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Digital Twin in Government

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ABSTRACT

Governments worldwide are investing in large-scale infrastructure projects, smart city initiatives, and digital transformation efforts. In recent years, the public sector has increasingly recognized the potential of digital twins to address complex societal challenges. Digital twin technology represents a monumental leap forward in the capabilities of government and public administration. A digital twin is regarded as an integrated, data-driven virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity. By bridging the physical and virtual worlds, digital twins empower policymakers to transition from reactive management to proactive, data-driven governance. By leveraging real-time data, artificial intelligence, and advanced simulations, governments can enhance decision-making, optimize resource allocation, and improve public service delivery. Digital twins are increasingly being deployed in both public and private sector organizations. This paper reviews the applications of digital twin technology across various domains of the public sector.

KEYWORDS: *digitalization, digital twin, data twin, digital twin technology, government, public sector, public administration.*

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INTRODUCTION

As global governments face mounting pressures from rapid urbanization, climate change, geopolitical instability, and aging infrastructure, traditional policy-making and urban planning methods are proving inadequate. Digital twins offer a paradigm shift: the ability to simulate the outcomes of policy decisions and infrastructure investments in a risk-free virtual environment. Digital twin technology represents a paradigm shift in how governments operate, plan, and interact with citizens. A digital twin is defined as a virtual representation of an object or system that spans its lifecycle. Figure 1 shows a typical digital twin [1]. It is regarded as the next generation of digitalization for decision making support. The current development of digital technologies has dramatically increased the adoption of digital twin (DT) systems into the AEC sector. Figure 2 shows the conceptual model of a digital twin [2].

The integration of digital twin technology into the public sector represents a paradigm shift in how governments plan, manage, and optimize services and infrastructure. Governments at various levels are exploring digital twins to optimize infrastructure, enhance urban planning, and improve public services. By providing a dynamic, data-driven replica of the physical world, digital twins enable policymakers to move beyond historical analysis and embrace predictive, simulation-based decision-making [3].

CONCEPT OF DIGITAL TWIN

The concept of the digital twin was introduced in 2002 by Michael Grieves of Florida Institute of Technology. He applied the concept in manufacturing and proposed the digital twin as the conceptual model underlying product lifecycle management (PLM). The concept was being practiced since the 1960s by NASA. The concept of digital twin consists of three distinct parts: the physical product, the digital/virtual product, and connections between the two products [4]. Figure 3 shows the historical evolution of DT technology [5].

A digital twin is much as it sounds: creating a digital duplicate of the physical entity.

It has two sides, one pertaining to a physical device and the other to a digital rendition of this device. DT is a real time digital replica of a physical device using 3D modeling and sensors. The DT is an emerging paradigm focusing on an enterprise asset such as a system, product or process. Its core goal is to virtually represent this asset as close to reality as possible. A digital twin may exist before its physical counterpart is made. Technologies enabling DT include AI, IoT, 5G, virtual reality, augmented reality, wearables, and cloud computing. Realizing the full potential of DTs requires a convergence of these technologies. Digital twins integrate AI, IoT, machine learning, and software analytics with spatial network graph to create living digital simulation models that change as their physical counterparts change.

The three main pillars of the digital twin technology are visualization, emulation, and simulation. The foundation of DT is the physical world, which may consist of devices/products, physical systems, process, or an organization. Service is an essential component of DT in view of the paradigm of everything-as-a-service. DT-related services include application service, resource service, knowledge service, and platform service. The process of implementing DT can be divided into four steps: digital representation, synchronous mapping, simulation and prediction, and virtual and physical fusion. Figure 4 depicts the digital twin conceptual architecture [6], while Figure 5 shows DT enabling technology [7].

There are numerous requirements to describe "digital twin." To be considered a digital twin, the model must have some specific characteristics such as [8]:

1. Data is the carrier of information and the key driver of DT. Real-time data is important for knowing the status of the product. Data-driven digital twin can perceive, respond, and adapt to the changing environment.

   Integration of the different nodes is essential for creating valuable data. Sensors communicate the data to the digital world through integration technology between the physical world and the digital world, and vice versa.
2. Scalability (ability to analyze different scales of information);
3. Interoperability (ability to convert, match and establish equivalence between representation models);
4. Expansibility (ability to integrate models);
5. Fidelity (ability to conform to the physical model); the core of any DT is a high-fidelity virtual model.
6. Connectivity that indicates the level of communication with its physical counterpart; connectivity by design through IoT which is a paradigm for ubiquitous connectivity. Connect the products/services to a central location with streaming, big data, in-memory, and analytic capabilities to capture sensor data and enrich it with business and contextual data.

