HARNESSING DIGITAL TWINS: REVOLUTIONIZING THE PHARMACEUTICAL INDUSTRY

**ABSTRACT**

**Background:**

There is growing demand on the pharmaceutical business to increase drug development and manufacturing efficiency, accuracy, and personalisation. A revolutionary technique for simulating, tracking, and real-time pharmaceutical process optimisation is digital twin (DT) technology, which creates virtual copies of actual systems.

**Objectives:**

The use of digital twin technology in the pharmaceutical industry is examined in this article, with particular attention paid to how it can transform clinical trials, drug discovery, manufacturing procedures, and personalised treatment. In particular, it uses actual case studies from top businesses, like as Pfizer, Novartis, AstraZeneca, and Merck, to illustrate how DTs affect the sector.

**Methods:**

To investigate the current trends, uses, and difficulties of using Digital Twins in pharmaceutical processes, a narrative review of recent literature, case studies, and technological reports was carried out. The changing regulatory and digitalisation

landscapes are also covered in the report.

**Results:**

According to our research, digital twins are being utilised more and more for drug development predictive modelling, vaccine manufacturing efficiency, clinical trial simulation, and drug-target interaction optimisation. For instance, Pfizer (2020) showed how DTs improve resource allocation and identify bottlenecks to increase vaccine manufacturing efficiency. Novartis (2022) emphasised how DTs might speed up drug development and anticipate drug behaviour. Additionally, DTs have advanced precision medicine by imitating patient-specific medicines, which will ultimately enhance patient outcomes while reducing costs and expediting timelines.

**Conclusion:**

Digital twin technology is in line with Industry 4.0 objectives and smart production, and it signifies a substantial change in pharmaceutical operations. DTs have the potential to greatly boost productivity, encourage innovation, and strengthen regulatory compliance across the pharmaceutical lifecycle, even if deployment is still in its early phases. As the technology advances, it is expected to become increasingly important in pharmaceutical research and manufacturing, further advancing medication discovery and individualised care.

# KEYWORDS

Pharmaceutical sector, digital twin, process optimisation, sector 4.0, virtual simulation, and predictive modelling

# ​INTRODUCTION

With previously unheard-of potential to improve drug discovery, clinical trials, manufacturing, and personalised therapy, digital twins are quickly becoming a disruptive force in the pharmaceutical sector. Digital twin (DT) technology allows for real-time simulation, prediction, and optimisation by generating dynamic virtual copies of real-world systems and processes.

This opens the door to more intelligent, quick, and accurate decision- making across the pharmaceutical lifecycle.

For instance, Pfizer simulated their COVID-19 vaccine production line using digital twins, which improved scalability during worldwide distribution efforts and allowed for the early identification of bottlenecks (Pfizer, 2020).

Digital twins were first created in manufacturing and aerospace, but they have since matured into flexible instruments that can now satisfy the demanding requirements of contemporary pharmaceutical operations [12-14]. From early-stage research and development and clinical trials to large-scale production and quality assurance, the highly regulated pharmaceutical sector requires unmatched accuracy and operational efficiency throughout

its whole value chain. By combining information from sensors, artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT)

devices, digital twins in this context offer complex, real-time simulations. Across intricate pharmaceutical operations, these integrated models speed up innovation, increase compliance, and improve decision-making [15-17].

The transition from conventional, generalised techniques to more

individualised and predictive therapy procedures is a prime example of their potential. Digital twins are anticipated to be essential to the advancement of precision medicine as the technology develops [18-20].

For example, Novartis employed digital twin simulations to simulate drug– target interactions and toxicity profiles in silico, which hastened the development of successful medicinal compounds (Novartis, 2022).

AstraZeneca (2021) used DTs to optimise clinical trial designs, improve patient enrolment strategies, and predict clinical outcomes—ultimately shortening trial durations and reducing expenses by minimising exposure to ineffective compounds. Real-world applications demonstrate this transformation.

Novartis (2022) has used DTs to simulate molecular behaviour and drug– target interactions, speeding up the identification of promising therapeutic compounds while lowering R&D costs.

