MIT Technology Review Insights

Next-level automation, driven by the convergence of advanced technologies—particularly robotics and AI—is poised to transform industry.

A vision for the future of automation

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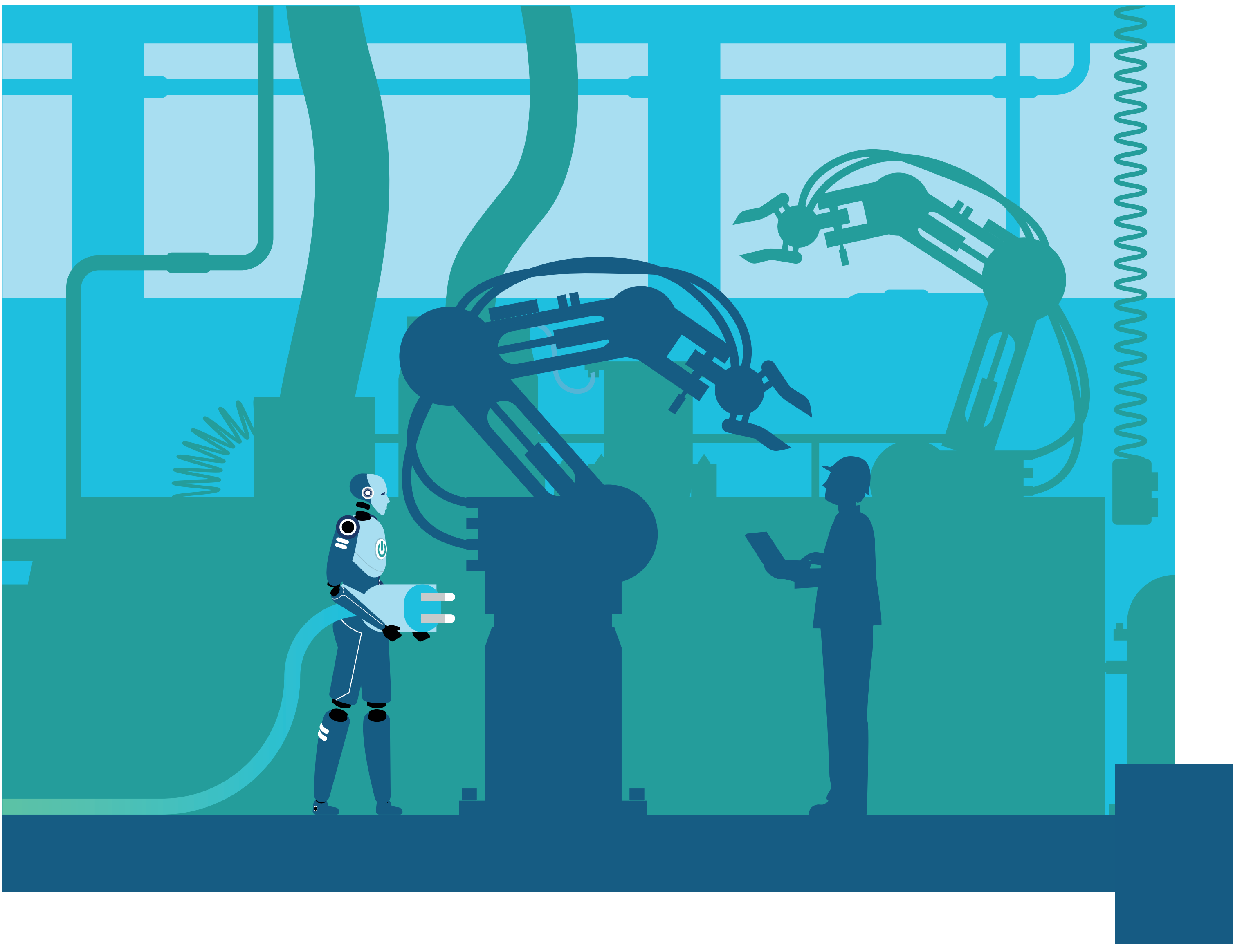


Key takeaways

1. The future of manufacturing likely will be driven by the convergence of software and hardware, bringing seamless connections between digital and physical processes and technologies.

2. Flexible, adaptive automation and AI co-pilots aim to replace today's task-oriented automation, enabling production adjustments in real time.