These are the most frequent requirements of digital twins.

DIGITAL TWIN IN GOVERNMENT

In an era characterized by rapid urbanization, climate change, and increasingly complex public policy challenges, governments worldwide are seeking innovative tools to enhance decision-making and public service delivery. Among the most promising technological advancements is the "digital twin." A digital twin is a dynamic, virtual representation of a physical object, process, or system that is continuously updated with real-time data. By integrating data from sensors, the Internet of things (IoT), and historical records, digital twins allow for sophisticated simulation, predictive analytics, and optimization [3].

By its very nature, critical infrastructure requires high reliability and minimum downtime to support essential mission operations, whether that involves keeping production on schedule for much-needed military aircraft, maintaining power plant operations, or ensuring rapid development of an essential highway project. It is not surprising to see that 63% of federal agencies are already investing or planning to invest in digital twins. Governments are utilizing digital twins to model everything from individual buildings and transportation networks to entire cities and national defense systems [9].

Digital twin technology holds transformative potential for government operations, offering unprecedented capabilities for urban planning, infrastructure management, and crisis response. It is a powerful tool transforming government construction projects. By offering real-time modeling, predictive maintenance, and safety forecasting, digital twins help teams deliver projects that are safe, efficient, and sustainable [10]. By creating dynamic, data-rich virtual replicas of physical assets, systems, and even entire cities or nations, governments can simulate policies, optimize infrastructure, and enhance disaster response before real-world implementation. By modeling "what if" scenarios before construction begins, governments can identify potential bottlenecks, optimize designs, and implement a "dig once" policy, thereby minimizing disruptions and reducing the risk of costly delays. For digital twins to truly serve the public interest, governments must prioritize transparent data governance, invest in workforce development, and actively engage citizens in the design and application of these powerful virtual models. Figure 6 is a representation of the DT in government [11].

APPLICATIONS OF DIGITAL TWIN IN GOVERNMENT

The applications of digital twins in government are diverse, spanning multiple domains and levels of administration. DT technology finds applications in urban planning, infrastructure management, defense, healthcare, food production, and public policy. Governments are recognizing the potential of digital twins to address complex societal challenges, from rapid urbanization and climate change to infrastructure decay and national security threats. Common applications of DT in government include the following [3,12,13]:

- *Urban Planning*: One of the most prominent applications of digital twins in the public sector is in the development of smart cities. Urban digital twins integrate data from various sources, including Geographic Information Systems (GIS), Internet of things (IoT) sensors, and administrative records, to create comprehensive 3D models of urban environments. These models allow city planners to simulate traffic patterns, assess energy usage, and prepare for disaster scenarios. For example, the Virtual Singapore project is a highly detailed 3D digital twin of the city-state that enables government agencies to optimize land use, manage underground utilities, and simulate the impact of new infrastructure projects. Figure 7 depicts urban planning [10].
- *Infrastructure Management*: Governments are responsible for managing vast networks of critical infrastructure. Digital twin technology represents the next frontier in government infrastructure management. Digital twins facilitate predictive maintenance, minimizing downtime for bridges, roads, and public transit systems. They play a crucial role in optimizing large-scale capital investments. According to McKinsey, digital twins could improve public sector capital and operational efficiency by 20 to 30 percent by enabling accurate modeling of complex interdependencies, such as capital costs, transit modalities, and carbon emissions. Figure 8 shows DT for government infrastructure planning [14].
- *Smart City Infrastructure*: Smart city infrastructure represents the backbone of modern municipal development, transforming how cities operate, serve residents, and address sustainability challenges. A comprehensive smart city implementation roadmap combines IoT deployment, integrated data platforms, AI-driven analytics, and citizen-centric digital services to create responsive, efficient urban environments. Whether you are a municipal leader, IT director, or urban planner, understanding the strategic steps of smart city development is essential for maximizing ROI and ensuring long-term success. Smart city IoT deployment is the physical foundation upon which all analytics and citizen services rest. This involves strategically placing sensors, connectivity infrastructure, and edge computing devices across municipal assets—traffic systems, utility grids, parking facilities, public spaces, and environmental monitoring stations. Figure 9 shows smart city infrastructure [14].
- *Disaster Management:* As climate change accelerates the frequency of extreme weather events, digital twins are becoming critical tools for disaster preparedness. The Pacific island nation of Tuvalu, facing an existential threat from rising sea levels, has initiated a project to create a digital twin of the entire country to preserve its culture and ensure the continuity of government services even if the physical land becomes uninhabitable. Training and planning by emergency response could be conducted in this virtual environment, eliminating the time and cost resources of being physically present at the location.
- *"Social" Digital Twins*: Beyond physical infrastructure, digital twins are increasingly being used to model social systems and inform public policy. These "social" digital twins can simulate the behavior of populations in response to policy interventions, economic changes, or public health crises. This allows policymakers to rehearse policies in a synthetic environment before real-world implementation, potentially avoiding unintended negative consequences.
- *Defense:* In the defense sector, real-time digital twins are emerging as mission-critical tools. Real-time digital twins are revolutionizing logistics and mission readiness. They provide unprecedented situational awareness and operational readiness. They continuously process battlefield data, live telemetry, and predictive modeling to provide actionable intelligence. By ingesting surveillance data, digital twins can track the movement of hostile units and friendly assets, enhancing situational awareness and optimizing military logistics. The military utilizes digital twins to

