, metaverse technologies are fast gaining mainstream traction. Companies can begin to reap the potential of those advances today, assembling the talent, technologies, and strategies they will need to participate in the emerging industrial metaverse. As the real and digital worlds become increasingly interconnected, the results will forever change the consumer, employee, industrial, and human landscapes.

"One of the most important elements for participating in the industrial metaverse is business agility. Unless large companies become more agile, they won't be able to participate effectively in these partnership ecosystems that can create really powerful solutions."

Leslie Shannon, Head of Trend and Innovation Scouting, Nokia



08

Afterword: Interoperability and ecosystems: Assembling the industrial metaverse

This chapter was contributed by Siemens.

Building the industrial metaverse is not just a matter of having the right technologies. It also requires their seamless integration. This, however, is a complex challenge. Peter Körte, chief technology and strategy officer at Siemens, highlights the critical role of collaboration in this process: "This is about bringing together diverse industry players with their unique strengths – be it computing power, AI, cloud and edge capabilities, spatial content creation, software, or specialized domain knowledge." Four essential elements are required to piece together this complex puzzle: interoperability, standardization, open APIs for data integration, and ecosystems.

Combining the real and digital worlds

The foundation of the industrial metaverse lies in developing and visualizing digital twins of real-world objects. These systems are dynamic, requiring a continuous feedback loop that integrates and analyzes data, monitoring and managing real assets. This process also enables interactive evaluation, simulation, and prediction with the digital twin. It's a complicated interplay between information technology (IT) and operational technology (OT), where physical data collected by sensors and IoT devices is merged with the analytical capabilities of advanced software, including data analytics and AI models.

> "This is about bringing together diverse industry players with their unique strengths – be it computing power, AI, cloud and edge capabilities, spatial content creation, software, or specialized domain knowledge."
>
> Peter Körte, Chief Technology and Strategy Officer, Siemens

Interoperability enables innovation and efficiency: As real-world systems and their digital twins grow in complexity, the challenge of interoperability intensifies. However, embracing interoperability and openness can create new opportunities for innovation and efficiency. Connected digital twins, for instance, can enhance supply chain collaboration, allowing for real-time tracking and optimization at every stage, from raw material sourcing and manufacturing to delivery, recycling, or repurposing of products.

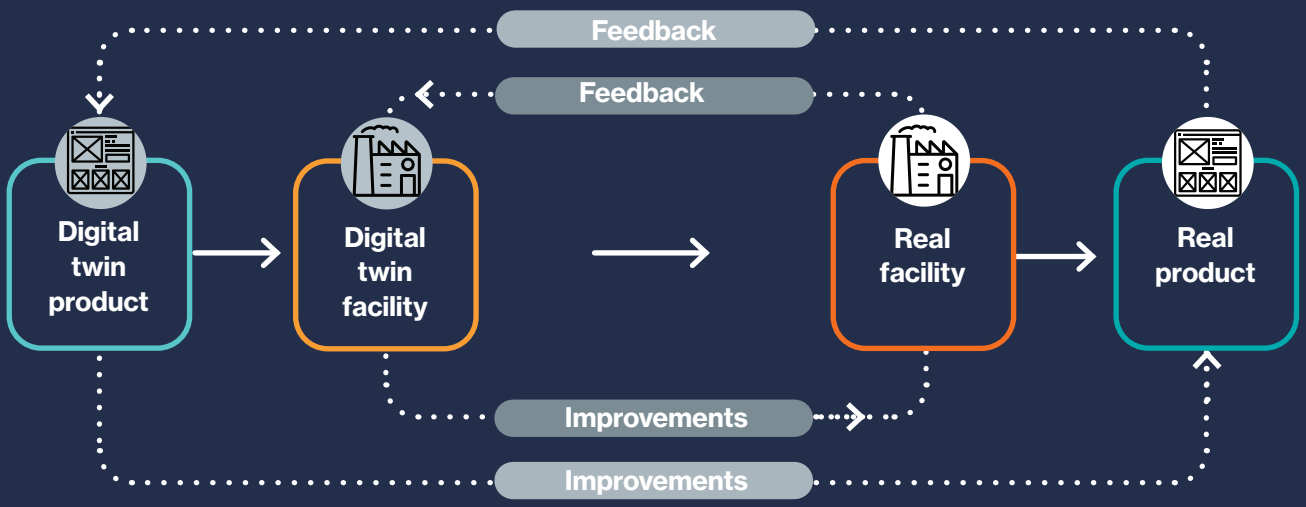
Take, for instance, Bentley Systems' work on infrastructure digital twins, enabling the integration of data from different systems and sources to optimize infrastructure delivery and performance. One example is Singapore, which uses a national digital twin, built on Bentley's technology, to improve data availability, information extraction, and urban planning. "Infrastructure digital twins provide a single view of truth, allowing users to visualize, simulate, and monitor the current state and future projections in areas like transportation, energy, and water," says Mike Campbell, chief product officer at Bentley Systems. "By connecting the physical and virtual worlds, engineering firms and infrastructure owners can make better, data-driven decisions."

Standardizing the future: To facilitate and enhance the integration of IT and OT – and to enable the industrial metaverse – key players across industries are actively working to develop, refine, and optimize standards. "Just as the internet thrived on open standards like HTML and TCP/IP, these efforts are necessary to enable seamless interoperability and integration of diverse industrial systems," says Rev Lebaredian, vice president of Omniverse and simulation technology at NVIDIA.