3. Companies need to think beyond efficiency and cost savings for their automation programs – automation could be key to scaling operations and solving labor challenges.

The manufacturing industry is at a crossroads: Geopolitical instability is fracturing supply chains from the Suez to Shenzhen, impacting the flow of materials. Businesses are battling rising costs and inflation, coupled with a shrinking labor force, with **more than half a million unfilled manufacturing jobs in the U.S. alone**. And climate change is further intensifying the pressure, with more frequent extreme weather events and tightening environmental regulations forcing companies to rethink how they operate. New solutions are imperative.

Meanwhile, advanced automation, powered by the convergence of emerging and established technologies, including industrial AI, digital twins, the internet of things (IoT), and advanced robotics, promises greater resilience, flexibility, sustainability, and efficiency for industry. Individual success stories have demonstrated the transformative power of these technologies, providing examples of AI-driven predictive maintenance **reducing downtime by up to 50%.** Digital twin simulations can significantly reduce time to market, and bring environment dividends, too: **One survey found 77%** of leaders expect digital twins to reduce carbon emissions by 15% on average.

Yet, broad adoption of this advanced automation has lagged. "That's not necessarily or just a technology gap," says John Hart, professor of mechanical engineering and director of the Center for Advanced Production Technologies at MIT. "It relates to workforce capabilities and financial commitments and risk required." For small and medium enterprises, and those with brownfield sites – older facilities with legacy systems – the barriers to implementation are significant.

In recent years, governments have stepped in to accelerate industrial progress. Through a revival of industrial policies, initiatives like the CHIPS Act and Inflation Reduction Act in the U.S., Europe's Green Deal, and China's Dual Circulation policy, governments are incentivizing high-tech manufacturing, re-localizing critical production processes, and reducing reliance on fragile global supply chains.

All these developments converge in a key moment for manufacturing. The external pressures on the industry – met with technological progress and these new political incentives – may finally enable the shift toward advanced automation. "Automation is not just about efficiency anymore," says Enno Danke, managing director at Accenture's Industry X. "It's crucial for overcoming labor challenges and scaling operations faster, especially as manufacturers are pushed to shorten time-to-market and adapt to decentralization." And Eryn Devola, head of sustainability at Siemens Digital Industries, emphasizes that "the same toolset that helps companies improve time, cost, and features is now essential for decarbonization and resource efficiency."

Jeff Burnstein, president of the Association for Advancing Automation, sees the economics and the technology lining up to enable automation adoption. "Companies are looking for an edge," he says, "and robotics and automation can be that edge."

Toward adaptive and autonomous systems

The transition from today's manufacturing facilities to the factory of the future will be a journey of many incremental steps. Just as with the first modern forays into automation in the 1950s and 1960s, and the advancements of the ensuing decades, progress will unfold as an evolution, this time from automated to adaptative to autonomous.

At present, most factories have applied traditional automation to their production – systems that are not enhanced by smart connectivity or industrial AI. Although quite effective, they are not adaptive: They follow programmed instruction and cannot readily adjust to changing conditions. The key limitation is their reliance on static automation – systems must be programmed in advance and cannot deviate from their defined instructions. "Automation today excels in repetitive tasks but struggles with adaptation," says Franz Menzl, senior vice president of technology and innovation at Siemens.

Emerging flexible automation and increasingly autonomous systems, however, are changing that. Menzl says, "By making automation adaptive, easier to use and operate, we can unlock its potential in industries where flexibility is essential." These adaptive to autonomous systems use real-time data, software-defined automation, AI, and digital twins to enable adjustments to production on the fly. The convergence of "AI copilots, high-performance computing, and the adaptive cloud will enable faster adjustments and reprogramming for specific tasks," explains Jana Kirchheim, director of manufacturing for Microsoft Germany.

As factories evolve, they will increasingly leverage real-time production data and advanced self-optimization capabilities, creating a cycle of continuous improvement. "This approach doesn't just enhance efficiency; it accelerates the journey toward autonomous factories," says Jelena Mitic, head of technology field "Future of Automation" at Siemens. She envisions a world "where intelligent systems and technologies will work alongside humans, empowering them to focus on creativity, problem-solving, and strategic decision-making."

