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INTELLIGENCE REPORT

The Digital Twin Age: Using simulations to boost real-world business

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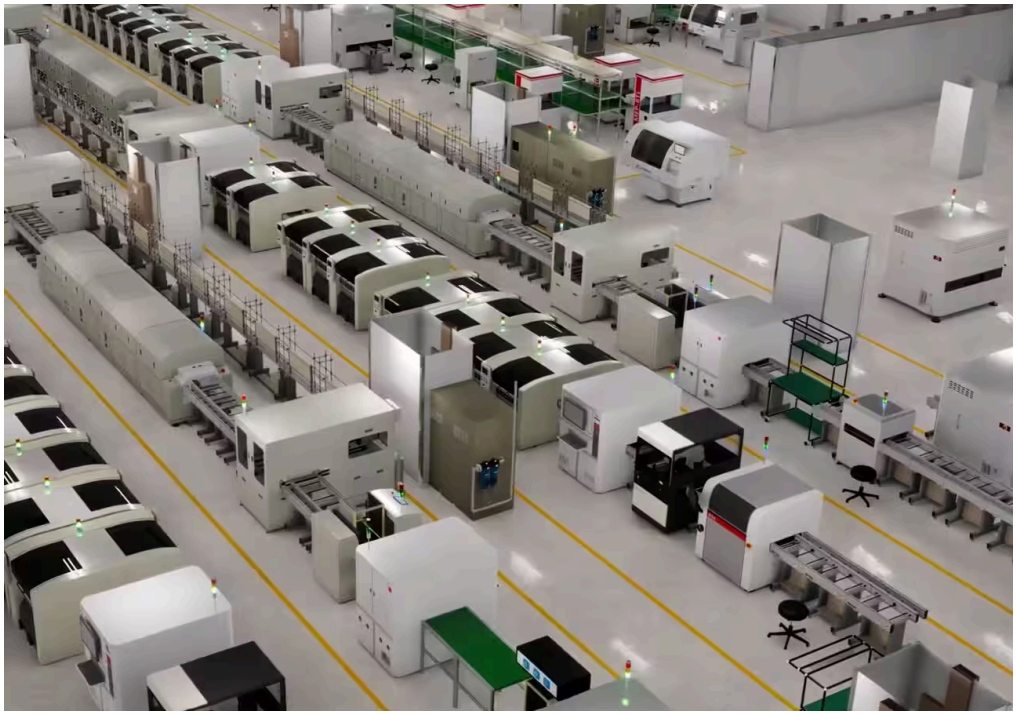
New virtual technology is fundamentally changing how companies plan and run their physical operations to be more reliable and efficient



A digital twin of a Wistron factory, which the company credits with bringing the physical factory online in half the time. (Courtesy of Nvidia / Wistron)

Key Takeaways

Virtual technologies are changing how businesses plan and operate factories and other facilities. "Digital twins" have evolved from static design tools to dynamic, predictive systems that mirror real-world assets. By integrating real-time operational data, these models allow companies to optimize facility layouts, predict component failures, and identify design glitches before construction even starts.

The technology provides a strategic asset for U.S. manufacturing, significantly shortening the time between planning and production. For example, tools from Nvidia and Siemens are enabling Foxconn to bring an advanced AI-server plant online in Texas in just seven months, compared to the typical one-to-two-year timeline.

A major challenge in training AI is the lack of physical-world data compared to text data. Companies are working to overcome this by using generative AI and physics-based models to synthesize data, creating a "renewable source" of information.

"Living" digital twins provide critical operational insights that can help mitigate unplanned downtime that costs large global companies an

estimated $1.4 trillion annually. Functioning like “instant replay” in sports, these systems let technicians review historical data to find the root cause of disruptions, and even suggest preventative fixes to problems before they occur.

Summary: Using virtual worlds for real business impact

The tech industry hasn’t always delivered on its promise for digital realities. The much-ballyhooed metaverse — where our avatars supposedly would shop and socialize — has failed miserably to live up to the hype of a few years ago.

