MIT Technology Review
Insights

Adaptive production could transform how factories function. Businesses that embrace it can reinvent themselves and redefine the rules of competition.

The business of the future is adaptive

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Key takeaways

1. A robust foundation of technologies, including efficient data management and analysis, IT/OT convergence, and modular planning and operations enable interconnected feedback and optimization cycles, allowing for continuous adaptation and improvement across the production process.

2. A cohesive enterprise-wide strategy, spearheaded by leaders with a clear vision, is fundamental to creating a truly adaptive business. Leaders must equip the workforce with the technical skills and confidence to embrace an adaptive mindset.

3. Constant evolution and flexibility is key. Manufacturers should take a phased approach to execution and incorporate emerging technologies to stay competitive. Partnerships and ecosystems can help to mitigate gaps in skills and assets: businesses don't need to do it alone.

Manufacturing is in a state of flux. From supply chain disruptions to rising costs, tougher environmental regulations, and a changing consumer market, the sector faces a series of competing challenges. But a new way of operating offers a way to tackle complexities head-on: adaptive production hardwires flexibility and resilience into the enterprise, drawing on powerful tools like artificial intelligence, digital twins, and robotics. Taking automation a step further, adaptive production allows manufacturers to respond in real time to demand fluctuations, adapt to supply chain disruptions, and autonomously optimize operations. It also facilitates an unprecedented level of personalization and customization for regional markets.

Time to adapt

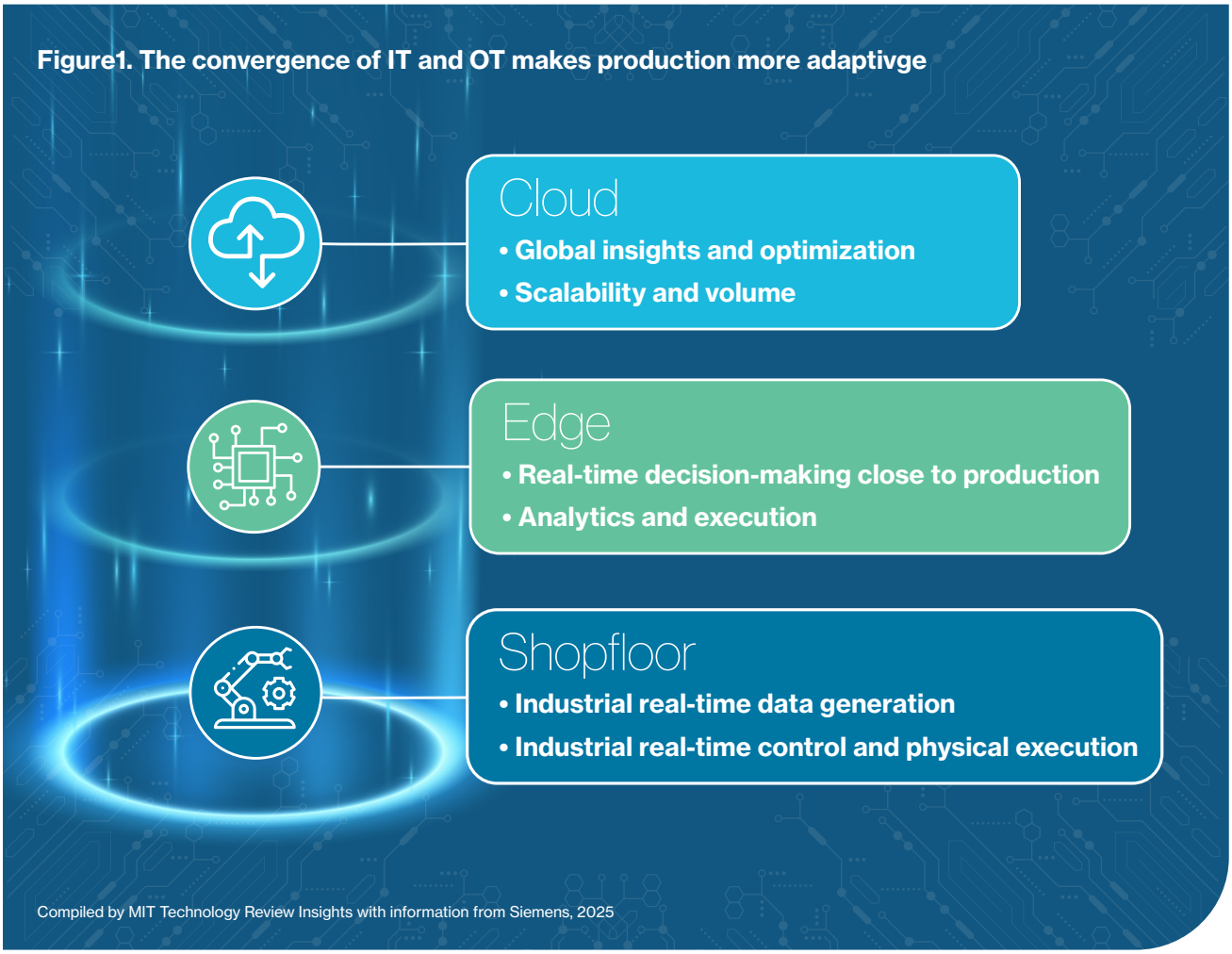
The journey to adaptive production is not just about addressing today's pressures, like rising costs and supply chain disruptions – it's about positioning businesses for long-term success in a world of constant change. "In the coming years," says Jana Kirchheim, director of manufacturing for Microsoft Germany, "I expect that new key technologies like copilots, small language models, high-performance computing, or the adaptive cloud approach will revolutionize the shop floor and accelerate industrial automation by enabling faster adjustments and re-programming for specific tasks." These capabilities make adaptive production a transformative force, enhancing responsiveness and opening doors to systems with increasing autonomy – designed to complement human ingenuity rather than replace it.

