MetaConstructs

The Evolution of Digital Twins in the Metaverse Era

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CHAPTER 1

Privacy, security, and ethical considerations

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1.1 Introduction

With the rapid emergence of technology, highly interconnected and intelligent systems are constantly emerging, where there is no distinction between the physical world and the digital world. One of the advancements is a cyber-physical system (CPS) and digital twin (DT), which are two important technologies to facilitate real-time interactions between the physical and virtual environments [1]. It opens the gate to their integration as a part of the Metaverse, a virtual universe consisting of numerous interconnected digital spaces in the industry of healthcare, manufacturing, smart cities, and so much more. At the same time, this convergence also presents quite challenging privacy and security challenges that must be dealt with one way or the other to create a safe and trustworthy digital physical ecosystem.

1.1.1 Overview of cyber-physical systems and digital twins

CPS are defined as components of computing and physical ones that are interconnected and communicate with each other in real time [2]. These systems cipher sensors, actuators, networks, and control mechanisms to link the worlds of the digital and the physical, to facilitate automation, increase efficiencies, and furnish it with alternative decision-making capabilities. CPSs have broad application in various areas such as industrial automation, healthcare, transportation, and energy management. Some examples of CPS are smart grid, autonomous car, and robotic surgical system, in which real-time data processing and precise control are vitally important.

Among many other things, CPS is closely related to the idea of DTs, that is, virtual representations of physical objects, processes, and systems that are continuously synchronized with their real-world counterparts [3]. DTs are based upon real-time sensor data, machine learning (ML) algorithms, and artificial intelligence (AI) to simulate, predict, and optimize physical processes. DTs have found a place in manufacturing, aerospace, and urban planning, for example, as companies there are looking to improve efficiency, reduce downtime, and improve predictive maintenance, among other things.

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The synergy between CPS and DTs promotes natural and data-driven decision-making between the physical and the digital worlds. For example, in the manufacturing sector, DTs of equipment in factories allow for predicting failures and anomalies and optimizing the operations. DTs of patients have the same applications in smart healthcare, where they can be used to simulate treatments and tailor medical interventions.

1.1.2 The emergence of the Metaverse

The Metaverse is a quickly developing idea of a continuous, submersed, and interconnected computerized space where clients associate with one another and advanced resources utilizing expanded reality (AR), mixed reality (VR), and blended reality (MR) innovations [4]. Now, there are companies that are at the center of Metaverse development and have invested greatly in AI, Blockchain, immersive technologies, etc. There is Meta (formerly Facebook), Microsoft, Google, and NVIDIA.

The Metaverse is the extension of Web 3.0, a decentralized platform with user-centricity and is the next version of the Internet that includes blockchain, decentralized finance, and cryptocurrency [5]. However, unlike the standard digital platforms such as the Internet, a Metaverse intends to create an immersive, perpetual, and compatible virtual reality world where individuals participate in social, professional, and monetary activities. The applications and challenges of the metaverse are depicted in Fig. 1.1.

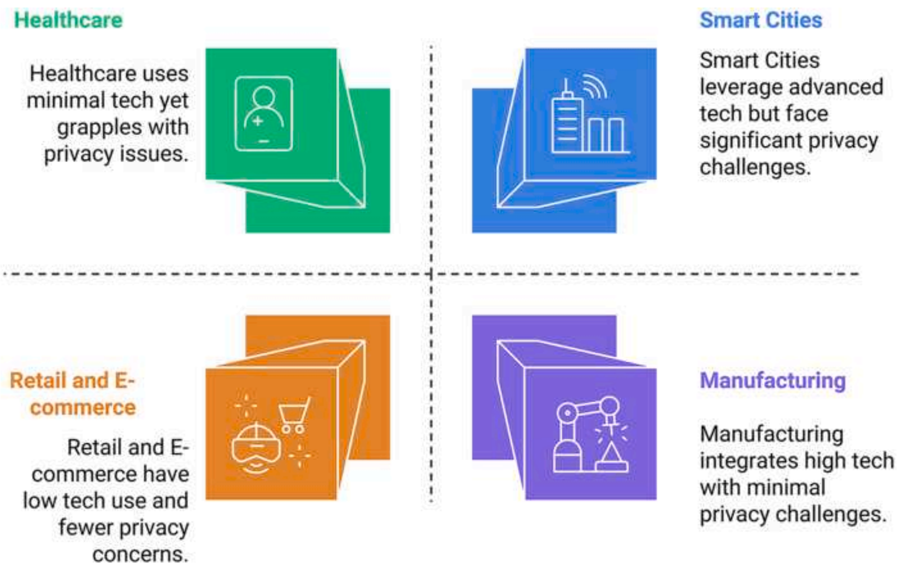

Figure 1.1 Metaverse applications and challenges.

