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The future of pharmaceutical production: **smart manufacturing** as a strategic imperative

From therapy complexity to sustainability pressures – why embracing digital transformation is key to unlocking next-generation pharmaceutical manufacturing operations.

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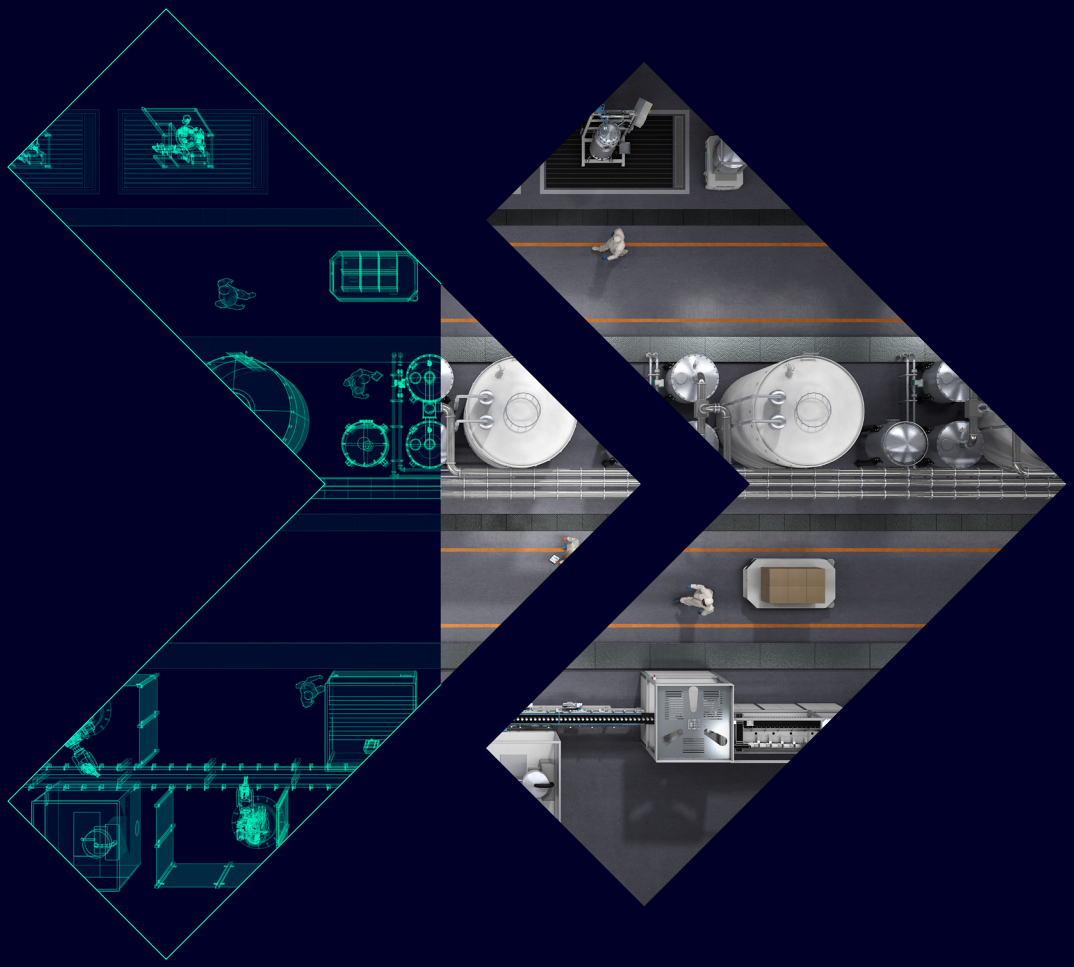


Smart manufacturing for pharmaceuticals – an introduction

The pharmaceutical industry is at a pivotal moment. Despite record growth and unprecedented advancements in medicine, companies face an increasingly complex production landscape. Heightened sustainability demands, rising pharmaceutical complexity, fragmented supply chains, and operational inefficiencies are converging to challenge even the most robust manufacturing models.

At the same time, patient expectations are evolving, regulatory scrutiny is intensifying, and market dynamics are becoming more volatile. In this environment, one goal is emerging as paramount: making pharmaceutical production sites more adaptable, efficient, and resilient – without compromising on quality.

Achieving this is no small feat. Traditional production paradigms are being tested by the scale and speed of change. However, digitalization has emerged as one of the most effective ways to navigate this complexity. From digital twins and software-defined automation to artificial intelligence (AI) and, ultimately, the Industrial Metaverse, next-generation technologies are enabling a new era of smart manufacturing – one defined by agility, precision, and data-driven decision-making.

Pharmaceutical production at a crossroads – design, realize, and optimize

Despite record growth, the pharmaceutical industry faces an urgent reckoning – one that could reshape its entire production landscape. Sustainability pressures, rising demand for complex therapies, operational inefficiencies, and supply chain fragmentation are converging, creating a high-stakes environment that demands urgent transformation.

Uncertainty in drug approvals and greenfield projects

Clinical-trial uncertainties make drug approval timelines difficult to predict. With failure rates for new drugs being as high as 90%,[1] production planning becomes a moving target, creating ripple effects throughout the industry. Moreover, a single day of delay can cost up to USD 1.5 million in unrealized sales.[2]

This uncertainty and the associated costs particularly impact new manufacturing projects, known as greenfield, which typically take years to complete and involve substantial financial investment.[3] When drug approvals are delayed or fail unexpectedly, newly built manufacturing sites can become obsolete before they even go online. The industry must develop more agile, modular production capabilities to mitigate these risks and adapt to shifting regulatory landscapes.

Rising demand for complex therapies

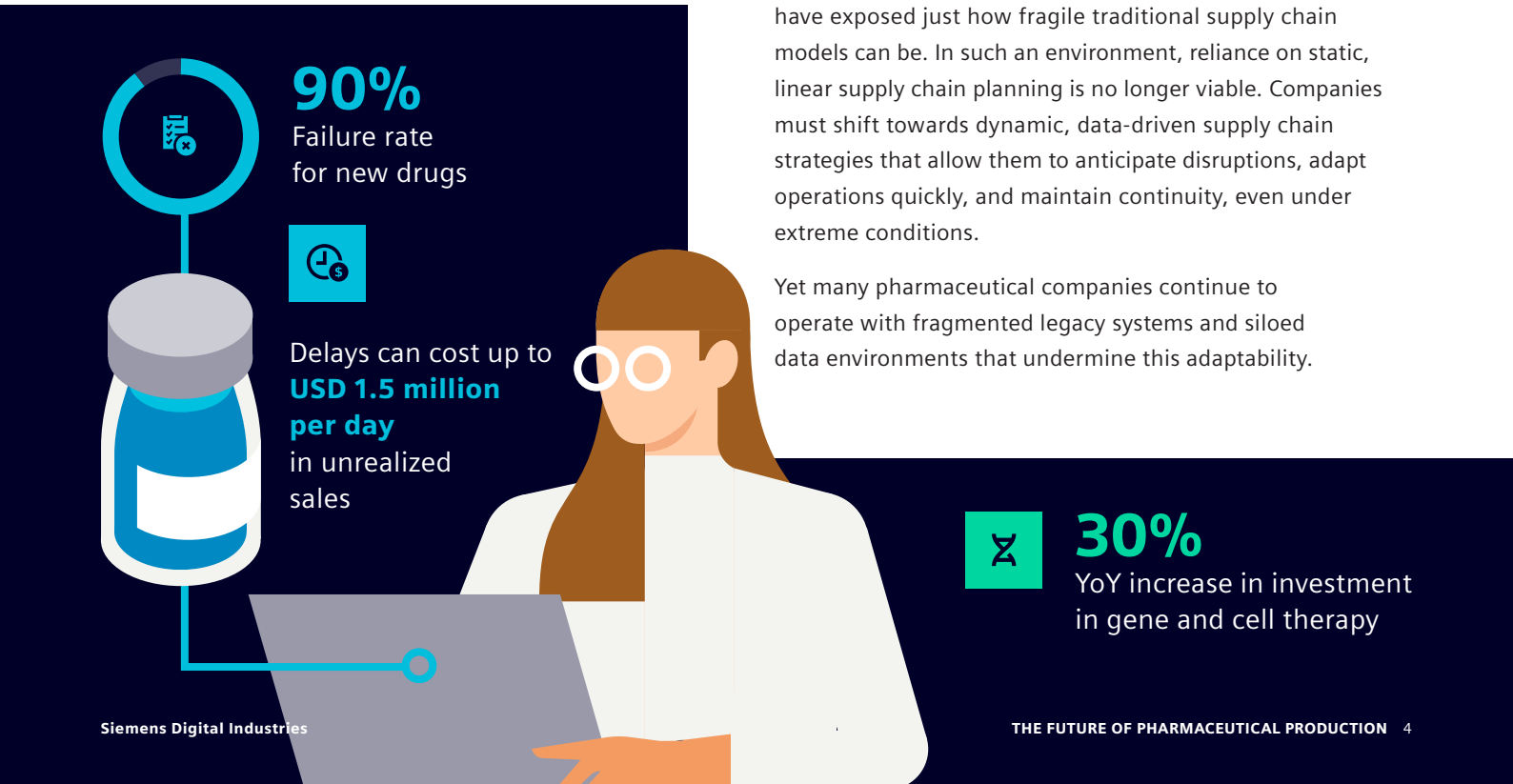
Beyond uncertainty, the industry is under mounting pressure to meet rising demand for complex therapies such as biologics, personalized medicine, and diverse drug portfolios, so much so that investment in these areas has increased significantly with investment in cell and gene therapy (CGT) witnessing a 30% year-over-year increase, surging to USD 15.2 billion in 2024 alone.[4]