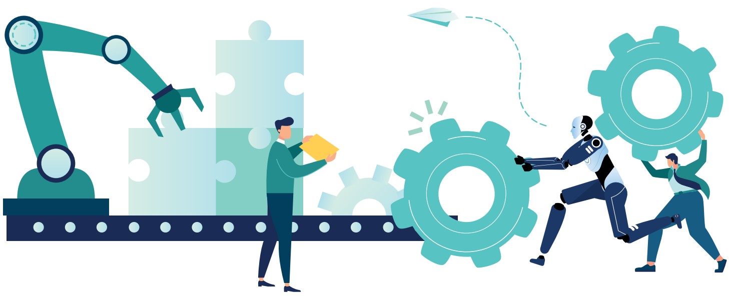
> "Automation is not just about efficiency anymore. It's crucial for overcoming labor challenges and scaling operations faster."
>
> **Enno Danke**, Managing Director at Accenture's Industry X

A tour of the technologies

The future of manufacturing won't be driven by a single technology. It will instead emerge from a convergence of software and hardware, and of operational technology with information technology. This increasing integration of physical processes and equipment with IT networks and infrastructure will enable seamless connections between physical and digital technology. "You can no longer separate physical automation from information automation," says Danke. "They must work together, from planning production to running maintenance and adapting in real time."

Industrial artificial intelligence. AI is increasingly a generalized tool in production, applicable to a wide range of industry challenges. Scheduling agents, for instance, can fine-tune decisions in areas like maintenance, downtime, and demand prediction. One such agent **saved a manufacturer up to 40% of yield losses** by using reinforcement learning to predict the most likely order flow.

Data, advanced analytics, and AI are unlocking new capabilities. "The biggest impact I've seen over the past three to five years is companies doing more with data: predictive maintenance, understanding hidden variables, and doing more advanced statistical process control using advanced data analysis methods and connecting their machines to the network," says Hart.



Industrial automation, past, present, and future

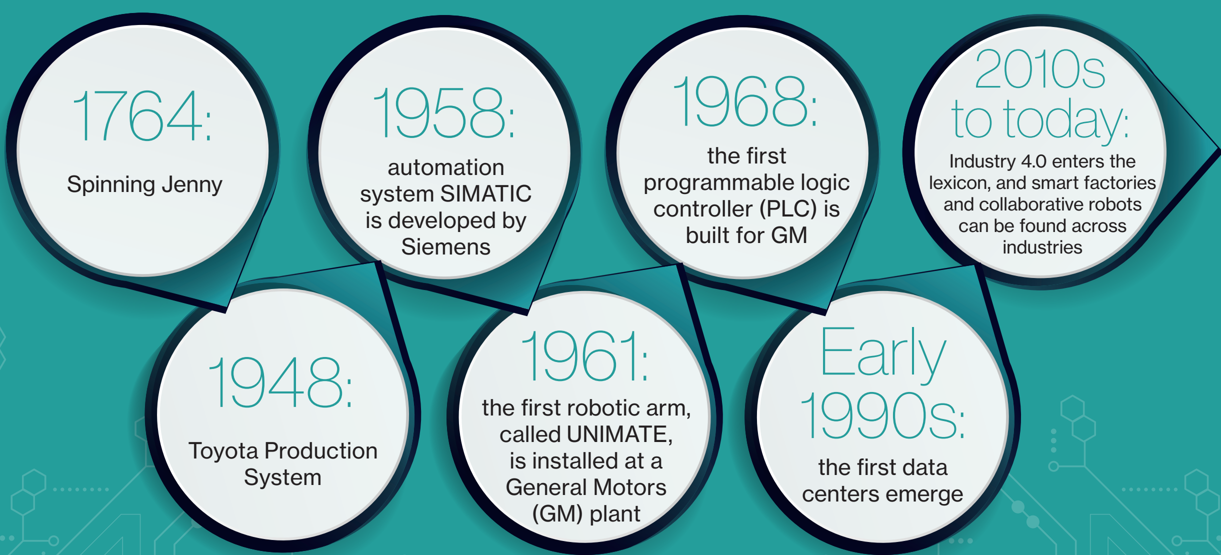
The **world's first robotic arm**, patented in 1961, was used to lift and stack hot metal parts in a General Motors (GM) factory. It was a historic step in the manufacturing industry's ambition to replace muscles with machines.