simulate complex systems, such as aircraft fleets and defense supply chains. Digital twins are employed in cybersecurity to create virtual duplicates of physical systems. This enables defense organizations to simulate cyber threats, run test scenarios, and develop robust countermeasures without compromising actual networks.

- *Public Health:* The COVID-19 pandemic underscored the critical need for agile and responsive public health systems. Digital twins offer a paradigm shift in epidemiological modeling and emergency response. In public health, digital twins can simulate the spread of infectious diseases, allowing policymakers to evaluate the efficacy of interventions such as lockdowns or vaccination campaigns. At the individual level, "medical digital twins" integrate patient data (e.g., electronic health records, genomic data) to personalize treatment plans and predict health outcomes. On a macro scale, applying the Prevention, Preparedness, Response, and Recovery (PPRR) framework, digital twins facilitate real-time disaster modeling, helping agencies refine evacuation strategies and allocate medical resources efficiently during crises.
- *Policy Formulation:* Policy formulation is the phase where strategies are developed to solve the issues identified during agenda-setting. In this phase, policymakers collaborate with technical experts and community representatives to design solutions that meet public needs (i.e., align with public values). Digital twin technology (DTT) helps simulate policy outcomes, enabling stakeholders to evaluate the long-term effects of different approaches. Ethical issues may arise when these simulations are based on biased data or overlook stakeholders, reinforcing inequalities.
- *Policy Rehearsal*: Digital twins introduce the concept of "policy rehearsal," allowing governments to test the socio-economic impacts of proposed regulations in a simulated environment before implementation. For example, simulating changes in tax administration or environmental regulations can reveal unintended consequences and help refine policy design. Moreover, making digital twin data accessible to the public fosters transparency and democratic engagement. Citizens can interact with 3D models to understand how a proposed infrastructure project will affect their neighborhood, bridging the gap between policymakers and the community.
- *Food Production:* The US Department of Agriculture (USDA) is currently developing digital twins across crop production processes, work that can help accelerate the development of sustainable agricultural operations at a time when food security is becoming a more salient risk factor to national policymakers. This digital twinning initiative covers two areas: (i) researchers are installing sensors on individual plants to monitor and predict the status of individual organisms, allowing for insights into plant genetics and physiology that will enable more efficient plant breeding; and at the same time, (ii) they are also creating a digital twin of the entire production process that can help inform decisions around planting, irrigation, and pesticide usage. This digital twin of the food production system could be coupled with a weather digital twin and perhaps then a supply chain digital twin.

BENEFITS

The benefits of digital twins in the public sector are vast and transformative. The adoption of digital twins offers several compelling advantages for government operations. Significant benefits include improved decision-making and operational efficiency. Other benefits of DT in government include the following [3,12]:

- *Predictive Maintenance:* One of the most significant advantages of AI-enabled digital twins is their ability to perform predictive maintenance. In the operational phase, digital twins enable predictive maintenance. By continuously monitoring the structural health of bridges, roads, and utilities via sensor data, governments can predict component failures and schedule maintenance before a critical breakdown occurs, cutting maintenance costs and reducing downtime. Predictive maintenance, driven by machine learning algorithms analyzing telemetry data from digital twins, ensures that military assets remain combat-ready while reducing the costs associated with unexpected equipment failures.
- *Enhancing Disaster Response*: The ability to simulate complex systems makes digital twins invaluable for disaster management. As extreme weather events become more frequent, governments require sophisticated tools to predict impacts and coordinate responses. Digital twins can integrate meteorological data, topographical maps, and infrastructure layouts to model the effects of natural disasters such as floods, hurricanes, or wildfires. For example, a digital

twin of a coastal city can simulate storm surge scenarios, allowing emergency management agencies to identify vulnerable populations, optimize evacuation routes, and pre-position resources . This predictive capability shifts disaster management from a reactive posture to a proactive strategy, ultimately saving lives and minimizing economic damage.