But, in the business world, the idea of parallel realities is only gaining momentum. Advances in artificial intelligence and other technologies are generating a tectonic shift in the way factories, warehouses, and other facilities are designed and run — enabling high-fidelity simulations that can help companies increase efficiency and reduce disruptions in the physical world.

Far beyond the static, computer-assisted designs of years past, these “digital twins” can be dynamic and predictive. Businesses such as the automaker BMW Group and the electronics manufacturer Foxconn are using technology from companies such as Siemens, Autodesk and Nvidia to optimize layouts and fix in advance the kinds of design glitches that otherwise might not be discovered until launch.

After production starts, these virtual facilities can run in parallel, integrating actual operational data from the array of sensors known as the industrial “internet of things” to spot potential problems early — and anticipate when components will wear out, or how safety problems might arise.

Variations of this digital twin technology are being deployed across industries from manufacturing and logistics to retail and energy. It is also being embraced by governments around the world for planning and vetting things like infrastructure proposals. A bipartisan group of U.S. lawmakers recently introduced a bill to require the Department of Transportation to

embrace digital twins to accelerate the evaluation of proposed infrastructure projects.

Done right, digital twin technology can shorten the time from planning to production in a way that companies say could help efforts to build out American manufacturing. And it is being used to develop more advanced robotic systems — so-called “physical AI” — as companies look to further automate their facilities to meet serious labor shortfalls.

Capitalizing successfully on this boom isn’t simple. It requires companies to improve the quality of their data systems, train staff and navigate the complexities of a fast-moving technology to use it effectively.

“The pace at which things are happening is like nothing else I’ve ever seen,” said Todd Bengtsson, a decades-long veteran of manufacturing technology who is director of manufacturing portfolio and strategy for Siemens Digital Industries Software, a unit of the German industrial giant. “Being able to apply the right technology in the right place, and not misuse it in the other areas, is something we’ve all got to discover.”

Digital twins have cross-sector reach:

AGRICULTURE

- Optimize agricultural supply chains
- Improve precise models for expected yields.

OIL AND GAS

- Provides improved simulation of drilling scenarios, reservoir behavior, and supply chains
- Maximizes extraction and overall efficiencies.

PORTS

- Replicate their energy consumption to simulate an energy transition to climate-neutrality.

CONSTRUCTION

- Monitor the process and identify potential problems
- Ensure projects are completed safely, on schedule, and within approved budgets.

RETAIL

- Enhance data analysis.
- Optimize re-stocking.

UTILITIES

- Manage real-time data.
- Integrate analytics systems that may have previously been siloed through government bureaucracy.

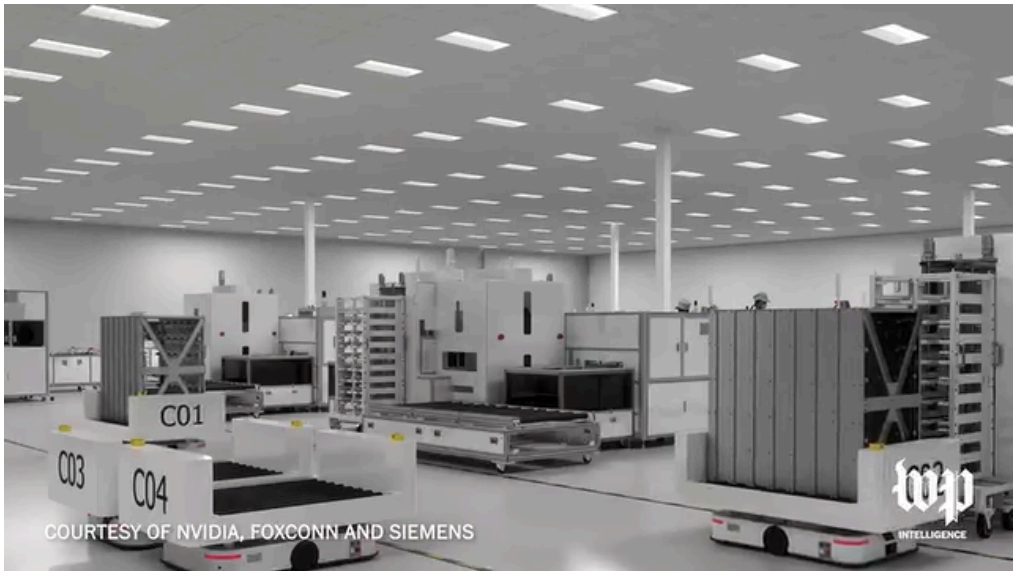
Analysis: How digital twins are changing corporate operations