These advances enable more than technical upgrades – they drive fundamental shifts in how manufacturers operate. John Hart, professor of mechanical engineering and director of MIT's Center for Advanced Production Technologies, explains that automation is "going from a rigid high-volume, low-mix focus" – where factories make large quantities of very few products – "to more flexible high-volume, high-mix, and low-volume, high-mix scenarios" – where many product types can be made in custom quantities. These new capabilities demand a fundamental shift in how value is created and captured.

Fundamentals of adaptive production

A robust technological foundation is the basis for any adaptive production strategy. This includes data management, information technology/operational technology (IT/OT) convergence, and modular planning and operations. All supported by the right software.

Figure1. The convergence of IT and OT makes production more adaptivge



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The first priority is developing a data management strategy that collects, organizes, and analyses the vast volumes of data that internet of things (IoT) devices and sensors collect. When analyzed effectively, this data can provide invaluable insights and enable real-time decision-making, enhancing operational agility.

Integrating IT with OT is the next critical step for adaptive production, enabling seamless data flow across the enterprise – from shop-floor machinery to enterprise-wide systems. "IT/OT convergence," explains Franz Menzl, CTO of factory automation at Siemens, "combines the computational power of IT with the stability of OT for optimized production."

Then, to achieve truly adaptive systems, manufacturers need to extend IT/OT convergence throughout the whole production process, from inception to completion, enabling a seamless data flow across the enterprise. "You need to find a way to build a digital thread to integrate product development, manufacturing, engineering, and supply chain," says Enno Danke, managing director at Accenture's Industry X. This enables the organization to "instantly see any product change, identify if it causes a collision on the production line, and update your machine programs accordingly," he says.

Creating this interconnection between the digital world and physical realities allows companies to optimize processes at all stages of production. "Engineers can model thousands of what-if scenarios before they build it both in the product space and in the production space," says Eryn Devola. "With the digital twin, they can set up machines, simulate workflows, and monitor performance in real time, before they implement it in the real world."

"When you have the virtual representation, you can also use the same assets both in the virtual and the real world. This makes it much faster to bring new features to the shop floor," adds Jelena Mitic, head of technology for the future of automation at Siemens.

These interconnected feedback and optimization cycles can enable a state of continuous adaptation and improvement. Extending these adaptive production practices to the business side can help create a blueprint for an adaptive business model.

Designing the adaptive business

Beyond the technology, companies need a cohesive strategy that aligns every part of the organization, enabling them to continuously improve.

