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REPORT

The Industrial Metaverse

Making the invisible visible to drive sustainable growth

BLUE SHIFT

BY ARTHUR D. LITTLE

"

"What am I? The data? The process that generates it? The relationships between the numbers?"

— Greg Egan, science fiction author,
Permutation City

The Industrial Metaverse

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Executive summary

In business and popular media, the Metaverse hype wave is already entering its disillusionment phase, superseded by artificial intelligence (AI). Yet the *Industrial* Metaverse, perhaps less exciting in the popular imagination, has never really been part of the hype. Is this where the real value of the Metaverse will be realized?

There are differing views about what the Industrial Metaverse is versus the Metaverse as a whole, and how it differs from existing digital twin technologies normally considered under Industry 4.0. In this Report, we provide an evidence-based perspective, assessing current technology status, summarizing use cases and market potential, and offering recommendations for companies going forward.

We conclude that the Industrial Metaverse is best defined as a "connected whole-system digital twin with functionalities to interact with the real system in its environment, allowing decision makers to better understand the past and forecast the future." As such, the Industrial Metaverse is a further evolution of discrete digital twin technologies that already exist today (e.g., for factories or plants) but progressively extended to ultimately represent an end-to-end, real-world industrial system, including external elements outside the company and the environment within which it operates. The Industrial Metaverse thus provides a transformative tool to elevate the use of digital simulation technology to the level of strategic decision-making. This is important for dealing with the increasing complexity and accelerated pace of development company leaders face and is especially valuable for developing effective sustainable growth strategies.

While achieving a full-scale, connected, end-to-end, whole-system digital twin may be five or more years away — especially due to development gaps in connectivity, computing capacity, and scaled-up AI — intermediate steps are possible in the short term, and many Industrial Metaverse use cases already exist. These can be grouped into four categories: (1) optimization (e.g., digital twins and augmented reality [AR] for operations/maintenance efficiency and productivity improvements); (2) training (e.g., virtual/remote training tools); (3) technical tools (e.g., design/construction/maintenance digital tools); and (4) management tools (e.g., virtual meeting/collaboration/interaction tools). The next development steps will include extending digital simulations beyond discrete physical assets toward multiple connected assets, internal processes, and functions, and finally extended upstream and downstream activities involving the entire industrial system.

The Industrial Metaverse provides a transformative tool to elevate the use of digital simulation technology to the level of strategic decision-making.

We estimate the current Industrial Metaverse market to be around US $100-$150 billion, with a conservative 2030 forecast of around $400 billion but with a potential upside of more than $1 trillion. The benefits to business in terms of productivity could be multiple double-digit percentages. The growth of the Industrial Metaverse will not necessarily depend on widespread adoption of the consumer Metaverse because its utility and value for business depend more on the quality of complex system simulation and less on features such as immersivity and human-machine interface technology. Our conclusion is that the Industrial Metaverse has elements of both evolution and revolution: **evolution** in terms of the potential for further stepwise penetration of Industry 4.0 technologies, and **revolution** in terms of how the convergence of these technologies — especially connectivity, AI, complex systems simulation, and visualization powered by increasing computing capacity — has the potential to transform business productivity.

Companies need to consider their strategy for the Industrial Metaverse in the context of their broader digitalization strategy, while also considering implementation barriers. We recommend that companies consider four steps to reap the benefits:

1. **Review strategy.** Develop a clear picture of the digitalization strategy, journey, and current position.
2. **Identify opportunities.** Discover value-adding Industrial Metaverse opportunities and develop a roadmap.
3. **Implement pilot projects.** Adopt a test-and-learn approach and manage change proactively.
4. **Build and align the ecosystem.** Create a win-win situation with ecosystem partners.

Preamble

When I was a child, 10 or 11 years old, I remember thinking that if it were possible to “scan” the positions and speeds of all the atoms and molecules that make up my body at a given moment and put all this information in a computer capable of simulating all the physico-chemical reactions that govern the universe, then this digital copy would not be distinguishable from the original. There would then be two of “me” — the original, based on carbon chains, and the digital copy, whose substrate would be silicon. The copy would be as conscious as the original, and it would be just as convinced of being me.

I didn't know it yet, but I had a materialistic approach to consciousness. I didn't know about Heisenberg's uncertainty principle, which prohibits knowing with infinite precision the position and the speed of the same particle. Thus, the perfect scan was therefore not possible. Not to mention the computing power required to run such a simulation is still quite far from being available. However, without knowing it, I had conceptualized what the industry would one day call "digital twins."

Many years later, my friend David Louapre, Scientific Director at Ubisoft and creator of the popular "Science étonnante" YouTube channel, recommended that I read the science fiction book *Permutation City* by Australian author Greg Egan, released in 1994.

Immersing myself in *Permutation City*, the digital twin story of my childhood suddenly came back to me like a Proust digital madeleine. Because indeed, one of the key elements of the plot is based on the fact that in the near future, around 2050, it became possible to upload one's consciousness to a computer. The problem is that in order for a person's digital twin to be able to interact with a person in the real world, their simulation must run fast enough — that is, enough computing power must be available. If the computing power is insufficient, the time of the simulated person, although remaining subjectively unchanged, passes more slowly than the real time. And if, on the contrary, the computing power is excessive, the simulated world unfolds faster than the real world. It then becomes possible to foresee the future.

There would then be two of "me" — the original, based on carbon chains, and the digital copy, whose substrate would be silicon.

These are exactly the objectives that we seek to achieve with the Industrial Metaverse. The Industrial Metaverse is the extension of what has been called "Industry 4.0" for at least a decade. It is the digital twin of a complex system that allows you to project yourself through time and immerse yourself in space. It makes it possible to numerically anticipate the future consequences of a decision or an event on a complex system — whatever this system: a machine, a factory, a company, a value chain.

As we will see in this Report, the Industrial Metaverse has three major advantages over Industry 4.0:

1. **Modeling and simulation of complex systems** — approaches that were still part of the academic world 10 years ago and that are now changing the game in the industrial world — make it possible to create virtual what-if scenarios. The accessible data is no longer just data from the past and the present, but is now also data about the future. It becomes possible to project in time.
2. Thanks to **AI and virtual reality (VR)**, it finally becomes possible to bring out meaning and visualize the industrial system that must be managed and thus overcome the limits of the human brain, which is not well adapted to apprehend a complex system and its emergences — the famous butterfly effect, resulting from a decision or an event.
3. **Interoperability and interconnection** between the physical industrial system, its digital twin, and the various stakeholders now, more and more, make it possible to manage it optimally.

Thanks to the Industrial Metaverse, it has become possible to make the invisible visible to drive sustainable growth. While ensuring economic growth, we believe that the Industrial Metaverse will be part of the solution to the climate challenge.

And, actually, it is interesting to note that an anagram of *Métavers Industriel* (Industrial Metaverse) is:

verdures militantes/ militant greenery

This is quite intriguing and, as always, anagrams move in mysterious ways.

— Albert Meige, PhD

CHAPTER 1

WHAT IS THE CONTEXT FOR THE INDUSTRIAL METAVERSE?

1 What is the context for the Industrial Metaverse?

Industrial Metaverse is a term commonly applied to the set of Metaverse applications designed for business users. In our previous Report, "The Metaverse, Beyond Fantasy," we looked at the Metaverse as a whole, its applications, underlying technologies, and impact. In this Report, we focus specifically on Metaverse applications for businesses and enterprises, therefore excluding applications and experiences for individual consumers (e.g., gaming, entertainment, and social interaction), although there is an overlap where consumers interact with businesses at the customer interface.

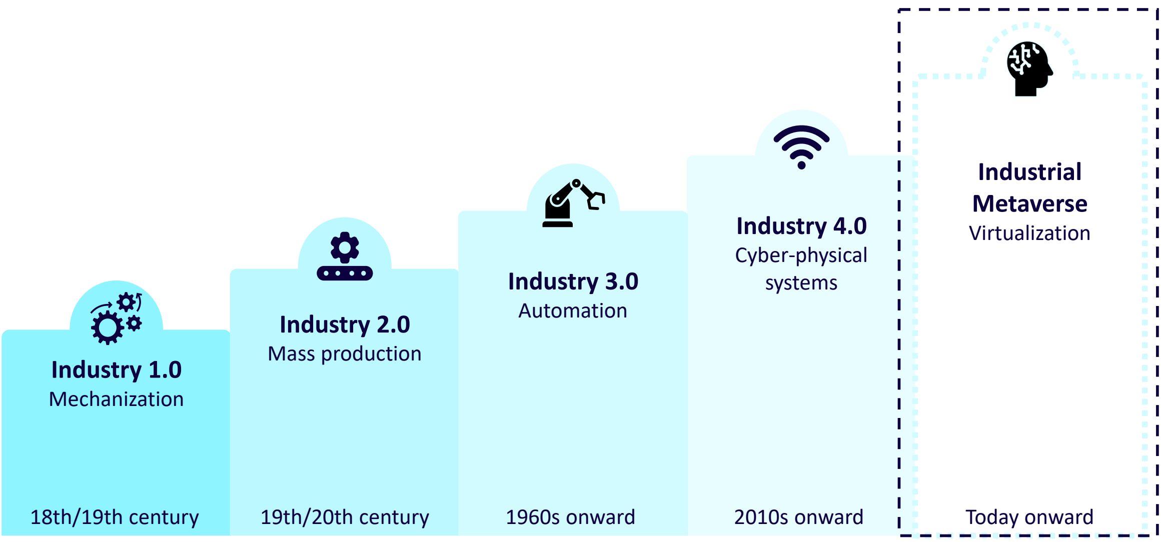
Today, the Industrial Metaverse as a concept is both commonly understood and, at the same time, variously interpreted. Business managers are already well-versed in the potential of digitalization, and many are already well along the digital transformation journey. Digital models of physical products and assets, increased connectivity, and new visualizations are very much part of this journey. So what does the Industrial Metaverse really bring in addition? How significant is the creation of an immersive virtual environment to running a typical business? Is Industrial Metaverse really revolutionary, or is it in fact more evolutionary?

In this Report, we examine the background and context of the Industrial Metaverse, define what it means, set out a conceptual architecture, explore its key technological building blocks, assess its value to business both now and in the future, and propose how businesses should go about exploiting its potential. The Report is based on in-house research, client experience, and contributions from interviews with experts across industry and academia.

Industry 4.0 & the Industrial Metaverse today

The Industrial Metaverse is frequently cited as the next phase of evolution after Industry 4.0, moving from cyber-physical systems to a fully virtualized world (see Figure 1).

Fig 1 — The Industrial Metaverse is often seen as the next phase of evolution after Industry 4.0



Source: Arthur D. Little

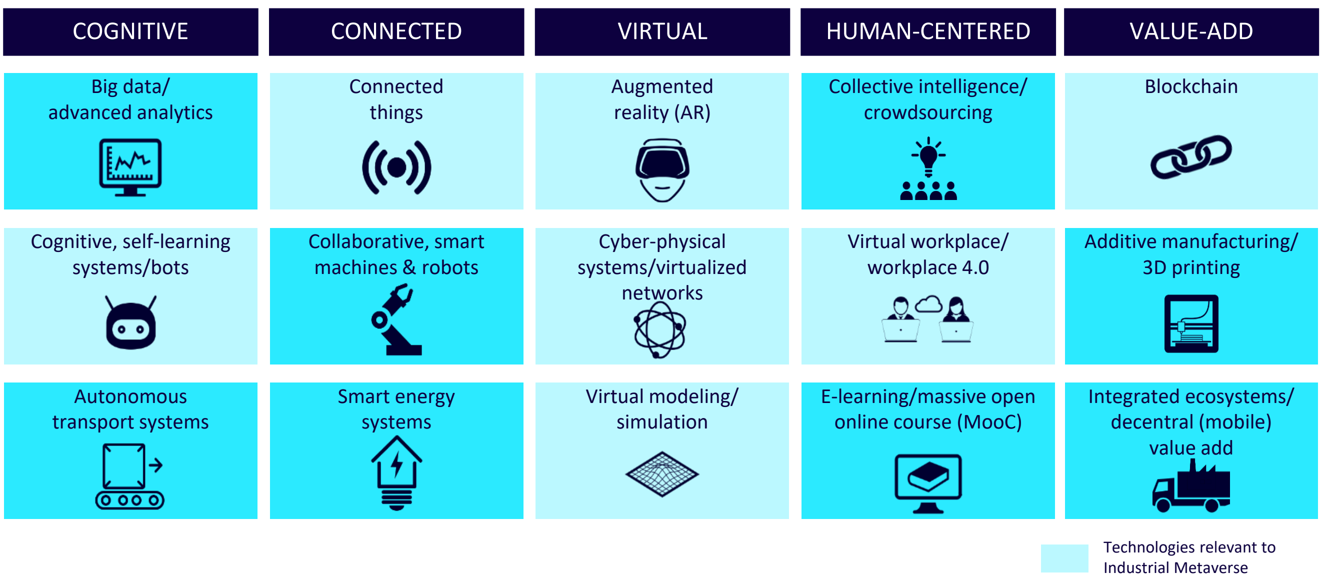
The term "Industry 4.0" (or the Fourth Industrial Revolution) was popularized around a decade ago and refers to the deployment of a wide range of technologies with the potential to transform industry through new cognitive tools, connectivity, virtual modeling (including digital twins), collaboration tools, and new techniques for manufacturing and supply chain, including advanced robotics and blockchain (see Figure 2).

Of these various technologies, some are especially relevant for the Industrial Metaverse. These include AI, connectivity technologies, virtualization and simulation technologies, and collaboration/ interaction tools (see Chapter 3 for further exploration of key technological building blocks).

Industry 4.0 technologies already provide significant benefits to those companies that have successfully deployed them to help transform their businesses. For example, according to data from case examples in Arthur D. Little's (ADL's) Operational Excellence Database, these benefits are often double-digit in scale:

- 15%-30% reductions in operational capital deployed
- 10%-30% reductions in supply chain costs
- 30% increased utilization of production capacity
- 10%-40% reductions in maintenance costs

Fig 2 — Industry 4.0 building blocks



Source: Arthur D. Little; Operational Excellence Database, 2020

Making progress on implementation of digital and Industry 4.0 technologies is challenging for any large company.

However, overall progress in achieving Industry 4.0 maturity still has a long way to go. For example, a 2020 survey of 70 German companies by Acatech that measured progress against a six-stage Industry 4.0 maturity scale showed that the vast majority of firms (80%) were still in the second stage (connectivity), with only a minority (4%) having progressed toward the next stage of creating digital twins (visibility).[1] No companies had progressed toward the last three maturity stages, which involved modeling complex interactions, simulating future-oriented what-if scenarios, or creating self-governing systems. As we will show later in this Report, these functions are key parts of what the Industrial Metaverse promises to deliver.

It is well-known that making progress on implementation of digital and Industry 4.0 technologies is challenging for any large company. This is because it typically involves fundamental transformation of the way the business operates; it is not possible to simply "bolt on" these new technologies to existing assets, business processes, and ways of working. Typical challenges include:

- High initial investment, especially in data gathering and management
- Limitations imposed by legacy IT systems
- A reluctance to embrace the extent of the required business transformation
- Difficulties in realizing the targeted business returns from digital investments within short-enough timescales

The Acatech study also highlighted common barriers toward Industry 4.0 progress, including:

- A lack of common standards
- Fragile information system integration
- A reluctance to engage in interdepartmental cooperation
- Inadequate employee involvement in change processes

If we accept that the Industrial Metaverse is a further stage of evolution beyond Industry 4.0, then it follows that its successful implementation at scale will also require overcoming these common barriers toward Industry 4.0 implementation.

1 Schuh, Günther, et al. "Using the Industrie 4.0 Maturity Index in Industry: Current Challenges, Case Studies and Trends." Acatech, German National Academy of Science and Engineering, 2020.

Why the changing business landscape is leading to unmet needs

It is useful to consider how the business landscape has transformed since the early days of Industry 4.0. Today, as well as the constant need to further improve productivity, one of the biggest challenges facing business leaders is how to achieve sustainable net-zero impact growth. Contributing to this challenge are three key factors, as illustrated in Figure 3: complexity, acceleration, and cognition.

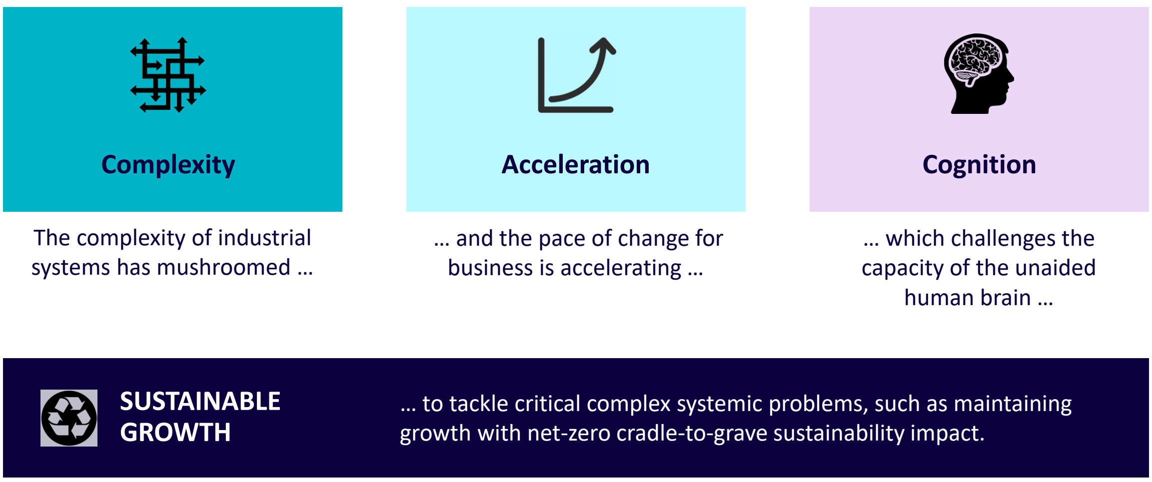
Complexity

Industrial systems are increasingly becoming complex systems that are subject to emergent properties making them much harder to manage. A complex system is a system having a large number of:

- Elements (or parts)
- Relations (connections between the parts)
- Nested systems (systems within the system)

Examples of complex systems include cities, the climate, and living organisms. **Complex** systems differ from **complicated** systems. Complicated systems run essentially like clockwork, in a predictable manner. They may have many elements, sub-elements, and interactions, but the structure remains stable over time and they lend themselves to problem solving using structured analysis through decomposition of the elements. Up to now, most business management approaches have been based on the idea that a company's assets, processes, and organization can be approximated to behave, at least in large part, like a complicated system.