Invested in Metaverse, by integrating CPS with DTs, and will have an effect to transform the industry by bringing up hyper reality simulating, improving the remote operation, and enabling the new business models [6]. Some key applications include:

- Smart cities: DTs of the entire city help urban planners to optimize infrastructure, monitor factors affecting the environment, and raise efficiency in emergency response systems.
- Healthcare: Virtual patient DTs can be used for simulation of accurate medical treatments and personalized treatment plans as well as remote diagnosis.
- In manufacturing plants, CPS and DTs are used to optimize production, predictive maintenance, and increase workers' safety.
- DTs are used for a virtual shopping experience in the retail and E-commerce sector: With it, customers can have personalized recommendations, augmented reality fitting rooms, and digital product previews.

Even though the existence of Metaverse offers tremendous opportunities, increasing dependence of the Metaverse on CPS and DTs brings numerous privacy and security challenges that have to be addressed to assure security, trust, and compliance with the regulation.

1.1.3 Cyber-physical systems and digital twins in the Metaverse: opportunities and risks

1.1.3.1 Opportunities

The benefits of this are immense when CPS, DTs, and the Metaverse meet [7]. Some key opportunities include:

1. With the union of CPS and DTs with the Metaverse, organizations can examine an immense extent of real-time information to conquer productivity and responsiveness.
2. Advanced simulations are immersive and interactive, and they help in optimizing processes, creating better training programs, and better remote collaboration.
3. AI-powered DTs can predict when things may fail, optimize the usage of resources, as well as making operations resilient.
4. CPS integration allows the critical infrastructure being monitored to be operated remotely, thereby reducing not only human error but operational costs.
5. Blockchain-based technology has proven to enable safe transactions, decentralized identity (DID) management, and enhanced digital asset possession inside the Metaverse.

1.1.3.2 Risks and challenges

Despite these numerous advantages, the integration of CPS and DTs into the Metaverse also entails great challenges, especially along the privacy, security, and ethical channels [8]. Key risks include:

1. Privacy violations and data exploitation: The Meteserver stores a lot of user data, which brings up questions like how personal data is used, provided for, and not allowed to be used.
2. CPS and DTs are cyber threats, including hacking, data breach, ransomware, and denial of service (DoS) attacks.
3. Digital identities in the Metaverse can be misused in identity theft and fraudulent activities, which would affect personal and corporate security.
4. Attackers who maneuver DTs: The perpetrator can manipulate the DTs to introduce chaos in operations, create misinformation, or compromise decision-making processes.
5. The evolving technology of Metaverse and DT technology is a challenge in defining the legal and ethical standards for enforcing in different jurisdictions; hence leading to the evolution of the legal and regulatory uncertainty for the same.
6. These types of mission-critical applications can lead to catastrophic failures, having serious implications on human life in the near future, for example, in the case of autonomous vehicles, healthcare DTs and CPS being compromised.

The combination of CPS, DTs, and the Metaverse enables a technological revolution that can revolutionize industry, add an advance of automation, and make better decision-making [9]. Nevertheless, these gains come at the cost of considerable privacy, security, and regulation issues that need to be dealt with in order to prevail in a secure, dependable, and ethical digital environment.

In light of industries increasingly onboarding these technologies, it is of utmost importance that cybersecurity frameworks, strong encryption techniques, DID management, and AI-detected threats are given due importance. Moreover, Metaverse-driven CPS and DT environments must have precise regulations for the protection of the user's privacy, data integrity, and security.

1.1.4 Structure of the paper

The privacy and security issues related to CPS and DTs in the Metaverse, which are composed of many facets, are the contents of this article. The subsequent sections are as follows.

- In Section 1.2some fundamental privacy and security putative(s) are explored in CPS and DT ecosystems.

- Section 1.3 then analyzes the threat landscape primarily in regard to cyber-attacks, data breaches, and identity risks.
- Section 1.4 provides technical solutions like cryptography, AI-based security, secure communication protocols, etc.
- Section 1.5 provides privacy-preserving mechanisms, such as the identity management and data protection strategy.
- Section 1.6 focuses on DTs and their security implications within CPS environments.
- Section 1.7 puts forward future research directions, regulatory framework, and emerging technologies.
- Finally, Section 1.8 concludes the paper with key takeaways and gives recommendations regarding securing CPS and DTs in the Metaverse.

1.2 Privacy and security in cyber-physical systems and digital twins

With CPS and DTs more and more woven into the Metaverse, the Metaverse, as we predicted in 2019, presents some critical problems pertaining to privacy and security [10]. This set of technologies, however, being interconnected, comes with difficulties of data integrity, unauthorized access, and regulatory compliance. These concerns require an understanding and being addressed in order for CPS and DTs to be safely and ethically adopted.

1.2.1 Defining privacy and security in cyber-physical systems and digital twins

Privacy is the ability for an individual or an organization to regulate information about themselves with a view to maintaining secrecy [11]. In terms of CPS and DTs, privacy issues include:

- Personal identifiable information (PII): CPS and DTs gather an immense amount of personal data in various forms, such as biometric data, geolocation, and behavioral patterns. Access to this data without authorization means there would be severe privacy breaches as well as identity theft.
- Corporate and industrial data: CPS is used for manufacturing, automation, and infrastructure management by organizations. Exposure of sensitive operational data can be used for industrial espionage or sabotage, which would affect economic stability and trade secrets.
- DTs in the healthcare segment need large amounts of patient data to simulate the medical scenario. The ethical and regulatory concerns of any leakage or misuse of such data arise with laws such as Health Insurance Portability and Accountability Act (HIPAA) and the General Data Protection Regulation (GDPR).