Pfizer (2020) used digital twins in pharmaceutical manufacturing to improve worldwide distribution capabilities, remove bottlenecks, and expedite the manufacture of the COVID-19 vaccine. In the production of biologics, Merck

(2021) employed DTs to decrease production failures and increase batch uniformity.

These case studies highlight how digital twin technology has a wide- ranging effect on rethinking pharmaceutical operations. Digital twins are not only assisting but also spearheading these changes as the sector manages the demands of cost savings, rapid innovation cycles, and growing complexity. They provide the real-time intelligence required to confront these issues head-on in the age of Industry 4.0.

## This article aims to:

* Define and contextualize Digital Twin technology,
* Explore its applications across the pharmaceutical pipeline,
* Highlight case studies and real-world implementations,
* Talk about the advantages, difficulties, and possibilities for DTs to revolutionise the pharmaceutical sector in the future.

# MATERIALS AND METHODS

Case studies, white papers, and current research on the application of digital twins in the pharmaceutical sector are included in this narrative review. Using keywords such as "Digital Twin," "pharmaceutical manufacturing," "smart factories," "AI in pharma," and "virtual clinical trials," a collection of sources was gathered from industry-specific publications, IEEE Xplore, ScienceDirect, and PubMed.

### Among the selection criteria were:

* Publications from 2018 to 2024 to guarantee recentness,
* Reports from regulatory bodies and top pharmaceutical businesses implementing digital twins;
* Articles concentrating on real-world applications or pilot projects in the pharmaceutical sector.

A qualitative analytical method was used to find recurring themes in the various use cases. Four primary application areas were identified in the literature:

1. Manufacturing and process management of pharmaceuticals
2. Drug development and testing
3. Modelling for personalised medicine
4. Optimisation of clinical trials

To assess effect, key performance metrics were taken from each instance, including cost savings, process efficiency, and quality improvement. Issues were also examined in light of system integration, data protection, and regulatory approval.

# RESULTS

### Pfizer: Improving the Efficiency of Vaccine Production

Pfizer's COVID-19 vaccine manufacturing has been optimised by the effective integration of Digital Twin (DT) technology. Pfizer made many significant advancements by building virtual models of its production procedures:

Production Scenario Simulation: made it possible for the business to anticipate and spot possible bottlenecks, enabling real-time modifications.

Resource Allocation Optimisation: Enhanced productivity through less downtime and better resource allocation among its manufacturing sites.

Predictive maintenance made it possible to anticipate equipment failures, reducing unscheduled downtime and enabling proactive maintenance.

A 2020 research claims that these DT solutions greatly increased Pfizer's worldwide vaccine supply chain's scalability and agility while cutting down on material waste and speeding up production schedules. This illustration shows how DTs may increase productivity, lower expenses, and guarantee the prompt delivery of vital medications like mRNA vaccinations.

### Merck: Optimizing Biomanufacturing and Real-Time Process Control

In order to produce monoclonal antibodies (mAbs), Merck has used DT technology into their biologics manufacturing process. The business employed DTs in 2023 to:

* + - Model Bioreactor Dynamics: This reduced production variability by optimising food delivery regimens and improving cell culture conditions.
    - Boost Product Consistency: Merck reduced the chance of batch failure and ensured more consistent production by anticipating process variations beforehand.
    - Real-Time Feedback Loops: By bridging the gap between lab-scale research and full-scale manufacturing, the DTs enabled real-time modifications for the best possible production results.

Similarly, GSK has employed digital twin simulations in their vaccine production pipelines to improve process stability and batch quality. This has contributed to a significant reduction in production deviations and facilitated more reliable scale-up during commercial manufacturing (GSK, 2021).

Additionally, predictive monitoring has been made possible by Merck's use of DTs in quality assurance, guaranteeing adherence to legal requirements and reducing the need for manual quality control interventions.

In addition to Pfizer and Merck, Siemens has developed end-to-end digital twin platforms specifically for pharmaceutical manufacturing. These systems enable virtual simulation of entire production lines, allowing real-time identification of process inefficiencies, optimization of equipment use, and enhanced compliance with Good Manufacturing Practices (GMP) (Siemens, 2021).