Fig 3 — The challenges to industrial organizations



Source: Arthur D. Little

However, increasingly this approximation is becoming unrealistic. For example, consider the recent changes in:

- **Elements.** In the last two years alone, the volume of enterprise data has risen by over 40% to more than 2 petabytes.[2]
- **Relations.** As a proxy for relations, the number of Internet of Things (IoT) connections grew by nearly 20% in 2022 versus 2021, reaching 14.4 billion.[3] Partner ecosystem networks have greatly increased in size and complexity in the last decade. Demonstrating this, the proportion of a typical car manufactured by third-party suppliers increased from 56% in 1985 to about 82% in 2015,[4] a proportion that is still largely the case today.
- **Nested systems.** The number of nested "layers" in industrial system architectures has increased. In aerospace, for example, the number of specification elements in the latest passenger jet designs is more than 10x that of its predecessors.

What this means is that the industrial system of any large company — plants, processes, people, finance, customers, supply chain, partners, shareholders, and their environment — increasingly has to be treated as a **complex system** for management purposes.

Complex systems are inherently difficult to manage due to three specific properties:

1. **Emergence.** New, unexpected properties emerge from the interactions between the parts.
2. **Non-linearity.** Feedback loops between the parts may lead to exponential behaviors.
3. **Resilience.** A small issue within part of the system does not necessarily lead to its failure.

These properties mean that the behaviors of a complex system are very hard to predict, introducing a high degree of uncertainty into the impact of management decisions. Managers relying on simplified models of their systems to help make decisions find that those models are often inadequate. Indeed, failure to adequately recognize inherent uncertainties is one of the main reasons why new IT systems often fail to deliver the expected benefits.

Acceleration

The pace of change for business is continuing to accelerate, causing these unpredictable emergent effects to occur faster and faster. Three factors are driving this acceleration:

1. **Knowledge and enabling technologies are being developed and adopted at an increasingly rapid rate,** with a greater number of exponential technologies driving transformational change.
2. **The lifecycle of companies and products is shortening.** For example, the average lifespan of S&P 500 companies has fallen from around 35 years in the 1970s to around 20 years today. Product lifespans in many sectors are reducing, with increasing rates of disruption by new entrants and faster market penetration times.
3. **Supply chains are increasingly subject to change and disruption.** Ever more complex supply chains and partner ecosystems are being impacted by global and rapid disruptions such as climate change, pandemics, war in Europe, and other geopolitical instabilities. Additionally, sustainability trends such as bio-sourcing are leading to more supplier variability.

This acceleration means that companies need to be able to respond to changing circumstances more rapidly and make strategic decisions faster.

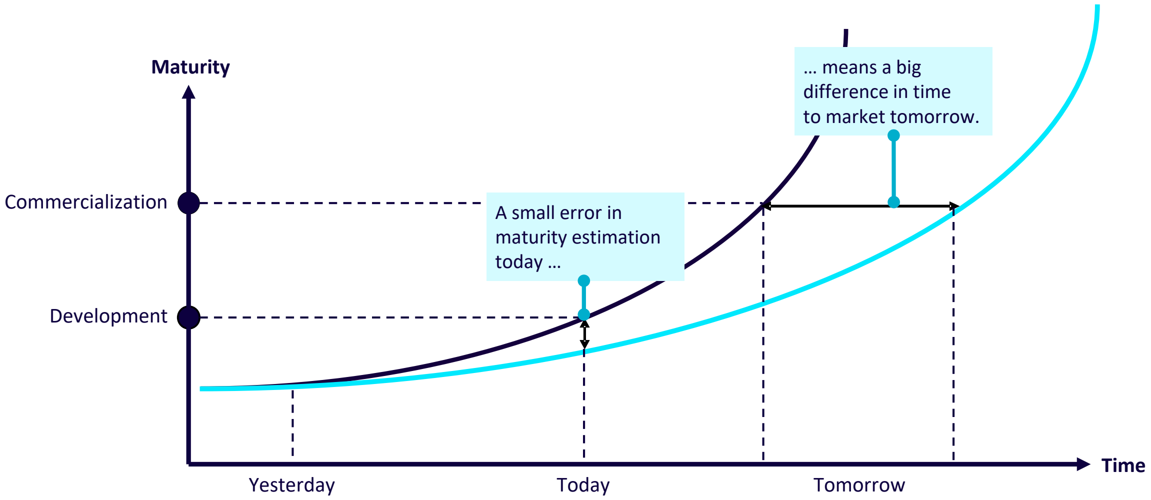
2 Taylor, Petroc. "Volume of Enterprise Data Worldwide 2020–2022, by Location." Statista, 23 May 2022.
3 IoT Analytics. "IoT 2022: Connected Devices Growing 18% to 14.4 Billion Globally." IoT for All, 1 September 2022.
4 Kallstrom, Henry. "Suppliers' Power Is Increasing in the Automobile Industry." Yahoo! News, 6 February 2015.

Cognition

The limitations of human cognition mean that making good decisions within these faster-moving, unpredictable systems is difficult. The human brain is not designed to deal well with **complex systems** — humans tend to think in a Cartesian way, breaking problems into smaller parts, which oversimplifies complexity. In these situations, humans tend to be especially susceptible to cognitive biases — relying on information that matches previous ideas and belief systems — which often leads to incorrect decisions being made.

More and more business phenomena feature **nonlinear or exponential behaviors**, which the human brain does not evaluate well. For example, a small error in a predicted technology development "curve fit" can cause a big discrepancy down the line, as shown in Figure 4. Examples of this include maturity in autonomous vehicles and nuclear fusion, both of which have been repeatedly overestimated, while recently AI has become exponential after many decades in the flat part of the curve.

Fig 4 — The impact of small errors grows over time



Source: Arthur D. Little; Miller, George A. "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information." *Psychological Review*, Vol. 63, 1956.

Sustainability

Meanwhile, sustainability imperatives mean that end-to-end complex industrial system control is growing in importance. Most developed countries have set goals to be net zero between 2040–2060. This means that companies face the challenge of continuing to achieve economic growth while reducing their environmental impact to net zero.

Achieving progress on net zero impact while maintaining growth requires companies to exert control across the end-to-end complex industrial system (e.g., managing Scope 3 as well as Scope 1 and 2 emissions). This means:

- Sharing current relevant data (e.g., operational and environmental performance data) across the entire industrial system of which they are a part, including all third parties involved.
- Being able to predict the sustainability impacts of changes to any part of this system, including supply chain, manufacturing, distribution, sales, in-service, and end-of-life disposal/recycling.

Today this control typically is attempted by conducting discrete impact analyses and collaborating with third parties to share information and take collective action. However, achieving true end-to-end control is difficult due to a mix of technical challenges and institutional, organizational, and cultural barriers around the necessary degree of data sharing and collaboration. On the technical side, the technologies required for gathering, monitoring, analyzing, and simulating the large amounts of data necessary to predict end-to-end sustainability impacts in a complex, large-scale industrial system are not fully mature.

While none of these challenges are completely new to business, approaches used to tackle them today will increasingly be inadequate to meet the needs of the coming years, given current trends.

How the Industrial Metaverse addresses these unmet needs

Industry 4.0 technologies, including digital twins, are already providing significant benefits, but as we have discussed, without further evolution they cannot meet all of tomorrow's needs for a variety of reasons:

- They are mainly limited to discrete physical systems, not the "whole system."
- Decision-making is too static and siloed.
- Net zero obligations on industry mean that more effective, whole-system management will be increasingly essential in the coming years.

The Industrial Metaverse provides a way to move beyond Industry 4.0 and overcome challenges around complexity, acceleration, and cognition to deliver sustainable growth by:

- Allowing companies to make informed C-level decisions based on a **dynamic, forward-looking, whole-system approach.**
- Identifying performance improvements and the impacts of change **more rapidly and effectively.**
- Helping deliver on obligations to manage overall impacts and achieve **sustainable growth.**

In the next chapter, we will consider in more depth what Industrial Metaverse means and look at its key components.

CHAPTER 2

WHAT DOES INDUSTRIAL METAVERSE REALLY MEAN?

2 What does Industrial Metaverse really mean?

In this chapter, our contention is that the concept of the Industrial Metaverse extends far beyond being merely a digital replica of a piece of machinery or a manufacturing plant. It fundamentally serves as a digital reflection of an entire corporation in its operational environment, furnishing decision-makers with insights into historical events and facilitating future predictions. The quintessential role of the Industrial Metaverse is to illuminate the unseen — make the invisible visible. It plays a crucial role in promoting a holistic perspective across compartmentalized units, enabling detailed what-if simulations that provide foresight into potential future scenarios. It unveils the intricate interrelationships within the system. Additionally, it enhances our understanding of the overall behavior and impacts of the entire system, an asset of immense importance for fostering sustainability.

Definition & framework

There are many definitions of what the term "Industrial Metaverse" means, as can be seen in the descriptions shown in Figure 5 from some of the key players contributing to its development.

While there are differing emphases, one element of broad consensus is that Industrial Metaverse is centered on the creation of digitalized models, simulations, or twins of the real world.

Another way to build a useful definition is to consider the technological building blocks that are relevant for the Industrial Metaverse, which, as we have seen, all exist already under the Industry 4.0 umbrella (see Figure 6).

Consider the technological building blocks that are relevant for the Industrial Metaverse.

Fig 5 — Industrial Metaverse definitions

SIEMENS

A virtual world in which we can **interact in real time with photorealistic, physics-based digital twins** of our real world. We believe **digital twins** are **the building blocks for the Metaverse.**

NVIDIA

Industrial Metaverse enables industrial companies of all sizes to create **closed-loop digital twins with real-time performance data, ideal for running simulations** and AI-accelerated processes for advanced applications such as **autonomous factories that rely on intelligent sensors and connected devices.**

IndustrialMetaverse.org

A real-time, persistent simulation space that is the **sum of all virtual worlds, digital twins, and augmented reality** that **connects digital economic assets and infrastructure** on a global scale in the **industrial and commercial setting.**

Microsoft

Industrial Metaverse enables **humans and AI to work together to design, build, operate, and optimize physical systems** using digital technologies.

sme

A **systematic discipline that combines hardware** [...] **data conversions** through analytics/machine learning, **time histories** through cyber-infrastructure, **cognition** through human-machine interface**, and configuration** through the Metaverse.

COSMOTECH

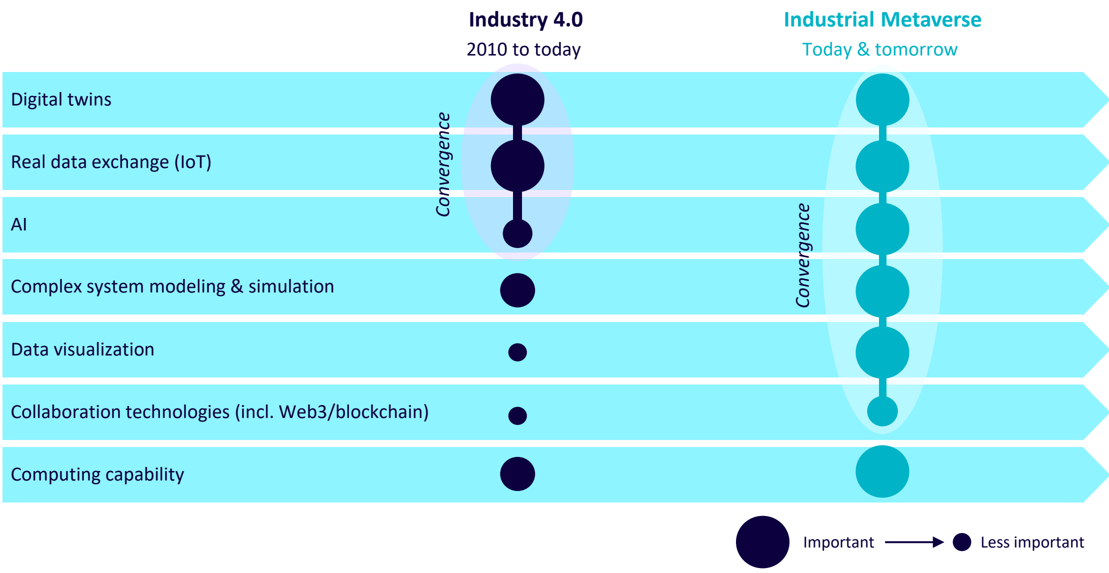
The Industrial Metaverse enables the creation of **digital twins of places, processes, real-world objects, and** the **humans** who interact with them.

Source: Arthur D. Little

As shown in Figure 6, what makes the Industrial Metaverse distinct from Industry 4.0 is the ongoing development and convergence of many of these technologies. Digital twins, with some form of real data exchange with their physical counterparts and application of AI to assist interpretation and analysis, already exist today (e.g., BMW's iFACTORY; see also Chapter 4 and Appendix 3). It is the further development and convergence of these technologies — alongside complex system modeling and simulation, data visualization, and collaboration technologies, all enabled by greater computing power — that are leading to the Industrial Metaverse as a new concept able to meet the challenges of complexity, acceleration, and cognition as well as sustainable growth, as set out in Chapter 1.

Based on all of this, we propose the following definition for what, ultimately, the Industrial Metaverse should become:

Fig 6 — The differences between Industry 4.0 and the Industrial Metaverse



Source: Arthur D. Little

“The Industrial Metaverse is defined as a connected whole-system digital twin with functionalities to interact with the real system in its environment, allowing decision makers to better understand the past and forecast the future.”

As defined, the Industrial Metaverse has the potential to transform how business decision makers analyze past activities and predict the future at strategic as well as operational levels. We have defined a conceptual framework for the Industrial Metaverse illustrating its key components (see Figure 7).

As shown in the figure, the core of the Industrial Metaverse is the creation and operation of a whole-system digital twin for a real-world industrial system, including all its elements, relations, and layers. Let's consider each of the key components in turn.

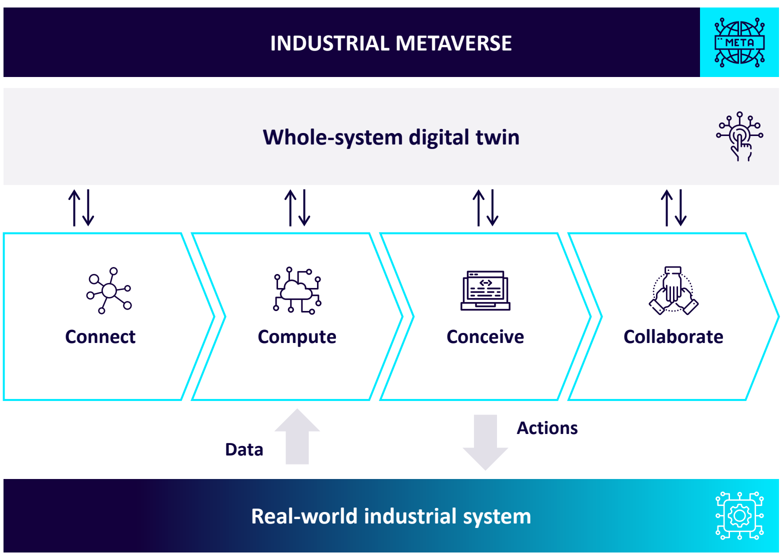
Whole-system digital twin

A whole-system digital twin differs significantly from what we would call a digital twin today, which tends to focus mainly on one or more physical assets, typically plants and products. Its functionalities are representative of an **end-to-end real-world industrial system,** including external elements outside the company and the broader environment within which it operates. It does not simply cover a factory, plant, or product line and is persistently and bidirectionally connected to the real-world system.

It therefore needs to be constructed as a complex system to enable realistic and dynamic system behaviors to be modeled across all functions, departments, processes, assets, and players. Extensive what-if simulation functionality is a key part of the twin. Simulations are not based on past data alone, but present and future data as well.

While it may include immersive and realistic rendering of a real system, asset, and/or product, this is not the twin's key defining feature. Visualizations may be in a variety of different forms, depending on the needs for management decision-making.

Fig 7 — The components of the Industrial Metaverse



Source: Arthur D. Little

Real-world industrial system

"Real-world industrial system" refers to the set of elements, relations, and nested systems that represents a business within its environment. It comprises all the strategy, processes, organization, and resources of a business. It stretches across all business functions and assets, including external players such as supply chain and other ecosystem partners, as well as the broader external environment in which the business operates.