- *Environmental Policy*: In the context of environmental policy, digital twins support the transition to sustainable practices. They can be used to monitor environmental indicators such as air quality, water levels, and biodiversity in real-time. By modeling the environmental impact of proposed policies—such as the implementation of low-emission zones or new energy regulations—policymakers can make evidence-based decisions that align with climate goals. The European Union, for example, is developing "Destination Earth," an initiative to create a highly accurate digital twin of the earth to model climate change and support sustainable development policies.
- *National Security:* Security must be a top priority during implementation to ensure seamless collaboration. The defense sector represents another critical area where digital twins are yielding significant benefits. National security threats are increasingly sophisticated, requiring militaries to process vast amounts of real-time data. Real-time digital twins of the battlespace can ingest data from satellites, drones, and ground sensors to provide commanders with unparalleled situational awareness. The US Department of Defense utilizes digital twins to model complex weapons systems, such as fighter jets and naval vessels. By simulating the performance of these systems under various conditions, the military can accelerate development cycles, identify design flaws early, and optimize supply chains.
- *Democratic Engagement*: A less obvious but equally profound benefit of digital twins in government is their potential to enhance democratic engagement and transparency. Public policy decisions, particularly those related to urban development or environmental regulation, can be highly complex and difficult for the general public to visualize. Digital twins provide an intuitive, visual medium for communicating policy impacts. Instead of presenting citizens with dense reports or abstract charts, governments can use immersive 3D models to demonstrate how a proposed park will look, how a new traffic layout will function, or how a flood mitigation project will protect a neighborhood. This reality-based visualization facilitates more meaningful public consultation, allowing citizens to provide informed feedback on proposed changes to their communities.
- *Improved Decision-making*: Decision-making involves selecting the most appropriate policy alternative from the options developed during policy formulation. Digital twins can be very effective in supporting decision-making. Given the scale and potential of government infrastructure projects—as well as the challenges involved in getting them right—data-driven, proactive, and accurate decision-making is vital. Policymakers rely on DTT to provide real-time data and model various policy scenarios. This helps them evaluate the likely consequences of their decisions, particularly in complex areas like transportation and environmental management. Ethical concerns arise when decisions are based on opaque algorithms that lack transparency or fail to consider all stakeholder interests. Also, ethical concerns arise when DTT replaces the human actor in decision-making.

CHALLENGES

In spite of their potential, the implementation of digital twins in government is fraught challenges. The primary hurdles hindering the widespread adoption and effective implementation of digital twins in government can be categorized into technical, economic, legal, ethical, and governance challenges. Substantial challenges such as data governance, privacy concerns, cybersecurity risks, ethical considerations, algorithmic bias, and high implementation costs persist. These challenges must be navigated carefully. Other challenges of DT in government include the following [3,12]:

- *High Implementation Costs*: Building and maintaining a digital twin is an expensive endeavor. Developing and maintaining high-fidelity digital twins requires substantial upfront investment in sensors, cloud computing, and analytical capabilities. The cost encompasses not only the initial software and hardware investments but also the ongoing expenses related to data capture, cloud hosting, cybersecurity, and system maintenance. This high cost can create access and affordability issues, potentially leading to inequities where only well-resourced municipalities can benefit from the technology. It can potentially lead to a "digital divide" where only wealthy cities can afford smart infrastructure.
- *Data Governance*: The most significant hurdle is establishing robust data governance. A functional

digital twin requires the integration of vast amounts of data from disparate, often siloed sources across public and private sectors. When digital twins incorporate data about citizens (e.g., mobility patterns, health records), they raise profound privacy and surveillance concerns. Ensuring data security, anonymization, and public trust is paramount.