Since then, automation has continued to evolve, driven by parallel advancements in operational technology (OT) and information technology (IT). In the late 1950s, early control systems like Siemens' SIMATIC laid the foundation. By the late 1960s, programmable logic controllers (PLCs) and industrial robots – both pioneered at GM – marked the next leap, allowing greater flexibility on the factory floor.

The innovations of subsequent decades – microprocessors in the 1970s, multi-axis robots and CNC machines in the 1980s, and data connectivity in the 1990s – continued to push the field forward. During recent years, the convergence of OT and IT in manufacturing, sometimes called Industry 4.0, allowed manufacturers to collect and analyze data across their operations.

Today, technologies such as virtual PLCs, industrial AI, smart robotics, and digital twins are ushering in an adaptive age of automation. Factories are becoming more responsive, optimizing operations in real time, and adjusting seamlessly to shifting conditions. Beyond that, forward thinkers project an age of autonomy, where continuous feedback and optimization loops enable factory systems to self-monitor and self-improve – eventually integrating into an industrial metaverse that seamlessly connects physical and digital systems.

Figure 1: A timeline of automation advancements



Source: Compiled by MIT Technology Review Insights with information from Siemens, 2025.

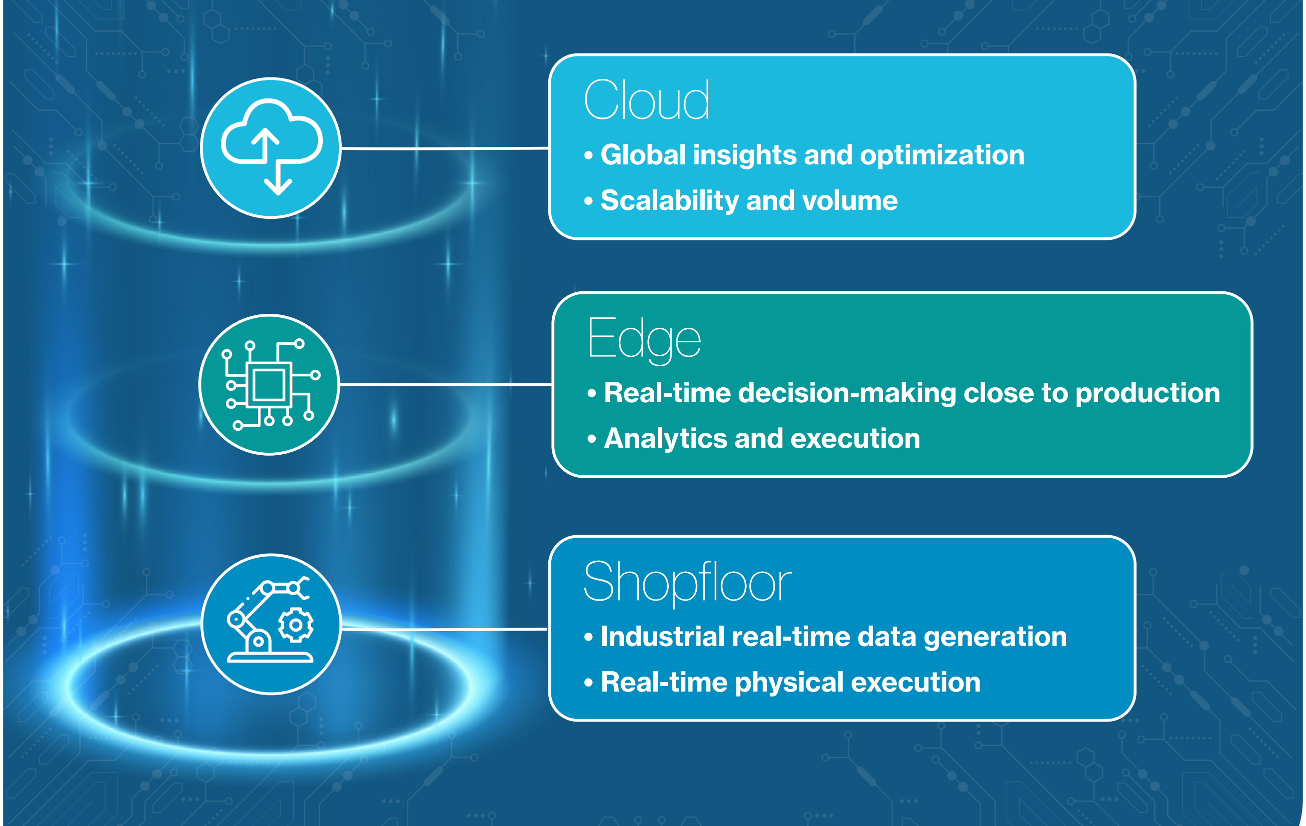
Among these advancements, generative AI stands out for its transformative potential. “It has the greatest potential for increasing productivity across the entire value chain,” says Menzl. In a collaboration between Siemens, Microsoft, and Thyssenkrupp, for example, generative AI-driven copilots are transforming the battery production line. Thyssenkrupp’s engineers work with a copilot for engineering to generate automation code, saving time and easing skilled labor shortages.

