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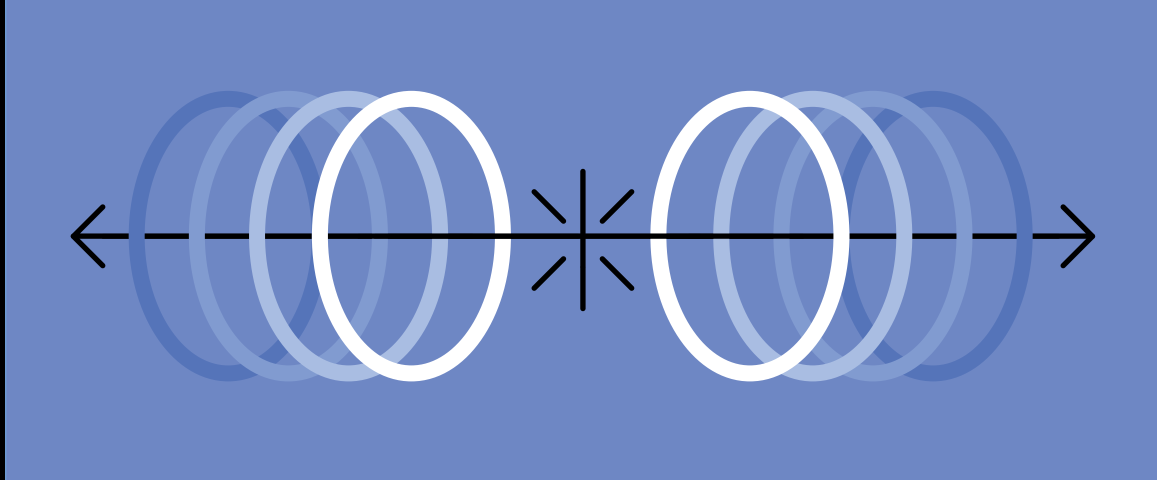

AI-Enabled Digital Twins

A New Pathway to Improving Health Care Efficiency

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The Transformative Potential of Digital Twins

At Johnson & Johnson, we are dedicated to leveraging cutting-edge scientific research to address the complex challenges of the modern health care landscape. As a proud sponsor of the report "AI-Enabled Digital Twins: A New Pathway to Improving Health Care Efficiency" in association with Harvard Business Review Analytic Services, we recognize the critical importance of integrating foundational research in mathematics, physics, and computer science to effectively tackle complex health care challenges that involve highly nonlinear, stochastic, and combinatorial decision-making problems.

This report underscores the transformative potential of digital twins in enhancing supply chain efficiency and productivity in the pharmaceutical sector. By employing sophisticated virtual models, organizations can achieve remarkable improvements in operational performance, which not only contribute to top-line revenue growth but also strengthen the bottom line. Digital twins enable real-time insights and predictive capabilities that allow proactive decision making and optimized resource allocation, ultimately leading to more efficient health care delivery.

Moreover, the adoption of digital twin technology fosters a robust risk management framework throughout the end-to-end life cycle of the pharmaceutical industry. By simulating various scenarios and assessing potential risks, organizations can better anticipate challenges and implement strategies to mitigate them. This risk-awareness culture not only ensures compliance with industry standards but also enhances overall resilience against disruptions, thereby safeguarding the integrity of supply chains and patient outcomes.

Our association with Harvard Business Review Analytic Services reaffirms our commitment to advancing research and innovation that drive efficiency and effectiveness in health care. Through this report, we aim to inspire industry stakeholders to embrace digital twin technology and the foundational sciences that underlie its development, fostering a future where health care systems are not only more efficient but also more adaptive and responsive to the needs of patients and providers alike.

As we move forward, Johnson & Johnson remains focused on building a collaborative ecosystem where scientific research and technological innovation converge to create lasting improvements in health care. We are excited to share the insights from this report and look forward to contributing to the ongoing evolution of the pharmaceutical industry.

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AI-Enabled Digital Twins

A New Pathway to Improving Health Care Efficiency

The health care landscape is undergoing a seismic shift fueled by technological advancements, empowered patients, and a burgeoning demand for accessible, personalized care. To navigate this turbulent yet promising era, the industry is looking to new technologies such as digital twins that are powered by artificial intelligence (AI).