However, unlike traditional pharmaceuticals, these sorts of therapies often require specialized and smaller-scale production processes.

Supply chain and data silo inefficiencies

Pharmaceutical supply chains operate in a world defined by volatility, uncertainty, complexity, and ambiguity (VUCA). Global disruptions – from pandemics and geopolitical instability to raw material shortages and regulatory shifts – have exposed just how fragile traditional supply chain models can be. In such an environment, reliance on static, linear supply chain planning is no longer viable. Companies must shift towards dynamic, data-driven supply chain strategies that allow them to anticipate disruptions, adapt operations quickly, and maintain continuity, even under extreme conditions.

Yet many pharmaceutical companies continue to operate with fragmented legacy systems and siloed data environments that undermine this adaptability.



Up to 55%
of organizational knowledge is effectively lost due to poorly harmonized systems

Despite generating vast volumes of information, including formulation data, clinical trial results, production metrics, and quality control records, much of this data remains unstructured, inaccessible, or disconnected. Some estimates suggest that up to 55% of organizational knowledge is effectively lost due to poorly harmonized systems.[5] This fragmentation impedes real-time decision-making and hinders responsiveness to shifting demand or regulatory changes. To navigate the VUCA landscape, manufacturers must implement integrated, data-driven supply chain systems that deliver the agility, insight, and foresight needed to turn volatility into a strategic advantage.

The OEE imperative

Operation efficiency also remains a significant challenge. Overall equipment efficiency (OEE) for the pharmaceutical industry is currently just 35%, hindered by factors such as suboptimal equipment management, equipment breakdown, and speed losses. However, by deploying technologies such as AI, companies could potentially increase their OEE by 50% to 100% – a shift that could revolutionize and redefine the industry.

If OEE were to reach 60% or more, it would have the capacity to even make 70% of pharmaceutical sites redundant, further enhancing the industry's efficiency.[6] Yet realizing this potential also requires breaking down siloed functions and fragmented data systems, which continue to hinder progress.

The sustainability challenge

One of the most pressing issues is sustainability. The most recent studies show that the pharmaceutical industry's emission intensity is around 55% higher than that of the automotive sector in terms of how many tons of CO_2 equivalent are produced for every USD 1 million the industry generates.[7] This is an astonishing statistic given the latter's reputation as a major polluter. Moreover, some studies reveal that manufacturing accounts for a staggering 80% of the industry's indirect emissions, underscoring the urgent need for change.[8]

Pharmaceutical companies must rethink their entire value chain by investing in research and development for more efficient packaging and transportation, cutting emissions from manufacturing and operations and ensuring sustainability compliance across suppliers, distributors, and contract manufacturers. The industry is also being pushed to embrace renewable energy, a shift that could redefine competitive advantage in the years ahead.[9]

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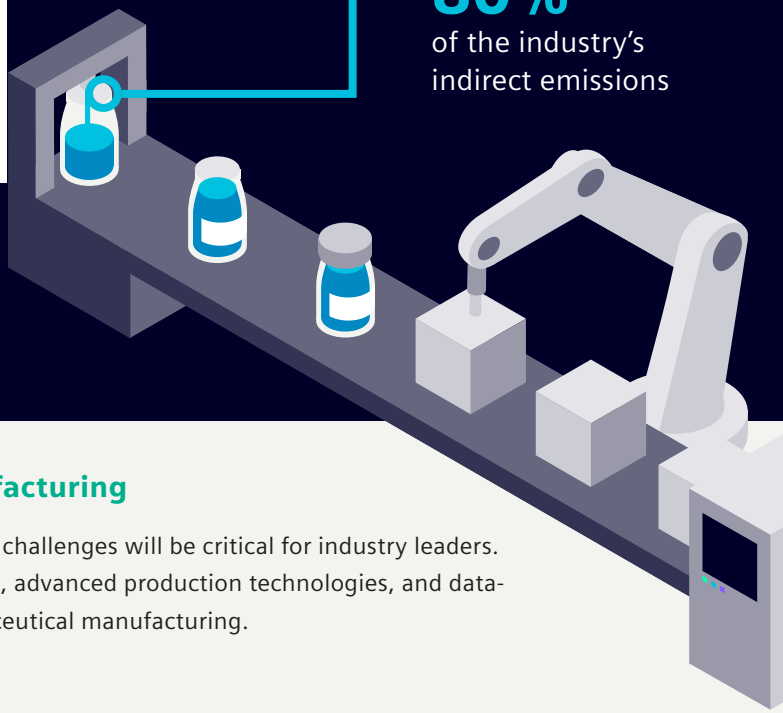


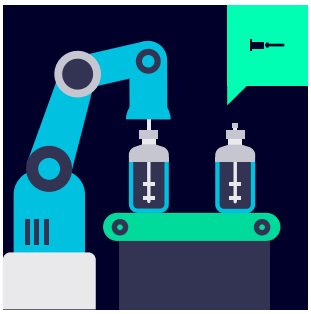
By deploying technologies such as AI, companies could increase their OEE by
50% to 100%

Navigating the future of pharmaceutical manufacturing

In such a high-stakes environment, navigating these interwoven challenges will be critical for industry leaders. Those who can successfully integrate sustainable manufacturing, advanced production technologies, and data-driven decision-making will be ready for the next era of pharmaceutical manufacturing.

Key trends shaping the pharmaceutical industry

The pharmaceutical industry is undergoing a major transformation, driven by scientific breakthroughs, regulatory advancements, and shifting patient needs. Among the most significant trends are the rise of RNA/DNA-based drugs, the expansion of cell and gene therapies, and growing investment in antibody-drug conjugates. At the same time, personalized precision medicine is gaining traction, enabling more targeted and effective treatments, while evolving patient needs are reshaping how treatments are developed and delivered.