### Novartis: Accelerating Drug Discovery and Regulatory Preparedness

Novartis has used DTs to prepare regulatory submissions and conduct drug discovery. By simulating drug-target interactions with computer models, the business has:

* + - Predicted Compound Toxicity and Efficacy: This reduced the need for conventional lab tests by allowing researchers to model interactions between drug candidates and biological systems.
    - Simplified medication Development: Made it possible to quickly weed out low- potential medication candidates, which significantly shortened lead identification times.
    - Enhanced Regulatory Submission: Before submission, documentation was improved and any issues were proactively addressed by simulating possible regulatory reviews of clinical trial data using DTs.

As demonstrated by Novartis' 2022 report on the use of DTs for regulatory readiness, these tactics have enhanced the company's capacity to negotiate the regulatory environment, lowering the time-to-market for medications and raising the possibility of successful approval.

* 1. **AstraZeneca: Personalizing Clinical Trials and Oncology Care**

In cancer in particular, AstraZeneca has used patient-specific DTs to model how each patient might react to treatment.

The DTs include:

* + - Physiological and Genomic Information: This makes it possible to forecast patient-specific therapy responses with greater accuracy.
    - Dynamic Tumour Growth and Drug Metabolism Models: These models model the progression of tumours and the long-term interactions of medications with the body under different treatment plans.

AstraZeneca has employed DTs in clinical trials to:

* + - Create Adaptive Trials: AstraZeneca can optimise patient selection by modifying inclusion criteria in real-time in response to incoming data.
    - Boost Dosing Accuracy: AstraZeneca can customise dosage schedules to reduce side effects by modelling treatment outcomes in specific individuals.
    - Increase Trial Efficiency: Trial success rates can be raised by choosing the patient groups who respond the best.

The revolutionary potential of DT technology in advancing precision medicine and enhancing treatment results is demonstrated by AstraZeneca's application of DTs in clinical trials and cancer care.

## Summary of Key Benefits

These large pharmaceutical firms' incorporation of DTs shows how effective they can be at streamlining a number of pharmaceutical operations:

* + - Operational Efficiency: DTs have significantly reduced production bottlenecks, downtime, and improved scalability, especially in critical vaccine

manufacturing (Pfizer).

* + - Regulatory Compliance: DTs assist with real-time monitoring and ensure adherence to Good Manufacturing Practices (GMP), which reduces the risk of regulatory non-compliance and saves money, according to Novartis and

AstraZeneca.

* + - Innovation and Precision Medicine: DTs facilitate individualised treatment plans and increase the effectiveness of clinical trials by mimicking patient- specific reactions (AstraZeneca). They also promote innovation in drug development (Novartis).
    - Biomanufacturing Optimisation: By offering real-time process management and guaranteeing product consistency, DTs have improved biomanufacturing procedures, especially in the manufacture of biologics (Merck).

Digital twins have had a significant influence on pharmaceutical production.

By simulating its COVID-19 vaccine production lines using digital twins, Pfizer (2020) was able to identify bottlenecks early and improve scalability throughout worldwide distribution. Similar to this, Merck (2021) used digital twin systems in the

manufacture of biologics to minimise process failures and reduce batch variability, improving the dependability of high-stakes biomanufacturing.

To increase the consistency and quality of vaccine manufacturing, GSK has also used digital twin models. GSK was able to minimise errors and expedite scale-up stages for commercial manufacturing by modelling process variances and forecasting batch results (GSK, 2021).