THE AIM OF A DIGITAL TWIN is to create a functional model that syncs with an individual, asset, process, or system, reflecting changes in real time. "The main benefit of digital twins comes with real-time assessment and diagnostics," confirms Maria Jesús Saénz, director of the Massachusetts Institute of Technology (MIT) Digital Supply Chain Transformation Lab and executive director of MIT's master's program in supply chain management in Cambridge, Mass. "For example, you can compare current information with past history about demand or geography. Or you can examine operational contingencies in a particular location or the prices of a competitor. Then you can propose decisions that are executed by the system."

Digital twins' ability to personalize treatment plans and evaluate the impact of interventions comes as health care costs become more of a mounting concern across industrialized nations; these costs currently claim 6.1% of global GDP with forecasts suggesting a rise to 6.26% by 2029.[1] While numerous factors drive this trend, logistical inefficiencies within hospitals, health clinics, and pharmacies significantly contribute to escalating expenses.

Not surprisingly, value-based care has emerged as a proven way to reduce costs, minimize complexity, and ultimately improve patient outcomes. Enter the AI-enabled digital twin, which is a virtual replica of a physical object, process, or system that can simulate and predict real-world behaviors and support real-time decisions.

At a micro level, digital twins give doctors and researchers a deeper

HIGHLIGHTS

These sophisticated virtual models offer the potential to **optimize medical and pharmaceutical supply chains**, improving the overall efficiency of the health care system.

By replicating health care value chains, these digital solutions can proactively **identify bottlenecks**, **streamline patient flows**, and **improve clinical outcomes**.

Digital twins incorporate feedback loops by **collecting data from a physical system to update a virtual model**, which, in turn, drives changes in the physical system.

> **“Genomic data, imaging data, drug-interaction data, and many other sources of information are coming together to develop a 360-degree view of the patient.”**
>
> Nimita Limaye, research vice president, life sciences R&D strategy and technology at International Data Corp.

understanding of the body’s complexity—from DNA to tissues to organs to entire human beings.

At a macro level, these sophisticated virtual models offer the potential to optimize medical and pharmaceutical supply chains, improving the overall efficiency of the health care system. They also represent a significant leap forward in personalized medicine, enabling a more proactive and predictive approach to patient care. By replicating health care value chains, these digital solutions can proactively identify bottlenecks, streamline patient flows, enhance patient experiences, and improve therapeutic outcomes—all while reducing risk and lowering costs.

“Genomic data, imaging data, drug-interaction data, and many other sources of information are coming together to develop a 360-degree view of the patient,” says Nimita Limaye, research vice president, life sciences R&D strategy and technology at International Data Corp. (IDC), a market intelligence and advisory service based in Needham, Mass. “How these data points interact will influence drug discovery, precision medicine strategy, medical equipment inventory, holding costs, delivery times, and ultimately patient satisfaction.”

This report describes how AI-enabled digital twins can significantly improve the efficiency, reliability, and cost-effectiveness of today’s health care supply chains and ultimately benefit patients by ensuring timely and cost-effective access to essential medications and treatments. It also explains how these virtual replicas can predict patient outcomes, patient experiences, and total cost of care, enabling better risk management and fewer harmful side effects. By proactively identifying potential health issues, AI-enabled digital twins can facilitate early interventions and improve preventive care.

Understanding Digital Twins

By shifting the focus from volume to value, health care providers are incentivized to deliver high-quality care while efficiently managing resources. Measurement is key, which has given rise to a broad array of methods for assessing patient outcomes, such as quality-adjusted life year (QALY) and disability-adjusted life year (DALY) rubrics that consider both the quantity and the quality of life gained by the patient.

For example, digital twins can revolutionize QALY measurement by personalizing treatment plans and evaluating the impact of interventions. By creating virtual replicas of patients and simulating various scenarios, health care providers can predict treatment outcomes, identify the most effective interventions, and optimize resource allocation. Moreover, digital twins can enhance DALY computations by modeling cascading life events—where an initial health condition leads to a series of secondary effects, compounding disease burden over time. This capability enables more accurate assessments of long-term health impacts and helps refine public health strategies.

Beyond clinical applications, digital twins can also optimize the associated supply chains that deliver these life-saving therapies. By forecasting demand, identifying logistical bottlenecks, and simulating disruptions in real time, digital twin technology ensures that critical medications, medical devices, and other therapeutic interventions reach patients when and where they are needed most. This integration of digital twins into both clinical and logistical decision making enhances health care efficiency, reduces delays in treatment, and ultimately improves patient outcomes at scale.