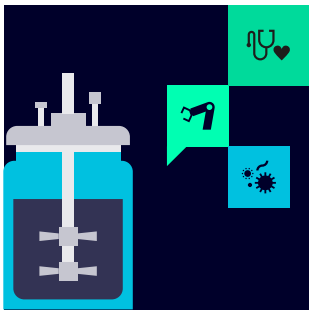


Rise of RNA/DNA-based drugs

A key outcome of the COVID-19 pandemic was the rapid advancement of mRNA technology, which has paved the way for new vaccines and treatments beyond infectious diseases.[10] Manufacturers have heavily invested in mRNA infrastructure, but they must now adapt their processes to support a wider range of RNA-based therapeutics, including personalized medicine. Instead of relying on a single bioreactor, next-generation facilities may require hundreds of smaller-scale production units to accommodate individualized treatments.[11]

A compelling example of this transformation is BioNTech's collaboration with Siemens during the COVID-19 response. Siemens supported BioNTech in rapidly scaling up its mRNA vaccine production by deploying advanced automation and digital solutions, including the SIMATIC PCS 7 process control system and the Opcenter Execution Pharma manufacturing execution system. These technologies enabled the creation of a highly automated, paperless production environment, significantly accelerating the development and rollout of the vaccine.[12]

This case highlights the critical role that flexible, digitally enabled manufacturing systems play in supporting RNA- and DNA-based therapies. As these treatments expand into areas such as oncology and rare diseases, the ability to rapidly adapt production to meet shifting scientific and clinical demands will be essential.



Growth of cell and gene therapies

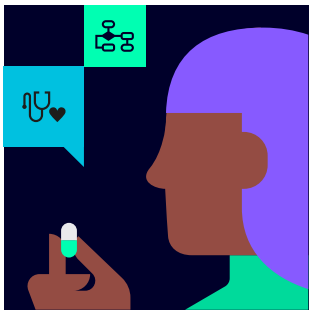
While the concept of cell and gene therapies has existed since 1972, the treatments have gained significant momentum in recent years. In 2023, the US Food and Drug Administration (FDA) approved five therapies targeting rare genetic diseases, followed by nine additional approvals in 2024, including the first adoptive cell therapies for solid tumors.[13]

These therapies offer transformative benefits to many patients who may have run out of treatment options,[14] and their market is expected to increase more than tenfold in the coming years, driven by the growth and progress of the clinical pipeline and regulatory advancements.[15] However, these come with challenges, including the need for specific, costly equipment and complex manufacturing processes that add to production expenses.[16]

Adoption of antibody-drug conjugates

Antibody-drug conjugates, cancer drugs that combine targeted therapy and chemotherapy, are one of the fastest-growing fields in oncology – a critical area as cancer remains a leading cause of death among people under 70 in 112 countries. There are currently 13 approved conjugates on the market and over 360 clinical trials currently underway globally, with various formats being explored.

Despite their promise, antibody-drug conjugates have faced efficacy challenges, but ongoing innovation is driving new strategies to improve their performance and establish them as a cornerstone of future cancer treatments.[17]



Personalized precision medicine

Beyond advancements in drug development, the rise of personalized precision medicine is also driving change in the industry. These treatments are designed for increasingly specialized patient groups and, in some cases, are tailored to an individual, which represents a significant departure from traditional one-size-fits-all approaches.

However, while many global companies are still mass-producing chemically developed drugs for widespread health issues, the adoption of personalized therapies requires low-volume, highly adaptable production processes. These treatments are not only tailored to rare diseases but are even manufactured based on genetic, biological, social, or environmental factors,[18] demanding flexible manufacturing systems capable of accommodating high variability and small batch sizes.

As a result, personalized precision medicine is poised to become the new standard in specific therapeutic areas, particularly in oncology and rare diseases.[19] To support this shift, manufacturers must invest in technologies and production models that enable rapid changeovers, modular design, and digitally integrated workflows, ensuring that personalized treatments can be delivered efficiently, safely, and at scale.

Production challenges and transformative technologies reshaping pharmaceutical manufacturing

Pharmaceutical manufacturing is under growing pressure to ensure regulatory compliance and quality, while also improving cost efficiency and production scalability. The industry is shifting toward smaller batch sizes and more complex manufacturing processes – trends that are making traditional production models less effective.

At the same time, rising operational costs, tighter traceability requirements, and supply chain vulnerabilities are driving the need for smarter, more efficient production methods. Fortunately, emerging digital technologies such as digital twins, software-defined automation, AI, and the Industrial Metaverse are set to transform pharmaceutical production, enhancing efficiency and scalability, while continuing to support the highest levels of quality and compliance.

Maintaining quality and keeping costs under control

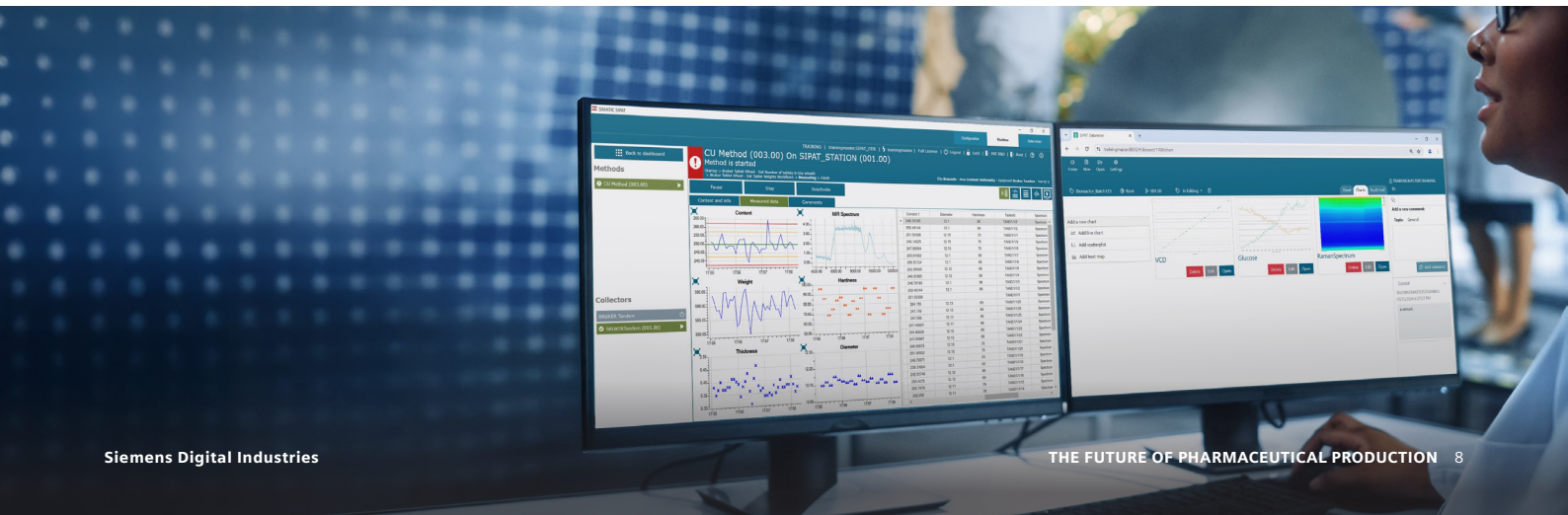
The pharmaceutical industry maintains a quality score of 94%, meaning that the average company loses 6% of its goods as scrap. Although this reflects its commitment to excellence, companies must target 100% for quality, as even a 6% failure rate can lead to regulatory non-compliance, production delays, and costly recalls.[20] This challenge becomes even more critical as manufacturers shift to personalized medicine, where a single defective batch could lead to severe complications for the patient, including death, like in the case of non-Hodgkin's lymphoma, multiple myeloma, and other blood and bone marrow cancers.