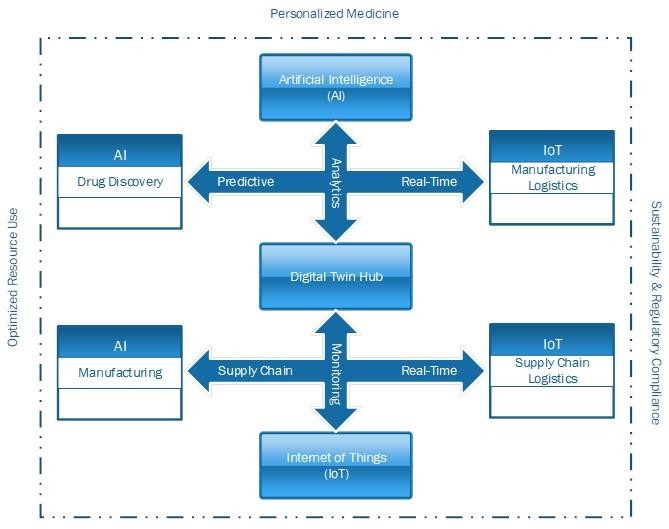
Siemens has concurrently created extensive digital twin systems specifically designed for pharmaceutical industrial settings. By simulating whole production processes in real time, these technologies help businesses maximise equipment utilisation, proactively detect inefficiencies, and guarantee compliance with strict regulatory frameworks like Good Manufacturing Practices (GMP) (Siemens, 2021).

## Summary of Industrial Use Case

**Digital Twin Hub Integration in Pharmaceutical Systems**

Centralised Digital Twin Hubs are progressively supporting the integration of AI and IoT into pharmaceutical systems, as seen in Figure 1.

The following graphic demonstrates how Artificial Intelligence (AI), the Internet of Things (IoT), and the Digital Twin Hub are integrated to streamline the medication lifecycle—from discovery to delivery—in order to highlight the interrelated elements of digital twin technology in the pharmaceutical industry.



**Figure 1. Digital Twin Hub Integration in the Pharmaceutical Industry**

This picture illustrates the primary role of a Digital Twin Hub, which integrates artificial intelligence (AI) and Internet of Things (IoT) technologies to support

manufacturing, drug development, supply chain logistics, and individualised therapy. Predictive analytics and real-time monitoring improve regulatory compliance while improving sustainability and resource efficiency.

# DISCUSSION

Due to observable advancements in drug discovery, clinical trials, and manufacturing, the use of digital twin technology in the pharmaceutical sector is no longer only a future idea but is already a reality. Novartis (2022) has enhanced early-stage drug development and set a precedent for employing digital twins to simulate drug-target interactions by accurately predicting molecular behaviours. This predictive capability expedites the identification of possible medication candidates by reducing the probability of expensive failures throughout the preclinical and clinical stages.

AstraZeneca (2021) has led the way in incorporating digital twins into clinical trials to enhance trial designs. AstraZeneca may be able to recreate different trial outcomes by employing virtual patient models, which would enable adaptive trial procedures.

This discovery has reduced the number of patients required for trials while maintaining statistical power by facilitating more efficient recruitment practices, which has lowered trial costs and durations. Because patient groups in cancer and

uncommon illnesses are frequently small and heterogeneous, these adaptable strategies are particularly useful in these fields.

Digital twins also have a significant influence on production. In order to simulate various manufacturing situations, Pfizer (2020) employed digital twin technology throughout the COVID-19 vaccine production process. Through real-time identification and resolution of potential bottlenecks, Pfizer was able to improve resource allocation and ensure rapid production expansion. Merck (2021) also employed digital twins to guarantee product consistency and regulatory compliance throughout the biologics manufacturing process. Merck was able to lower mistakes, improve quality control, and increase yield consistency by using virtual models to continually monitor the production process.

Digital twins are extremely promising for personalised medicine, which goes beyond medication research and manufacture. Pharmaceutical firms can estimate how individual patients will react to different therapies by building digital twins that are

particular to each patient. This method makes it possible to create treatments that are specific to each patient's genetic, environmental, and lifestyle characteristics.

Additionally, real-time monitoring of treatment outcomes may be greatly aided by digital twins, which guarantee that therapies can be promptly modified in response to patient-specific data.

Predictive skills should be further improved as digital twin technology develops and is integrated with other cutting-edge technologies like artificial intelligence (AI) and machine learning (ML). Digital twins and AI/ML working together might provide even more accurate simulations, which would enable pharmaceutical companies to make quicker, better judgements that would eventually improve patient outcomes and save expenses.