Ashkan Afkhami, senior partner of the digital and analytics build unit in health care at Boston Consulting Group Inc. (BCG), headquartered in Boston, puts health care-specific digital twins into three categories: patient digital twins, product digital twins (also known as customer digital twins), and process digital twins. This paper is primarily focused on using customer and process digital twins to improve health care delivery and efficiency.

Customer digital twins provide insights into service levels that can be achieved with specific health care value chain designs and customer preference behaviors. In the

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health care context, a "customer" can be either a patient, a pharmacy, or a health care provider. For example, customer digital twins simulate the interactions of drugs and devices with different patient cohorts and help predict and optimize their therapeutic efficacy and safety. They can simulate and forecast the performance of a drug product in terms of the likely patient cohorts that will have access to those drugs as a function of different pricing, insurance, and promotional policies. These digital twins help manufacturers and providers maximize access to targeted therapies by designing the right commercial policies given various market constraints.

Customer digital twins can also help forecast patient populations in need of early- and advanced-stage therapies based on epidemiological incidence, mortality rates of specific diseases, and associated treatment success rates from those therapies. Such forecasts can help manufacturers and providers plan capacity investments several years in advance.

Process digital twins simulate the impact of resource allocation policies across supply chain networks. These digital twins focus on operational KPIs at factories, warehouses, and pharmacies to optimize health care supply chains and ensure access to therapies. Process digital twins also simulate temporal events and workflows at hospitals, clinics, and pharmacies to predict the impact of different operational and resource allocation policies on patient issues, such as wait times and the total cost of care.

Optimizing Health Care Supply Chains

Today's global health care supply chains are critical to ensuring that essential medicines and medical products are available to patients. According to the Healthcare Distribution Alliance, a Washington, D.C.-based organization representing primary pharmaceutical distributors, each day the industry delivers 10 million products from more than 1,200 manufacturers to 330,000 pharmacies, hospitals, providers, and other health care facilities. The supply chain that safely and reliably delivers these prescription medicines not only is crucial for patient health but also serves as the cornerstone of health care economics in the U.S.[2]

Pharmaceutical distributors work with multiple stakeholders to provide patients with access to their medications. They must manage fluctuating demand, ensure product integrity, optimize delivery routes, and comply with strict regulations. While these are age-old logistics challenges, digital twins offer a new way for stakeholders to address them. They can proactively identify bottlenecks and coordinate the flow of equipment and supplies to hospitals, clinics, physician groups, and other health care providers. With better data on inventories, carrying costs can be reduced and timely deliveries ensured. This possible improvement is especially crucial for drugs that expire, since pharmaceutical manufacturers can align their supply with demand based on patient volumes and other variables.

Jointly minimizing inventories based on accurate information about needs helps all parties in the supply chain. According to a recent report from ZS Supply Chain & Manufacturing, a management consulting and technology firm based in Evanston, Ill., digital twins can increase machine utilization by up to 10% because they can simulate a disruption's global impact in just 24 hours, whereas the standard simulation takes four to six months.[3]

Ultimately, product and process digital twins can work together to help optimize health care supply chains with the goal of ensuring access to low-cost therapies for targeted patient cohorts, with minimal wait times. They can improve care delivery by virtually simulating different design options. For example, as described below, certain cancer therapies might require a mix of continuous monitoring and scanning of specific drugs. Product and process digital twins can help identify optimal levels of investments into scanning machines at the right points in time and across specific regions in order to avoid the bottlenecks that increase patient wait times.

When designed with the right mechanistic models of disease progression, patient digital twins can provide causal pathways of therapeutic efficacy of specific treatments rather than act like "black box" AI models. A prime example is the susceptibility, exposure, infection, recovery (SEIR) models that form the basis of digital twins that track the progression of epidemics. These models can help epidemiologists and clinicians identify key cohorts for minimizing epidemic transmission.

However, real-world disease spread is highly nonlinear and stochastic, influenced by factors such as heterogeneous contact patterns, population mobility, viral mutations, and intervention policies. Digital twins enhance SEIR models by incorporating probabilistic variations in transmission rates, super-spreader events, and dynamic changes in population immunity, allowing for more adaptive and realistic epidemic forecasting. This stochastic approach ensures that policymakers and health care providers are not only reacting to observed trends but also preparing for a range of potential outbreak scenarios.