"Conventional methods alone – such as lean methods – may eventually hit performance limits," explains Stefan Krug, head of global manufacturing and digitalization at Siemens Motion Control. "To go beyond those limits, businesses need a digital-enabled adaptive production – not just as a set of tools but as a comprehensive framework." This approach builds on and evolves concepts like lean or agile management, and combines them with the latest digital and automation technologies, enabling manufacturers to dynamically respond to changing conditions in real time while paving the way for increasing operational autonomy. "By integrating feedback loops and continuous improvement at every stage of the process, adaptive production creates a foundation for resilience, efficiency, and long-term growth," Krug says.

"You need to find a way to build a digital thread to integrate product development, manufacturing, engineering, and supply chain."

Enno Danke, Managing Director, Industry X, Accenture

Time to adapt: Transforming business across sectors

Emerging examples demonstrate how adaptive production is already transforming business models—and customer expectations—across industries:

Automotive

The ongoing shift toward mass customization allows manufacturers to offer tailored vehicles at scale.

Health care

The production of custom prosthetics and implants through additive manufacturing is becoming quicker and cheaper, bringing personalized medicine closer to reality.

Consumer goods

On-demand manufacturing is allowing industries like fashion to produce custom-fit clothing with minimal waste.

Food and beverage

From tailored formulations to modular micro-factories for local water and food production, adaptive systems are reducing supply chain dependencies and meeting regional needs.

Industrial equipment

Subscription-based models for tools and machines are gaining traction, allowing businesses to scale usage dynamically while reducing up-front costs.

Key elements for implementing an adaptive production business framework include:

Leadership and workforce. "The biggest enabler is courageous leadership," says Amy Webb, CEO of the Future Today Strategy Group. Creating an adaptive business requires organization-wide modernization. A leader with "a crystal clear vision" is imperative to take the necessary strategic risk, Webb says.

A common misstep is viewing adaptive production as a one-time investment. Instead, a successful leader should act like a "balance wheel in a clock," driving incremental change every day, says Christoph Hauck, CTO of German precision manufacturer Toolcraft. This continuous approach limits massive, disruptive

"Prove the technology, then pilot it, and gradually scale up. Be rigorous with what your return on investment is and avoid jumping into technology for the sake of hype."

Aaron Saunders, Chief Technology Officer, Boston Dynamics

The brownfield challenge

Industry enters this automation transition with a sizeable infrastructure legacy. According to the National Institute of Standards and Technology, as of 2017, the U.S. manufacturing industry managed machinery and equipment worth $2.65 trillion, as well as buildings and structures valued at $661.8 billion. While starting from a clean slate may appeal, these investments cannot simply be discarded.

"With a greenfield site, it is more straightforward to invest in higher-level automation, better connectivity, and edge computing," explains Eryn Devola, head of sustainability at Siemens Digital Industries. "However, in a brownfield situation, you're looking at significant capital expenditure and fundamentally changing operations, so you have to balance the costs and benefits of implementing it within an existing operational environment."

Some technologies are straightforward to incorporate. Sensors, for example, can be easily integrated into active production lines, and humanoid robots have the potential to fit into spaces originally designed for humans.

A key first step is improving communication and network capabilities on active production lines. "Right now, there isn't much 5G and certainly not much 6G on factory floors, and there's not much AI being deployed either," says John Hart, professor of mechanical engineering at MIT. "The key improvement is to better connect network devices and to more straightforwardly interface pieces of hardware together."

transformation and creates a culture where manageable small changes gradually transform the organization.

Leaders also must equip their workforce with both the technical skills and the confidence to adapt to shifting technologies to ensure that everyone is empowered to embrace an adaptive mindset. It can be a "chicken and egg" situation, says Hart. "You need the business case, you need the finances, and you need the skills and the people to make it work." Without skilled talent, automation is hard to implement, but without automation, there's little case for upskilling. Addressing this requires a cultural shift where employees at every level are empowered to embrace an adaptive mindset.

Continuous execution. Execution is where strategy is put to the test. An iterative, phased approach allows the organization to adjust as technologies evolve. "Our digitalization strategy is a marathon spread over four to five years," says Hauck.