On the outskirts of Houston, Foxconn is building one of its most futuristic factories. The world's largest manufacturer of electronics — which is famous for producing the iPhone — plans to use humanoid robots and other cutting-edge technology at the plant to build servers for Nvidia's most advanced AI chips.

But before the factory is constructed in Texas, it is being built in a virtual world. New simulation technology enables planners to lay out the inside of the factory, place digital copies of the manufacturing and testing equipment, and simulate the traffic patterns that will be taken by the factory's human employees and autonomous workers to maximize the chances they will move efficiently and safely.

Mike Geyer, Nvidia's head of industrial digital twins, said the factory will be able to get through the planning phase and come online in about seven months, compared to one to two years for a typical factory.

On a recent morning in the AI giant's Silicon Valley headquarters, Geyer demonstrated a Digital Twin Builder tool that Siemens has been developing, using it to place various pieces of virtual equipment on a screen into a realistic-looking version of a planned server-testing room inside the Foxconn facility. He then demonstrated how operating the equipment virtually can enable testing of decisions such as the placement of chiller units and the optimal number of servers moving through the system at any one time.



Foxconn's digital twin shows testing of traffic patterns in the planned plant to avoid robot-human collisions.

On another screen, Geyer showed how a similar technology has been used to develop a virtual version of a giant logistics facility, navigating through towering conveyor belt systems as boxes whizzed by. The system's virtual eye zoomed in on a section where robotic arms were sorting packages in location, then shifted to observe the foot traffic for virtual employees. "This

is not just a static digital twin, this is actually a living, breathing model of the facility," he said.

How digital twins evolved from CAD

Digital twins such as the one Geyer was working with are the descendants of the computer-aided design, or CAD, systems developed late in the last century for designing buildings and industrial products — but digital twins are far more capable.

Today's twins are highly detailed digital models of complex systems — they can be power grids, refineries or even supply chains — that can mirror the behavior of the real infrastructure so that companies can simulate a huge range of scenarios and contingencies without putting real assets or people at risk. Digital twins are useful for exploring how systems might respond in cases of an equipment failure, say, or a weather disaster — and design strategies to head off costly problems.

Several factors are accelerating the development of digital twins. Artificial intelligence can help integrate data buried in company operations. Advanced computing systems enable the incredibly complex operation of these virtual systems and the creation of synthetic data to enhance realistic testing. Generative AI can simplify the ability of humans to interact with these systems and, with AI agents, enable automated responses when the systems discover issues including parts that need replacing.

The effort to digitize the building process gained new momentum several years ago alongside the explosion of the explosion of hype over the metaverse — the idea of an all-encompassing internet that drew Mark Zuckerberg to rename his company from Facebook to Meta Platforms in 2021.

That same year, after beta testing, Nvidia launched Omniverse Enterprise, its platform for AI-enabled tools, applications and services for industrial digitalization. And Autodesk launched Tandem, its digital twin platform, which is designed to incorporate data from the construction phase into a new model that can live on after the facility is built.

How an industrial technology grew out of 'Toy Story'

While Meta is shifting spending away from the consumer metaverse after nearly $80 billion in losses, industrial systems for making virtual realities have taken off.

This modern digital twin technology shares roots with Woody from "Toy Story." For its animated features, the film studio Pixar developed a set of rules governing the descriptions, traits and behaviors of physical spaces in its imagined worlds. A decade ago, Pixar decided to release that set of rules as an open-source standard called Universal Scene Description, or OpenUSD.