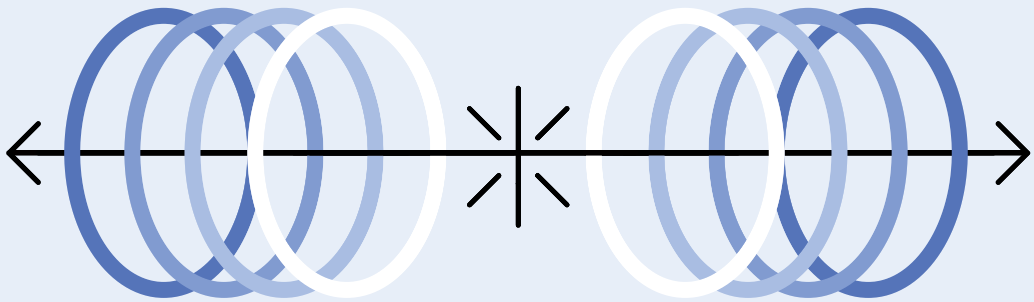
Artificial Intelligence's Elevating Effect

Digital twins can be comprised of simple mechanistic models, AI models, and blends of both. AI plays a crucial role in these initiatives by enabling advanced analytics, predictive modeling, and real-time decision making. Machine learning algorithms can process vast amounts of data, identify patterns, and simulate clinical and administrative scenarios, helping health care providers make informed decisions and establish personalized treatment plans. Smart optimization engines within AI-enabled digital twins can automate inventory management, balancing placements at drug manufacturers, pharmacies, and health providers to minimize carrying costs.

As MIT's Saénz writes in *MIT Sloan Management Review*,[4] digital twins can oversee many internal and external moving parts in these end-to-end supply chains and build nonlinear supply chain models. With their ability to compute thousands of what-if scenarios, these systems learn from these decisions and gain maturity over time. "What distinguishes digital twins and makes them so powerful is their ability to emulate human capabilities, support critical decision making, and even make decisions on behalf of humans," she writes.

Digital twins can help by learning from live data and simulating real-world situations. For example, if a pharmaceutical company faces a shortage of a certain type of medicine in one of its warehouses, perhaps due to a transportation delay, it needs a way to recover in order to fulfill product orders within a reasonable time frame. "Previously, supply chain management systems had [mechanistic] rules-based decision trees, but with AI you can create optimization models that find the best solution for each process, such as automated fulfillment, based on demand, historical data, and forward-looking predictions," Saénz explains. "The digital twin keeps learning while making decisions. Understanding how to interact [in] real time is very powerful."

By analyzing the simulated outcomes in terms of potential QALY gains, researchers can prioritize treatments that are most likely to reduce adverse effects in patients. For example, Frederick National Laboratory for Cancer Research, a U.S. National Laboratory sponsored by the National Institutes of Health/National Cancer Institute in Frederick, Md., has been one of many collaborators working with the Food and Drug Administration (FDA) on a precision toxicology initiative that aims to identify factors that could lead to toxic effects or adverse drug reactions so they can find ways to predict and avoid them.



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Caroline Chung, vice president and chief data and analytics officer at the University of Texas MD Anderson Cancer Center

In addition to delivering best-in-class therapies, minimizing any treatment-related adverse effects can further boost patient outcomes, eliminate costs associated with those adverse reactions, and free up scarce provider resources, which can be redeployed toward improving the QALYs of other patients. Customer digital twins can help quantify the impact of precision toxicology initiatives to help providers and other caregivers make the right kinds of medical toxicology investments.

In this context, AI-enabled digital twins can improve patient access to high-impact therapies by recommending the right types of capacity investments for manufacturers and providers. Simulating patient journeys through different treatment pathways can inform the optimal mix of investments in diagnostics and scanning, surgical technologies, and patient monitoring equipment based on forecast disease incidence rates, disease progression patterns, and costs of care across the treatment continuum.

“We will have increasingly precise cohorts as we determine how the models work for different populations,” says Eric Stahlberg, a research scientist who served for 10 years as the director of cancer data science initiatives at Frederick National Laboratory for Cancer Research and recently accepted a position at The University of Texas MD Anderson Cancer Center in Houston.

Learning from Feedback

Digital twins incorporate feedback loops by collecting data from a physical system to update a virtual model, which, in turn, drives changes in the physical system. Internet of things (IoT) sensors and wearable devices allow clinicians and researchers to gather biometric data from a human to feed the models with current information. Commonly referred to as the “twinning rate,” this steady synchronization of the virtual model with the real-world instance is an essential element of a successful digital twin.