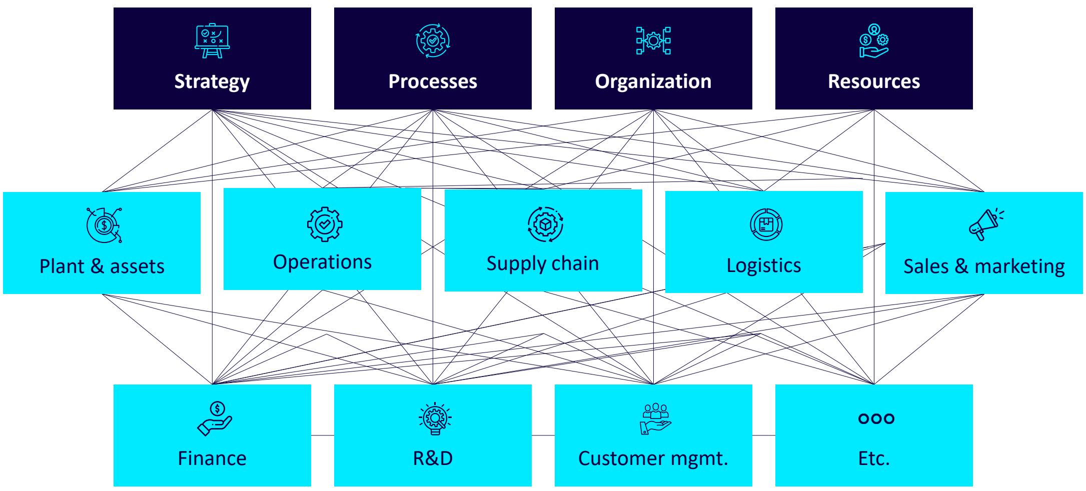
By its nature, a real-world industrial system is therefore a complex system, including multiple elements, relations, nested systems, and subsystems, as shown in Figure 8. It is subject to emergent and nonlinear effects.

Connect, compute, conceive & collaborate

The Industrial Metaverse needs to include four key functions to enable a whole-system digital twin that adequately represents the real-world industrial system. These are:

1. **Connect** — real-time bidirectional connections between the whole-system digital twin and the real-world industrial system to enable data collection and actuation back onto the system.
2. **Compute** — processing of very large data volumes from the real system, including analytics, complex system modeling, pattern recognition, and simulation, to enable future-scenario formulation.
3. **Conceive** — visualizations of both physical and nonphysical data, which may or may not be fully immersive. These visualizations interpret and present complex data in different ways, not only to simulate reality but also to facilitate understanding and to illustrate what-if scenarios.
4. **Collaborate** — functionality to enable a range of interactions, including between internal staff, ecosystem partners, value chain players, customers, and others. Interactions may include commercial transactions as well as everyday coworking.

Fig 8 — The components of a real-world industrial system



Source: Arthur D. Little

How the Industrial Metaverse helps meet executive challenges

The essence of the Industrial Metaverse based on the above definition and model is to **make the invisible visible**. By accomplishing this, Industrial Metaverse offers some key capabilities that are very valuable to C-level decision makers (see Figure 9). Among these, it helps take a systemic view across the silos. It also helps see into the future through enabling realistic what-if simulations. And it helps to make visible the complex interactions across the system. Finally, it offers better visibility on overall whole-system behaviors and impacts, which is invaluable for achieving sustainability.

The essence of the Industrial Metaverse is to make the invisible visible.

Fig 9 — How the Industrial Metaverse solves today's executive challenges

Executive challenges	Industrial Metaverse offers ...			
Complexity	Systemic	*"See across the silos"*	... a whole-system enhanced digital twin, including not just plant but also organization, processes, supply chain, customers & the wider environment.	C-level decision support tool
Acceleration	Dynamic	*"See the future"*	... real-time, realistic future-scenario simulation to anticipate all consequences of a decision.	
Cognition	Visual	*"Understand complexity"*	... new visualizations to enable complex system parameters to be better understood by human brain.	
Sustainability	Holistic	*"Manage overall impact"*	... capability to model overall system impacts on the environment of strategic decisions.	

Source: Arthur D. Little

Industrial Metaverse vs. Industry 5.0

A legitimate question would be: Why speak about the Industrial Metaverse if it is just the next phase of Industry 4.0? Why not call it Industry 5.0?

The answer can be found in the fact that this next phase of Industry 4.0 shares properties with the Metaverse, as we defined it in "The Metaverse, Beyond Fantasy":

"The future version of the Internet blending the frontiers between reality and virtuality, at the convergence of immersive spaces, collaboration platforms, social experiences, and the creator economy."

The Industrial Metaverse shares the three key features of the Metaverse that distinguish it from the Internet — namely, immersion, interaction, and persistence — although there are also some differences of emphasis (see Figure 10).

As shown in the figure, immersion and interaction are key for the Consumer Metaverse. Immersion, in the sense of realistic rendering, is still important but not key for the Industrial and Enterprise Metaverse. For example, it is perfectly possible to interpret, analyze, and visualize complex system data without being immersed in a virtual environment. Interaction and persistence are, however, both key for the Industrial and Enterprise Metaverse — business management relies heavily on interaction, and digital twins need to be "permanent," just like their physical counterparts.

One obvious key difference is that the Industrial Metaverse will generally comprise discrete areas only accessible to authorized persons, rather than the vision of the Metaverse, which is to create an open environment accessible to all. This lowers one of barriers toward greater Metaverse adoption, namely full interoperability.

Fig 10 — Differences between Industrial Metaverse and other segments

FEATURES / *SEGMENT*	IMMERSION	INTERACTION	PERSISTENCE	
Consumer	Very important	Very important	Important	Interaction is key; persistence is important for e-commerce; immersion not essential for now but will be key for future
Enterprise	Important	Very important	Less important	Interaction is key; immersion not essential but growing; persistence is not so relevant for enterprise Metaverse tools
Industrial	Important	Very important	Very important	Interaction and persistence are key for industrial systems; **immersion is not essential** but will increase in importance over time as the broader Metaverse matures

Very important · Important · Less important

Source: Arthur D. Little

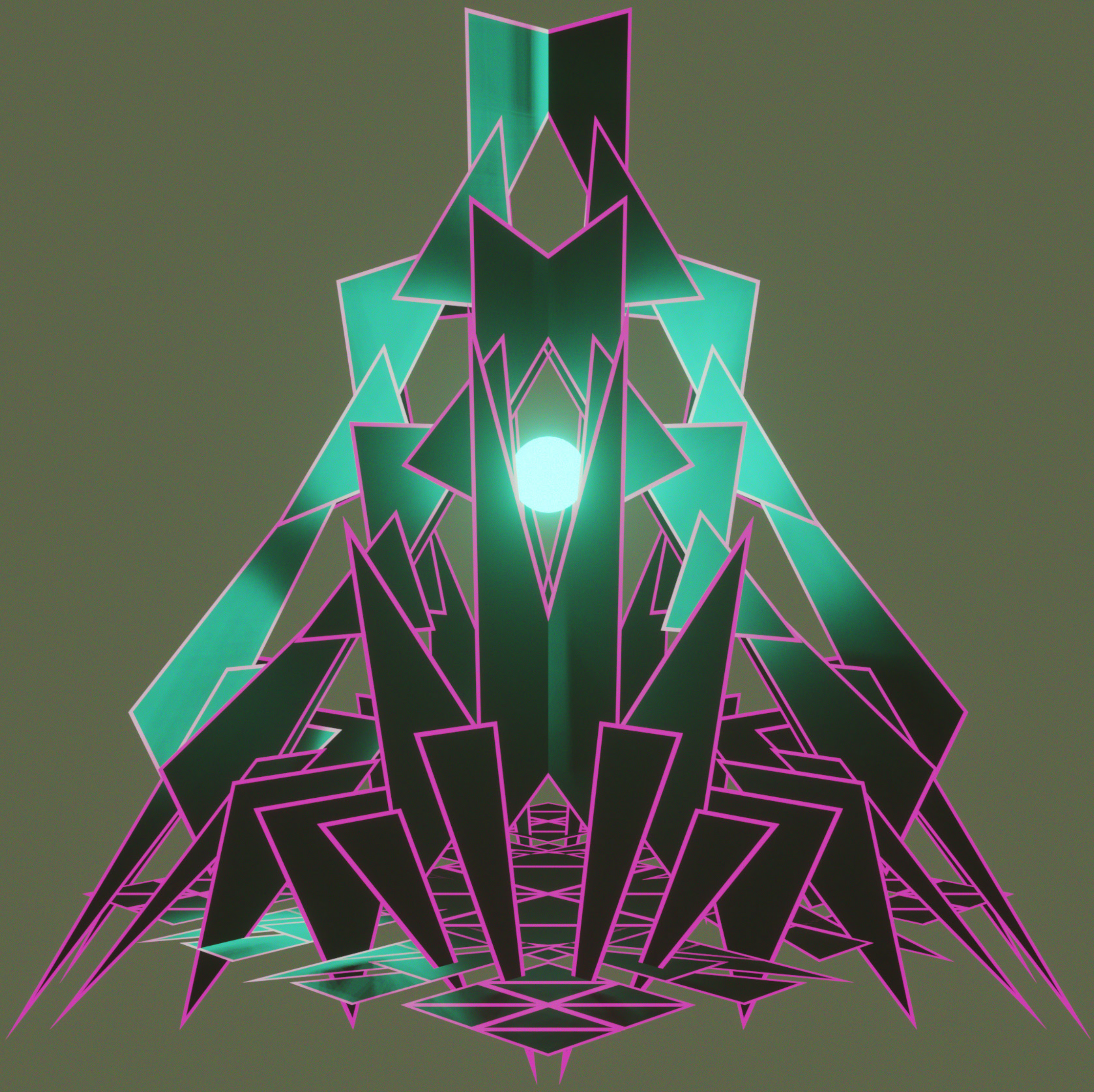
INTERLUDE Make the invisible visible

My art reflects my life, a set of connected yet separate facets, moving together in the digital space.

With a PhD in computational biology from Harvard University and a master's degree from the Ecole Normale Supérieure (ENS), my research centered on computational methods to understand developmental biology. In parallel, I cofounded the nonprofit organization Just One Giant Lab to promote open science across the globe.

Utilizing my expertise in data science and machine learning (ML), I developed musical and visual artistic practices that center around art-science and the question: what is data? A child of the cyberspace, I brought my fascination for immersivity into my research and my art by working with virtual reality as a medium to reveal the invisible threads, from cellular trajectories to the link between projected consciousness and avatar embodiment.

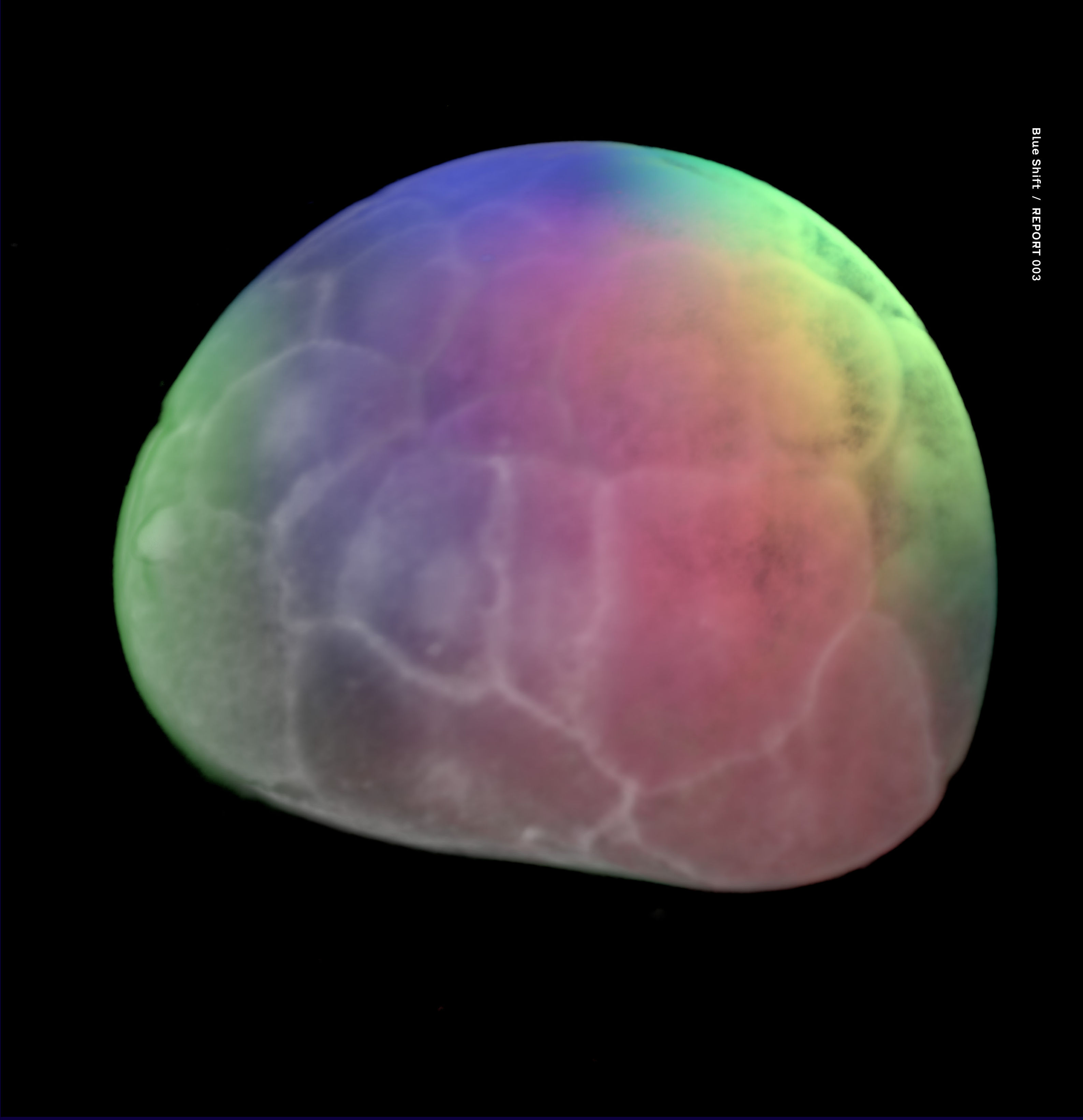
– Leo Blondel, Cyber Wizard



echo cos(pi) > /dev/null[5]

Objects are not always what they appear to be. When everything around us is data, what happens when we manipulate it to reveal hidden meanings? The secrets behind complexity can sometime be revealed by changing our perspective. Starting from a pyramid, applying transformation can reveal other shapes in their complexity. In the virtual realm, data is meaning, but only through the eyes of one who seeks to look beyond the visible layer.

5 The title is a reference to a Linux command line that sends a repeating value to /dev/null, which is the void — the abyss.



Light is matter, matter is light

Modern science has opened the doors to digitizing information in unprecedented ways. By recording the photons emitted by molecules, matter becomes light, which then becomes bytes. Entering the cyber realm, we can shine a new light on reality. In the virtual world, the limits are bounded only by the imagination. Here, an embryo simulated from light data becomes matter again, with simulated photons coloring its invisible matter. From a transparent embryo, where light goes through only slightly scattered, the digital process allows the generation of an opaque object, upon which light will reflect: from transparency to opacity, revealing invisible shapes and processes.

CHAPTER 3

WHERE IS INDUSTRIAL METAVERSE TECHNOLOGY TODAY?

3 Where is Industrial Metaverse technology today?

In this chapter, we explore the technological building blocks of the Industrial Metaverse: their maturity, challenges to overcome, and what this means for the timescales at which the full potential of the Industrial Metaverse could be realized by business.

Evolution of technologies relevant for Industrial Metaverse

Consider the technological building blocks that are relevant for the Industrial Metaverse.

It is helpful to begin by considering relevant technologies that are already in place in industry as a result of the wave of computerization and connectivity that has been ongoing for at least three decades (see Figure 11).

Technologies that involve digital simulation and virtualization, such as building information management (BIM), computer-assisted design (CAD), and digital process control, are already mature although still not fully deployed. The use of AR (e.g., for improving asset construction, maintenance, and inspection) has also become well-established, although there is still further to go in terms of adoption by industry.

In more recent years, digital twins to represent plants, factories, and products have started to be deployed, although often still more as pilot schemes and trials (see also Chapter 4 and Appendix 3 for selected use cases). These are already being used effectively to improve operational efficiency, maintenance, and quality. And in many industries, virtual simulations are already being used for operational training.

In this sense, therefore, aspects of the Industrial Metaverse already exist, overlapping with Industry 4.0, as shown in Figure 11. However, the availability of "connected whole-system digital twins with functionalities to interact with the real system in its environment," as per our definition in Chapter 2, is still five or more years away (we provide more detailed analysis later in this chapter).

Fig 11 — Evolution of the Industrial Metaverse

Industry 4.0 (spans Computerization & connectivity and Discrete digital twins)

Industrial Metaverse (spans Discrete digital twins and Whole-system digital twins)

	Computerization & connectivity	Discrete digital twins	Whole-system digital twins
Typical applications	• Apply IT to operations & business management • Connect & integrate processes • Building information mgmt. • Design tools (e.g., CAD) • Asset inspection/maintenance (AR tools) • Digital process control	• Operational staff training • Plant/line operational efficiency optimization • Predictive maintenance optimization • Product-quality optimization • Remote asset troubleshooting/problem-solving • Design/construction integration	• Whole-life product management/circularity • Whole-system industrial design • Strategic what-if decision-making • Supply chain & ecosystem optimization • Financial/investment strategy • Management training • Collaboration tools • Virtual transactions
Critical technologies	• Data visualization, HMI devices • Real data exchange (ERP)	• Data visualization, HMI devices • Real data exchange (IoT & ERP) • AI	• Data visualization, HMI devices • Real data exchange (IoT & ERP) • AI • Complex system simulation • Blockchain/Web3/transaction tools
Current maturities	TRL 7 to 9	TRL 6 to 9	TRL 3 to 8
	1990 to present	*2010 to present*	*Present onward*

TRL = technology readiness level
Source: Arthur D. Little

Moving toward connected whole-system digital twins

There is a fairly clear path of evolution toward whole-system digital twins that involves progressively extending and integrating digital simulation beyond discrete plant operations. Starting with technology that is already deployed today, this could mean, for example, the following steps:

- **Step 1: Digital twins for discrete, selected plant operations** — including the use of AI-enabled data analytics, increased automation, AR tools for maintenance, and virtual training
- **Step 2: Digital twins created for multiple plant operations** — including supply chain linkages and data integration; increasing the extent of simulation, such as by including sourcing and/or logistics optimization
- **Step 3: Digital twins created for the whole operational system** — including upstream and downstream players. In this step, various management processes are increasingly integrated into the simulation in addition to purely operational processes
- **Step 4: Digital twins created for the whole end-to-end industrial system** — including all management and operational processes, assets, people, and the environment

Some early examples of Step 2 already exist today. Michelin, for instance, has already piloted an approach that involves digital twin simulation for global sourcing strategy optimization, enabling the company to test and compare different strategies for optimization across a range of parameters and achieving impressive results (see sidebar "Michelin: Evolving digital twins beyond plant level to optimize global sourcing strategy").