Maintenance inefficiencies also exacerbate production bottlenecks, with unplanned downtime contributing to the 23% of drug shortages that are caused by manufacturing issues.[21] As pharmaceutical processes become more intricate, proactive maintenance strategies and real-time monitoring will be essential to maintaining high-quality production.

How digitalization is transforming pharmaceutical manufacturing

To meet these evolving demands, pharmaceutical manufacturers are increasingly turning to next-generation digital solutions. Digital twins, software-defined automation, AI-driven analytics, and predictive maintenance are reshaping quality control and production efficiency, leading to tangible cost savings and performance improvements. Beyond this, digitalization is fundamentally reshaping pharmaceutical manufacturing, improving agility, efficiency, and regulatory responsiveness.

In addition, an important enabler of this shift is Process Analytical Technology (PAT), which allows quality to be built directly into production processes rather than verified only at the end. By enabling real-time monitoring and control at the unit operation level, PAT helps reduce production costs, facilitate continuous manufacturing, and improve the consistency of product quality, ultimately supporting faster decision-making and enabling real-time product release.



These digital capabilities are already delivering measurable benefits across pharmaceutical operations, including:

Plant capacity utilization
Downtime can be reduced by up to 40% through digitalization and analytics, which also leads to improvements in OEE.[22]

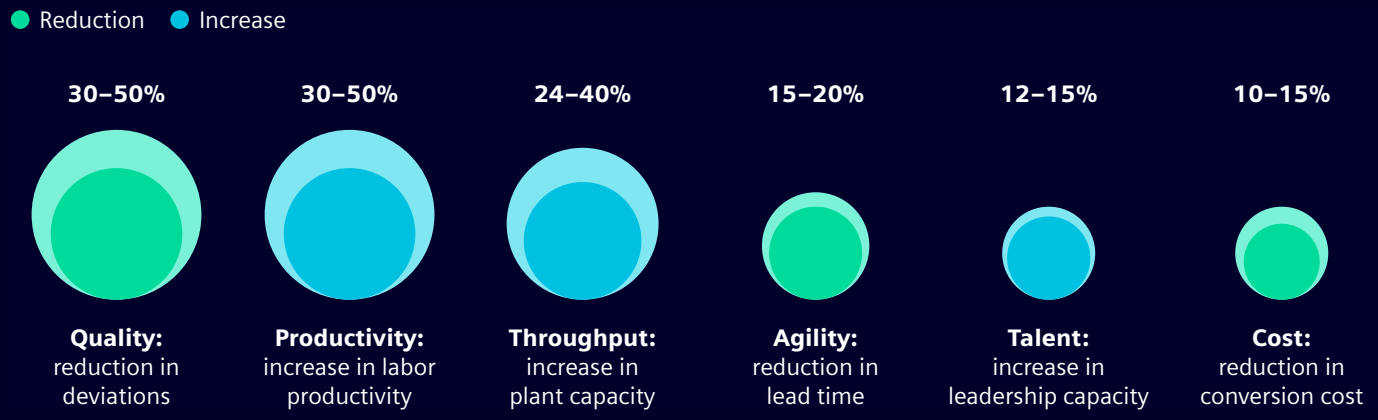
Lead times
Quality control lab lead times can be reduced by up to 70% with improved agility and shorter testing times.[23]

Deviation management
A large global pharmaceutical company was able to reduce deviations by 80% and accelerate deviation closure by 90% with advanced analytics.[24]

Traceability and compliance
Traceability systems strengthen regulatory compliance and can help during unexpected disruptions, improving the flexibility of the supply chain.[25]

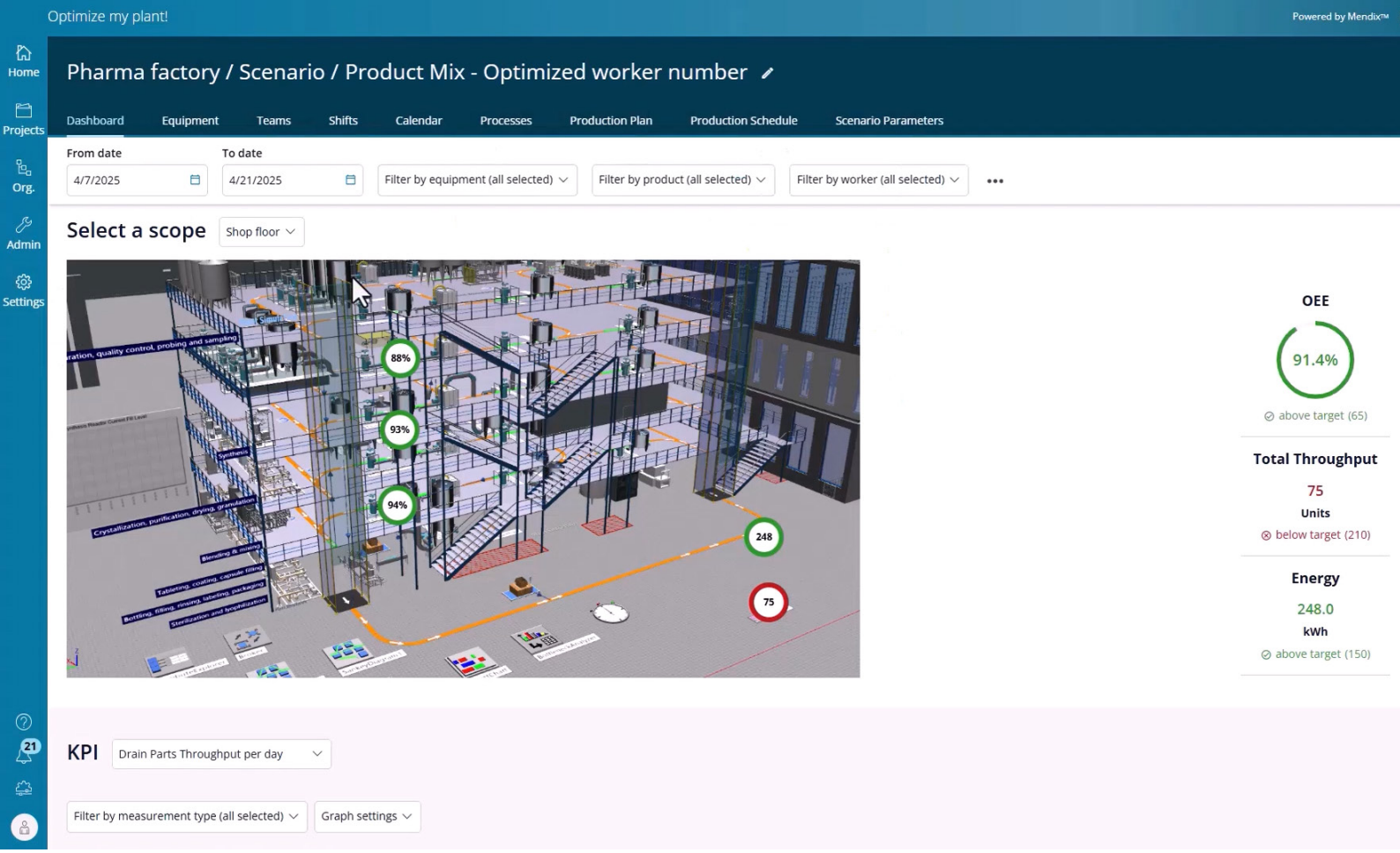
With the adoption of smart, connected production facilities, digital technologies and analytics have the power to unlock real value across key performance metrics such as quality, productivity, and throughput.