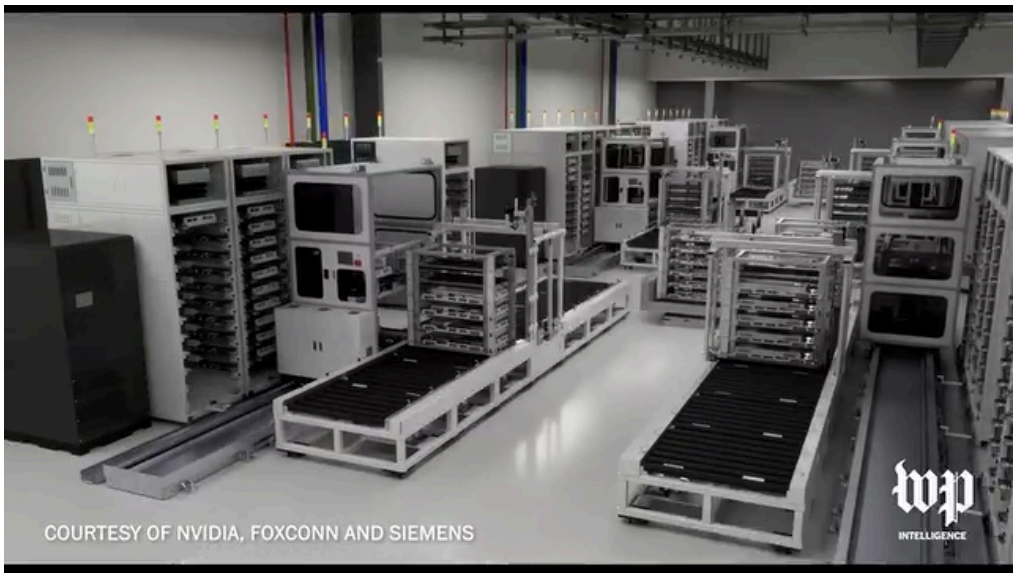
Initially intended for makers of movies and video games, OpenUSD was adopted by companies with broader industrial ambitions as a way to standardize the treatment of objects in digital twins. In 2023, Pixar and Nvidia, along with Autodesk, Adobe and Apple, formed the Alliance for OpenUSD to promote this interoperable standard for tools and data across the 3D ecosystem.

Rev Lebaredian, Nvidia's vice president for Omniverse and simulation technology, likens the utility of OpenUSD to the way HTML standardized the system for making and using websites, providing a common language for different companies to build digital components that can interact with each other.

"Describing, in a standard way, every aspect of everything in the physical world is really tough," he said, adding that there is still a lot more work needed to refine the system. "We're kind of at the beginnings of that," he said.

An asset for America's manufacturing push?

The business ramifications of digital twin technology are potentially huge. Industry executives say it can help reduce disruptions that are extremely costly. Unplanned downtime costs the world's 500 biggest companies $1.4 trillion, or more than a tenth of their revenue, according to an estimate from Siemens.



Virtual equipment is placed in the digital-twin version of a testing room at a Foxconn plant that will produce AI servers.

Proponents say that digital twin technology's ability to streamline the planning and building of new factories will be critical for meeting U.S. ambitions for rapidly reviving manufacturing as the Trump administration looks to replace imports and reduce the country's reliance on Chinese production.

"We don't have time to do that with the pace that it was done at until now," said Ales Alajbegovic, a global program manager Siemens Digital Industries Software. "If we want to be successful, we have to do it at a pace that is unprecedented so far, and the only way that's going to be possible would be with AI."

Siemens, a pioneer in industrial technology, is betting big on digital twins, with CEO Roland Busch planning announcements around its offerings at the CES technology conference next month in Las Vegas.

Creating data for virtual worlds

One challenge of creating realistic virtual worlds is a dearth of data — not only company-specific data but general information about the physical realities that real-world systems might encounter. That information is scarce compared to the oceans of text used to train the large language models at the heart of most generative AI applications.