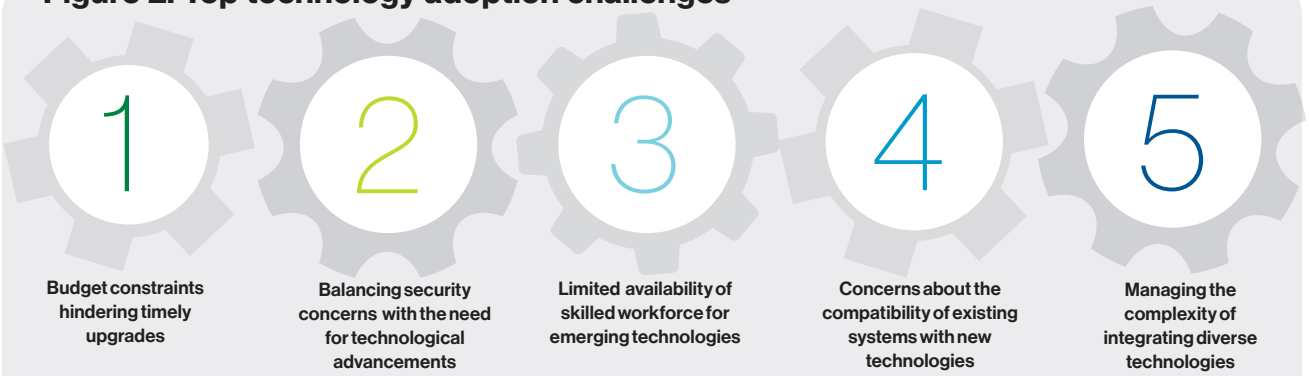
Companies can start small, identifying areas where adaptive production can deliver quick, tangible results. This could be improving real-time monitoring in production or optimizing logistics with AI-driven insights. Jeff Burnstein, president of the Association for Advancing Automation, advises manufacturers to "start smart. Don't take on everything at once." By focusing on manageable, high-impact projects, businesses can generate early wins that build momentum.

Aaron Saunders, chief technology officer of robotics firm Boston Dynamics, suggests breaking challenges into clear, manageable steps: "Prove the technology, then pilot it, and gradually scale up," he says. "Be rigorous with what your return on investment is, and avoid jumping into technology for the sake of hype."

> "With these new technologies finding their way to the shop floor, new business models will be democratized as well. Instead of large-scale integrators managing entire systems, new integrators will emerge, offering 'equipment as a service,' like 'robots as a service.'"
>
> Jana Kirchheim, Director of Manufacturing, Microsoft Germany

As companies move from initial use cases to broader implementation, speed to market will be critical, especially in industries where new, agile entrants can rapidly deploy. "You have new attackers that come from adjacent spaces or that come in completely greenfield and don't have any legacy," says Danke.

Figure 2. Top technology adoption challenges



Source: Compiled by MIT Technology Review Insights, based on data from Manufacturers Alliance Foundation, 2025

Adaptive production success stories

Kellanova

Multi-national food giant Kellanova, which owns well-known brands like Pringles, Rice Krispies, Nutri Grain, and more, uses digital twins, AI, and the industrial metaverse to revolutionize its operations, improving production output and efficiency. Recipes can be designed and evaluated without the need for extensive physical testing; the production process and equipment performance can be simulated to optimize production; and a comprehensive model of the factory demonstrates integration within the overall production workflow, identifying optimization opportunities—all before the product is manufactured in the real world. All data generated throughout the digital twin process is fed back to R&D and engineering where the journey began, laying the foundation for the next generation of products.

Siemens Erlangen Factory

At Siemens' Electronics Factory in Erlangen, adaptive automation has transformed production. By integrating flexible robotics, AI-powered vision systems, and modular kinematics, the factory can adapt quickly to changing demands. "Traditional systems were built for static tasks, but today's shorter product cycles demand flexibility," explains Stefan Krug, head of global manufacturing and digitalization at Siemens Motion Control. Initially reliant on specialized machinery, the factory shifted to lightweight robots and dynamic systems that can be reconfigured during operations. This adaptability has driven a significant boost in productivity and energy efficiency.