Digital and analytics can unlock significant value across critical performance metrics[26]



While digitalization enhances efficiency across the pharmaceutical supply chain, it is also reshaping the workforce. Concerns that automation, digital solutions, and AI will replace jobs are largely misplaced as pharmaceutical companies are, in fact, seeing a surge in demand for digital expertise. In the past five years alone, job postings for data engineers have increased by 69%, while demand for data scientists has risen by 16%.[27] These professionals play a critical role in leveraging advanced analytics, optimizing digital workflows, and ensuring compliance in an increasingly data-driven industry. Yet as digital transformation accelerates, a growing talent gap is becoming evident, with the number-one workforce challenge facing the industry is how to replace retiring employees with skilled talent.[28] Bridging this gap will be essential to sustaining momentum in smart manufacturing and digital innovation.

However, digitalization is just the beginning. As the industry embraces smarter ways of working, four core technologies are emerging as game-changers. Digital twins allow pharmaceutical manufacturers to simulate and optimize products, processes, and facilities in a virtual environment. Software-defined automation brings new levels of flexibility by decoupling control from hardware, enabling rapid adaptation to changing production needs. AI is emerging as a transformative force, pushing pharmaceutical manufacturing toward predictive maintenance, real-time process optimization, and a new era of intelligent quality control. These innovations converge in the Industrial Metaverse – an immersive environment where digital and physical systems interact in real time to enable collaboration, data-driven decision-making, and continuous improvement.

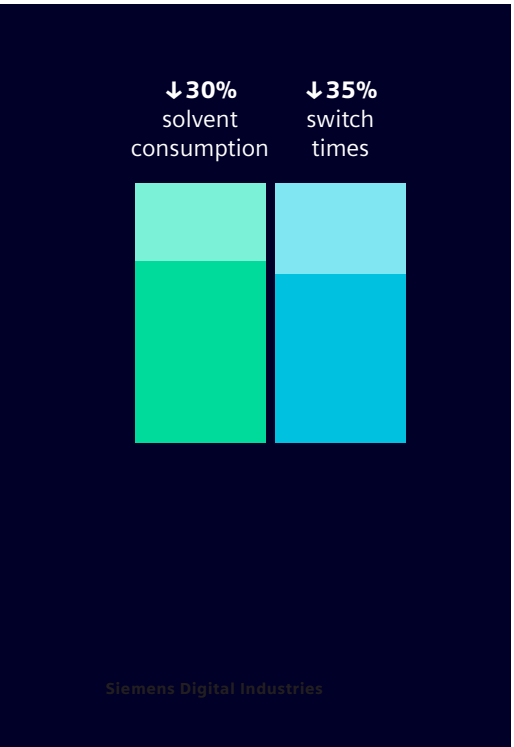


Digital twins

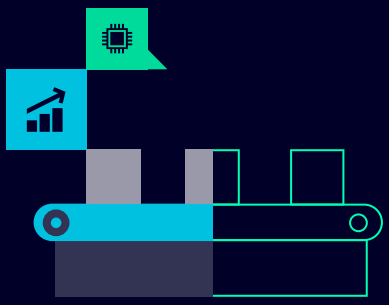
Digital twins remain in the early stages of adoption in pharmaceutical manufacturing – some organizations are using them to enhance collaboration and precision in design while others are using digital twins of their own facilities, but there is a lot of untapped potential and opportunity for growth in the sector.

The digital twin in the pharmaceutical manufacturing market is therefore projected to grow significantly from USD 307.4 million in 2024 at a CAGR of over 31% through 2034. This rapid expansion is fueled by a growing need for greater agility and innovation in the manufacturing process.[29]

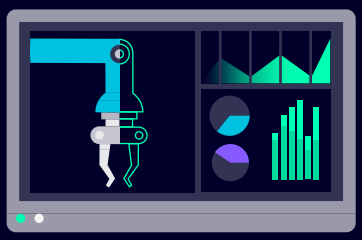
Beyond these high-impact applications, digital twins also offer a wide range of manufacturing-specific advantages that are already transforming pharmaceutical production:



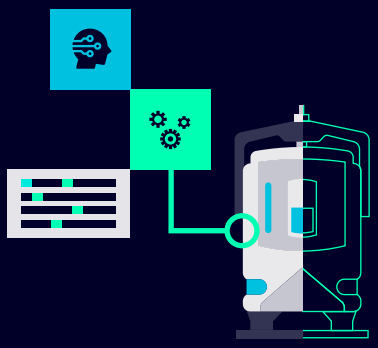
Faster time-to-market thanks to simulations that help optimize the production process at various scales.
Johnson & Johnson Innovative Medicine deployed Siemens' digital process twin to model and optimize solvent-switch steps in their active ingredient pilot production. The virtual simulations reduced solvent consumption by 30% and switch times by 35%, significantly cutting total costs and time-to-market. By applying the digital twin early in the lab phase, they avoided costly large-scale experiments and ensured that process changes were GMP-compliant. This virtual-first approach allows Johnson & Johnson Innovative Medicine to accelerate new product launches while maintaining high safety and quality standards.[30]



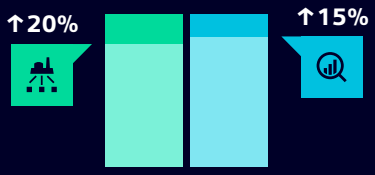
Greater manufacturing flexibility by reducing validation runs and increasing process adaptability.
GSK is leveraging Siemens' digital twin technology to enhance vaccine development and production. By simulating and monitoring adjuvant technologies – a critical component in vaccines – through a hybrid model using Process Analytical Technology (PAT), GSK can predict product quality in real time and adjust parameters proactively. This reduces the need for repeated validation runs and enables faster, more adaptable manufacturing, supporting the rapid rollout of high-quality vaccines.[31]



Improved scalability with adaptive manufacturing to meet market demand.
At the Centre for Process Innovation (CPI) in Glasgow, Siemens' digital technologies enable pharmaceutical companies like AstraZeneca and GSK to simulate and optimize entire production systems using tools like Tecnomatix. Real-time data from facility operations feeds into digital twins, helping manufacturers reconfigure layouts, adjust parameters, and scale up or down efficiently in response to market shifts. This flexibility reduces bottlenecks and material waste, enabling manufacturers to meet variable demand without sacrificing quality or compliance.[32]