Michelin: Evolving digital twins beyond plant level to optimize global sourcing strategy

Global tire manufacturer Michelin has 70 production plants with operations in more than 170 countries and a growing number of product models. In 2021, the logistics costs alone for these operations was $2.1 billion. As Michelin's strategy is to manufacture products near the point of sale, global sourcing is a major challenge. The company was looking for a way to test different sourcing strategies and scenarios against each other to identify the best options and to ask "how-to" questions to help determine the best actions to optimize cost, quality of service, carbon footprint, and stock levels.

Although Michelin had used digital twins in product development for around 30 years, it had not applied the technology to sourcing, given the complexity of the global sourcing system with its multiple elements, relations, and nested subsystems.

Working with technology partner Cosmo Tech, Michelin built a complex systems digital model for global sourcing, including key indicators such as service levels, CO2 emissions, inventory, distribution, and plant capacity. This covered 1,700 product models, all within a complex manufacturing and distribution matrix. This simulation digital twin allowed Michelin to run more than 80,000 simulations, each with more than 3,000 different and dynamic decision variables, as well as built-in optimization algorithms to determine the best strategy to adopt.

As a result, Michelin was able to identify an actionable strategic sourcing plan for the next five years that would reduce its logistic costs by approximately $11 million annually. This also optimizes the global profit margin by several percentage points and reduces transport and customs costs by more than 60%.

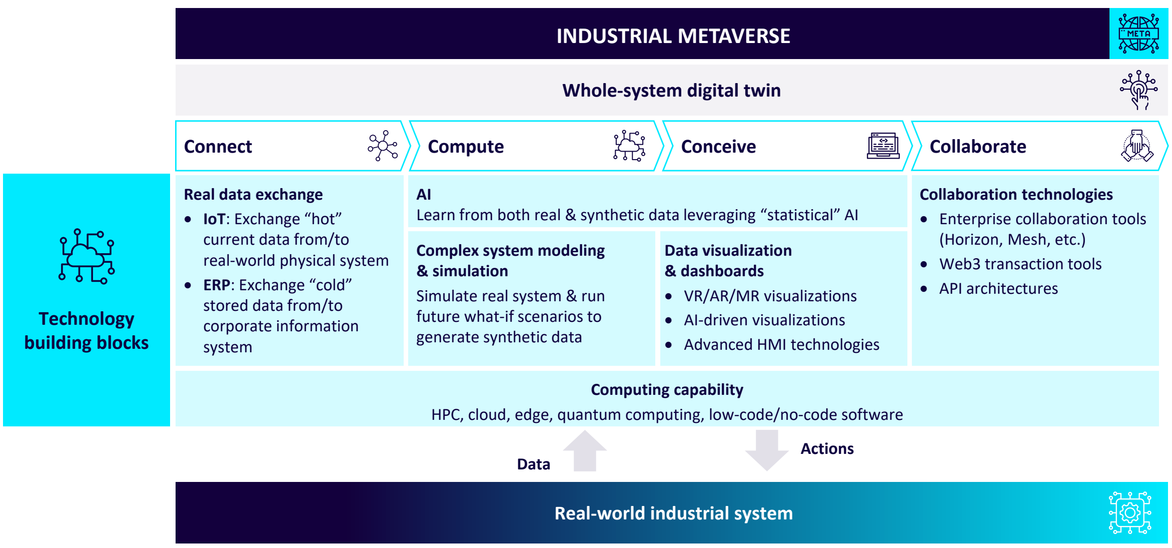
Technology building blocks — Maturity & further development needs

Realizing the next phase of the Industrial Metaverse at a whole-system scale will require further development and integration across a range of technology building blocks, as outlined in Figure 12, and must consider the four functions we discussed earlier:

1. **Connect** — requires bidirectional data exchange between the digital twin and the real-world system, comprising both "hot" current data via IoT technology and "cold" stored data via enterprise resource planning (ERP) systems.
2. **Compute** — requires technology to simulate complex systems and enable future scenarios to be run. It also leverages AI for data analytics and interpretation, especially for prediction.
3. **Conceive** — requires VR, AR, and mixed reality (MR) visualization technologies, as well as other types of visualization for complex data interpretation, sometimes integrated with AI. Advanced human-machine interface (HMI) technologies are also a key building block.
4. **Collaborate** — requires a range of technologies, including enterprise collaboration tools (such as Mesh and Horizon in use today), and transaction-based tools such as those often linked to Web3, including blockchain and non-fungible tokens (NFTs). API architecture that ensures easy software interoperability and data exchange is also important.

Underpinning all this functionality is the need for increased computing capability, which involves a wide range of developing technologies at different levels in the stack, from new chip design, quantum computing, and high-performance computing through to cloud and edge infrastructures and availability of low-code/no-code software solutions.

Fig 12 — Developing technology building blocks for the Industrial Metaverse



Source: Arthur D. Little

Table 1 summarizes our assessment of the maturity levels of each of these technology building blocks, including key development needs and timescales to full maturity.

In Table 1, "scale of development gap" refers to the extent of development still needed to be able to deliver the functionality envisaged for adoption of large-scale whole-system connected digital twins. "Degree of uncertainty" refers to the likelihood that current challenges may not be overcome during development. It may be seen that for the most part, the various technology building blocks have only moderate development gaps. All have only moderate degrees of uncertainty in terms of if/when current challenges will be overcome.

Overall, the picture suggests a timescale of five or more years before whole-system digital twins as described in our Industrial Metaverse definition could be realized, although in the meantime there will be continued progress with intermediate steps. AI is assessed as having a larger development gap than others mainly due to the challenges of algorithm scalability, data volumes, and computing-capacity limitations. Computing capability itself is a critical enabler for achieving very large, connected digital twin simulations. For example, many optimization problems involving multiple elements and interactions qualify as "intractable problems," where the solution complexity rises exponentially beyond the reach of conventional computing power. Such problems would be suitable for quantum computing approaches, but this technology is probably at least 10 years away from maturity.

Table 1 — Snapshot of maturity/development of Industrial Metaverse technology building blocks

TECHNOLOGY	SIGNIFICANCE FOR INDUSTRIAL METAVERSE	SCALE OF DEV. GAP	DEGREE OF UNCERTAINTY	KEY DEVELOPMENT NEEDS & CHALLENGES	LIKELY TIMESCALES TO FULL MATURITY
Real data exchange (IoT)	Provides the means by which digital twins can exchange "hot" (current) data to/from real-world industrial system	•	•	New sensor technologies and applications will be required to extend data capturing to include a wider range of parameters across industrial system; further AI integration is also key	5-10 years
Real data exchange (ERP)	Provides the means by which digital twins can exchange "cold" data to/from corporate industrial system	•	•	Increasingly sophisticated digital twins will pose heavy demands on data storage, sharing, and processing; development areas are around scalability and flexibility	2-4 years
AI	Key tool for VR/avatar creation at scale; also for advanced HMIs and data analytics/interpretation, especially predictive	⬤	•	AI at scale poses multiple challenges, including algorithm scalability, data volume, and computing-capacity limitations; data quality, privacy, ethics, and security are also key areas for development	3-5 years
Complex system modeling & simulation	A critical technology building block for simulation of large-scale industrial systems to enable what-if scenarios and strategic decision-making	•	•	Core challenges include system decomposition and algorithm methods that would be capable of coping with complexity of a whole end-to-end industrial system; computational capacity and data acquisition are also key challenges	1-3 years (limited scale) 3-5+ years (whole industrial systems)
Data visualization & dashboards	VR/AR/MR visualizations enable staff and managers to understand and interpret complex data; they also enable realistic digital twin rendering	•	•	Graphics, presence, logic, and physics engines still require significant further development for real-world rendering; immersive complex system data visualizations are still relatively immature	3-5 years
Collaboration technologies	Facilitates person-to-person collaborations in virtual environment, including commercial transactions	•	•	Improving quality of experience, network speeds, and security are current challenges	1-3 years
Computing capability	High HPC, cloud, and edge computing capacity will be needed to operate complex whole-system digital twin; quantum computing could be a solution for complex simulations; low-code/no-code is a key enabler for required new software	⬤	•	Increases in capacity of up to an order of magnitude could be needed for large-scale whole-system digital twins; development areas include edge/cloud hybridization, new HPC technology, and, at much lower maturity, quantum computing	3-5 years 10 years+ for quantum

⬤ **High** • **Moderate**

Source: Arthur D. Little

In the section that follows, we provide more details of the status, maturity, and implications for the Industrial Metaverse of each of these technology building blocks.

Real data exchange (IoT)

Key data[6]

Global market size (2021): >$150 billion
Maturity: TRL 7-8 — while basic IoT technology is mature, further tech development potential is still significant
Forecast market growth: >20% CAGR next five years
Development gap: moderate
No. of machine-to-machine connections: 10-30 billion (2022–2025)
Degree of uncertainty: moderate

Description

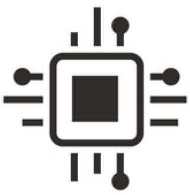
IoT technology provides the means by which digital twins can exchange "hot" (current) data to and from the real-world industrial system. IoT has applications across nearly all industry sectors as well as for cities and domestic use. The basic technology is already fairly mature at technology-readiness level (TRL) 7-8 (see Appendix 1 for full description of TRLs), but further developments are needed to enable more sophisticated digital twins with real-time end-to-end connectivity.

Development needs

Current development priorities include improving cybersecurity platforms and extending edge computing solutions (edge IoT devices), smart sensors and AI convergence, sensor fusion/miniaturization, and new sensor applications. Convergence with AI (smart sensors), improving performance, and extending applications across a wider range of parameters are all enablers for developing more sophisticated digital twins.

Real data exchange (ERP systems)

Key data[7]



Global market size (2021): >$45 billion
Maturity: TRL 8-9 — ERP technology is mature, but the Industrial Metaverse will require significant new capacity development
Forecast market growth: >9% CAGR next eight years
Development gap: moderate
Degree of uncertainty: moderate

Description

Increasingly sophisticated digital twins, which include business processes as well as data from IoT, AI, and other new tech applications, will pose heavy demands on ERP data storage, sharing, analytics, and visualization.

Development needs

Current development priorities include end-to-end security, data storage systems (such as the cloud), greater scalability and flexibility, adoption of blockchain (such as for crypto transactions), and additional cloud-based services (such as remote assistance and ML-driven data analysis).

6 Arthur D. Little, IoT Analytics.
7 Arthur D. Little, Oracle, Fortune Business Insights.

Artificial intelligence

Key data[8]

Global market size (2022): >$100 billion
Maturity: TRL 6-7 — different subgroups of AI are at different maturities; we may now be entering a much steeper phase of development
Forecast market growth: >38% CAGR next eight years
Development gap: high
Degree of uncertainty: moderate

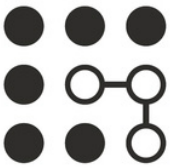
Description

AI categories include general intelligence, reasoning, knowledge representation, planning, learning, natural language processing (NLP), perception, and the ability to move and manipulate objects. Its applicability for industry and society is vast. Some NLP apps are now growing exponentially after decades of slower-than-expected AI development and adoption. AI is a key technology for the Industrial Metaverse across multiple areas. It is a tool for VR/avatar creation at scale, advanced HMIs, and data analytics/interpretation, especially predictive analytics. Convergence with other relevant technologies, such as IoT and complex system modeling, are also key for realizing sophisticated digital twins.

Development needs

While it is maturing rapidly, AI at scale faces multiple challenges including algorithm scalability, data volumes, and computing-capacity limitations. Current development priorities include improved processor chips (e.g., Tensor Processing Units), higher-speed networks, larger network-bandwidth guarantees, AI R&D cloud platforms, overcoming storage limitations (e.g., through high-quality labeled data sets), data quality, data security, and ethics.

Complex system modeling



Key data[9]

Global market size (2022): $10-$15 billion
Maturity: TRL 6-8 — while the basic approaches are well-developed, there is still limited experience in this type of very large-scale industrial system application, and many challenges remain
Forecast market growth: CAGR 10%-15% next eight years
Development gap: moderate
Degree of uncertainty: moderate

Description

A broad spectrum of approaches exists for modeling complex systems. The analysis of complex systems cannot be carried out with only classical methods of system decomposition and logic analysis; a framework is needed to integrate several methods capable of viewing the problem from different perspectives, including:

- **Structural/topological methods** — based on system analysis, graph theory, statistical physics, etc.
- **Statistical and logical methods** — based on system analysis, hierarchical and logic trees, Bayesian networks, etc.
- **Phenomenological methods** — based on transfer functions, state dynamic modeling, input-output modeling & control theory, agent-based modeling, etc.
- **Flow methods** — based on detailed, mechanistic models (and computer codes) of the processes occurring in the system

8 Arthur D. Little, Precedence Research.
9 Arthur D. Little. "Review of Complex Systems and Their Concrete Applications in the Transportation Industry." Presans, 2016.

Complex system modeling will have a key role in the development of the Industrial Metaverse. It will be essential in order to simulate real-world industrial systems, moving beyond physical asset operations, and running future scenarios for management decision-making.

Development needs

Core challenges to realizing the Industrial Metaverse include developing system decomposition and algorithm methods that would be capable of coping with the complexity of a real end-to-end industrial system. Computational capacity and data acquisition are also key challenges.

Data visualization & dashboards

Key data[10]

Data visualization
Global market size (2021): >$9 billion
Maturity: TRL 6-7 — there is scope for further development of immersive tools that may be suitable for understanding highly complex and dynamic data sets; HMI technologies also require significant further development
Forecast market growth: 10% CAGR next six years
HMI
Global market size (2021): >$4 billion
Forecast market growth: 10% CAGR next four years
Development gap: moderate
Degree of uncertainty: moderate

Description

Data visualization technologies are fundamental to the Metaverse in three areas:

1. **VR/AR/MR visualizations.** The "world engine" for the Metaverse comprises graphics, presence, logic, and physics dimensions. Complex data visualization is a further key category, in which novel visualizations and dashboards are used to enhance data interpretation (immersive or otherwise).
2. **AI-driven visualizations.** AI is a key tool for developing Metaverse simulations and representations. AI-based data analytics benefits from visualization technologies.
3. **HMI technologies.** "Output" HMI technology includes VR/AR headsets, holography, haptics, and brain-computer interfaces (BCIs). BCI and on-body tech are also key for "input" HMIs to pass data from humans to the machine.

Development needs

Graphics, presence, logic, and physics engines still require significant further development for real-world rendering. Computing power is also a barrier. However, for many Industrial Metaverse applications, a "perfect" reality is likely to be less important than in the consumer Metaverse, given that many non-immersive data visualization tools and dashboards already exist. However, poor HMI performance is still a barrier to greater use of immersive representations. There is scope for further development of immersive tools that may be suitable for understanding highly complex and dynamic data sets, while HMI technologies (particularly BCI) also require significant further development.

10 Arthur D. Little, GlobalNewsWire, Statista.

Collaboration technologies

Key data[11]

Global market size (2022): >$10 billion
Maturity: TRL 8-9 — collaboration tools are already deployed, although there are still significant improvement needs
Forecast market growth: >3% CAGR next five years
Development gap: moderate
Degree of uncertainty: moderate

Description

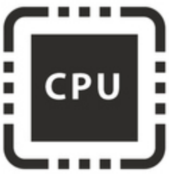
In the Metaverse, collaboration technologies take three distinct forms:

1. **Enterprise collaboration tools.** Virtual work environment tools such as Microsoft Mesh and Meta Horizon Workrooms already exist, although the user experience requires further development.
2. **Web3 transaction tools.** These relate to token-based economics and decentralization to facilitate commercial transactions in the Metaverse. Blockchain, cryptocurrencies, and NFTs are all relevant Web3 tools.
3. **API architectures.** APIs enable applications to exchange data and functionality easily and securely. They are an enabler for software innovation and interoperability.

Development needs

While collaboration tools are already deployed, they require significant improvements. This is particularly true of enterprise collaboration tools. As this is the first experience most employees will have of the Industrial Metaverse, the current poor user experience acts as a significant barrier to adoption. While Web3 tools do not depend on the Metaverse, their availability and effectiveness would help to drive further Metaverse adoption by businesses. Current areas for development in collaboration technologies include cybersecurity, higher-speed networks, larger network-bandwidth guarantees, and cloud-based storage systems.

Computing capability — Microcontrollers



Key data[12]

Global market size (2021): >$80 billion
Maturity: TRL 7-8 — hardware technology is mature, although further tech development is still required to adapt to Metaverse applications
Forecast market growth: >4% CAGR next eight years
Development gap: moderate
Degree of uncertainty: moderate

Description

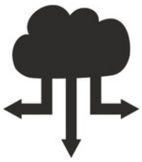
A scalable processing unit capability is required to operate an Industrial Metaverse system or integrate other technologies into its architecture. This computing capability is driven by two distinct types of microchips — general-purpose central processing units (CPUs) that determine data-processing speeds and specialized graphical processing units (GPUs), used for rendering images or videos and underpinning high-performance computing (HPC), AR/VR, AI, or ML applications. While CPU performance will only see limited efficiency improvements, due to Moore's Law, the optimal utilization level for GPUs has not yet been reached, and there are still software challenges.

