scientific reports

OPEN

EDITORIAL

Digital twins: past, present and future

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Over the past few decades, digital twin technology has evolved into a highly versatile tool. Initially used in the aerospace industry, digital twins can now form the dynamic backbone of systems in manufacturing, healthcare, smart cities, and planetary-scale climate models. They facilitate predictive 'what if' simulations, ranging from virtual hearts to interactive Earth twins. Progress in the future will rely on the integration of heterogeneous data, the validation of models and the embedding of human-centric governance in order to build robust and trustworthy digital twins across disciplines for the benefit of society.

Historical background

The concept of the 'digital twin', which is a virtual representation of a physical system, can be traced back to the early days of the space age. In the 1960s, NASA pioneered the idea of a digital twin to simulate spacecraft and troubleshoot issues in real time. The term 'digital twin' itself was formulated much later, in 2002, by Michael Grieves in the context of product lifecycle management to guide industrial design and management. By around 2010, NASA had adopted digital twins as detailed virtual models of physical assets, emphasising that a true digital twin comprises three interconnected elements: a physical entity, a virtual model and the data connections that enable them to mirror each other in real time[1]. Advances in simulation, sensor ubiquity, and data integration laid the groundwork for digital twins to move from theory into practice. Propelled by the convergence of sensors, Internet of Things (IoT) connectivity, cloud computing and artificial intelligence (AI), digital twins have become widely applied in many different fields[2]. The concept of a digital twin has evolved from a niche idea to a broad framework: a dynamic, data-driven model that updates alongside and continuously learns from its physical counterpart. It is the dynamic, bidirectional link, where sensor data flows into the model and simulation insights flow back to inform the physical system, that elevates a digital twin beyond a static blueprint or 3D model[3]. What began in the fields of aerospace and manufacturing has now spread to healthcare, urban planning, climate science and beyond.

Application domains of digital twins

The industrial sector was one of the first to utilise digital twins, building on decades of virtual prototyping and simulation. In advanced manufacturing, digital twins now serve as living models of machines, production lines, and entire factories. This enables engineers to perform "what-if" simulations on the digital twin to optimize operations, predict failures, and refine designs long before changes are implemented. Similarly, in aerospace manufacturing, companies maintain digital twins of aircraft components (from engines to avionics) to anticipate maintenance needs and minimize downtime[4]. In the automotive sector, virtual twins coupled with real-time production data help to identify bottlenecks or quality issues and suggest fixes in a risk-free virtual environment[5].

The medical field is also embracing digital twins as a way of providing truly personalized care. A digital twin, or virtual organ, can help clinicians and patients make better decisions, and assist in designing more efficient clinical trials[6]. One example is a "virtual heart", a patient-specific cardiac model that can be used to test how a patient might respond to different therapies or surgical interventions[7]. In cardiology and oncology, in particular, where treatment outcomes can vary widely between patients, digital twins of organs or tumors potentially allow doctors to simulate various treatment strategies on the virtual patient before attempting them in reality. Such twins draw on a fusion of data (e.g., clinical measurements, medical imaging, genomic and proteomic profiles) to create a highly detailed personal model[8]. In clinical trials, virtual patient twins can serve as control groups or help optimize trial design by simulating how populations might respond to a drug[6]. Ultimately, the vision is that each person could have an individualized digital twin to track their health over time, enabling a new era of preventive, precision medicine[1].

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As the concept of digital twins extends beyond machines and bodies, cities themselves are becoming candidates for digital twins. Urban digital twins are live computational models that integrate data on buildings, roads, public transport, utilities, and even people's movement in real time[9]. In the future, city planners might simulate traffic flows, changes in air quality, and emergency evacuation scenarios in real time using IoT and AI integrations, as well as proactively adjust infrastructure in response. However, before these urban applications can aid sustainable development, issues such as data silos and and standardization must be overcome[9].

One of the most ambitious applications of digital twin technology is taking shape on a planetary scale. Climate scientists and computational experts are collaborating on digital twin earth projects, creating replicas of Earth's environmental systems and aiming to capture everything from the atmosphere and oceans to the biosphere. The vision is to create interactive Earth simulators that can run „what-if" scenarios for climate change and extreme events, providing policymakers with a powerful decision-support tool[10]. For example, a digital twin of the Earth could be used to simulate the impact of specific emissions reduction policies on future climate, or to virtually rehearse responses to a hypothetical hurricane before it strikes. Companies such as NVIDIA are developing an "Earth-2" simulation platform with the aim of mapping and forecasting the Earth's complex processes using computer modelling in silico[11]. Early examples are promising, e.g., digital twin models of rivers and watersheds could assimilate weather forecasts, hydrological data and infrastructure information to optimize water management in real time[12].

Future challenges and potential

As digital twins become more widespread across different sectors, the coming years will be crucial in determining the extent to which the digital twin technology can fulfil its potential. In the technical area, researchers need to overcome key challenges to achieve widespread adoption. One major hurdle is data integration and quality: digital twins are only as good as the data streams that power them. Integrating heterogeneous data in real time, from physics-based sensors to human-generated inputs, remains difficult. The lack of interoperable data standards impedes the creation of a cohesive twin, as fragmented data sources and the use of different devices prevent the development of a standardised framework[3]. Another challenge is model validation and uncertainty. In domains such as healthcare and aerospace, decisions may depend on twin predictions, so it is essential to quantify the accuracy and reliability of the digital twin's predictions if users are to trust them for critical decisions. Advances in uncertainty quantification and continuous calibration against real-world measurements will be needed to validate digital twins as reliable decision-making tools[13].

In terms of computing, scaling up digital twins will require new approaches to simulation science and AI. While many twins currently operate at a relatively modest scale or update frequency, current research questions involve increasing complexity and data volumes. Consequently, there is growing interest in hybrid modeling techniques, where traditional physics-based models are augmented with machine learning to accelerate computation. The emerging field of physics-informed machine learning is especially promising, as it combines physics-based digital twins with data-driven AI to create models that are both fast and physically consistent[13].

The future of digital twins relies not only on technology, but also on human and organizational factors. As digital twins of critical infrastructure, cities or individuals become more prevalent, questions regarding ethics, data privacy, cybersecurity and governance must be addressed. As Hazeleger et. al emphasize, humans must be „accounted for both within and outside" digital twins: internally, to model human behavior, and externally, to regulate access and use[10]. To ensure societal acceptance of digital twin technology, it is essential to involve all relevant stakeholders in the technology co-creation process and adopt human-centric design approaches.

In summary, digital twins have swiftly evolved from a concept to a valuable tool across various disciplines. However, we are only at the beginning of using their potential. Realizing the full vision, whether it is a planetary-scale climate twin or a personal health twin for every individual, will require to overcome technical barriers and navigate societal concerns. While the past decade has been about proving the concept in pilot projects, the next will focus on scaling and interconnecting digital twins to create powerful digital counterparts of complex systems. Digital twins could enable an era of truly predictive and proactive decision-making in diverse fields such as healthcare, urban governance, aerospace and climate action, continuously learning, adapting, and providing advice.

Published online: 27 March 2026

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Declarations

Competing interests
The author declares that there is no conflict of interest.

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