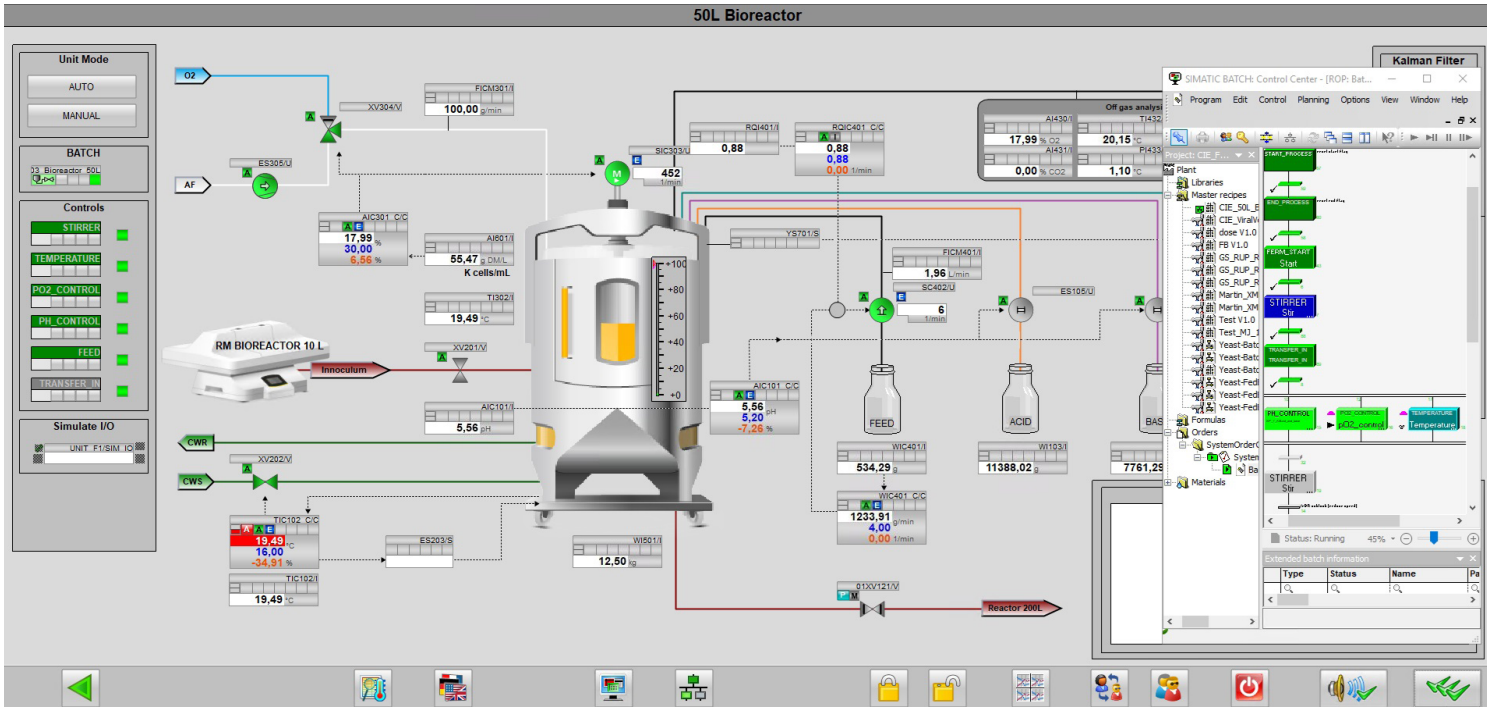


Prompt optimization of bioreactor efficiency and critical process parameters to address changing operating environments and meet quality targets.
Digital twins can be used to develop executable models of manufacturing processes, enabling simulation-driven decision-making in dynamic production environments. By applying AI-augmented parameter space exploration and sensitivity analysis, these models help identify optimal settings and can be converted into reduced order models for run-time use. This allows manufacturers to take rapid, data-backed decisions, maintain control of critical process parameters (CPPs), and consistently achieve critical quality attributes (CQAs).



Enhanced data traceability and integrity through real-time process insights.
Deloitte states that a biopharma company that struggled with real-time data integration and visibility also experienced operational inefficiencies and increased costs as a result. By deploying digital twins to address this, the company was able to optimize inventory levels by 20% and increase forecast accuracy by 15%, among other things.[33]

As the pharmaceutical industry leans further into smart manufacturing, digital twins are emerging not just as a technological innovation but also as a strategic necessity. Their ability to combine simulation, automation, and real-time analytics is transforming how pharmaceuticals are developed, scaled, produced, and delivered. Organizations that invest early and scale wisely will be best positioned to lead in an increasingly competitive and precision-driven market.



Software-defined automation

The shift from hardware-bound automation to software-defined paradigms marks a turning point in how industrial operations are conceived, implemented, and scaled. Software-defined automation (SDA) applies software mechanisms, such as virtualization and containerization, to the OT world, bringing IT-caliber benefits like modularity, scalability, and continuous innovation.

Traditional automation systems are rigid, being tightly coupled to specific hardware and burdened by long development and update cycles. SDA decouples the control logic from proprietary programmable logic controllers (PLC) hardware, allowing engineers to develop, deploy, and maintain automation functions (e.g., PLC logic, motion control, safety) using software containers and standard IT tools. This model shifts the innovation bottleneck away from hardware and opens the door for continuous iteration and rapid scalability.[34]

At Siemens, this vision has materialized through Industrial Edge, a robust platform that merges the strengths of IT and OT. It enables manufacturers to run edge applications directly on the shopfloor, offering centralized management, flexible deployment, and compatibility with standard IT ecosystems. This foundation supports SDA by allowing software components like virtual PLCs and visualization systems to be operated, scaled, and maintained like modern cloud-native apps.[35]

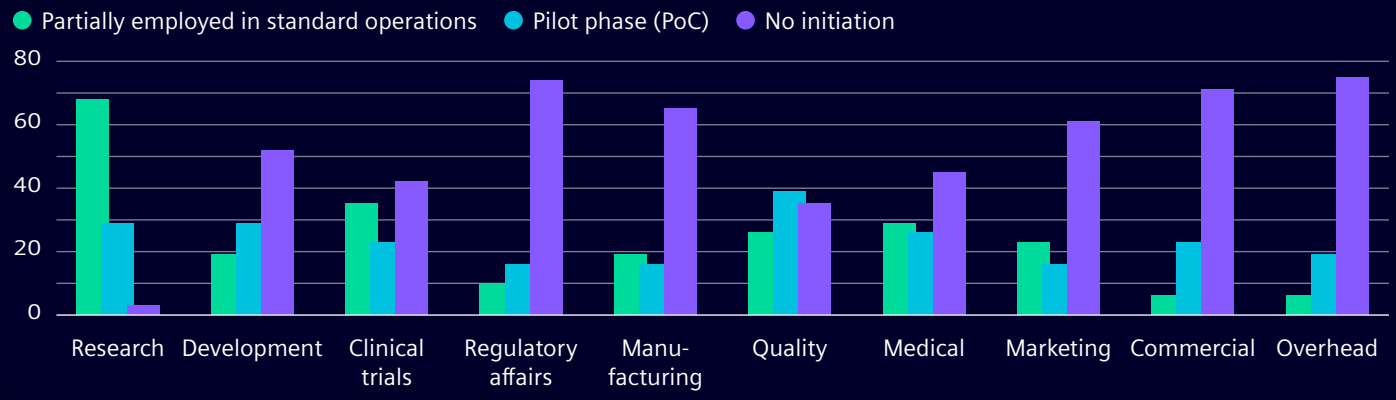
Industrial Edge also addresses the practical demands of industrial environments: enabling high-performance automation while ensuring resilience, security, and ease of use for operational teams. For example, the SIMATIC S7-1500V delivers PLC functionality as an Industrial Edge app, allowing for dynamic scaling and reuse of existing projects within Siemens' TIA ecosystem. Similarly, the SIMATIC WinCC Unified system for Industrial Edge allows no-code, browser-based visualization on any HTML5-capable device, streamlining human–machine interaction without overhauling legacy systems.[36]

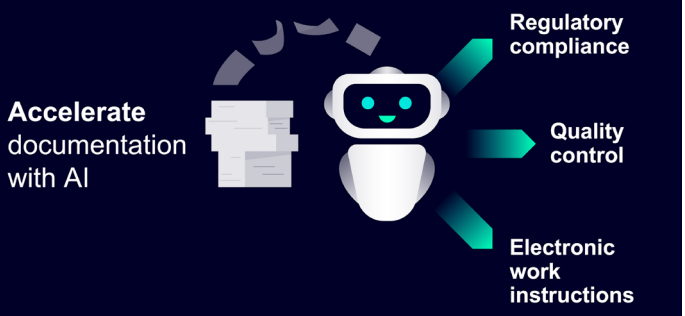
These capabilities make SDA not just a technical evolution, but a strategic enabler for more adaptive, scalable, and intelligent production. By bringing IT flexibility to the deterministic world of automation, solutions like Industrial Edge help manufacturers respond to smaller batch sizes, volatile markets, and sustainability goals, all while simplifying complexity and accelerating time-to-market.