“We have petabytes and petabytes of this [language] data sitting around on the internet already,” said Nvidia’s Lebaredian. “But information about the physical world, to feed examples into these AI factories to produce the algorithms we need about the physical world, that’s not readily available.”

Nvidia is attempting to solve that by synthesizing data, based on models of real-world physics that it builds in Omniverse, to replicate as realistically as possible what the inside of a warehouse or other building looks, feels and acts like.

“Once we have that, we essentially have an unlimited source of information about the physical world,” said Lebaredian. “It’s a renewable source of data.”

This is useful not only for digital twins but for training robots — the “physical AI” that has the potential to greatly expand AI’s economic impact. For all of its limitations, synthetic data enables roboticists to educate the brains of their creations in ways that otherwise wouldn’t be possible.

“The twin has become a ‘gym’ where robots learn to walk, grasp and navigate before they ever touch a physical object,” said Colin Masson, director of research for industrial AI at ARC Advisory Group and a former longtime manufacturing-technology director at Microsoft.

Moving from planning to parallel operation

Actual real-world data also is vital for digital twins to go from simple construction-planning tools to parallel virtual operations.

Enabling that kind of living twin — with data flowing in real time between a plant and its virtual doppelganger — is one of the most important recent advances in twin technology.

Living digital twins can combine specs and maintenance data for all the factory's machinery with live information about how those components are operating and interacting. They can be used to catch operational problems before they spread, or even to predict issues before they happen.

A living digital twin can, for example, tell a facility technician not only the location and current performance level of a potentially faulty factory machine, but its past performance hours or weeks ago, its maintenance history, where the shutoff switch is, and which processes or people would be affected by a malfunction.

"That's game changing, just having that data at their fingertips," said Robert Bray, the Autodesk vice president who manages Tandem, its digital-twin platform business.

Like instant replay for industrial mishaps

One Autodesk client, a large manufacturer in the U.S., is implementing Tandem on a single paint line in an older factory. Among the changes it is enabling, Bray said, is that the company no longer needs an employee to walk the line once per hour with a clipboard capturing sensor readings and inputting them into a spreadsheet.

That data is now captured and incorporated automatically to enable analysis and troubleshooting of the line's equipment. Bray says the changes will save the company an estimated $400,000 a year.

When a disruption does happen in a factory or other industrial facility, staff are focused on fixing it as quickly as possible — and then trying to recover lost production. There may not be time to perform a detailed examination of what really triggered the incident.

With sufficient data captured in the virtual version of the plant, technicians can review the episode repeatedly to determine the root cause.

"Think of it like the instant replay in a football game," said Siemens' Bengtsson. "I have the time in the digital world to do that where, in the physical world, I had no time."

The skills gap and other limits

As with any AI-related technology these days, there is a risk of getting carried away with hype over digital twins. While the systems help, they can also create false confidence, according to people who have used them. Virtual simulations are not a guarantee of readiness for real-world events, which almost always contain elements that were not anticipated in the simulations — especially in modern power systems, where critical dynamics often unfold along nanosecond timescales.

Aspects of the technology are still in their infancy, in particular the use of AI to recommend decisions based on virtual modeling. AI's black box means you can't look behind the curtain of the logic behind AI-driven decisions, which can have disastrous consequences when modeling for critical infrastructure. Ultimately, human operators remain legally responsible for any outcomes.

And executives also say there is a dearth of people who understand how to use the technology. "The skills gap is a major bottleneck," said ARC Advisory's Masson.

Making virtual cars to avoid real-world production problems

Still, several industries are adopting the technology, with auto manufacturers among the most aggressive.