- *Data Ownership:* A fundamental challenge is determining who owns the data that feeds the digital twin, especially when that data is generated by private citizens or managed by third-party corporations. Public-private partnerships are often necessary to build digital twins, but they can lead to situations where proprietary algorithms and corporate interests obscure public accountability. Establishing clear data governance frameworks that define data rights, access controls, and transparency requirements is essential to prevent "black box" decision-making.
- *Data Quality*: The effectiveness of a digital twin is entirely dependent on the quality of its underlying data and models. If the data used to train the twin is flawed or unrepresentative, the resulting simulations and predictions may be inaccurate or biased, leading to discriminatory policy outcomes.
- *Data Privacy*: Urban digital twins often rely on massive amounts of data collected from public spaces, including traffic cameras, mobile phone signals, and smart meters. This extensive data collection raises profound privacy concerns. When digital twins model human behavior or track individuals' movements to optimize city services, the line between smart governance and mass surveillance becomes blurred. Governments must navigate stringent data protection regulations (such as the GDPR in Europe) and ensure that data is anonymized and aggregated to protect individual privacy.
- *Ethical Concerns:* Models are inherent simplifications of reality. If the data used to train the machine learning algorithms within a digital twin is biased or incomplete, the resulting policy recommendations may disproportionately negatively impact marginalized communities. Ensuring equity and representativeness in digital twin models is a critical ethical imperative for public administrators. Governments must implement ethical governance frameworks that include auditing for bias, ensuring transparent algorithms, and protecting citizen privacy.
- *Interoperability:* One of the most significant technical barriers to effective digital twin implementation in government is the lack of interoperability. Developing a city-scale or national digital twin requires integrating disparate datasets from various government departments, which often operate in silos. Achieving interoperability between different software systems, legacy databases, and IoT devices remains a significant technical hurdle.
- *Lack of Standards:* Without standardized frameworks for data exchange, creating a cohesive "system of systems" becomes nearly impossible. The UK's National Digital Twin Program explicitly recognized this challenge, focusing heavily on developing the "Gemini Principles" to establish a framework for secure and interoperable data sharing across sectors.
- *Legacy Systems Integration*: Underpinning the success of digital twins is the thorny issue of data integration and access; they all require the ability for different sectors to be able to contribute and share information and to gain insights. Federal and local governments often rely on aging IT infrastructure that was not designed to handle the massive, real-time data flows required by digital twins. Integrating modern Internet of things sensors and cloud-based AI analytics with these legacy systems requires substantial technical effort and investment. In many cases, the physical infrastructure itself lacks the necessary sensor networks to provide the real-time feedback loop that distinguishes a digital twin from a static 3D model.
- *Skills Gap:* The public sector frequently struggles to compete with the private sector in attracting and retaining top-tier technical talent. Developing and managing a digital twin requires a multidisciplinary team skilled in data science, machine learning, systems engineering, and cybersecurity. The current shortage of these specialized skills within government workforces severely limits the capacity to implement and sustain complex digital twin projects without heavy reliance on expensive external contractors.
- *Cybersecurity Risks*: A digital twin provides a centralized, highly detailed model of critical physical infrastructure. If compromised, a digital twin could offer malicious actors a blueprint for cyber-physical attacks. If the twin has two-way control capabilities (allowing the digital model to alter the physical system), hackers could directly manipulate physical infrastructure, such as power grids or traffic networks, through the digital

interface. Consequently, robust cybersecurity measures, including Zero Trust architectures and continuous monitoring, are absolute prerequisites, adding to the complexity and cost.

- *Transparency*: Transparency in digital twin technology (DTT) models is a key issue, as the complexity of these models can obscure accountability and raise ethical concerns. The transparency of decision-making processes can be compromised. For example, algorithms used in DTT simulations may not always be understandable to the public or even policymakers, leading to a lack of accountability. The same holds that, when digital twins are utilized by policymakers, its underlying data and the platform itself must be designated as legally valid and holds in court against stakeholders that object to the decision-making process and/or outcomes.

FUTURE OF DIGITAL TWINS IN GOVERNMENT

The future trajectory of digital twins is inextricably linked to advancements in artificial intelligence (AI) and machine learning (ML). The integration of machine learning and generative AI will enable digital twins to not only monitor real-time data but also automatically detect anomalies, learn from historical patterns, and suggest optimized solutions without heavy manual modeling. AI integration transforms digital twins from passive observational models into active, predictive systems. The incorporation of generative AI enables continuous monitoring and the rapid generation of data visualizations that highlight strategic concerns in real-time. Machine learning algorithms process massive streams of incoming telemetry data, allowing digital twins to learn from historical patterns and detect subtle anomalies. The future of digital twins in government represents a profound shift toward predictive, data-driven governance. As the technology matures and data integration capabilities improve, digital twins will undoubtedly become a foundational tool for smart governance [3].