Artificial intelligence

AI is already being used or piloted in pharmaceutical research. However, its adoption in manufacturing remains limited. In fact, 65% of managers and board-level executives surveyed in a recent study reported that their companies have not yet initiated AI adoption in pharmaceutical manufacturing.[37]

Distribution of AI technology adoption in the pharmaceutical industry worldwide by area in 2024, by percentage of respondents





This slow uptake is concerning, given the significant advantages AI offers when integrated into manufacturing. AI-driven technologies have the potential to:

Improve equipment efficiency by optimizing performance and minimizing downtime.
Pharmaceutical company Pfizer has used AI-powered manufacturing processes to increase throughput by 20%.[38]

Reduce unplanned breakdowns through predictive maintenance.
A pharmaceutical company deploying an AI-based predictive maintenance system was able to improve failure prediction accuracy by more than 70%.[39]

Enhance production quality by detecting deviations in real time.
AI-based use cases among manufacturing Lighthouses, i.e. manufacturing sites leading in AI and digital innovation to boost productivity and operational excellence, have seen a 99% reduction in deviations.[40]

Lower unit costs by optimizing resource allocation and reducing waste.
The same manufacturing Lighthouses were also able to decrease energy consumption by 30%.[41]

Despite these clear benefits, many companies remain hesitant to implement AI at scale. Overcoming this gap between potential and adoption will be critical for the future of pharmaceutical manufacturing.

A notable example of this transition is Sanofi, a global pharmaceutical leader currently executing one of the industry's most extensive rollouts of a manufacturing execution system (MES). As part of its plan to deploy Opcenter Execution Pharma across more than 50 sites globally, Sanofi has encountered a key challenge: the time- and resource-intensive nature of recipe creation, further strained by a shortage of skilled professionals.

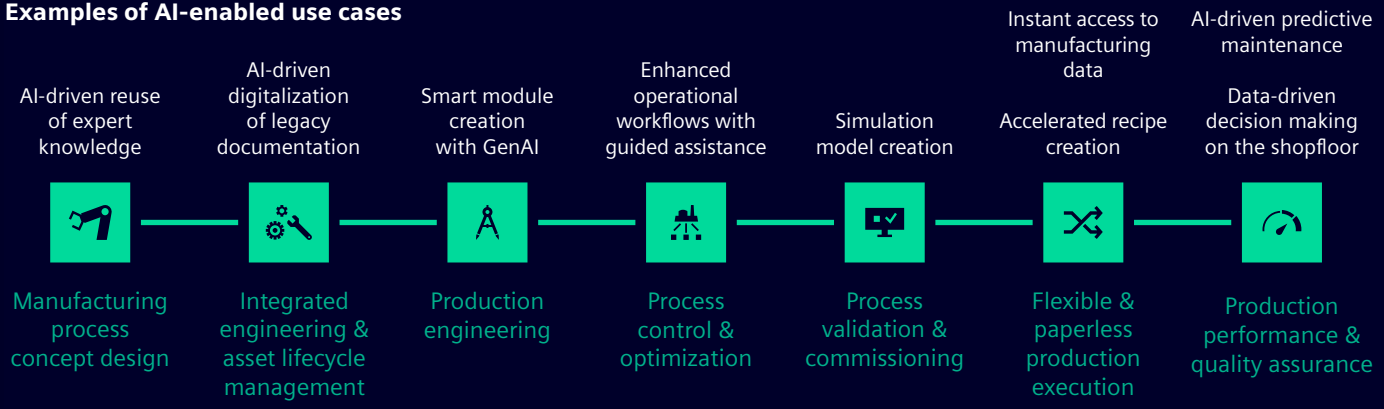
To address this, Siemens has introduced an AI-powered solution that leverages existing documentation to streamline recipe generation and enable intuitive electronic work instruction creation. In collaboration with Capgemini, this generative-AI-driven solution has been integrated into Sanofi's MES delivery model, resulting in significant operational gains, including up to 85% faster generation of work instructions and a projected 20% acceleration in MES deployment timelines. This case underscores how targeted AI applications can not only reduce project effort but also support workforce adoption and scale manufacturing transformation effectively.[42]

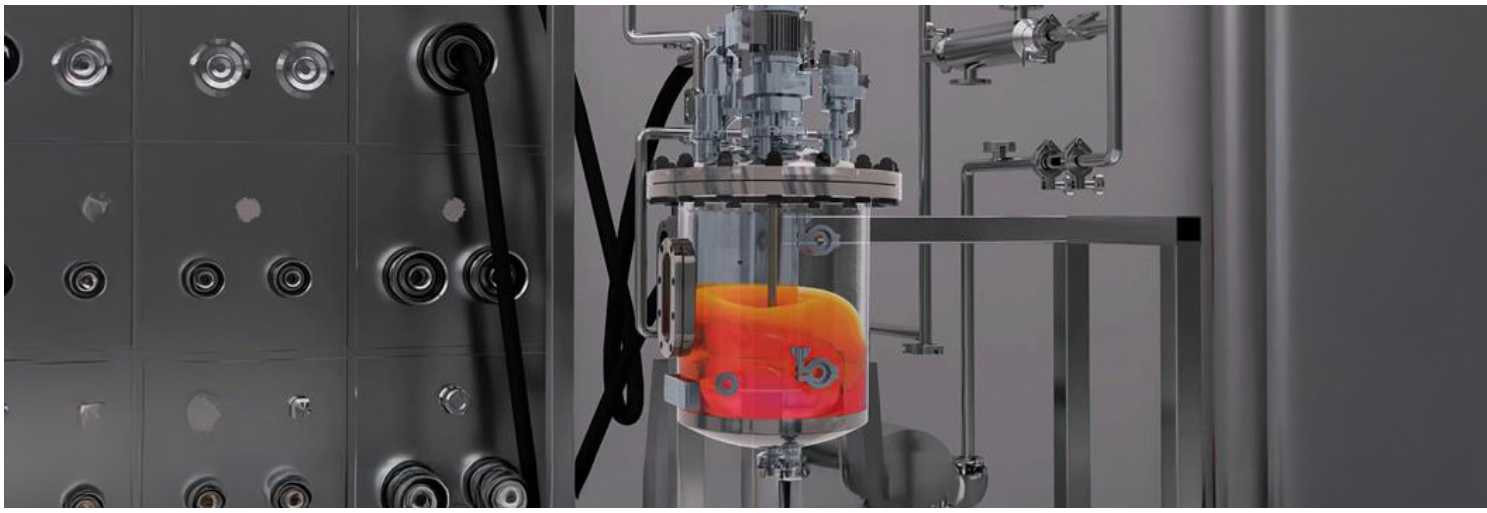
As manufacturers continue to explore the value of AI, many are also turning to complementary technologies like digital twins that, when integrated with AI, can further accelerate efficiency, flexibility, and innovation.

Industrial AI with purpose

Drive efficiency with AI-powered smart manufacturing for pharmaceuticals

Examples of AI-enabled use cases





The Industrial Metaverse

As pharmaceutical manufacturers face mounting complexity, struggles with operational efficiency, and sustainability pressures, the Industrial Metaverse offers a transformative way forward. By uniting digital twins, AI, and SDA, it provides an immersive, real-time environment where fast engineering decisions are made with confidence, leveraging robust, contextualized data from both the physical and digital worlds.

At its core, the Industrial Metaverse is a physics-based, interactive digital space that mirrors reality. Stakeholders can collaborate, experience, and interact with the comprehensive digital twin in real time, enabling them to simulate, test, and continuously optimize products, processes, and production systems, all in a risk-free digital environment.

The Industrial Metaverse supports closed-loop optimization by ingesting data from real-world assets and digital systems. Within this environment, AI-powered analytics deliver real-time insights, allowing users to monitor, analyze, and manage physical operations while simulating potential outcomes. This dual perspective enables manufacturers to anticipate disruptions, ensure quality, and accelerate innovation.

SDA further enhances operational agility, allowing pharmaceutical plants to reconfigure processes on demand and reduce time to validation. With platforms like Siemens' Industrial Edge, production systems gain the flexibility to scale efficiently, adapt quickly, and maintain high levels of compliance and efficiency.