One such initiative is the Alliance for Open USD, which is evolving the Universal Scene Description (USD) standard. Originally developed for the movie industry, and later adopted by the gaming sector, USD is now being enhanced for industrial applications. This involves adding physical properties, such as density and behavior under physical stress, to 3D objects. Complementarily, within the Metaverse Standards Forum, the Industrial Metaverse Interoperability Group brings together a diverse group of companies that are working to create a unified and standardized environment for the industrial metaverse.

The comprehensive digital twin closes the loop

A digital twin product can be used to create specifications for a digital twin facility. This leads to the creation of a real facility used to produce the real product. Real-world feedback and changing conditions from the real product and real facility are fed back to the digital twin product and digital twin facility, which continuously update and then supply specifications for ongoing improvement to the real facility and product.



Source: Compiled by MIT Technology Review Insights, 2024.

"Just as the internet thrived on open standards like HTML and TCP/IP, these efforts are necessary to enable seamless interoperability and integration of diverse industrial systems."

Rev Lebaredian, Vice President of Omniverse and Simulation Technology, NVIDIA

Building the industrial metaverse: A step-by-step approach

As industries collaborate to standardize and integrate IT and OT systems, businesses are also exploring how to practically build the industrial metaverse. The potential is enormous. After all, "the industrial sector is producing the largest amount of data," notes Douglas Bellin, global lead of business development for smart factories at AWS, "but often only a fraction of that data is actively used." The key to unlock this potential is a step-by-step approach, beginning with laying the foundations for interoperability: robust data integration.

Leveraging open APIs and data management: The journey to an interoperable industrial metaverse requires robust data integration. "Leveraging open APIs is essential," says Selim Köklü, digitalization lead at Siemens Mobility Turnkey. "They are like doors to access data – but then you have to be able to work with what you find behind these doors. In this process, standardization and robust data governance are crucial, ensuring data quality, security, and compliance across systems."

For businesses, especially those grappling with legacy systems, developing a solid data strategy, one that ensures data accessibility and governance,

is fundamental. This, in turn, will lay the groundwork for efficient data management through data lakes or warehouses, which will be instrumental in facilitating the development of analytics, AI models, digital twins, and industrial metaverse applications, benefiting the entire organization.

Embracing ecosystems and platforms: For businesses to effectively enable interoperability, they must also integrate into open, collaborative ecosystems. These ecosystems, often anchored in robust, open platforms, lay the groundwork for cross-industry collaboration and recombinant innovation.

Marshall Van Alstyne, a digital fellow with the MIT Initiative on the Digital Economy and Questrom Chair at Boston University, highlights the intrinsic value of such platforms: "Platforms are not just about cost and speed efficiencies; they open up avenues for recombinant innovation. By enabling different components and subcomponents to be recombined in new ways, platforms become a powerful tool for innovation."

Siemens Xcelerator exemplifies this ecosystem approach. This open digital business platform offers flexible solutions that integrate with existing systems. In addition to addressing the challenges of technology scaling and data integration, the platform's marketplace and developer portal foster a collaborative environment for innovation, providing access to a rich ecosystem of know-how, resources, and open APIs.

The software company Youl Systems has leveraged Siemens Xcelerator's open APIs to develop custom digital twins. These advanced solutions are now being used by KHNP, one of South Korea's leading energy companies, which supplies about a quarter of the nation's energy.

Interoperability and ecosystems: A strategic imperative

In shaping the industrial metaverse, interoperability and collaborative ecosystems are not just beneficial. They are the necessary foundation upon which this digital world is being built, allowing diverse technologies and processes to come together. Embracing these principles is imperative for any digitalization strategy meant to enable participation in the industrial metaverse – and the innovation, operational efficiency, and competitive edge it is about to bring.

The potential of recombinant innovation

Innovation often emerges not from a singular technological breakthrough but rather from a creative fusion of existing concepts. This process, known as recombinant innovation, brings together ideas from across fields or contexts, creating something entirely new.

These innovations range from the mundane, such as fast food (a synthesis of assembly-line efficiency and the restaurant) and the rolling suitcase (the combination of luggage with wheels), to some of today's most disruptive technological innovations.

The smartphone, for instance, was not just about combining functionalities including a music player, watch, and camera. More fundamentally, it emerged from the advanced integration of key technologies such as miniaturized processors, high-density batteries, touch-screen displays, and fast, reliable connectivity – and catalyzed a revolution not just in communication but in how we interact with information and one another.

In the industrial domain, recombinant innovation has been a transformative force since the first industrial revolution, which witnessed the fusion of steam power with mechanical manufacturing. The 20th century saw the combination of electrical energy and assembly-line techniques, enabling an era of mass production. And this evolution continued with the integration of computer technology and automation, leading to the advent of robotics and digital manufacturing.

Today, the advancement and convergence of technologies including digital twins, AI, and the IoT is about to spark the next transformational recombinant innovation: the industrial metaverse. Widespread interoperability and the rise of collaborative ecosystems will help assemble this new digital world and unlock its potential to foster the next wave of recombinant innovation.

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About Siemens

Siemens AG is a technology company focused on advancing the backbone of economies and societies through industry, infrastructure, transport, and healthcare. At Siemens, more than 300,000 people work together to create technology with purpose and adding real value for customers: from more resource-efficient factories, resilient supply chains, and smarter buildings and grids, to cleaner and more comfortable transportation as well as advanced healthcare. By combining the real and the digital worlds, Siemens empowers its customers to transform their industries and markets, helping them to transform the everyday for billions of people. Today, the company offers the industry's most comprehensive digital twin capabilities and is working to make this the key building block for an immersive, concurrent, persistent, and real-time industrial metaverse.

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Footnotes

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Illustrations

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