CONCLUSION

Digital twins represent a transformative tool for modern governance, offering unprecedented capabilities to simulate, analyze, and optimize the complex systems that underpin society. From smart cities like Singapore to national infrastructure programs in the UK, the public sector is beginning to harness this technology to improve efficiency and service delivery. By establishing strong ethical frameworks and leveraging the predictive power of AI, governments can use digital twins to build more resilient, responsive, and equitable societies. From optimizing urban infrastructure and enhancing national security to revolutionizing public health responses, the applications are vast and transformative. However, realizing this potential requires more than just technological adoption. Governments must cultivate cross-sector partnerships, invest in digital infrastructure, and develop comprehensive policy frameworks that address privacy, security, and ethical concerns. As digital twins continue to mature, they will undoubtedly become an indispensable asset in building resilient, efficient, and citizen-centric societies.

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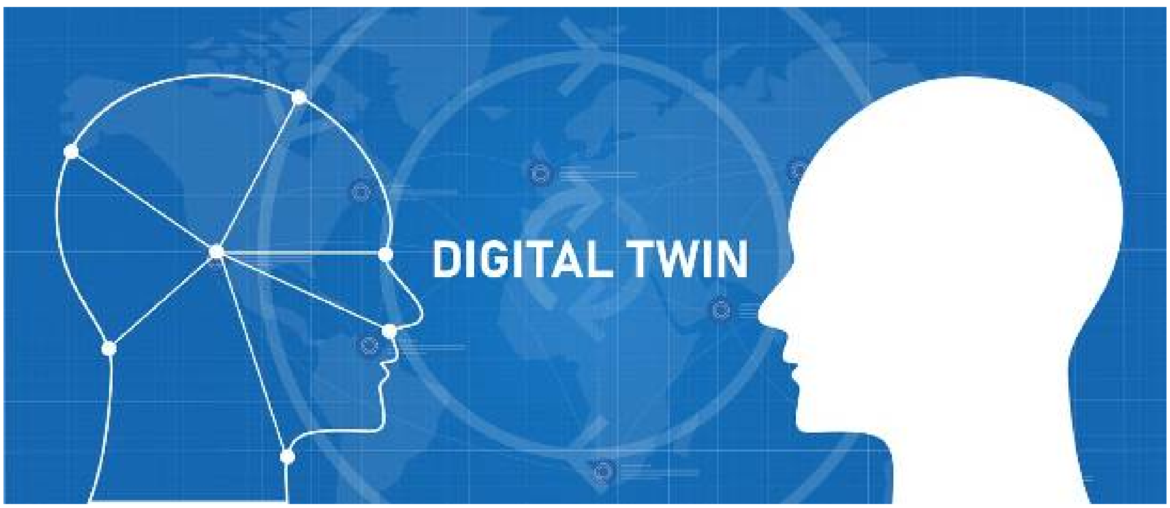

Figure 1 A typical digital twin [1].

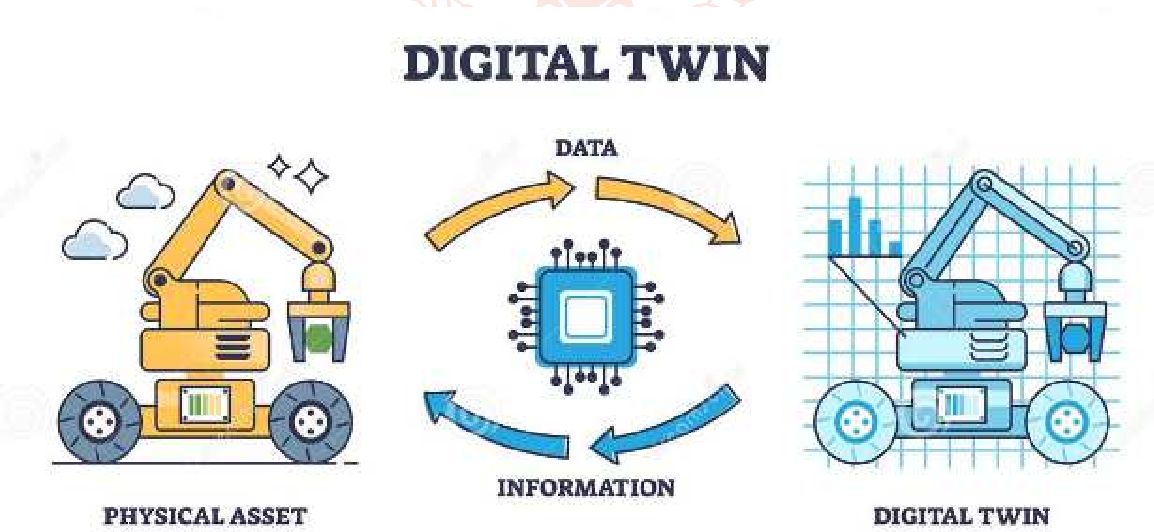

Figure 2 Conceptual model of a digital twin [2].