By breaking down silos and offering a unified view of assets, workflows, and performance, the Industrial Metaverse empowers pharmaceutical manufacturers to operate smarter and faster. It is not just the next step in digital transformation – it is the foundation for a resilient, flexible, and innovation-driven pharmaceutical future.

Smart manufacturing for pharmaceuticals – from a vision to a competitive advantage

The pharmaceutical industry is no longer operating in a world of gradual change – it's navigating a landscape of compounding complexity and accelerating transformation. Sustainability and regulatory pressures, drug development uncertainties, personalized therapies, and supply chain fragility demand a rethinking of how medicines are manufactured and delivered.

Smart manufacturing presents a powerful response. By leveraging advanced technologies like digital twins, software-defined automation, AI, and the Industrial Metaverse, pharmaceutical companies can move beyond reactive models towards more predictive, agile, and resilient operations. And the results speak for themselves: improved equipment efficiency, reduced lead times, enhanced quality control, and better alignment with regulatory demands.

Yet the journey is far from complete. Many organizations remain in the early stages of adoption, and siloed data systems, cultural inertia within the industry, and infrastructure gaps still stand in the way. Leaders who proactively embrace smart manufacturing today will not only mitigate risks – they will unlock lasting strategic advantages in speed, flexibility, and cost-effectiveness.

Smart manufacturing is therefore no longer a futuristic concept. It is fast becoming the operational backbone of successful pharmaceutical production – a necessity for those aiming to stay competitive in a precision-driven world.

References

1 https://www2.deloitte.com/us/en/insights/industry/health-care/life-sciences-and-health-care-industry-outlooks/2025-life-sciences-executive-outlook.html#endnote-11

2 https://csdd.tufts.edu/sites/default/files/2025-02/Aug2024%20Day%20of%20Delay%20White%20Paper%20Final.pdf?1750688827#:~:text=In%20October%202023%2C%20the%20Tufts%20Center%20for%20the,cost%20of%20a%20day%20conducting%20a%20clinical%20trial.

3 https://pharmaphorum.com/rd/how-pharmaceutical-companies-can-speed-construction-projects#:~:text=shift

4 https://www.cellandgene.com/doc/catalysts-of-change-how-the-cell-and-gene-therapy-market-has-evolved-0001#:~:text=Investment%20in%20cell%20and%20gene,its%20autoimmune%20cell%20therapy%20mission

5 https://www.cas.org/resources/cas-insights/digital-transformation-pharma

6 https://www.mckinsey.com/capabilities/operations/our-insights/operations-can-launch-the-next-blockbuster-in-pharma

7 https://www.sciencedirect.com/science/article/abs/pii/S0959652618336084

8 https://www.contractpharma.com/sustainability-in-pharma-cdmos-move-fast-to-cut-carbon-footprint/#:~:text=Studies%20suggest%20that%20manufacturing%20is,of%20indirect%20emissions

9 https://www.weforum.org/stories/2022/11/pharmaceutical-industry-reduce-climate-impact/

10 https://pmc.ncbi.nlm.nih.gov/articles/PMC10856271/#:~:text=being%20treated%20in%20many%20countries,era%20with%20respect%20to%20nucleotides

11 https://themedicinemaker.com/manufacture/2025-predictions-for-rna-therapeutics

12 https://www.siemens.com/us/en/products/automation/topic-areas/process-industries/pharmaceutical/pharma-covid-19-biontech.html

13 https://www.cellandgene.com/doc/catalysts-of-change-how-the-cell-and-gene-therapy-market-has-evolved-0001#:~:text=ZOLGENSMA%20was%20approved%2C%20setting%20new,cell%20therapies%20for%20solid%20tumors

14 https://www.iqvia.com/insights/the-iqvia-institute/reports-and-publications/reports/strengthening-pathways-for-cell-and-gene-therapies

15 https://www.biospace.com/cell-and-gene-therapy-manufacturing-market-is-rising-rapidly

16 https://www.pwc.be/en/news-publications/2023/how-to-overcome-manufacturing-challenges.html

17 https://www.sciencedirect.com/science/article/pii/S1359644624003660#b0030

18 https://www.strategyand.pwc.com/de/en/industries/pharma-life-sciences/data-driven-future-pharma.html

19 https://www.pharmiweb.com/press-release/2025-03-04/personalized-medicine-market-trends-insights-and-future-projections-2024-2035

20 https://scw.ai/blog/world-class-oee-in-pharma/

21 https://www.thepowerscompany.com/resources/maintenance-performance-pharmaceutical/

22 https://www.strategyand.pwc.com/gx/en/insights/2016/digitization-in-pharma/digitization-in-pharma.pdf

23 https://www.mckinsey.com/~/media/McKinsey/Industries/Pharmaceuticals%20and%20Medical%20Products/Our%20Insights/Digitization%20automation%20and%20online%20testing%20The%20future%20of%20pharma%20quality%20control/Digitization-automation-and-online-testing-The-future-of-pharma-quality-control.pdf

24 https://www.mckinsey.com/~/media/McKinsey/Industries/Pharmaceuticals%20and%20Medical%20Products/Our%20Insights/Digitization%20automation%20and%20online%20testing%20The%20future%20of%20pharma%20quality%20control/Digitization-automation-and-online-testing-The-future-of-pharma-quality-control.pdf

25 https://www.mdpi.com/2071-1050/15/1/649

26 https://www.mckinsey.com/industries/life-sciences/our-insights/reimagining-the-future-of-biopharma-manufacturing

27 https://www2.deloitte.com/us/en/blog/health-care-blog/2024/smart-manufacturing-digital-supply-chains-may-help-pharma-boost-value.html

28 https://assets.kpmg.com/content/dam/kpmgsites/xx/pdf/2024/11/kpmg-2024-life-sciences-ceo-outlook-report.pdf

29 https://www.globenewswire.com/news-release/2024/07/31/2921611/0/en/Digital-Twin-Technology-in-Pharmaceutical-Manufacturing-market-is-projected-to-grow-at-a-CAGR-of-31-3-by-2034-Visiongain.html

30 https://www.siemens.com/global/en/company/stories/industry/process-industries/johnson-johnson-digital-process-twin.html

31 https://www.siemens.com/global/en/company/stories/industry/2021/pharma-vaccine-digitalization.html

32 https://www.siemens.com/uk/en/company/stories/industry/cpi-medicines-manufacturing-innovation-centre-digital-enterprise-digitalization-pharma-uk.html

33 https://www2.deloitte.com/content/dam/Deloitte/us/Documents/consulting/us-google-cloud-digital-twins-biopharma-supply-chain-at-scale.pdf

34 https://www.siemens.com/global/en/products/automation/topic-areas/industrial-operations-x/software-defined-automation.html

35 https://blog.siemens.com/2024/09/software-defined-automation-part-1-living-on-the-industrial-edge/

36 https://blog.siemens.com/2024/10/software-defined-automation-part-2-how-automation-benefits-from-it-mechanisms/

37 https://www.statista.com/statistics/1538057/ai-adoption-in-pharmaceutical-industry-by-area/

38 https://healthtechmagazine.net/article/2025/02/ai-in-drug-manufacturing-perfcon#:~:text=Using%20AI%2C%20Pfizer%20is%20able,the%20company%E2%80%99s%202023%20annual%20review

39 https://www.quantzig.com/case-studies/pharmaceutical-manufacturer-set-up-predictive-maintenance/

40 https://www.mckinsey.com/capabilities/operations/our-insights/how-manufacturings-lighthouses-are-capturing-the-full-value-of-ai

41 https://www.mckinsey.com/capabilities/operations/our-insights/how-manufacturings-lighthouses-are-capturing-the-full-value-of-ai

42 https://hm.virtualevent.siemens.com/share-event/6nm5XAPHQFiFeEh0-gYpss7cy/?path=/en/

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