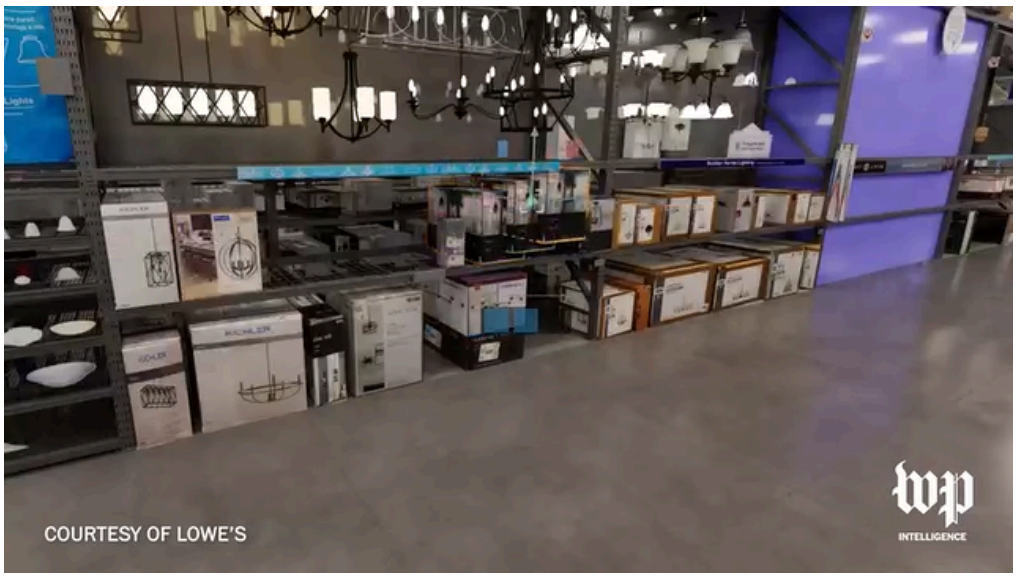
BMW, for example, has projected that its "Virtual Factory" will reduce production planning costs by up to 30 percent. The system links building, equipment, logistics and vehicle data to simulate processes at over 30 production sites — which the company is using to do testing in advance on the production of more than 40 new or updated vehicles planned to go into production by the end of 2027.

Car manufacturing is a precisely choreographed process. Updating a production line to make a new model with, say, a longer hood risks introducing physical collisions in the process that could hamper production or hurt vehicle quality.

So BMW is modeling the precise movement and rotation of its vehicles through the production lines to automatically check for any possible collisions — vastly simplifying a process the company has said previously required almost four weeks of real testing.

Where digital twins are useful

Retailers also are using the technology to enhance data analysis and optimize restocking. In-store associates can use a store digital twin in real time to see which products in which places need replenishing, while sales teams can analyze customer heat maps and simulate alternative traffic setups to optimize sales.



A digital twin of a Lowe's retail store allows associates to monitor inventory in real time and enables sales teams to analyze customer movement patterns and test store layout configurations.

“The platform understands the location and status of almost everything in the store, including signage, fixtures, landmarks, equipment and even, in some cases, devices used in-store,” said Chandhu Nair, senior vice president of data, AI and innovation for Lowe’s. “It opens the door to faster

decisions, smarter operations and, ultimately, a more seamless experience for customers."

Modeling supply chains

Twins aren't just for buildings; companies can use them to model other systems as well. The complexity of supply chains — collections of warehouses, transportation fleets and inventories belonging to both a company and its vendors — provides a natural opportunity for virtual simulation, said Alex Cosmas, a senior partner who leads advanced analytics for the logistics sector at McKinsey & Company.

Every small decision in supply chain management — for example, which warehouse to use to meet a particular order — can affect the ability to make other decisions several steps down the line, a game of 3D chess so complicated that it lends itself to digital modeling, said Cosmas. "You can't expect a human supply chain workforce to play that game of inches," he said.

Government use for planning and approvals

Governments around the world are using the technology for activities ranging from evaluating projects to modeling disasters.

Singapore's government is using a digital twin that cost approximately $56 million to enhance public planning and weather resistance. Flash floods are a particular problem for the low-lying city-state, and the twin, "Virtual Singapore," helps officials model protective infrastructure and continued real estate expansion within its limited surface area.

Some U.S. city governments also are using digital twins, but the federal government's interest for years has been seen as lackluster. Trump administration officials haven't talked up digital twins, despite their potential for aiding the White House's manufacturing push.