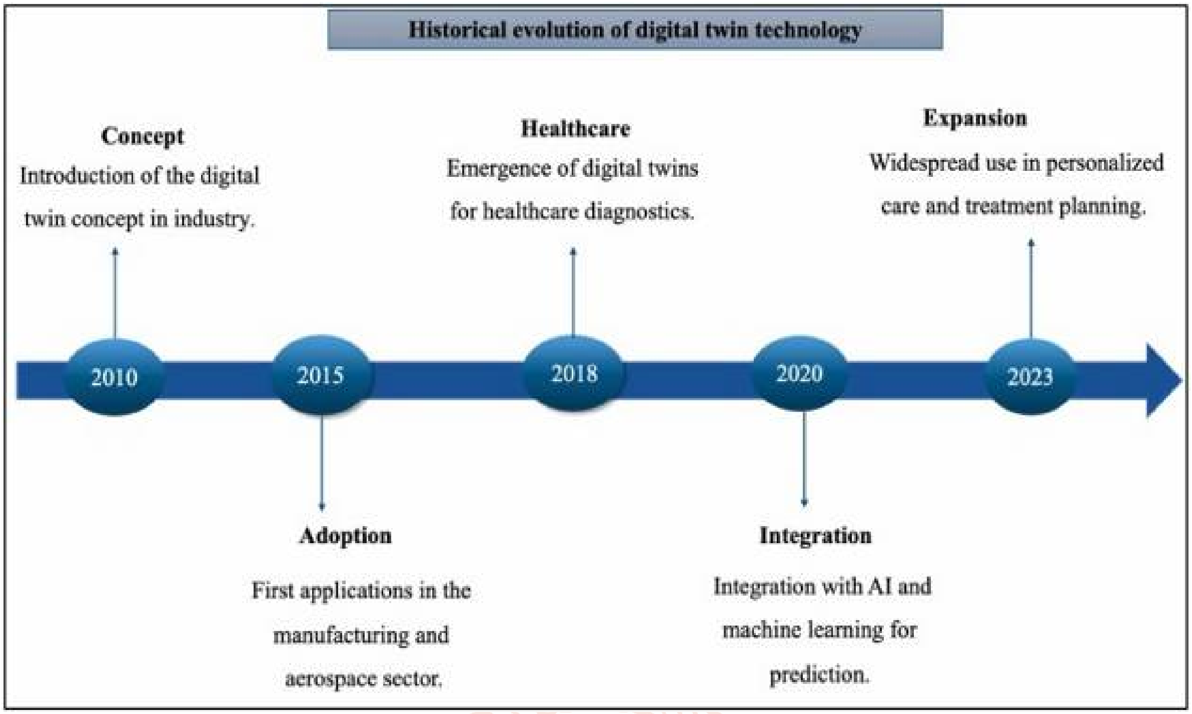

Figure 3 The historical evolution of DT technology [5].