“The aim of a digital twin is to create a functional model that syncs with an individual, asset, process, or system, reflecting changes in real time,” IDC's Limaye notes. “If there’s latency, then the value of the digital twin is lost in any kind of simulation or planning scenario.”

MD Anderson Cancer Center is working on developing digital twins to model tumor growth and treatment response across various cancers, empowering clinicians with data-driven insights to improve diagnostic accuracy and response assessment. Data inputs include patient-specific parameters such as anatomy, tumor cell proliferation rate, tumor location, and other biological features, in conjunction with responses to treatments like radiotherapy, chemotherapy, and immunotherapy. Based on continued inputs over time, the model can compute tumor cell count, estimate tumor cell death, and predict time to progression, helping oncologists recommend specific dosing schedules and personalized treatments.

Process digital twins can optimally match treatment resources to patients in different stages of tumor progression, compressing the time it would normally take to execute the personalized treatment plans. They also enable feedback loops that make it easier for oncologists to continually reassess and adapt these treatment plans. For example, if after one week of radiation treatment, incorporating the new scan reveals how the tumor will respond or progress, the oncologist can adjust the treatment to optimize outcomes and minimize side effects.

A process digital twin can immediately reschedule the use of equipment and availability of treatment personnel in response to such “course corrections,” thereby minimizing the loss of the hospital’s treatment capacity due to such changes.

“Leveraging these emerging and promising technologies, we are building toward the capability of having every patient who comes in for care to have all of their tumors measured throughout their body at each time point so we can use this information to predict how they will respond to treatments,” says Caroline Chung, vice president and chief data and analytics officer at MD Anderson. "In order to truly leverage digital twins, we are investing in quantitative imaging and even quantitative measures of biology without necessarily sticking in a needle or cutting someone open. Informed in this way, we are investigating how we can best customize treatment based on individual tumor measurements, instead of adhering to standardized treatment schedules."

Chung codirects MD Anderson's Institute for Data Science and Oncology and runs a computational imaging lab that focuses on quantitative imaging and computational modeling to detect and characterize tumors and toxicities of treatment, with the goal of enabling personalized cancer treatment. According to an extensive report from the National Academies of Sciences, Engineering, and Medicine in February 2024, which she coauthored,[5] digital twins are being used across various domains to gain deeper insights into the performance and behavior of natural, engineered, and social systems. These tools integrate models and data for better decision making, creating dynamic virtual representations that evolve over time.

"Traditional tumor measurements are 2D, but we want to leapfrog into 3D imaging and obtain biologically representative imaging measurements to better understand the therapeutic mechanisms, especially as we investigate novel treatments that may have different interactions to impact the tumor cell survival or proliferation," Chung adds.

Ultimately, this type of imaging data can be used to create tighter patient cohorts characterized by tumor geometry, size, and disease progression risk. Based on the disease progression risk of such cohorts, process digital twins can recommend optimal schedules for treating higher-risk patients while also accommodating lower-risk patients based on available medical resources.

Sizing Up the Data Challenges

According to Kartik Hosanagar, a professor at the Wharton School of the University of Pennsylvania and the founding director of the college's AI center, AI models—within digital twins and elsewhere—learn best by consuming lots and lots of data and examining patterns in that data. With the right inputs, these models can even learn to train themselves—without requiring constant input from experts.

For example, instead of asking doctors to define a set of rules for how they diagnose diseases, an AI model can make these determinations by ingesting data from millions of hospital visits and then correlating patient symptoms and outcomes with clinical diagnoses. If a patient has chills and a fever and the fever has been there for over a week, along with acute sinus congestion, then the system might conclude that it is more likely a bacterial infection than a flu virus.

However, if the data is biased, incomplete, or inaccurate, Hosanagar cautions, the AI model will also be biased, incomplete, or inaccurate. For example, if the training data represents a specific demographic (such as older white males), it might fail to accurately predict risks or recommend treatments for individuals from underrepresented groups (young women, ethnic minorities, etc.). This dichotomy could lead to misdiagnoses, inappropriate treatment plans, and potentially harmful outcomes. Similarly, if the training set is missing crucial data points, such as family history, lifestyle factors, or previous medical conditions, it may result in an incomplete and inaccurate representation of the patient.