Development needs

Current developments are therefore focused on creating solutions, often cloud-based, that parallelize CPU/GPU processing power while optimizing the capacity and utilization of GPUs.

11 Arthur D. Little, The Business Research Company.
12 Arthur D. Little, Future Market Insights, Grand View Research.

Computing capability — Conventional



Key data[13]

Global market size HPC (2021): ~$65 billion
Maturity: TRL 6-8 — infrastructure technology is mature, although further tech development is still required to adapt to Metaverse applications
Forecast market growth HPC: >7% CAGR
Development gap: moderate
Degree of uncertainty: moderate

Description

The conventional computing-capability category covers three areas:

1. **Edge computing.** A distributed IT architecture in which client data is processed at the periphery of the network, as close to the originating source as possible.
2. **Cloud computing.** On-demand delivery of IT resources over the Internet with pay-as-you-go pricing, instead of needing to buy, own, and maintain physical servers.
3. **High-performance computing.** Using supercomputers and computer clusters to solve advanced computation problems.

Development needs

The infrastructure around conventional computing capacity is evolving at a fast pace. A hybridization of edge and cloud computing will be extremely valuable for the Industrial Metaverse. These hybrid clouds will help providers increase operational efficiencies while hosting the Industrial Metaverse and help eliminate outage issues by bringing hosting resources closer to end users while safeguarding personal information. As well as hybrid clouds, current development priorities include cybersecurity, improving enabling technologies (such as cooling), increasing bandwidth, and creating a more diverse range of solvers/compilers to allow flexible and parallel utilization of computing capacities, combined with the semiautomated selection of computing power mixture. Limitations on processing speed at a microchip level can be compensated for by these current developments in conventional computing, with the actual demand defined by the Industrial Metaverse application.

13 Arthur D. Little, The Business Research Company.

Computing capability — Quantum

Key data[14]

Estimated global investment (2022): ~$25 billion

Maturity: TRL 3-4 — quantum computing technology is still at the proof-of-concept lab scale, with commercial penetration likely 10-30 years away

Growth projection 2030: <$5 billion to >$60 billion (depending on the source)

Development gap: high

Degree of uncertainty: high

Description

Quantum computing (QC) harnesses the properties of arrays of entangled quantum bits (qubits) to provide computing power suitable for tackling problems with exponentially scaling complexity. It can be applied in areas including complex system simulation, optimization, AI/ML processing, and cryptography.

Development needs

QC is still at least 10 years away from commercial viability and is still at proof-of-concept lab scale (TRL 3-4). There are at least five competing hardware paradigms and major technical challenges still to be overcome. Consequently, there is a high degree of uncertainty that QC will bridge the wide development gap to achieve maturity.
If successful, the first Industrial Metaverse QC applications are likely to be around communications, security, and encryption. QC power could also ultimately provide a solution to key Industrial Metaverse complex system simulation tasks, which would be beyond conventional computing. To be viable, QC processing would need to be available in real time via cloud access, probably in combination with conventional computing power.

14 For an in-depth review of quantum computing technology and impact, see: Meige, Albert, et al. "Unleashing the Business Potential of Quantum Computing." Arthur D. Little, 2022.

"

"Overall, the picture suggests a timescale of five or more years before whole-system digital twins could be realized."

CHAPTER 4

WHAT IS THE POTENTIAL VALUE OF THE INDUSTRIAL METAVERSE TO BUSINESS?

4 What is the potential value of the Industrial Metaverse to business?

In this chapter, we assess the size and future growth of the Industrial Metaverse market, provide an overview of current use cases across different functional categories and industries, and look at potential future use cases that could be possible when the Industrial Metaverse evolves further.

Market size of the Industrial Metaverse

In order to assess the size of the Industrial Metaverse market, it is important to be clear on what is included and excluded.

We have defined the Industrial Metaverse market to include the following:

- All of the digital twin market
- The industrial segment of the VR/AR/MR market, excluding the consumer segment
- Most of the IoT, AI, and blockchain markets (>50%, depending on definitions)

Other Industry 4.0 technologies such as robotics and 3D printing are excluded. Computing and telecoms infrastructure markets are also excluded, as they are relevant for the entire digital market.

Based on this scope, we have looked at a range of market forecasts from different sources to indicate market potential (see Figure 13). Note that we have not conducted any bottom-up primary research.

As shown in Figure 13, the Industrial Metaverse market size in 2023 is in the **$100-$150 billion** range. This is smaller than many existing Industry 4.0 market estimations, which is logical given that it excludes technologies such as robotics and 3D printing.

There is much variability in forecast market growth from Industry 4.0 from different sources, and, indeed, any such forecasts should be treated with a great deal of caution. Our conservative 2030 forecast for the Industrial Metaverse market is **$400 billion**, although the upside could be **>$1 trillion**, with CAGR between 20% and 30%.

This range is wide but in line with previous ADL estimates of the broader Metaverse, which included a conservative $500 billion low end and a multi-trillion-dollar high end (see "The Metaverse, Beyond Fantasy"). Irrespective of the actual number in eight to 10 years' time, it is clear that the market potential is very significant.

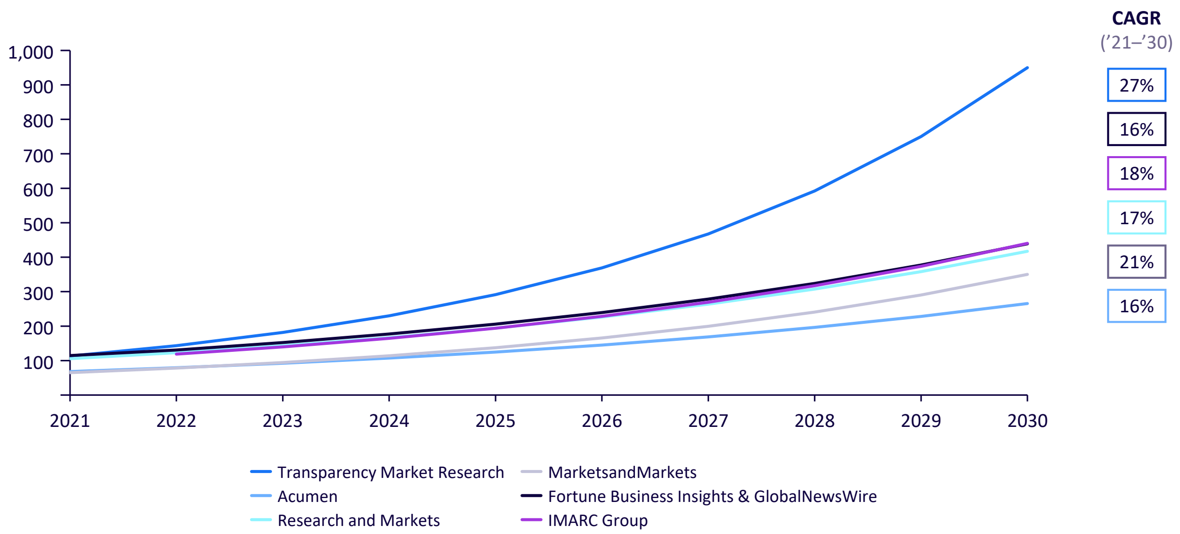
Current Industrial Metaverse use cases

Today's Industrial Metaverse use cases can be broadly divided into four categories: optimization, training, technical tools, and management tools. Each of these has a number of subcategories, as follows:

Optimization

- Plant/line operational-efficiency improvements
- Predictive maintenance optimization
- Product-quality optimization
- Supply chain operational improvements
- Sales operational improvement
- Customer service improvements

Fig 13 — Sizing the Industrial Metaverse market, 2021–2030 (in US $ billion)



Source: Arthur D. Little

There is much variability in forecast market growth from Industry 4.0 from different sources.

Training

- Operational staff training
- Safety and emergency training
- Remote training
- Product training

Technical tools

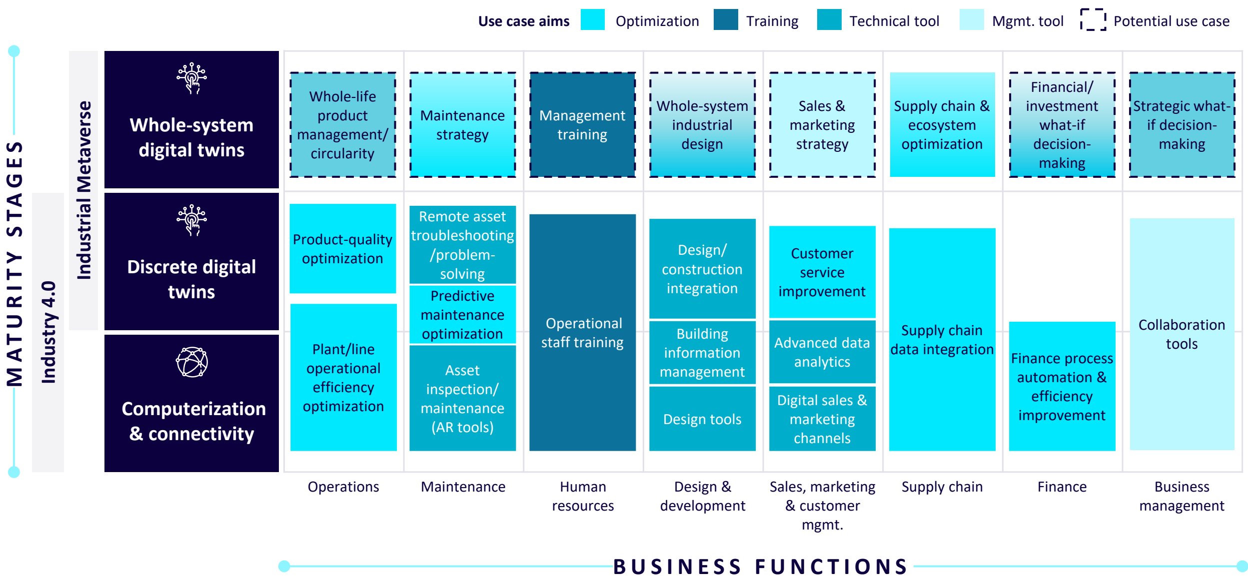
- Design/construction integration and design tools
- Asset inspection/maintenance tools
- Remote asset troubleshooting/problem-solving
- Advanced data analytics
- BIM

Management tools

- Virtual meeting tools
- Virtual collaboration/workshop tools
- Customer-interaction tool

These use case categories stretch across most business functions of a typical company, as shown in Figure 14.

Fig 14 — Current and potential use cases for Industrial Metaverse



Source: Arthur D. Little

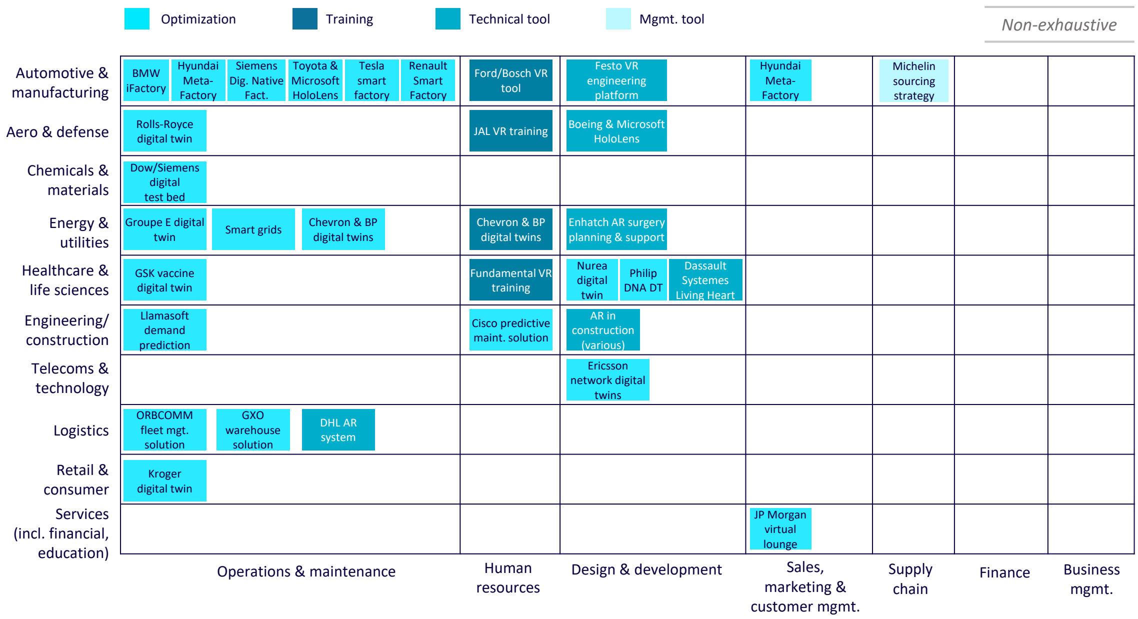
Current use cases cover the first stage of maturity of the Industrial Metaverse, overlapping with Industry 4.0. Please see Appendix 3 for a non-exhaustive list of 30 use cases based on real-world examples and organized by industry, category, and aim. These are illustrated in Figure 15.

Future Industrial Metaverse use cases

Taking an in-depth look at future use cases demonstrates that they provide major breakthrough benefits to large companies by enhancing strategic management effectiveness, as shown in Figure 16.

Although it is impossible at this stage to predict absolute numbers, it is safe to assume that they could deliver double-digit percentage performance improvements.

Fig 15 — Illustrative use cases organized by industry and category



Source: Arthur D. Little

Fig 16 — Potential benefits of future Industrial Metaverse use cases

	Whole-life product management/ circularity	Maintenance strategy	Management training	Whole-system industrial design	Sales & marketing strategy	Supply chain & ecosystem optimization	Financial/investment what-if decision-making	Strategic what-if decision-making
What would be enabled	• Simulate sustainability impacts end to end from raw material to end of life	• Simulate entire maintenance effort including people as well as physical assets	• Extension of VR/AR training beyond operational to include business management	• Holistic, integrated approach to designing products & processes	• Simulate sales networks, customer relationships, customer behaviors	• Simulate entire supply chains & partner ecosystem networks	• Simulate business impacts of financial options	• Simulate business impacts of strategic options
Potential benefits	• Identify sustainability impacts of key strategic decisions & investment options • Identify optimal net-zero growth strategies • Increased control of sustainability impacts, better transparency	• Better design of optimal maintenance strategy, processes & organization • Reduced maintenance costs, improved effectiveness & efficiency	• Provide tailored training in top-level business strategy & management, using whole-system digital simulations • Virtualization of all functional & professional training	• Assess business value-add of new/modified products • Optimize production systems, integrating products & processes	• Better optimization of sales networks & operations • Assessment of likely impacts of marketing strategies	• Optimize sourcing & procurement strategies • Understand better supply chain vulnerabilities & risks	• Better understand overall impacts of acquisitions & divestments • Faster strategic response to changing situations	• Better understanding of unexpected or hard-to-predict outcomes • Find optimized solutions prior to committing funds • Faster strategic response to changing situations

Source: Arthur D. Little

Current players in the Industrial Metaverse

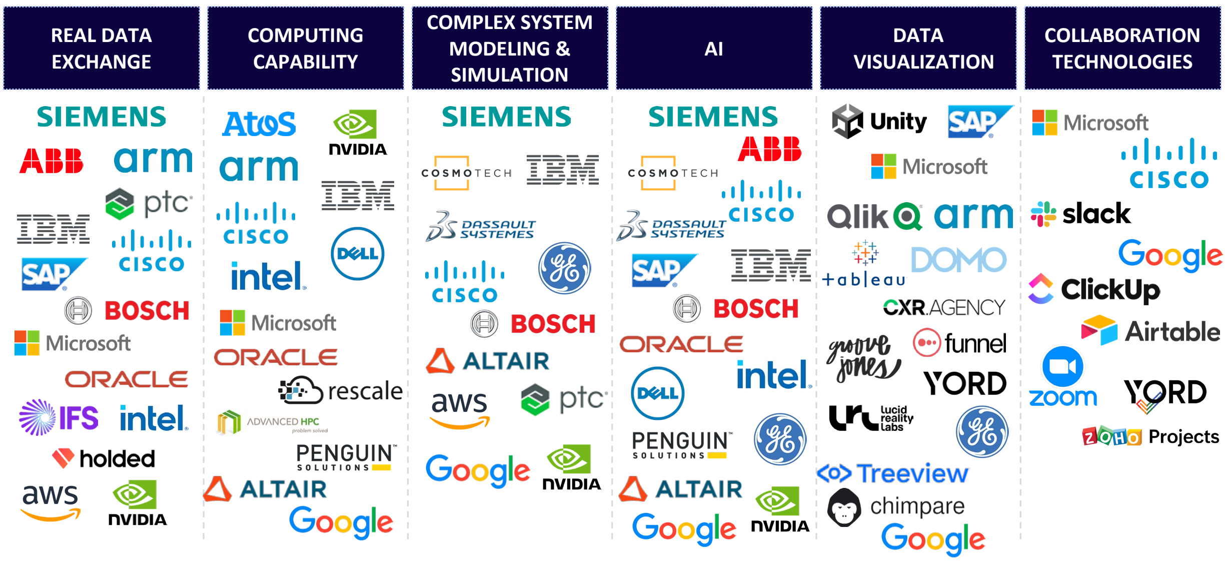
There are hundreds of companies currently active in providing the technologies that underpin the Industrial Metaverse. Figure 17 shows a limited selection of these companies, grouped according to the technology building blocks outlined in Chapter 3. We share more detailed profiles of selected Industrial Metaverse/digital twin players in Appendix 2.