Yet, implementing AI in manufacturing is complex, requiring a highly robust data foundation and specialized guidance to translate technology into real-world impact. “With our clients, we start by translating different data types – from CRM systems to IoT sensor data – into a usable format,” explains Menzl. “Next, we relate this data, creating connections that give a cohesive view across systems. Finally, we calculate actionable insights using machine learning and real-time processing. This structured approach ensures that industrial AI delivers real results on the factory floor.”

Digital twins. Digital twins play a pivotal role in adaptive production, acting as a virtual control room. These models enable manufacturers to simulate and refine their operations without disrupting production, creating a continuous feedback loop between the digital and real worlds.

With digital twins, “factories can use both historical and real-time data to run billions of simulations across different variables,” explains Amy Webb, CEO of the Future Today Institute. “This enables manufacturers to make more informed decisions, improve process optimization, and enhance supply chain resilience.”

Figure 2: The convergence of IT and OT makes production more adaptive



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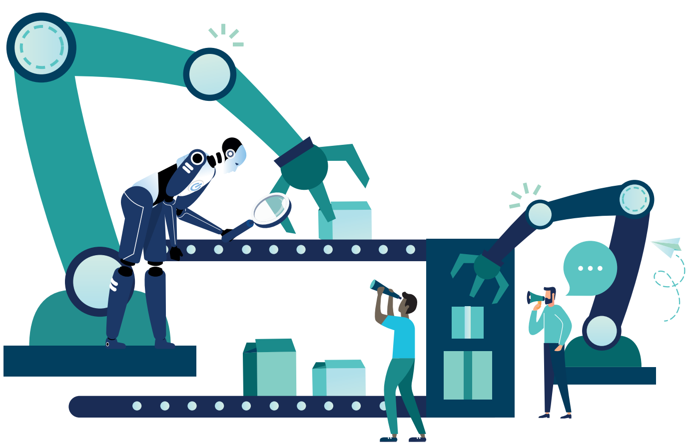
Franz Menzl, Senior Vice President of Technology and Innovation at Siemens

TRAK Machine Tools, a company based in California and Nevada, demonstrates how digital twins are transforming manufacturing. “I can see the entire machine in exact 3D before it’s even built,” says Leo Gammaitoni, the vice president of engineering at TRAK Machine Tools. “I can customize the machine, make changes, and see what happens. I can trace a tool path and be confident that it’s 100% accurate.” By testing designs virtually, TRAK has been able to optimize machine configurations, enhancing precision, accelerating time-to-market, and improving adaptability.

Other use cases for digital twins include optimizing production and maintenance. At the Siemens Electronics Factory Erlangen, for example, digital twins enables engineers to test new technologies, optimize layouts, and even train industrial robots in a virtual environment before any physical implementation.

“Digital twin technology will enable faster adoption of new technologies,” says Mitic. “A virtual representation of the shop floor speeds the whole process of validating, testing, and simulating new features before implementing them in reality.” And in the future, digital twins will anchor an emerging industrial metaverse, where physical and digital systems can be seamlessly connected across entire value chains.



Software-defined automation. Traditionally, factory systems rely on hardware-based programmable logic controllers (PLCs). Making changes to hundreds or thousands of these devices requires time-consuming reprogramming. In many facilities, this means technicians still physically move from machine to machine – sometimes even by bike – to reprogram each device, making changes time-consuming, costly, and vulnerable to delays.