There are also pressing issues of data security. As the Healthcare Distribution Alliance points out in a report on the role of AI in health care, because AI systems increasingly handle sensitive data, the risk of data breaches is growing, with the potential exposure of personal and confidential information highlighting the need for stringent security measures and robust governance frameworks to protect against cyber threats.[6]

To mitigate the risks of incomplete, inaccurate, or misplaced data, Chung stresses the importance of having a comprehensive clinical, scientific, and technological team that includes people who understand data governance, master data management, data quality, and data security. In other words, we need "all the best practices across perspectives, from data scientists to clinicians to subject-matter experts," she says. "We will also need new math and new computational skills to address the verification, validation, and uncertainty quantification challenges for emerging AI and digital twins. These checks and balances are key. Are you still on the trajectory of predicting truth or are you starting to veer off above or below where you're supposed to be chasing patterns? These are the questions we need to be asking."

Stahlberg, who has accepted the executive director position at the Institute for Data Science and Oncology at MD Anderson, echoes Chung's concerns. "Large language models have a tremendous potential within the context of digital twins," he says. "They can play an extremely powerful role of harmonizing data and providing suggestions utilizing large amounts of data. While potentially useful, such suggestions will need to be evaluated, with more research needed to effectively quantify and communicate the confidence of these responses."

To assess population health trends, BCG's Afkhami suggests rolling up patient data to longitudinally study large cohorts in conjunction with other enterprise data and publicly available data. For example, a researcher studying obesity could train a product digital twin-based large language model using synthetic data or legacy data to create an archetype of that patient population that includes behaviors, comorbidities, and other factors, with the goal of predicting outcomes during individual patient journeys.

"Think of it as custom ChatGPTs that are built for specific therapeutic areas or patient populations or treatment types," Afkhami says. "Once you've established that digital twin persona, you can ask how a patient or an entire cohort might react to a specific drug or treatment or procedure. This allows a physician, a clinician, or a manufacturer to test out treatments and medications and procedures virtually. You can train a large language model within this very targeted domain so that it could give you answers based on its understanding of the subject."

This exercise becomes the starting point for creating digital avatars that embody specific demographics, genders, geographies, lifestyle events, and more. "So even within one language model, you could have subcategories and subgroups that would then essentially branch out to represent a family or ethnic group or other population segment," Afkhami adds.

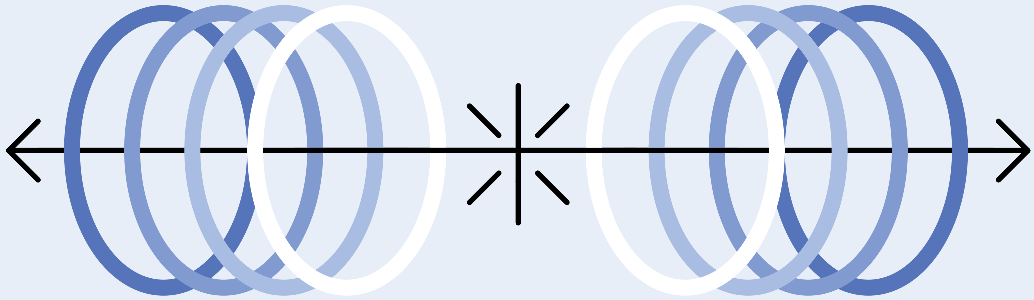
Understanding the Current State

Clearly, AI-enabled digital twins hold tremendous potential. But are they making a difference on the front lines?

A recent IDC awareness, readiness, and commitment survey with 1,363 respondents revealed that while digital twins are a rapidly emerging concept, only one-fourth of life sciences workers and one-third of health care professionals expressed high awareness of the technology. However, looking ahead, greater uptake is anticipated. According to the IDC FutureScape report, "Worldwide Life Sciences 2025 Predictions," published in October 2024, by 2030, 30% of life sciences firms will scale from digital twins of entities to digital twins of humans, moving from "egosystems" to ecosystems, scaling the growth of safer precision therapies by 50%.[7] "Egosystems" refers to individual entities, whereas "ecosystems" refers to more complex interconnected ecosystems of health data and processes.

Digital twins start with answering specific questions of interest and supporting key decisions, Stahlberg notes. The capability of the digital twin grows as additional factors are incorporated to further improve the predictive models and supported decisions. "The artificial pancreas is one example of a digital twin designed for a specific purpose in use today," he explains. The system uses smart sensors to measure the blood sugar level of the individual and then predicts the appropriate response for the level of insulin that's needed. "It is observing, adapting, predicting, and responding to the current state of that individual," he adds.