It should be noted that many players are involved in multiple technology building blocks. Obviously, many of these companies are also involved in developing the architecture of the wider Metaverse, as set out in "The Metaverse, Beyond Fantasy."

Many players are involved in multiple technology building blocks.

Fig 17 — Current players in the Industrial Metaverse ecosystem

Non-exhaustive



Source: Arthur D. Little

Recent market movements in the Industrial Metaverse

The Industrial Metaverse market is still relatively immature, with predicted major growth likely to come in the medium term. Given the current pressures on the technology industry, and the Industrial Metaverse's current lack of significant revenues, this has led to the scaling back of some initiatives as part of wider technology industry downsizing. For example:

- In November 2022, Meta announced that it would lay off 11,000 employees, 13% of its workforce. Plans to cut a further 10,000 employees were announced in April 2023.
- In February 2023, Microsoft shut down its 100-person Industrial Metaverse team, founded just four months earlier, as well as closing its AltspaceVR and Mixed Reality Toolkit teams. This was part of a wider 10,000-person downsizing initiative. However, a Microsoft spokesperson stated the company "remains committed to the Industrial Metaverse."[15]

At the same time, multiple companies have recently announced partnerships:

- **Microsoft/Meta (2022)** — product integration between Teams, Office, and Windows software and Meta's VR headsets
- **Microsoft/NVIDIA (2022)** — collaboration on AI, including cloud AI computing, AI applications, and services
- **Siemens/NVIDIA (2022)** — connecting the NVIDIA Omniverse and Siemens Xcelerator platforms to enable full-fidelity digital twins and software-defined AI systems. The partnership is focused on the manufacturing industry
- **Unity/Hyundai (2022)** — developing Meta-Factory, a Metaverse-based digital twin factory to optimize plant operation and allow virtual problem solving

From these recent events, it seems reasonable to conclude that, despite short-term setbacks and retrenchments, which reflect the prevailing global economic climate, the longer-term drivers for Industrial Metaverse growth remain strong. As we have shown, the business benefits are significant, and the barriers toward adoption are less dependent on key obstacles for the broader Metaverse, such as consumer willingness to engage in immersivity and level of realism.

15 Miller, Rosemarie. "Microsoft's Industrial Metaverse Aspirations Can Wait." *Forbes* Digital Assets, 14 February 2023.

“Despite short-term setbacks and retrenchments, which reflect the prevailing global economic climate, the longer-term drivers for Industrial Metaverse growth remain strong.”

CHAPTER 5

WHAT SHOULD COMPANIES DO?

5 What should companies do?

In this chapter, we draw some overall conclusions on where the Industrial Metaverse is today and look at what companies should do to ensure that they respond appropriately to ongoing developments and reap the benefits.

Overall conclusions

The extended and enhanced use of digital twins is at the core of the Industrial Metaverse. Digital twin technology has already existed for many years and is part of many digitalization and Industry 4.0 transformation programs. In this sense, therefore, the first stage of the Industrial Metaverse is already well underway. This is a source of confusion in many discussions where people question whether the Industrial Metaverse is really anything new, or if it is instead just hype. It is the extension of digital twin concepts to cover the entire organization at operational, management, and strategic levels that is the essence of what the Industrial Metaverse will bring in the coming years.

The Industrial Metaverse does not depend fully on general Metaverse adoption in order to be successful. Many Industrial Metaverse applications, such as the use of digital twins for operational improvement, are not heavily reliant on a "perfect" rendering of reality or providing a truly immersive user experience. They also do not depend on full interoperability between competing Metaverse worlds. In this sense, further progress is possible even if adoption of the consumer Metaverse fails to take off, as some observers have predicted.

The convergence of several key technologies is providing a strong driver for Industrial Metaverse development in the coming years. The convergence of further technology developments in real data connectivity, AI, data visualization, collaboration, and complex system simulation, powered by new computing capacity, acts as a powerful driver for progress in the Industrial Metaverse. This is despite shorter-term barriers resulting from global economic conditions.

The key technologies for achieving extended whole-system digital twins are not yet mature, and there are other barriers including data sharing between players. While progress is accelerating in areas such as AI, realizing the next stage of development of the Industrial Metaverse will require further development across all key technologies, as well as overcoming barriers that prevent data sharing between players in an industrial system.

Moving ahead with the Industrial Metaverse is inextricably linked to the digitalization journey. Companies therefore need to consider their strategy for the Industrial Metaverse in the context of their broader digitalization strategy. It will usually not be possible to "leapfrog" to Industrial Metaverse implementation unless digitalization is already fairly mature.

How companies should respond

Essentially, the approach companies should take for moving forward on the Industrial Metaverse should be based around normal IT or ERP system implementation good practice. Generically, we suggest considering four main steps (see Figure 18).

Review strategy: Develop a clear picture of the digitalization strategy, journey & current position

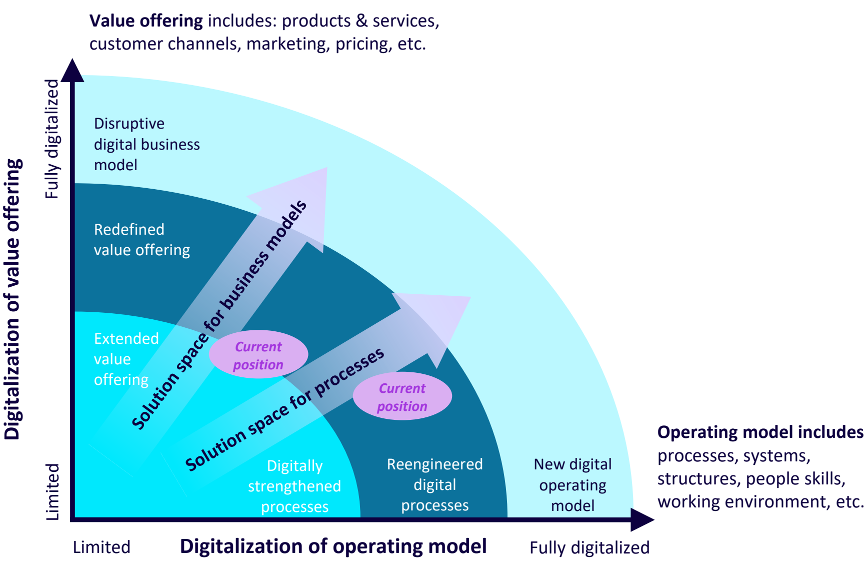
As a starting point, companies must have a clear vision and pathway for their overall digitalization journey. For most companies, this is already far-reaching, starting with the introduction of digitally strengthened processes and value offerings and culminating in fully digitalized operating and business models (see Figure 19).

Fig 18 — What companies should do

1	**Review strategy**	Develop a clear picture of the digitalization strategy, journey & current position
2	**Identify opportunities**	Discover value-adding Industrial Metaverse opportunities & develop roadmap
3	**Implement pilot projects**	Adopt test-and-learn approach & manage change proactively
4	**Build & align ecosystem**	Create win-win situation with ecosystem partners

Source: Arthur D. Little

Fig 19 — Digitalization journey toward Industry 4.0 and beyond



Source: Arthur D. Little

Digitalization usually requires fundamental reengineering and transformation of the business and typically takes place over several years. Understanding the current position on the digitalization journey helps to determine:

- What still needs to be done in terms of digitalization basics before embarking on Industrial Metaverse development (such as data availability and infrastructure)?
- What is a realistic pace of development going forward?
- What would be a feasible target destination to align with the rest of the digitalization journey?

The initial applications for Industrial Metaverse are likely to be along the "operating model" dimension — such as improving the efficiency and effectiveness of engineering, operations, maintenance, and training. Indeed, these are the measures that overlap most with Industry 4.0.

As we have shown, however, an even bigger prize that the Industrial Metaverse can deliver is to enable better and faster strategic what-if decision-making. As an example, if a company's broader digitalization strategy encompasses, say, moving toward high-value digitalized services, changing its role in the value chain, or shifting the boundaries of its business, the use of complex system simulations will be a key enabler to help assess the impact of different business model options prior to committing investment.

Initial applications for Industrial Metaverse are likely to be along the "operating model" dimension.

Identify opportunities: Discover value-adding Industrial Metaverse opportunities & develop a roadmap

The next step involves identifying Industrial Metaverse opportunities that add value and developing a roadmap.

There are many existing applications and uses cases. In developing the roadmap, companies should consider:

- **What potential applications and use cases would add greatest value?** For example, in manufacturing- and process-based sectors, operations, maintenance, and supply chain business cases are often initially the most attractive.
- **What is already technically feasible today versus potentially feasible in the coming years?** As we have seen, although there are many currently feasible opportunities, large-scale complex industrial system simulations are still some way away.
- **What is the vision and ambition for Industrial Metaverse applications in a 5+ years' time frame?** The scale of ambition may depend on the scale of digital transformation that companies may already be committed to.
- **What level of detailed digital modeling is appropriate to aim for initially?** Companies should usually avoid taking on very detailed modeling at the start, since this is not necessary to implement initial use cases. Detailed modeling requires large amounts of data for setup and maintenance, slowing down early progress and diminishing economic attractiveness.
- **What new processes and approaches are needed to manage data?** As well as the use cases themselves, the roadmap should consider what new processes are needed to access, update, analyze, interpret, and act on the required data.

Implement pilot projects: Adopt a test-and-learn approach & manage change proactively

A long-term project pipeline involving learnings capture helps to ensure that there is enough value generation to begin to self-finance the transformation process.

An agile and responsive test-and-learn approach is important in implementing the roadmap, including the following features:

- **Short time to deploy.** Select initial proof-of-concept projects with a relatively short payback time. Ensure that initial projects don't require difficult and time-consuming IT platform upgrades.
- **Start small and prove value.** The first use cases should clearly create value that can be shown internally and externally to the company.
- **Internal projects first.** Start with projects that affect only limited numbers of staff and do not need involvement from external stakeholders.
- **High replication potential.** Try to focus on applications with high replication potential based on currently available technology. Multiple vendors should be allowed to trial their products and services.
- **Manage people impacts proactively.** The internal social impact of Industrial Metaverse implementation should not be underestimated. This may require employees to perform new roles and develop new skills that will require training and support.
- **Be prepared to support adoption over an extended period.** After deployment, employees will need support. The deployment team should not necessarily be the IT department. Using transversal teams helps to broaden involvement and embed the change. Especially for use cases involving field workers, the adoption curve is usually longer than expected. For example, AR/VR devices sometimes have a negative productivity impact initially, so strong support is key, both technically for procedures but also in terms of change management.

Build & align the ecosystem: Create a win–win situation with ecosystem partners

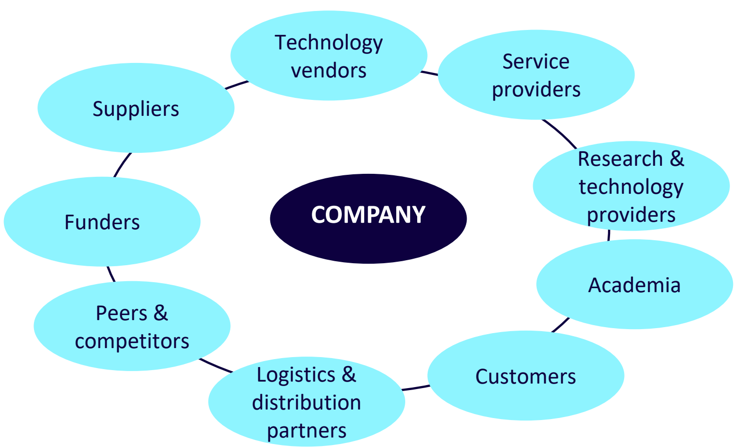
As we have described, the major benefits of the Industrial Metaverse are realized through involving not only internal operations but also the whole partner ecosystem and supply chain. This requires sharing much more data than is traditionally shared between commercial partners, requiring a new mindset and culture.

Moreover, developing the necessary capabilities to implement the Industrial Metaverse will require an ecosystem-based approach. This means that a key step is to actively engage with and align ecosystem partners on the project. For partners to be comfortable with sharing of internal data for this purpose, companies will have to ensure that, for example:

- **The benefits for partners are assessed and demonstrated.** The benefits are likely to be in areas such as faster customer response, reduced working capital, smoother customer/supplier interfaces, easier demonstration of sustainability impacts, greater overall efficiencies, and closer customer/supplier relationships.
- **Data safety and security is ensured.** Ecosystem partners will have to satisfy each other with regard to the safety and security of shared data.
- **Standards are defined and agreed.** Ecosystem partners will have to ensure that there are agreed standards and procedures for data management to manage the risks involved.

An ecosystem approach is essential for the success of the Industrial Metaverse (see Figure 20). Without it, the essential value of a digitally simulated business is hard to realize.

Fig 20 — Building an Industrial Metaverse ecosystem



Source: Arthur D. Little

APPENDIX 1

TECHNOLOGY READINESS LEVELS

TRLs provide a commonly accepted means of describing technology maturity.

1 Technology readiness levels

Fig 21 — Technology readiness levels

Pre-concept refinement	TRL 1	Basic principles are described or observed at theoretical or experimental stage
	TRL 2	Technological concepts are formulated and not yet necessarily tested
	TRL 3	Proof of concept is carried out in a laboratory at the level of technical process
Concept refinement	TRL 4	Technology is validated in the laboratory as a whole
Technology development	TRL 5	Technology model in a production-grade environment is created
	TRL 6	Technology prototype is demonstrated in an environment representative of intended use case
System dev. & demo	TRL 7	Prototype is evaluated in an operational environment
Production & deployment	TRL 8	Complete system has been evaluated and qualified
	TRL 9	Complete system is operational and qualified in production

Source: Arthur D. Little

“The Industrial Metaverse is the extension of what has been called ‘Industry 4.0’ … It is the digital twin of a complex system that allows you to project yourself through time and immerse yourself in space.”

APPENDIX 2

SELECTED COMPANY PROFILES

2 Selected company profiles

Bosch

Founded: 1886

HQ: Gerlingen, Germany

Revenues: ~$79 billion (2021)

Employees: 403,000 (2021)

Highlights

- Digital twin running on AWS
- VR training tool

Selected partnerships

- Amazon Web Services

Relevant products & services (within Industrial Software Solutions division)

- Digital twin — IAPM (Integrated Asset Performance Management) solution
- Digital twin maintenance
- IoT
- AI
- Analytics

Cosmo Tech

Founded: 2010

HQ: Lyon, France

Revenues: ~$4.8 million (2022)

Employees: >100 (2022)

Highlights

- Digital twin platform deployed with Microsoft Azure
- Digital twin platform to train AI
- Simulation for Michelin global sourcing strategy

Selected partnerships

- Microsoft
- SAS
- IBM

Relevant products & services (within Industrial Software Solutions division)

- **Simulation Digital Twins software solutions** — simulation software platform for industrial businesses in manufacturing, energy and utilities, and mobility
- **Cosmo Tech Supply Chain** — planning capabilities for all stages of the manufacturing process
- **Cosmo Tech Asset** — cloud-based solution to make strategic investment decisions for short-, medium-, and long-term operations
- **Simulation modeling** — ability to map real-world systems and their interconnections and relationships to create Simulation Digital Twins
- **Predictive and prescriptive analytics** — simulation and optimization to deliver optimal action plans
- **Platform as a service** — delivering Simulation Digital Twins in a scalable, powerful, and collaborative environment

Dassault Systèmes

Company	Highlights	Selected partnerships
Founded: 1981 **HQ:** Vélizy-Villacoublay, France **Revenues:** ~$5.8 billion (2021) **Employees:** 22,523 (2022)	– Digital twin of human heart – Digital twin of the Eiffel Tower – Plan to create NumSpot — a joint effort to build a European sovereign cloud service for the financial, health, and public sectors	– Multiple

Relevant products & services (within Industrial Software Solutions division)

- 3DEXPERIENCE portfolio — 3D modeling applications, simulation applications creating virtual twins of products or production systems, social and collaborative applications, and information intelligence applications
- Product lifecycle management
- Supply chain planning and optimization
- Analytics, big data, and AI
- Design and engineering
- Design and engineering simulation

General Electric

Company	Highlights	Selected partnerships
Founded: 1892 **HQ:** Massachusetts, USA **Revenues:** ~$74 billion (2021) **Employees:** 168,000 (2021)	– New generation of iFIX and CIMPLICITY software used in HMI/SCADA applications	– Amazon Web Services

Relevant products & services (within Industrial Software Solutions division)

- SmartSignal and Asset Performance Management (APM) solutions — create digital twins based on operational/fleet data of components (pumps or compressors), critical assets (turbines), or systems of assets (an entire power station)
- AI
- Cybersecurity
- HMI

Microsoft

Company facts	Highlights	Selected partnerships
Founded: 1975 **HQ:** Washington, USA **Revenues:** $198 billion (2022) **Employees:** 221,000 (2022)	– Microsoft Mesh collaboration and communications platform – HoloLens 2 (for training) – $10 billion investment in OpenAI	– Meta – NVIDIA

Relevant products & services (within Industrial Software Solutions division)

- **HP Reverb G2** — collaboration with Valve. MR headset that allows users to have a 144-degree field of view
- **HoloLens** — MR headset with sensors, cameras, microphones, and Holographic Processing Unit, enabling:
  - Virtual collaboration
  - Design reviews with spatial recognition
  - Remote user assistance
  - Hosting of virtual meetings

Siemens

Company facts	Highlights	Selected partnerships
Founded: 1847 **HQ:** Munich, Germany **Revenues:** ~$78 billion (2022) **Employees:** 311,000 (2022)	– Partnership with NVIDIA for AI-driven Industrial Metaverses	– NVIDIA

Relevant products & services (within Industrial Software Solutions division)

- Product and process digital twin solutions
- Siemens Xcelerator — open digital business platform for helping to achieve digital transformation
- Open application suites leveraging IoT and AI for different sectors (e.g., rail and buildings)

NVIDIA

Founded / HQ / Revenues / Employees	Highlights	Selected partnerships
Founded: 1993 **HQ:** California, USA **Revenues:** ~$27 billion (2022) **Employees:** 22,400 (2022)	– AI-driven Industrial Metaverse (with Siemens) – Mercedes-Benz to implement Omniverse	– Siemens – Microsoft – BMW

Relevant products & services (within Industrial Software Solutions division)

- **NVIDIA Omniverse** — platform for creating and operating Metaverse applications:
  - 3D design collaboration
  - Modular development platform for building and operating Metaverse applications
  - Large-scale world simulations (including digital twins and training AIs)

Unity

Founded / HQ / Revenues / Employees	Highlights	Selected partnerships
Founded: 2004 **HQ:** San Francisco, California, USA **Revenues:** ~$1.1 billion (2022) **Employees:** 5,200 (2021)	– Acquired WetaFX (digital visual effects)	– Hyundai

Relevant products & services (within Industrial Software Solutions division)

- Unity engine — 3D, AR, VR game platform
- Unity Industrial Collection — software bundle for industrial use
- 3D models — import and optimize 3D data, create and operate immersive experiences, use CAD models to create and operate 3D applications
- Develop and deploy applications — connect HMI development processes and create interactive, real-time 3D product configurators
- Training and simulation

“We will create a future in these metaverses before actually downloading the blueprints to be fab’ed in the physical world.”