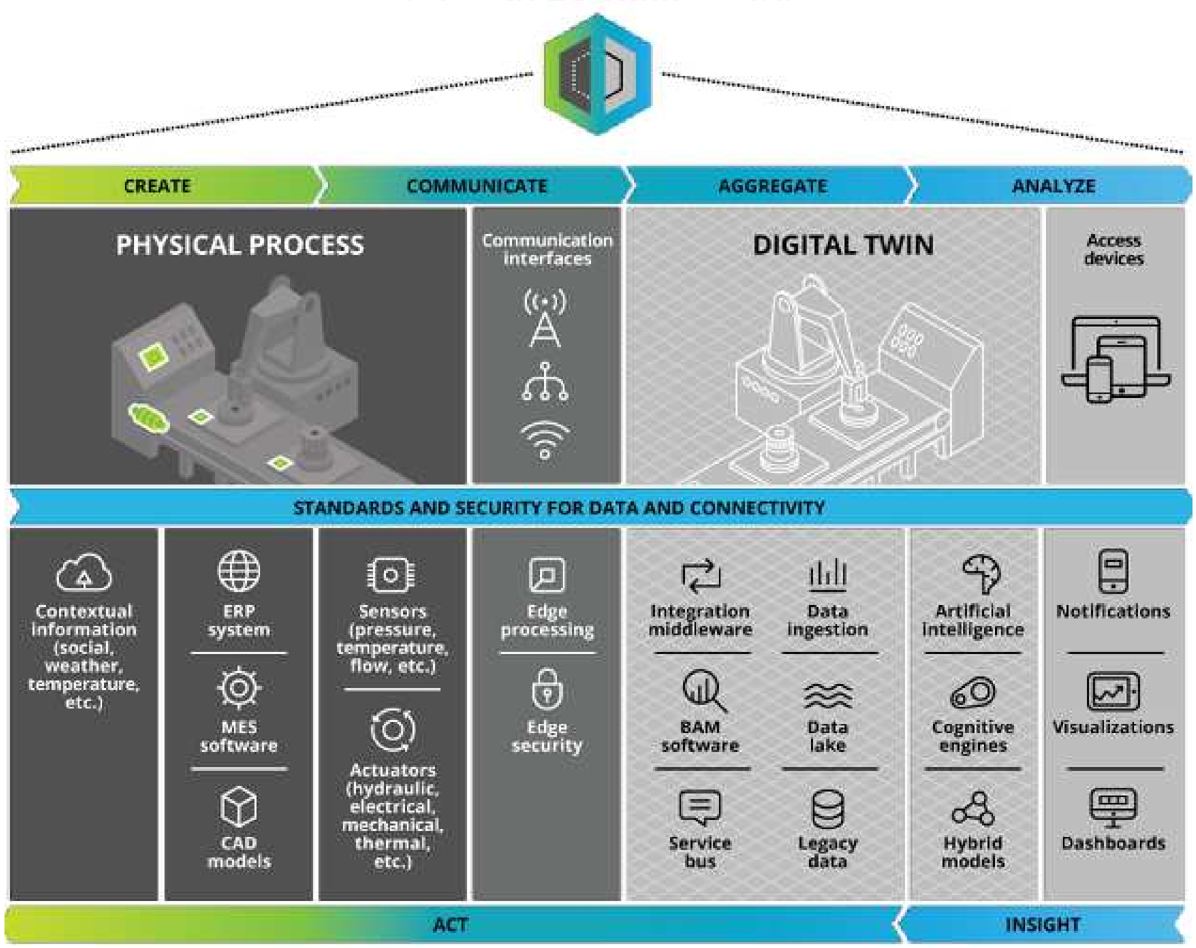

Figure 4 The digital twin conceptual architecture [6].

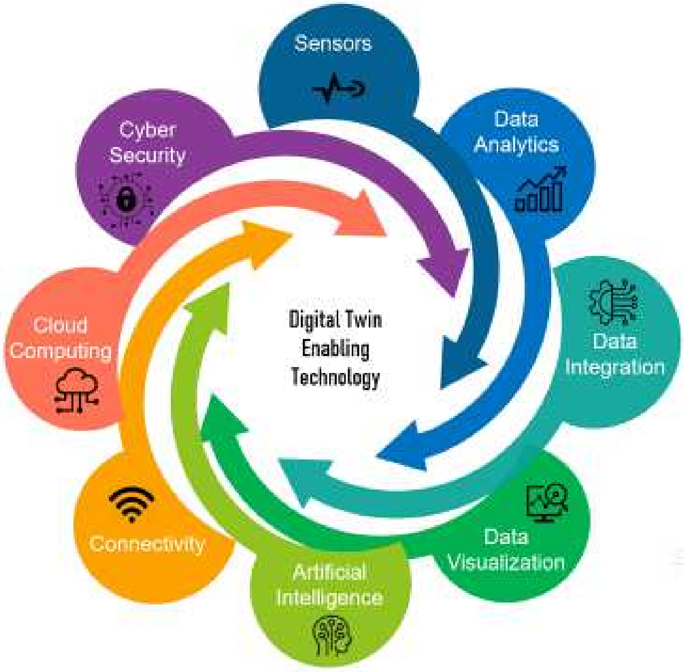

Figure 5 DT enabling technology [7].

Figure 6 A representation of the DT in government [11].

Figure 7 Urban planning [10].

Figure 8 DT for government infrastructure planning [14].

Figure 9 Smart city infrastructure [14].