The information that is gathered from these sensors can be fed into a downstream customer digital twin that alerts providers of patients that are at higher risk of abnormal spikes in their blood sugar levels.



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IDC FutureScape report, "Worldwide Life Sciences 2025 Predictions," October 2024

Of course, in order for these types of digital twins to receive widespread adoption, health care practitioners—and the patient population as a whole—must gain comfort and trust in these interactive tools. According to the February 2024 National Academies of Sciences, Engineering, and Medicine report, widespread adoption of digital twins in health care will not be possible until patients, biologists, and clinicians trust the process, which will first require education and transparency within the biomedical community.[8] "This sobering statement reflects the nature of the data and data literacy in health care today," Chung notes. "The magnitude of investment to effectively leverage this technology needs to reflect the magnitude of the risk and impact of the health care decisions that you're making using this technology."

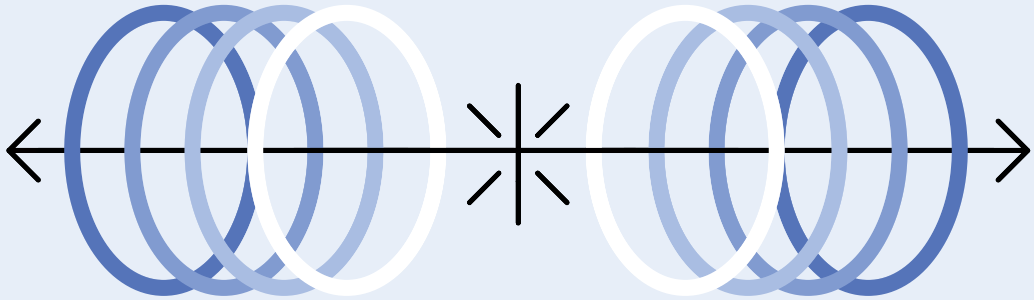
One way to drive adoption is to explicitly quantify business value at the provider, patient, and payer levels. For example, a customer digital twin might be more likely to find broad organizational acceptance if it can demonstrate increased access to underserved patient cohorts by activating specific therapy payment coverage plans.

To push the knowledge envelope and reassure the patient population, a variety of public/private partnerships are underway. In the United States, the FDA, National Science Foundation, and National Institutes of Health are collaborating to fund digital twin projects, with the goal of incorporating AI to improve patient monitoring, treatment, and medical device development. Their public research projects cover various topics, including the development of mathematical models for virtual clinical trials of cardiovascular medical devices, statistical tools for analyzing the ethical use of AI, digital twin-based studies of neurodegenerative diseases, and AI-informed decision making related to glucose metabolism in people with type 1 diabetes.[9] "These initiatives are focused on accelerating biomedical technological innovation. This will ultimately help [the industry] achieve a holistic perspective of the patient to enable precision therapies," Limaye says.

In Europe, Limaye points to the European Virtual Human Twins initiative, sponsored by the European Commission under the Digital Europe Program, which aims to develop integrated, validated digital representations of human health and disease states to support personalized care, medical research, and health care delivery. Another example from the European Union is the German Heart Center at Charité, which has transformed raw data into dynamic 3D models of the heart anatomy and hemodynamics, enhancing our understanding of complex heart conditions, and the Centro Diagnostico Italiano, which is developing a multidimensional representation of a complete patient that integrates numerical tables, graphs, images, videos, and textual reports. The objective is to create a user-friendly prototype for physicians, especially for those involved in specialized outpatient visits, to enable them to provide more-personalized care to patients based on pathology and risk stratification.[10]

Beyond health care, the European Council for Nuclear Research, or CERN, is leveraging AI-driven digital twins in particle physics research, where high-dimensional nonlinear models are essential to simulate and analyze complex particle interactions. These digital twins help physicists reconstruct subatomic events, optimize collider performance, and explore the fundamental forces of nature. The same challenges—managing vast data sets, modeling unpredictable dynamics, and refining simulations—are central to both physics and health care. As such, advances in AI-driven digital twins at CERN could inform similar methodologies in health care, particularly in personalized medicine and disease modeling, where biological systems exhibit similarly intricate, multivariable behaviors.

Stahlberg sees these efforts as an important precursor to using these models to develop actual treatments—but he cautions researchers to be conscious of the implications. "Who is responsible for sharing insights provided by the digital twin?" he asks. "Who owns the data? Who has rights to the data and to the predictive models [constituting] the personal digital twin? As you create a digital twin that becomes increasingly predictive, there are many areas that need to be revisited in terms of personal health literacy, risk stratification, insurance, and additional ethical questions."