Toolcraft

For Toolcraft, adaptability is more than just a principle; it's a way of working. This German leader in precision manufacturing has transformed its operations by fully integrating digital tools into every stage of its workflow. "It's about combining our manufacturing expertise with robotics, additive manufacturing, and seamless digital processes," says Christoph Hauck, chief technology officer at Toolcraft. Toolcraft's end-to-end digital approach enables real-time adaptability and precision. Their hybrid robotic cells, for instance, can handle tasks like milling and laser cladding while dynamically adjusting to new requirements. This allows them to meet the exacting needs of industries such as aerospace and advanced equipment manufacturing, including tooling for lithography systems.

TRAK Machine Tools

The business of TRAK Machine Tools has always been to help other companies adopt new technologies. But to guide its customers into the future, TRAK first had to transform itself. By adopting modular, flexible automation systems within its own operations, TRAK ensured it could adapt to changing market demands and refine its offerings. "Change is inevitable," says TRAK owner Steve Pinto. "But it doesn't have to overwhelm." This philosophy drives TRAK's approach to incremental modernization, from retrofitting existing machines with advanced controls to introducing robotics—empowering small manufacturers to embrace change.

Flexibility is key. Scalable, modular solutions that can grow and adapt give companies the agility to incorporate emerging technologies and to stay competitive in a rapidly changing environment.

Partnerships and ecosystems. Manufacturers need partners who can help with processes, from deploying AI and robotics to integrating software-defined automation with existing operational systems. "We are not experts in all the technologies, and we don't have all the technologies in-house," says Mitic. "By partnering with companies that have different but complementary expertise and assets, we can expand our capabilities and offer a more comprehensive solution to customers."

Standardization efforts, such as those by the Metaverse Standards Forum, the Alliance for OpenUSD, and the Smart Robotics Certification Initiative, are making it easier to integrate technologies like digital twins and robotics. This interoperability helps businesses optimize existing assets, improve efficiency, and minimize the disruption often associated with modernization.

But as systems become more integrated, they also become more vulnerable. Developing an infrastructure that balances openness with security brings the benefits of interoperability without exposure to unnecessary risks.

Tapping into existing ecosystems is an effective shortcut to automation. System integrators and industry partners can bridge the gap between new technologies and existing systems. Digital business platforms like Siemens Xcelerator offer a streamlined pathway to advanced automation with a network of partners, developers, and consultants, as well as software-as-a-service solutions that are easy to deploy and scale.

Kirchheim envisions additional as-a-service business models facilitating the transformation. "With these new technologies finding their way to the shop floor, new business models will be democratized as well," she says. "Instead of large-scale integrators managing entire systems, new integrators will emerge, offering 'equipment as a service,' like 'robots as a service.'"

Financial barriers can also be overcome with the help of strategic partners who understand the technology. "Financing is not just about securing funds; it's about working with partners who guide businesses through both the financial and technological aspects of transformation," says Madlen Junker, financing solution partner at Siemens Financial Services.

The future of adaptive production

For many manufacturers, the path to becoming a truly adaptive business is fraught with challenges. Bridging the gap between legacy systems and advanced capabilities requires a careful blend of strategic vision, innovation, and execution. This transition is especially critical for small and medium-sized enterprises with limited budgets and technical expertise, who face the complexity of integrating new systems into existing operations.

But for those willing – and able – to take the leap, the opportunities are vast – and imminent: "The cost for automation is rapidly declining," says Danke, "and what is technically feasible is evolving quickly." Scaling adaptive production has the potential to impact entire industries, reshape supply chains, enable more efficient manufacturing, and redefine the roles of people and technology in the workplace. Businesses that embrace these changes have the opportunity to shape the future of manufacturing, making it more resilient in the face of today's pressures and preparing it for long-term success in a world of constant change.

"The business of the future is adaptive" is an executive briefing paper by MIT Technology Review Insights. Laurel Ruma was the editor of this report, and Nicola Crepaldi was the publisher. MIT Technology Review Insights has independently collected and reported on all findings contained in this paper.

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Christoph Hauck, chief technology officer, Toolcraft

Madlen Junker, financing solution partner, Siemens Financial Services

Jana Kirchheim, director of manufacturing, Microsoft Germany

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