– Jensen Huang, founder & CEO, NVIDIA

APPENDIX 3

INDUSTRIAL METAVERSE USE CASES

This appendix contains more than 30 illustrative use cases for the Industrial Metaverse in its current stage of evolution (i.e., discrete digital twins). It is organized by industry and is non-exhaustive.

3 Industrial Metaverse use cases

1. Automotive & manufacturing

BMW iFACTORY — A complete production strategy based on using digital twins for all production sites

According to the company, the main focus of the BMW iFACTORY strategy is on applications from the fields of virtualization, data science, and AI to "link all the relevant product, process, quality and cost data between development, planning, and production processes." Virtualization plays an important role. In a first step, every detail of all the BMW Group's production sites is recorded via 3D scanning and used to create digital twins. Data science provides the foundations for fact-based, real-time, data-based decision-making. Consistent, transparent data allows root causes to be identified quickly and proactively so that processes can be optimized.

"Automotive manufacturing of the future requires a new, holistic way of thinking. With our BMW iFACTORY, we are leading the way and setting new standards in flexibility, efficiency, sustainability, and digitalization."

Milan Nedeljković, Member of the Board of Management for Production, BMW AG

Claimed benefits

- Lean — more flexible, efficient production
- Green — more consistent circularity and better sustainability across the supply chain
- Digital — fact-based/data-based real-time production decision-making
- Earlier integration of new products into the factory, reduction of planning time, investment optimization, real-time collaborations across different locations and time zones

Aim categories

- Plant/line operational efficiency optimization
- Design/construction integration
- Whole-life product management/circularity

Michelin partners with Cosmo Tech to develop simulation digital twins to help optimize strategic sourcing

Michelin's local-to-local strategy is to manufacture a product near the point of sale, which can make strategic sourcing a significant challenge. Working with partner Cosmo Tech, Michelin developed a simulation solution that could account for key indicators such as service levels, CO2 emissions, inventory, plant capacity, distribution, and 1,700 product models within a complex manufacturing and distribution matrix.

The technology allows Michelin to conduct what-if simulations, running more than 80,000 simulations, each with more than 3,000 different and dynamic decision variables, and built-in optimization algorithms to determine the best strategy to adopt. As a result, Michelin was able to identify an actionable strategic sourcing plan for the next five years that would reduce its logistic costs by approximately $11 million annually.

"We've been using digital twins in our product development for the past 30 years. Now, what you can do with simulation digital twins is completely different."

Thibaut d'Hérouville, VP Group Industrial Supply Chain, Michelin

Claimed benefits

- Faster supply lines
- Reduced carbon emissions
- Improved service levels
- Reduced transport and customs costs by more than 60%
- Reduced logistics costs by ~$11 million per year, resulting in higher profits

Aim categories

- Supply chain and ecosystem optimization.

Renault launches Industrial Metaverse project based on factory digital twin that includes supply chain data

Renault Group's industrial digital twin is based on data generated from all of its factories. It has connected 100% of its production lines (8,500 pieces of equipment), monitors 90% of its supply flows, and hosts 100% of its supply chain data in its Industrial Metaverse, which contains a real-time replica of its physical world. The Industrial Metaverse is based on four dimensions: mass data collection, digital twins of processes, connecting the supply chain ecosystem, and a set of advanced technologies.

"The agreement with Google Cloud and Renault Group is an example of the commitment of our teams in charge of IT, production, and supply chain management, that will enable us to accelerate the deployment of our Industry 4.0 plan."

José Vicente de los Mozos, EVP, Manufacturing and Supply Chain, Renault Group

Claimed benefits

- Inventory savings
- Reduction in vehicle-delivery time
- Reduction in vehicle manufacturing carbon footprint

Aim categories

- Plant/line operational efficiency optimization
- Whole-life product management

Hyundai & Unity create Metaverse-based digital twin factory to optimize plant operation & allow virtual problem-solving

A partnership with Unity has enabled Hyundai to create its Meta-Factory concept, a digital twin of an actual factory that is supported by a Metaverse platform that can run virtual tests of factory changes, optimize plant operations, and solve problems without having to physically visit the plant. The partnership includes a real-time 3D and virtual platform, providing Hyundai's customers with a range of services, including sales, marketing, and customer experience.

Hyundai is also working with Microsoft to expand and explore possibilities within AI training and autonomous driving simulation and to accelerate the development of smart manufacturing.

"Hyundai's vision for the future, including the digital twin of factory operations, represents a significant technological step forward in manufacturing with unlimited potential in its efficiency."

John Riccitiello, CEO, Unity Technologies

Claimed benefits

- Increased efficiency
- Fewer physical ("wet") experiments required
- Ability to monitor the physical plant from a virtual platform
- Higher engagement with customers as the Meta-Factory will include a 3D and virtual platform where a range of Hyundai customers will be able to interact with, engage, and test services and solutions across the sales and customer experience

Aim categories

- Plant/line operational efficiency optimization
- Whole-life product management
- Sales, marketing, and customer experience

Siemens digital native factory enables virtual optimization before construction and has helped improve productivity by 20%

Siemens has built a "digital-native" factory by consolidating its R&D, production, storage, and logistics into a single site built with a digital twin. The digital twin enables a continuous optimization loop in near real time. By using data from existing production lines, new production flows can be tested via VR, with employees wearing VR glasses walking around "inside" the new plant, providing feedback used to finalize the factory layout and operations.

"This digital factory is really taking digital transformation to the next level. We were able to reduce time to market by 200%. We have even been able to expand our manufacturing capacity by 200% while improving productivity by 20%."

Yu Rong Zhou, General Manager, Siemens Numerical Control

Claimed benefits

- Optimizing virtually before construction, machine utilization rates were improved and 40% less space was used compared to the previous plant
- Ability to deal with larger volumes, greater flexibility, and optimal placing of materials according to production sequences
- Other benefits include automated painting and packaging, leading to higher productivity thanks to robots while increasing employee safety

Aim categories

- Plant/line operational efficiency optimization
- Design/construction integration
- Whole-life product management/circularity

Tesla implements AI technologies in its manufacturing process

Tesla has implemented a number of AI-powered technologies in its manufacturing processes, including:

- **ML** — analyzing data from its manufacturing processes to identify opportunities for improvement
- **Predictive maintenance** — monitoring the condition of its manufacturing equipment and predicting when maintenance is needed
- **Quality control** — analyzing data from its manufacturing processes and identifying defects or issues that need to be addressed

"I said in the past that Tesla with the Model 3 was probably five to eight years ahead of everybody else, and now, in some cases, I think that in some areas of the car, Tesla is 10 years ahead, especially when it comes to the manufacturing."

Sandy Munro, CEO and automotive engineer, Munro & Associates

Claimed benefits

- Optimization of robot placement
- Reduced downtime
- Improved operational efficiency and product quality
- Earlier identification of defects in the manufacturing process
- Reduced risk of defects

Aim categories

- Plant/line operational efficiency optimization
- Whole-life product management

Toyota is using Microsoft HoloLens 2 to help workers solve issues faster

A Toyota worker was struggling to attach a door edge guard to a vehicle. So, he put on a HoloLens 2 MR headset, opened a holographic window, and called a colleague in California for help. With the ability to see and hear each other as though they were working side by side, he was able to follow the instructions and attach the piece by striking it at the right angle.

"The story shows how HoloLens 2 is a tool perfectly in tune with kaizen, a core Toyota principle of continuous improvement. And it explains why the device has sped out of Toyota's innovation labs and into its everyday workplace."

David Kleiner, Manager, Applied Technology Research Lab, Toyota Motor North America

Claimed benefits

- Collaboration with other departments in different locations
- Hands-free training — remote training through visual aids
- Faster training periods, leading to more time spent on production

Aim categories

- Operations and maintenance
- Training
- Plant/line operational efficiency optimization

Ford & Bosch provide VR tool to service & maintain the Mustang Mach-E without having to access a physical model

In 2019, Bosch developed VR-based automotive service training that Ford piloted in its all-electric Mustang Mach-E SUV. The solution enables technicians to be immersed in a simulated world using a VR headset, where they can diagnose, learn about, and operate the vehicle's components remotely around tasks including the removal and installation of the main battery.

"The virtual reality training solution is about new technology that builds efficiency. By improving the diagnostic process, technicians are able to perform maintenance and make repairs faster and more easily."

Geoff Mee, Director of Operations, Bosch

Claimed benefits

- Help employees to better understand the components and steps required to service a system
- Confidently perform diagnostics and maintenance

Aim categories

- Product training
- Systems operations and maintenance

2. Chemicals

Dow partnered with Siemens to create a digital twin test bed demonstrator

Dow and partner Siemens created a digital twin test bed in 2021 that incorporates state-of-the-art industrial IoT hardware, including sensors, automation controllers, networking, power distribution, and power-monitoring equipment, along with drives and motors. These technologies are used to determine and demonstrate ways to improve factory control, integrate modular automation, and adopt AR and digital twins.

"What's innovative about the test bed is that it demonstrates that integration can be achieved in a uniform way across process operations, but also extending to the enterprise level."

Iiro Esko, Chemical Industries Manager, Siemens

Claimed benefits

- Improved factory control and integrated modular automation
- Faster access to safety manuals, maintenance forms, and other resources to boost productivity

Aim categories

- Training
- Plant/line operational efficiency improvements

3. Healthcare & life sciences

GSK launched a digital twin initiative to create a real-time simulation of the vaccine-manufacturing process

In partnership with Siemens and Atos, GSK launched a digital twin initiative focused on the production of particles of a vaccine adjuvant. Data is combined with physical, chemical, and biological models to build a digital twin of the future vaccine, creating a live, in-silico replica of the physical production processes. Each step in the vaccine-manufacturing process is equipped with sensors.

In addition to production, the digital twin transforms the process of vaccine R&D, where the combination of high-throughput experimentation and twin models quickly produces the data needed to confirm theories, reducing experimentation and optimizing the use of materials and energy consumed.

"With digital twins, you're able to do huge amounts of digital experiments and minimize the number of wet experiments that you do."

Matt Harrison, Head of Sciences, Digital Innovation and Business Strategy, GSK

Claimed benefits

- Reduced manufacturing times and accelerated time to market
- Lower costs through reduced waste
- Optimized product quality
- Digital twin-based experiments can also eliminate the need to build a test facility, a potentially lengthy process

Aim categories

- Plant/line operational efficiency optimization
- R&D optimization
- Advanced data analytics

Philips DNA digital twin will underpin more personalized care

Philips and Illumina have partnered to integrate Illumina's sequencing systems for large-scale analysis of genetic variations and Philips' IntelliSpace Genomics clinical informatics platform and to coordinate associated marketing and sales. The solution will combine data from multiple sources — radiology, immunohisto-chemistry, digital pathology, medical records, and lab tests — to deliver a consolidated dashboard view.

"The value of genomic information for personalized care, and for the treatment of patients with cancer in particular, is tremendous."

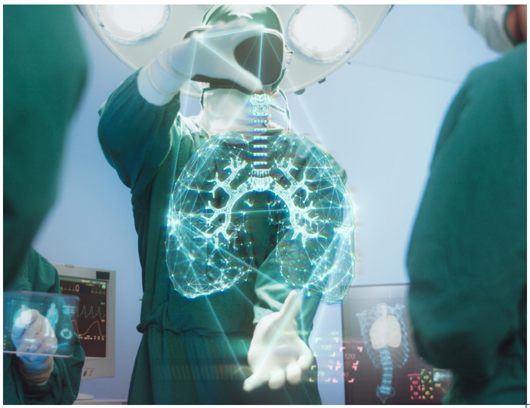
Jeroen Tas, CEO of Connected Care and Health Informatics, Philips

Claimed benefits

- Lower healthcare-delivery costs
- Improved health outcomes
- Ability to develop insights more efficiently

Aim categories

- Advanced data analytics
- Product-quality optimization



Enhatch AR headset provides surgeons with sterile control over critical information

Enhatch has created AR headsets specifically designed for the healthcare industry. These provide surgeons with sterile control over critical information without leaving the operating theater or even taking their eyes from the patient.

"We want to make surgeries better for the patient, but also create a better quality of life for the surgeon by reducing cognitive load."

Peter Verrillo, cofounder and CEO, Enhatch

Claimed benefits	– Access to patient's preoperative images and scans – Better preparation for surgery
Aim categories	– Operational staff training – Virtual collaboration/workshop tools

Nurea has developed AI software to provide cardiovascular information to physicians

Nurea has developed an AI solution for vascular diseases. This enables automated 3D reconstruction of the patient-specific digital vascular twin from CT angiographies. The software allows physicians to easily visualize the evolution of the aortic aneurysm through geometrical data. Based on this technology, Nurea has created the PRAEVAorta decision-making support software. This provides relevant and accurate information and is simple, fast, and intuitive to use around aortic aneurysms.

"By detecting weak signals of the presence of cardiovascular diseases, our aim is to reduce the number of cardiovascular accidents — which cause 18 million deaths a year — by roughly 20%."

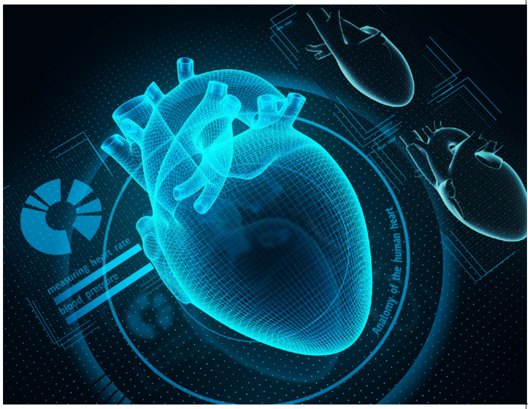
Florian Bernard, cofounder, Nurea

Claimed benefits

- Data visualization of complete information
- Early detection of diseases
- Optimized physician time
- Patient personalization

Aim categories

- Advanced data analytics
- Decision-making support



Dassault Systèmes has created a digital twin of the human heart to help develop, test & validate medical solutions

The Living Heart Project collaboration unites cardiologists, researchers, educators, and regulatory agencies in the development of personalized digital human heart models. The models replicate in vivo conditions and have a wide range of potential uses, including:

- **Education and training** — the ability to train on a full-fledged model of the human heart
- **Medical device design** — to help medical device companies develop and refine ideas faster, leading to more effective and safer products
- **Device testing** — improved testing, accelerated regulatory pathways, and reduced cost and need for clinical trials

Claimed benefits

- Shorten process of developing, testing, and validating drugs and medical devices, saving time and saving lives
- Improved effectiveness of drug and medical devices for cardiovascular applications

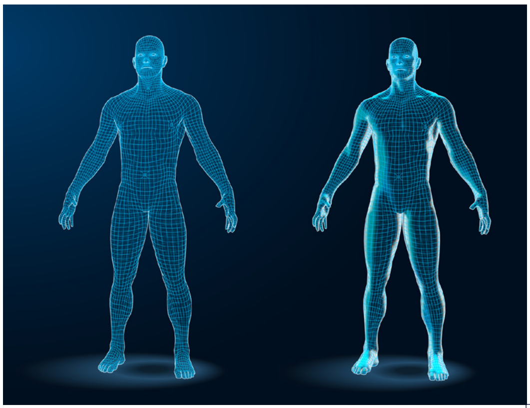
Aim categories

- Operational staff training
- Design/construction integration and design tools

FundamentalVR leverages VR & haptic feedback for more efficient surgery training

FundamentalVR has created a training system that simulates surgery. It is made up of a head-mounted display that allows the visualization of surgery from various angles, along with haptic devices that provide accurate feedback on the surgical process.

Claimed benefits	– Training/experience can be gained anywhere and at any time – Avoids the need to have to practice on actual patients
Aim categories	– Operational staff training



Fraunhofer has created a prototype digital patient model to help personalize & optimize treatment

Fraunhofer has created a prototype digital patient model by merging unstructured, multidimensional health and disease data sets to form a digital patient image, which can be used to test thousands of drugs on the digital twin to identify the best-performing drug for a particular disease.