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Eric Stahlberg, research scientist at MD Anderson and the former director of cancer data science initiatives at Frederick National Laboratory for Cancer Research

Integrating predictive analytics, internet of things data, and AI paves the way for a revolution in health care.

Limaye believes transparency is crucial and that patients should be informed when digital twins impact their treatments, such as changes in dosage therapy, to maintain transparency and build trust. There is also a significant ethical component regarding whose data is used and how it is utilized, encompassing aspects of data ownership and privacy. “People are generally comfortable using [their data] for training and simulation planning,” she notes. “However, for actual implementation on patients, we are in the early stages, as there is considerable hesitation due to the potential risks and consequences involved.”

Conclusion

The rising cost of health care is a multifaceted issue stemming from various inefficiencies and a fragmented approach to patient care. Key among these inefficiencies are outdated logistical practices, which impede timely access to care and resources.

Digital twins represent a powerful tool for resolving these cost and logistical challenges. At an ecosystem level, they facilitate collaborative partnerships among health care providers, pharmacy benefit providers, health systems, and integrated delivery networks.

Integrating predictive analytics, IoT data, and AI paves the way for a revolution in health care. The technology is bound to improve, since AI-driven digital twins continuously learn and adapt, augmenting their functionality over time. They aren’t static models but dynamic tools that can mimic complex health care processes, from individual patient journeys to global supply chains.

Through these and other emerging capabilities, digital twins are poised to revolutionize value-based care, ensuring that the right resources are available at the right time to enhance patient outcomes and improve operational efficiency. This shift toward a QALY-centric approach, facilitated by digital twin technology, not only improves patient outcomes but also contributes to more sustainable and cost-effective health care systems.

But the acceptance of digital twins in health care won’t be based just on their promised benefits. Patients will have to trust the process. “Patient ownership is key,” Stahlberg emphasizes. “When digital twins become truly effective, the patients will have become stakeholders in the whole operational loop of the information that’s being collected about them. They will know how personal information is incorporated and how the value is being delivered back to them.”

Endnotes

1 Statistica, “GDP Share of Health Expenditure Worldwide from 2014 to 2029,” January 30, 2024. https://www.statista.com/forecasts/1141705/health-expenditure-gdp-share-forecast-in-the-world.

2 Healthcare Distribution Alliance, “The Facts, Figures and Trends in Healthcare (2023–2024), 94th ed.,” 2023. https://www.hda.org/.

3 Dharmesh Ved, H. Caglar Ozdag, Sourabh Joshi, et. al., “How Supply Chains Can Use Digital and Virtual Twin Technology for Better Decision-Making,” ZS Supply Chain & Manufacturing, January 15, 2024. https://www.zs.com/insights/how-supply-chains-can-use-digital-twin-technology-in-pharma.

4 Özden Tozanli and Maria Jesús Saénz, “Unlocking the Potential of Digital Twins in Supply Chains,” MIT Sloan Management Review, August 18, 2022. https://sloanreview.mit.edu/organization-subscription/libraries/.

5 National Academies of Sciences, Engineering, and Medicine, “Foundational Research Gaps and Future Directions for Digital Twins,” February 2024. https://nap.nationalacademies.org/catalog/26894/foundational-research-gaps-and-future-directions-for-digital-twins.

6 Healthcare Distribution Alliance, “The Role of Artificial Intelligence in Drug Distribution,” 2024. https://www.hda.org/getmedia/b93aec3c-e3ab-421e-b7a6-60ce44eb89b0/The-Role-of-Artificial-Intelligence-in-Drug-Distribution.pdf.

7 IDC FutureScape, “Worldwide Life Sciences 2025 Predictions,” October 2024. https://www.idc.com/getdoc.jsp?containerId=US52618924.

8 National Academies of Sciences, Engineering, and Medicine, “Foundational Research Gaps.”

9 U.S. National Science Foundation, “NSF, NIH and FDA Support Research in Digital Twin Technology for Biomedical Applications,” October 3, 2024. https://new.nsf.gov/news/nsf-nih-fda-support-research-digital-twin-technology.

10 Silvia Piai and Federico Mayr, “The Value of Digital Twins in Healthcare: IDC Tech Buyer Presentation,” IDC, January 2024. https://www.idc.com/getdoc.jsp?containerId=EUR151776124.

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