Still, there is some indication that interest in Washington is growing — particularly around uses for transportation. Two of the teams announced this month by Transportation Secretary Sean P. Duffy as finalists in an

innovation contest run by his department's Advanced Research Projects Agency - Infrastructure (ARPA-I) were focused on using AI-powered digital twins to simulate the effects on urban transportation networks from the rise of autonomous vehicles, for example.

And last month, Sens. Mark Kelly (D-Arizona) and Cynthia Lummis (R-Wyoming) introduced a bill called the SMART Infrastructure Act (short for Streamlining Modeling for Advanced, Rapid Transportation) intended to overhaul development of critical transportation infrastructure by using cutting-edge digital twin technology. The bill would compel the Transportation Department to establish guidelines, pilot programs, and agency coordination to adopt digital twins for vetting and approving new projects.

What's next: AI automation

The next phase of digital twins entails greater use of AI to not only detect issues but respond.

AI agents inside a digital twin could, for example, send commands to physical equipment to optimize performance without human intervention, said Masson. Or they could use live data to automatically create a work order to fix or replace a piece of equipment before it stops performing well.

Agentic AI broadly is still in its early stages of development, and AI's penchant for making errors means users should be cautious in handing it the power to actually make decisions in digital twins, said Autodesk's Bray.

The use of agents is "more hype than reality right now," said Bray. But customers are pushing for it, and the potential is clear for agents to at some point be able to automatically make adjustments based on production needs or other factors. For now, he recommends caution, starting with recommendations rather than actually enabling agents to make decisions.

Recommendations: Building data and skill sets

1. Start small and build. Companies that want to deploy digital twins don't need to start with an entire factory. Even implementing digital twins on a narrower scope initially — a single production line, say — provides an opportunity to adapt the technology to a company's unique datasets and practical needs. Autodesk's Bray said too many companies think they have to boil the ocean at the outset. "The most common misconception is just that it's too hard. And I think that is just false today," he said.

Most companies already have the bulk of what they need to start the process, even if it might need better organization. "What surprises most of our clients," said McKinsey's Cosmas, "is that they've already got, in house, 70 percent to 80 percent of the logic and the data in their legacy systems that's necessary to build a twin."

2. Start with marshaling your data. To make digital twins work, businesses need clarity on what data they have about their operations and where it is stored — from production-line sensor data to machinery maintenance information stored in PDF files. And they need to ensure it is accurate, accessible and contextualized — where sensors are relative to each other, say. Success requires moving information in real time between a facility and its twin. ARC Advisory's Masson says problems with data quality and availability are the number one reason for failure of digital twin projects in their surveys.

AI can help to fill in some of the gaps in sparse datasets, but slapping a digital twin system on top of messy, siloed data won't work. In fact, Masson said, data quality is now more critical than ever, because AI can amplify the negative consequences of poor-quality inputs. "Bad data can destroy model accuracy and be propagated instantly across the enterprise, leading to automated decisions that are physically dangerous or financially disastrous," he said.

3. Be realistic about the challenges. Despite its advances, digital twin technology is still evolving. While vendors are working to make digital twin systems more standardized and off-the-shelf, they still need to be customized to companies' bespoke needs, systems and software environments. When models become too complex, they can actually become less useful: It may take too long to set up scenarios, run tests, and

work around approximations and limitations, which reduces the practical value for day-to-day operations. And human judgment remains essential — users need to avoid "automation bias," our tendency to assume that algorithmic recommendations are accurate.

4. Build needed skill sets in employees. Capitalizing on these virtual tools requires not only the right technological setup but the ability of employees to operate effectively in these twinned worlds. "Probably the biggest bottleneck to us using simulation to build better things in the physical world is just the lack of people and expertise in terms of using these kinds of tools," said Nvidia's Lebaredian. Masson said companies need to invest not only in data scientists but in "context engineers," who understand the physics of the machinery and its place in an operation, to be able to make the most use of digital twins.

Nour Wood contributed to this report.