“Software-driven automation, however, moves automation functions from hardware to software,” explains Mitic, “giving much more flexibility in how you deploy and engineer new functions on the shop floor.” This shift allows factories to scale incrementally, beginning with a single production line and expanding as needed, reducing downtime and minimizing operational disruptions.

Software-defined automation is also changing workforce roles. Employees are increasingly focused on managing systems through centralized control interfaces rather than performing repetitive manual updates across the factory floor, creating a more streamlined and responsive production environment.

Audi’s Neckarsulm facility exemplifies the transformative impact of this shift. By virtualizing its controllers and housing them in a remote data center, Audi has moved to a cloud-managed setup that provides real-time flexibility and scalability across its production lines. This new approach allows the manufacturer to implement updates instantly, adjust production in response to market changes, and reduce the energy and resources associated with traditional, hardware-bound systems. “In the next five to seven years, I expect software-defined automation will lead to quicker and more cost-effective changes, with businesses gaining the ability to program each step of their production process independently,” says Kirchheim.

Robotics. No longer just static machines performing repetitive tasks, robots are becoming highly capable collaborators that incorporate advances in AI, computer vision, and materials science. “We're in an era where robotics is being unbolted from the floor and moving around,” says Aaron Saunders, CTO at Boston Dynamics. “Places where there are still a lot of people in the manufacturing process are rich terrain for mobile robotics.”

Traditional industrial robots are now employing AI to reach new levels of precision and flexibility. SIMATIC Robot Pick AI, for example, trained on synthetic data in a virtual environment, enables robots to autonomously pick unknown items from bins. Automated guided vehicles (AGVs), once restricted to fixed paths, are now learning to navigate dynamic environments by identifying obstacles and adjusting routes in real time.

Robotics innovations are also helping small and medium-sized enterprises put the technology in place. Digital twins and universal robotics libraries, for example, are helping companies get robots up and running faster. “By leveraging these tools, we can integrate different robot brands without ad-hoc programming, making operations faster and more efficient,” says Franco Filippi, CEO of EPF, an Italian automation specialist.

Meanwhile, humanoid robots help manufacturers more easily apply advanced automation to existing facilities. “Humanoid robots are especially useful for automating work centers that have been designed for humans,” says Danke. “New sites can be designed with stationary robots in mind, but robots that can fill in human roles are helpful for automating brownfields.”

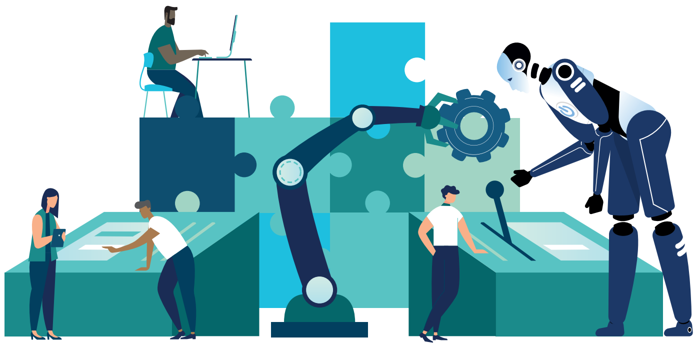
For robots to reach their full potential, however, they must be integrated into the broader adaptive production ecosystem, interacting with AI systems, digital twins, and software-defined automation. As Saunders explains, “A robot that produces data is only good if you can move that data into your system and act on it.”

Mastering the future of production

The technological convergence of AI, digital twins, software-defined automation, and robotics – coupled with the supply chain disruptions, rising labor costs, and sustainability pressures facing manufacturing – are creating a moment of opportunity for advanced automation.

“Disruption is coming, whether or not the industry wants it. Planning for the long term and taking strategic risks today will be essential for future gains.”

Amy Webb, CEO of the Future Today Institute



By weaving these technologies into a unified, data-driven ecosystem, companies can create the factories of tomorrow – factories that respond to real-time conditions, optimize production in the moment, and thrive in an increasingly complex global environment. Adaptive production doesn't just streamline processes; it builds resilience and flexibility, enabling manufacturers to adjust to sudden shifts in demand, supply chain challenges, or environmental pressures. Importantly, by embedding these capabilities now, manufacturers are also setting the stage for autonomous systems in the years to come.