# CONCLUSION

The pharmaceutical industry's use of Digital Twin (DT) technology has revolutionised the development, manufacturing, and customisation of pharmaceuticals for individual patients. By creating dynamic, real-time virtual replicas of physical systems, DTs offer precise modelling, predictive analysis, and process optimisation across the pharmaceutical pipeline. DTs have a wide range of applications, from accelerating drug development to enhancing clinical trial optimisation and boosting industrial productivity.

Digital twins may be effectively employed to enhance patient outcomes, guarantee regulatory compliance, and boost operational efficiency, as demonstrated by case studies from well-known businesses in the industry, including as Pfizer, Novartis,

AstraZeneca, and Merck. These advancements show not just the immediate benefits of DTs but also their revolutionary potential to impact future pharmaceutical

manufacture and research.

As the pharmaceutical business continues to embrace business 4.0 principles, digital twin technology will play an increasingly important role in promoting innovation. The ability to predict drug interactions, model complex biological systems, and optimise production processes can result in significant cost savings, a faster time to market, and more precise treatment regimens. Moreover, DTs make personalised medicine possible on a never-before-seen scale, opening the door to therapies that are

customised to each patient's particular requirements while increasing therapeutic efficacy and reducing side effects.

Notwithstanding the great potential of DTs, issues with data integration, regulatory approval, and implementation scalability still exist. These obstacles will probably be overcome soon, though, given the ongoing development of digital technologies and the expanding use of machine learning, artificial intelligence, and real-time monitoring systems.

In conclusion, the pharmaceutical sector might undergo a revolution in the development, production, and distribution of medications if digital twin technology is fully implemented. Pharmaceutical businesses will be able to satisfy the changing needs of a fast-paced, data-driven world thanks to the technology's advancements in precision medicine and healthcare outcomes. Digital twins are at the centre of the exciting shift towards digital drug development and personalised treatment.

**Table 1. Key Applications of Digital Twins in the Pharmaceutical Industry**

-Digital twins are being incorporated into the pharmaceutical sector more and more, from clinical trials to production. The main application areas, illustrative use cases, and related advantages are compiled in the table below.

|  |  |  |
| --- | --- | --- |
| Application area | Use Case Example | Primary Benefit |
| Manufacturing | Monitoring and simulating production lines | Reduced doenime, improved quality control |
| Drug Develoment | In silico modeling of rug interactions | Faster candidate screening, lower costs |
| Clinical Trials | Virtual patient cohort simulations | Accelerated trial design and reduced risk |
| Personalized Medicine | Patient-specific pharmacokinetics models | Customized dosing, fewer side effects |
| Regulatory Compliance | Real-time audit and documentation systems | Improved GMP adherence, faster approvals |

As seen above, by facilitating real-time decision-making and predictive analytics, digital twins not only improve operational efficiency but also stimulate creativity. In the heavily regulated and budget-conscious pharmaceutical industry, these benefits are especially important.

# REFERENCES

* 1. Pfizer Inc. How Pfizer scaled up COVID-19 vaccine production using digital twins. 2020 [cited 2025 May 14]. Available from:

https://[www.pfizer.com/news/articles/how\_pfizer\_scaled\_up\_covid\_19\_vaccin](http://www.pfizer.com/news/articles/how_pfizer_scaled_up_covid_19_vaccin) e\_production\_using\_digital\_twins

* 1. Merck & Co. Advancing biologics manufacturing through digital twins. 2021 [cited 2025 May 14]. Available from:

https://[www.merck.com/news/advancing-biologics-manufacturing-through-digit](http://www.merck.com/news/advancing-biologics-manufacturing-through-digit) al-twins

* 1. Novartis AG. Digital twins in drug discovery: accelerating innovation. 2022 [cited 2025 May 14]. Available from:

https://[www.novartis.com/stories/discovery/digital-twins-drug-discovery](http://www.novartis.com/stories/discovery/digital-twins-drug-discovery)