Claimed benefits	- Provide better patient outcomes - Improve cost-effectiveness of treatments
Aim categories	- Product-quality optimization

Bayer Crop Science has created digital twins for each of its nine US corn seed manufacturing sites

Bayer has created a dynamic digital representation of the equipment, process, and product flow characteristics, bills of materials, and operating rules for each of its nine US corn seed manufacturing sites. These digital twins enable Bayer to perform what-if analyses for each site.

As the commercial team introduces new seed treatment offerings or new pricing strategies, the business can use the virtual factories to assess the site's readiness to adapt its operations to deliver those new strategies. They can also be used for making capital purchase decisions, creating long-range business plans, identifying new inventions, and improving processes.

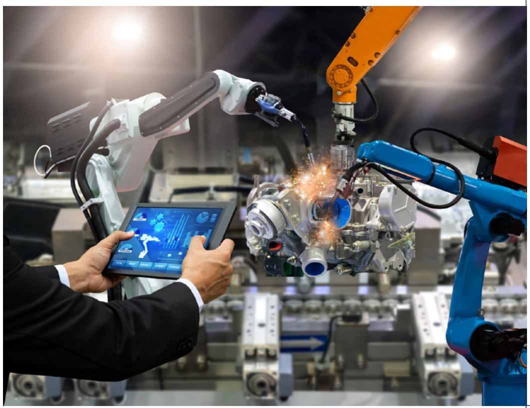
Claimed benefits

- Ability to run more than 100,000 simulations in less than 24 hours
- Ability to answer complex business questions regarding the SKU mix, equipment capability, process order design, and network optimization

Aim categories

- Plant/line operational efficiency optimization
- Supply chain operational improvements

4. Engineering & construction



Llamasoft's demand prediction software uses advanced ML to recognize demand patterns in industrial operations

Llamasoft's Demand Guru predictive demand modeling software uses ML to identify hidden patterns (such as those in seasonal demand or correlations between external weather, demand, and other influences) in historical demand data. Using historical sales data, including information such as date and time of purchase, number of items purchased, and so on, ML models in the system can potentially "learn" a particular trend and predict future demand.

"With Demand Guru, you can model different demand streams and create forecasts with that information. Demand Guru has information on many causal factors, which is not always readily available or readily accessible."

Amit Surve, Sr. Director Supply Chain Strategy and Network Design, Cummins, Inc.

Claimed benefits

- Ability to accurately test and predict multiple demand scenarios for greater confidence in strategic supply chain decisions
- Helps businesses identify ways to cut costs and increase operational efficiency across their supply chains (such as by holding lower inventory)

Aim categories

- Supply chain operational improvements
- Identification of demand patterns

Cisco predictive maintenance enables manufacturers to proactively monitor equipment state & condition to drive better business outcomes

Cisco's predictive maintenance solution creates a systematic framework to collect, transmit, process, store, and analyze IoT sensor data (temperature, vibration, motion, etc.) to drive relevant and actionable business insights. It delivers visualizations of real-time machine data, providing valuable insight into asset utilization, asset monitoring, and machinery health.

"Teams are more reactive, and with a predictive engine they will be able to fix an issue before it happens, which is really a game changer."

Nicolas Gachet, Global Head of Network Special Projects, The Adecco Group

Claimed benefits

- Reduce unscheduled downtime by creating predictive maintenance timelines and avoiding costly repairs or replacements
- Optimize energy utilization by highlighting idle times and peak usage periods
- Enhance human safety and avoid accidents

Aim categories

- Predictive maintenance optimization

Festo's 3D-based open engineering platform enables the intuitive development & efficient commissioning of production systems

The Festo Design Tool 3D is a 3D product configurator for generating product combinations. This makes the engineering process more intuitive and efficient by creating a virtual image of the production plant. All processes and functions of the value chain can be simulated and tested using this virtual image in the planning stage before the system is physically set up.

"Making automation easy starts with the design process."

Dr. Ansgar Kriwet, Member of the Management Board Research and Development, Festo

Claimed benefits

- Through automatic plausibility checks, companies can only select relevant components and configurations when creating systems
- Lower downtime as system modifications are minimized and production can be flexibly adapted to changing conditions

Aim categories

- Design/construction integration and design tools
- Supply chain operational improvements

AR in construction — Multiple providers offer AR technology to view digital information on the construction site

AR and MR software tools allow BIM and other design data to be viewed at the construction site, while allowing reality capture and enabling visual communication with construction management systems. A number of providers offer solutions, including Argyle, Trimble, GAMMA AR, XYZ Reality (HoloSite), and Insight AWP.

Claimed benefits	– Improved efficiency and avoidance of rework – Better communication between construction and design functions – Better QA/QC and error detection
Aim categories	– Design/construction integration and design tools – Asset inspection/maintenance tools – BIM

5. Telecoms

Ericsson has partnered with NVIDIA to build digital twins for 5G networks

The rollout of 5G networks is creating new challenges, particularly as network operators will be deploying over 15 million microcells and towers globally over the next five years. Ericsson and NVIDIA Omniverse Enterprise have created a real-time virtual world simulation and collaboration platform for 3D workflows. This involves building city-scale digital twins to help accurately simulate the interplay between 5G cells and the environment for maximum performance and coverage.

"Before Omniverse, coverage and capacity of networks were analyzed by simplifying many aspects of the complex interactions, such as the physical phenomena and mobility aspects. Now we'll be able to simulate network deployments and features in a highly detailed scale using Omniverse."

Germán Ceballos, Researcher, Ericsson

Claimed benefits

- Faster development cycles
- Better network optimization
- Swifter network deployment through fast insights into where to locate specific products

Aim categories

- Design/construction integration
- BIM

6. Energy & utilities

Swiss grid operator Groupe E uses digital twins to manage its assets & improve investment decisions

Swiss grid operator Groupe E has begun its transformation to a decarbonized, net-zero world. During this process it must be able to justify investment plans while keeping safety and reliability at their current levels.

Through digital twins, Groupe E is able to simulate everyday actions performed on each asset. The company can see exactly what impact different choices have in terms of OPEX, CAPEX, outage minutes, or any other metric. Simulations are performed for long periods of time, typically between 50 and 100 years.

"Getting results over such a long simulation period brings fresh insight into where we currently stand and where we're actually heading. It's only then that we can be sure to make the right decision for the next 10 to 15 years."

Aurélien Lair, Lead Strategic Asset Management, Groupe E

Claimed benefits

- Reduction of energy consumption
- Increased energy efficiency
- Promotion of renewable energy

Aim categories

- Supply chain operational improvements
- Advanced data analytics
- Asset management
- Investment decision-making

Barbara Smart Grids offers operators the ability to visualize the electricity distribution process

Technology provider Barbara has created a smart grid solution that provides all stakeholders in the ecosystem (including transmission operators, energy communities, and retailers) with visibility of all components, enabling greater flexibility. The solution provides a full virtualization of distribution transformers by installing an edge node within them, enabling data monitoring and processing.

"We value the fact that Barbara is technology-agnostic and most of all its agility and flexibility to find solutions to every challenge that emerged along the way."

Enrique Menéndez, Head of Innovation Projects, EDP

Claimed benefits

- Ability to digitize legacy systems
- Greater flexibility, effectiveness, and efficiency in operations and maintenance

Aim categories

- Operations and maintenance
- Advanced data analytics
- Plant/line operational efficiency improvements

Chevron & BP employ digital twins for asset optimization

BP began rolling out digital twins across its production systems globally in 2017. At Argos, its floating production unit, BP has implemented what it calls a "dynamic visual twin," which integrates real-time data and, through ML, can alert human operators to changes over time. The digital twin is also used for virtual training of new operational staff. Chevron is using digital twins for predictive maintenance in its oil fields and refineries and aims to incorporate sensor data from most of its high-value equipment by 2024.

"Fundamentally, it's changed the way we approach the integration of various technologies, such as the digital twin and the use of a mixed reality like the HoloLens. It allows us to be more immersive and to do things onshore and not have to go offshore."

Ken Nguyen, Principal Portfolio Manager, BP

Claimed benefits

- Faster optimization analysis
- Free up facility staff to focus on high-value tasks
- Operate more safely, reliably, and efficiently; reduce costs; recover more resources; and better manage risks

Aim categories

- Plant/line operational efficiency optimization
- Predictive maintenance optimization
- Operational staff training

7. Logistics

GXO provides AI solutions to underpin warehouse of the future

Körber has partnered with GXO to develop Operator Eye — an AI-based solution that tracks error patterns and minimizes downtime and human intervention. GXO uses AI to generate real-time insights from processes and logistics, which in turn permit intelligent decision-making to increase profits and improve efficiency.

"It is important that technology is not boxed off as just physical hardware, as it goes beyond that, spilling into artificial intelligence and machine learning."

Sandeep Sakharkar, CIO, GXO

Claimed benefits	– Helps predict maintenance requirements – Lowers downtime – Improves efficiency
Aim categories	– Plant/line operational efficiency improvements – Supply chain operational improvements – Operations and maintenance (e.g., inventory management) – Predictive maintenance optimization

ORBCOMM's fleet management solution viaFleet allows tracking, monitoring & managing of mobile assets

ORBCOMM's viaFleet application, combined with a vehicle modem and optional additional sensors, enables fleet operators to see the location of mobile assets in real time, monitor driver behavior, streamline vehicle maintenance schedules, and enhance driver communication. This allows users to significantly improve operational efficiency and productivity, minimize liability risk, and improve services.

"Given ORBCOMM's long-standing position as a leader and innovator in cold chain logistics, we made the right choice upgrading to its telematics system, and its excellent service and support have made our transition seamless and exceeded our expectations."

Jeff Bauer, VP, IWX Motor Freight

Claimed benefits

- Reduce fuel costs by optimizing travel routes
- Increase operational visibility
- Increase driver and cargo security by enabling remote control
- Easy and fast to implement
- Service-based solution lowers overhead IT expenses

Aim categories

- Asset and operations management
- Remote asset troubleshooting/problem-solving

DHL uses AR systems to enhance logistics & enable infrastructure layout planning

DHL has carried out a pilot project testing smart glasses and AR in a warehouse in the Netherlands. The technology was used to implement "vision picking" in warehousing operations. Staff were guided through the warehouse by graphics displayed on the smart glass to speed up the picking process and reduce errors.

"Vision picking enables hands-free order picking and greatly increases productivity. The technology significantly supports our staff and brings exciting value to our customers."

Jan-Willem De Jong, Business Unit Director Technology & Automation, DHL Supply Chain

Claimed benefits

- Optimized work streams and reduced costs
- Helps employees to connect remotely, assess, and adapt immersive virtual prototypes
- Increased safety when training employees in operating dangerous machinery

Aim categories

- Logistics improvements
- Plant/line operational efficiency improvements
- Supply chain operational improvements
- Virtual collaboration/workshop tools

8. Aerospace & defense

Boeing deploys Microsoft HoloLens headsets to improve the design process

Boeing engineers around the world will be connected via Microsoft HoloLens headsets to help them with the design and maintenance of aircraft. Additionally, Boeing's goal for its next aircraft is to build and connect digital twins of the aircraft and the production system, in order to be able to perform simulations. These digital mockups are supported by a "digital thread" that ties together every piece of information about the aircraft from its inception — from airline requirements to the millions of parts and thousands of pages of certification documents — extending deep into the supply chain.

"These new digital tools will enable faster, better quality, better communication, and better responsiveness when problems occur."

Dr. Greg Hyslop, Chief Engineer, The Boeing Company

Claimed benefits

- Improved quality and safety
- Reduced manufacturing problems

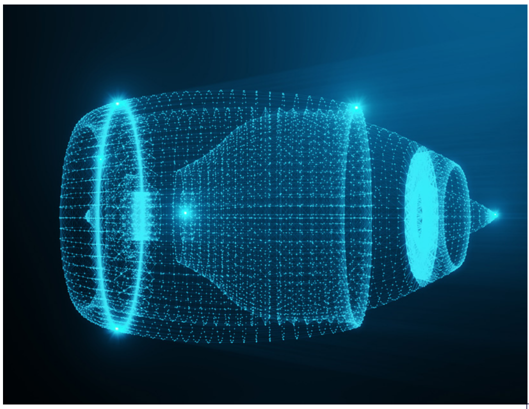
Aim categories

- Design/construction integration and design tools
- Virtual collaboration/workshop tools

Royal Danish Air Force provides fully immersive training on the ground using VR

The Royal Danish Air Force (RDAF) has partnered with VR aviation training provider VRpilot to introduce a fully immersive training experience on the ground. The virtual cockpit solution is specifically tailored to RDAF needs and includes VR headsets as well as a haptic feedback loop in the seat and controls, shared VR simulation for several students at the same time, and the ability for mentors to monitor student performance in real time and change simulation conditions.

Claimed benefits	– Reduced pilot training costs – Flexibility — ability to training in flight maneuvers on the ground as a supplement to actual flight training
Aim categories	– Operational staff training



Rolls-Royce deploys digital twin technology to optimize maintenance & reduce carbon emissions

Rolls-Royce has created a digital twin of each of its aircraft engines that is in service. This includes all data and metadata around the engine: real-time data captured during flights, operational data after landing, data on every original and replaced part, as well as its full maintenance history.

Claimed benefits	– Predictive maintenance effort extends the time between maintenance for some engines by up to 50%, enabling Rolls-Royce to dramatically reduce its inventory of parts and spares – Greatly improved engine efficiency and reduced carbon emissions per flight
Aim categories	– Predictive maintenance optimization

Japan Airlines uses VR content to provide training to flight crew for in-flight preparation & emergency evacuation drills

Japan Airlines uses VR content to train its crews on in-flight preparation and emergency evacuation drills. It includes a head-mounted display, dedicated controller, and voice-recognition software. The system can learn work procedures and areas that need to be checked.

Claimed benefits	– Simulates experience of daily operations as well as those that are difficult to perform, regardless of time and location
Aim categories	– Operational staff training

Amsterdam Schiphol Airport uses digital twins monitor & manage assets

Using a digital twin helps Amsterdam Airport Schiphol monitor and manage all the assets that make up its systems in real time from a single dashboard. The digital twin, known as the Common Data Environment, organizes data from multiple sources: building information model data, geographic information system data, and data collected in real time on project changes and incidents as well as financial information, documents, and project portfolios.

"The airport's digital asset twin provides the opportunity to run simulations on potential operational failures throughout the entire complex, which saves us both time and money."

Kees van 't Hoog, Head of the Development Operations Team, Amsterdam Airport Schiphol

Claimed benefits

- Ability to track and maintain more than 80,000 assets (both indoor and outdoor) from networks, runways, and lighting systems to information booths and fire extinguishers
- The airport can interact with and simulate different predefined scenarios, optimizing operations and saving money and time

Aim categories

- Predictive maintenance optimization
- Plant/line operational efficiency optimization

9. Retail & consumer

Kroger digital store twin will optimize performance & customer experience

Kroger and NVIDIA have built an AI lab and demonstration center to improve Kroger's shipping, logistics, and in-store shopping experience. This involves creating a digital twin of actual store layouts used to predict how a particular product will perform through real-time data. This will enable Kroger to optimize its in-store efficiency and processes.

"Our collaboration with NVIDIA supports Kroger's 'Fresh for Everyone' commitment. We look forward to learning more about how AI and data analytics will further our journey to provide our customers with anything, anytime, anywhere."

Wesley Rhodes, VP Technology Transformation and Research & Development, Kroger

Claimed benefits

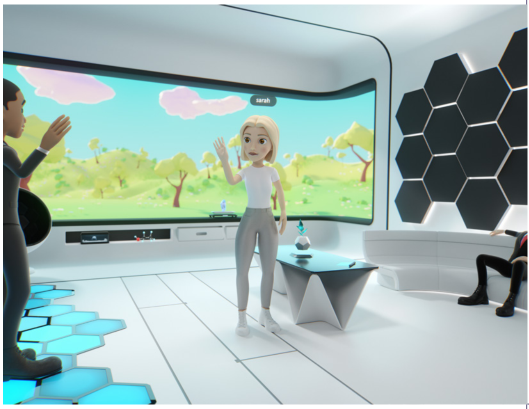
- Improve store efficiencies and operations
- Reduce checkout wait times

Aim categories

- Supply chain operational improvements
- Sales operational improvements
- Operations and maintenance
- Customer experience

10. Financial services

JP Morgan has opened a virtual lounge in the Metaverse to offer financial services



Aiming to play a major role in the Metaverse, JP Morgan has opened its Onyx virtual lounge. This provides a blockchain-based platform for the exchange of value, information, and digital assets. Onyx offers cross-border payments, financial assets creation, foreign exchange, trading, and safekeeping. The lounge provides the opportunity to experiment with decentralized finance collateral management.

"We are not here to suggest the Metaverse, as we know it today, will take over all human interactions, but rather, to explore the many exciting opportunities it presents for consumers and brands alike."

"Opportunities in the Metaverse." JP Morgan Chase & Co., 2022.

Claimed benefits	- Ability to offer full suite of payment services offerings (e.g., microloans, wallets)
Aim categories	- Customer-interaction tools - Customer experience - Financial services

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Luc Julia, Chief Scientific Officer, Renault
Xavier Perret, Director, Azure, Microsoft France
Michel Morvan, Executive Chairman & cofounder, Cosmo Tech
Hugues de Bantel, CEO & cofounder, Cosmo Tech
Thomas Lacroix, CTO, Cosmo Tech
Yves Caseau, Chief Digital & Information Officer, Michelin

Blue Shift, by Arthur D. Little, explores the impact of technologies on business, society, and humans. The Blue Shift Report covers these topics in depth, inviting guest authors, academics, and artists to contribute to the conversation.

Want to join the discussion? Please address your comments to our editorial office at Arthur D. Little, New Fetter Place West, 2nd floor, 55 Fetter Lane, London EC4A 1AA, United Kingdom — Telephone: +44 7710 536 471.

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