Industry leaders are already tackling the challenges of integrating these advanced technologies, preparing a future-ready workforce, and ensuring smooth collaboration between humans and machines. How they're navigating these complexities will be the focus of the next report in this series.

While businesses will take different routes to advanced automation, the question is when, not if, this transformation will take hold. “Disruption is coming, whether or not the industry wants it,” says Webb. “Planning for the long term and taking strategic risks today will be essential for future gains.”

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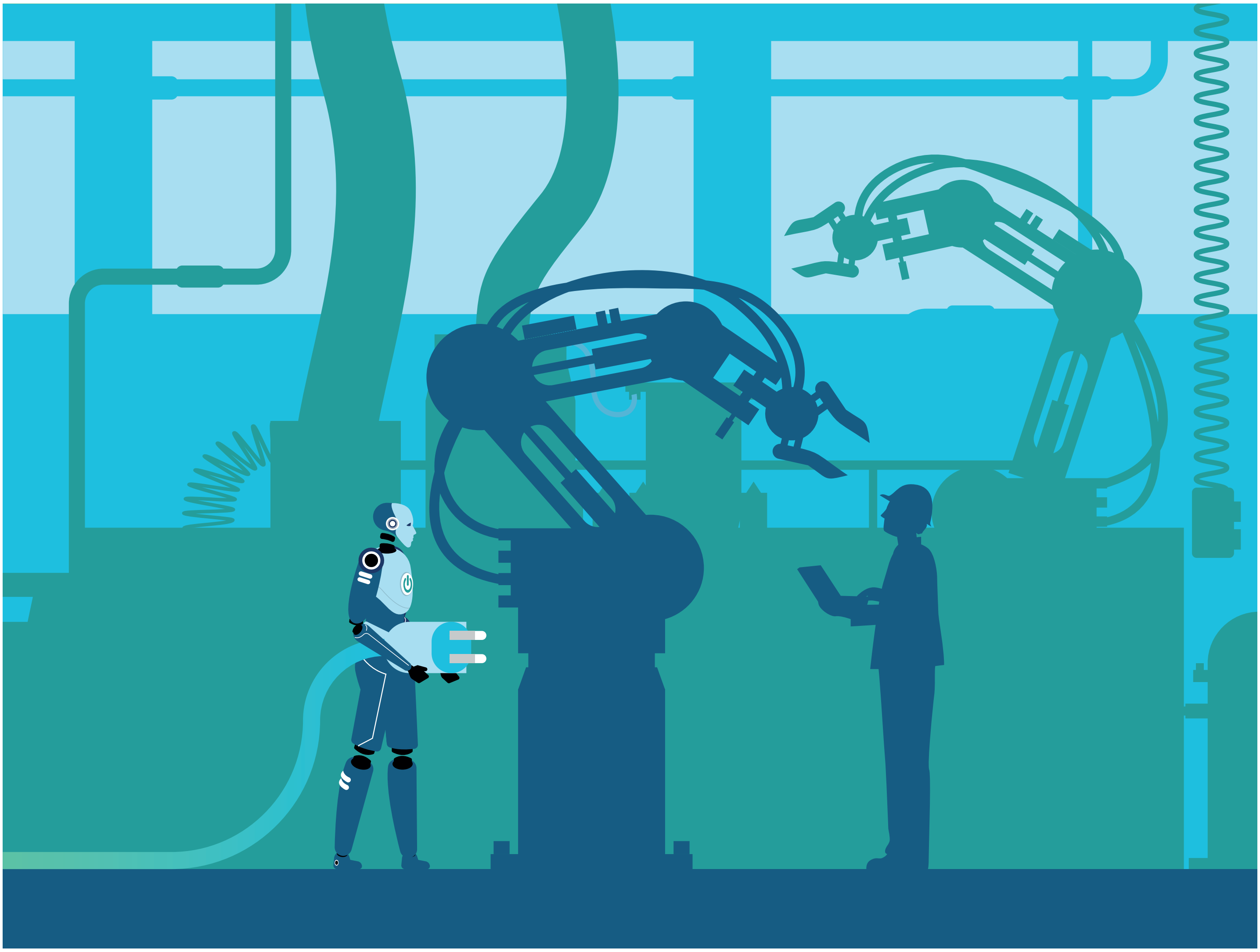

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