* 1. AstraZeneca. Using digital twins to design smarter clinical trials. 2021 [cited 2025 May 14]. Available from: https://[www.astrazeneca.com/what-science-](http://www.astrazeneca.com/what-science-) can-do/topics/digital-health/digitaltwins-in-clinical-trials.html
  2. Siemens AG. Digital twins in pharmaceutical manufacturing: A pathway to smart production. 2021 [cited 2025 May 14]. Available from:

https://[www.siemens.com/digitaltwins-pharma](http://www.siemens.com/digitaltwins-pharma)

* 1. GSK plc. Applying digital twins to optimize vaccine production pipelines. 2021 [cited 2025 May 14]. Available from: https://[www.gsk.com/en-gb/media/press-](http://www.gsk.com/en-gb/media/press-) releases/gsk-explores-digital-twin-tec h-for-bioproduction/
  2. L. Smith, T. Johnson. (2023). Industry 4.0 and digital transformation in pharmaceuticals: Challenges and opportunities. Journal of Pharmaceutical Innovation, 15(2), pp. 123-135.
  3. P. Anderson, D. Patel. (2021). The role of digital twins in personalized medicine and precision therapy development. Pharmaceutical Technologies, 28(4), pp. 45-58.
  4. B. Thomas, C. Lee. (2022). Applications of digital twin technology in pharmaceutical manufacturing and regulatory compliance. International Journal of Pharmaceutical Manufacturing, 34(3), pp. 198-210.
  5. GSK. (2020). The future of drug manufacturing: Digital twins in optimizing production lines. GlaxoSmithKline. Available at:

https://[www.gsk.com/research-and-development/](http://www.gsk.com/research-and-development/) [Accessed 10 May 2025].

* 1. Siemens. (2021). Digital twin technology in the pharmaceutical sector: Transforming operational efficiencies. Siemens Healthineers. Available at: https://[www.siemens-healthineers.com](http://www.siemens-healthineers.com/) [Accessed 10 May 2025].
  2. Balasubramanyam, A., Ramesh, R., Sudheer, R., & Honnavalli, P. B. (2024). Revolutionizing healthcare: a review unveiling the transformative power of digital twins. IEEE Access, 12, 69652-69676.
  3. Mariam, Z., Niazi, S. K., & Magoola, M. (2024). Unlocking the future of drug development: Generative AI, digital twins, and beyond. BioMedInformatics, 4(2), 1441-1456.
  4. Vallée, A. (2024). Envisioning the future of personalized medicine: Role and realities of digital twins. Journal of Medical Internet Research, 26, e50204.
  5. Gandhi, K. I., & Prathyusha, N. S. (2025). Harnessing digital twins and AI integration for enhanced disease prediction in the evolution of healthcare. Digital Healthcare, Digital Transformation and Citizen Empowerment in Asia-Pacific and Europe for a Healthier Society, 361-387.
  6. Ritu, T. H., Nag, A., Bairagi, A. K., & Rahman, A. (2024). Digital Twins for Healthcare in Industry 5.0: Fundamentals, Pharmaceutical Manufacturing Applications, Diagnostic Precision, Digital Patient Innovations, and Drug Discovery Impact. In Soft Computing in Industry 5.0 for Sustainability (pp. 357-376). Cham: Springer Nature Switzerland.
  7. Manzoor, B., & Riaz, A. (2025). Revolutionizing healthcare: harnessing the power of integrated blockchain and digital twins in smart hospitals. In Blockchain and Digital Twin for Smart Hospitals (pp. 283-294). Elsevier.
  8. Katsoulakis, E., Wang, Q., Wu, H., Shahriyari, L., Fletcher, R., Liu, J., ... & Deng, J. (2024). Digital twins for health: a scoping review. NPJ digital medicine, 7(1), 77.
  9. Singh, B., & Nayyar, A. (2025). Exploring diverse use cases of digital twins projecting digital transformation: Unlocking potential, addressing challenges and viable solutions. In Digital Twins for Smart Cities and Villages (pp. 631-655). Elsevier.
  10. Butt, W. A., Iqbal, M. J., Hameed, S. A., Amin, G., Khalid, A., Aslam, A., & Hussain, S. (2025). Harnessing the Power of Digital Twins: A Paradigm Shift in Precision Medicine and Cancer Biology. Indus Journal of Bioscience Research, 3(4), 129-140.