Security, however, targets the steps that may be taken to protect CPS and DTs from cyber threats. Key security mechanisms include:

- Data encryption: It encrypts sensitive information so that it cannot be accessed or manipulated by unauthorized persons.
- Multifactor authentication and role-based access controls: to prevent unauthorized access to the critical CPS element, thus reducing the vulnerability to cyber-attacks.
- AI security analytics: Threat detection and mitigation: AI-driven security analytics monitors continuously for potential threats and mitigates them before they affect the operations of CPS. To reduce the attack risks, ML models are able to detect anomalies as well as unauthorized access attempts.

The following table in Table 1.1 compares privacy and security concerns across different CPS applications:

1.2.2 Unique challenges in cyber-physical systems–Metaverse integration

Integrating CPS and DTs into the Metaverse brings forth new security ands privacy challenges. [12] Unlike traditional digital systems, CPS must interact in real time between real and digital worlds, with security becoming a complex problem. Below are some key challenges:

1. CPS processes real-time data: It handles a significant amount of real-time data that will come from the sensors. Since this data can be tampered with by any cyberattack, the latter can provide incorrect information to DTs, causing false decisions in industries such as healthcare, finance, and critical infrastructure.
2. Metaverse is built on decentralized data storage systems such as blockchain and peer-to-peer networks. Decentralized storage ensures data integrity, but makes data privacy an issue as the data is dispersed into a number of nodes whose security may vary, as well as the level of regulatory oversight.

Table 1.1 Comparison of privacy and security concerns across different cyber-physical systems applications.

CPS application	Privacy concerns	Security concerns
Smart cities	Surveillance, location tracking	Traffic and energy system hacking
Healthcare	Patient record and genetic data breaches	Medical device hacking, ransomware
Industrial automation	Trade secret exposure, data theft	Manufacturing sabotage, system manipulation
Autonomous vehicles	GPS tracking, data leaks	Vehicle control hijacking, signal spoofing

3. CPS devices run with different communication protocols. Introducing security vulnerabilities, as secure interoperability across many platforms of the Metaverse does not guarantee security and can enable a man-in-the-middle (MITM) attack targeting the data between systems.
4. Implementing identity management in virtual–physical environments: Avatars and digital identities used in the Metaverse must be associated securely with real people in the real world to avoid fraudulence and abuse. Synthetic identity fraud and deepfake technology render identity management difficult and force mechanisms of authentication to be more crucial than ever.
5. Data protection laws: Works with various local and international data protection laws, such as grouping protocols abiding by GDPR and California Consumer Privacy Act (CCPA) separately. Thus the Metaverse does not have developed regulatory frameworks, which makes it hard to impose privacy and security standards anywhere. Such a lack of standardization creates gaps in compliance and legal uncertainties.

All of these challenges were depicted in the following smart diagram in Fig. 1.2

1.2.3 Privacy concerns in digital twin–cyber-physical systems interactions

A DT is a virtual replica of a physical system, and so it relies on continuous data synchronization with CPS [13]. This raises several privacy concerns:

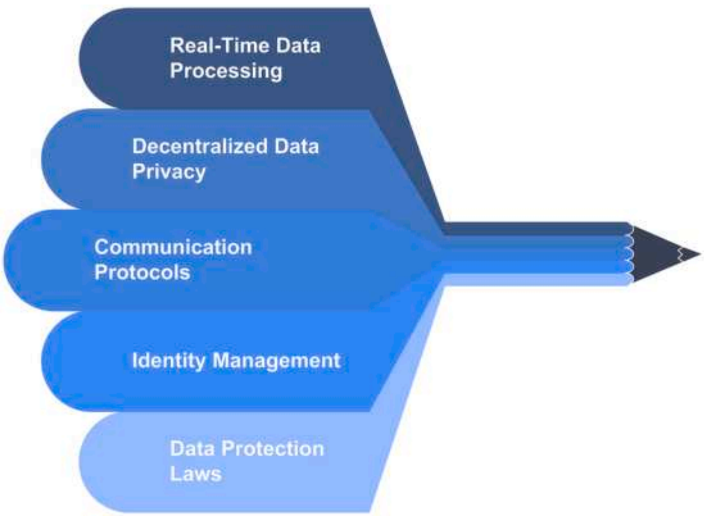

Figure 1.2 Navigating cyber-physical systems-Metaverse challenges.

1.2.3.1 Data collection and ownership

- Determining who owns the data generated from interactions between CPS and CPS DT is one of the biggest privacy challenges. For example, who owns the data, if one, in a smart factory, the manufacturer, the software provider, or the end user?
- Many organizations find it difficult to create a transparent data collection policy, thus attracting regulatory scrutiny and legal challenges. Ambiguity over data ownership plays a major role in determining how legally accountable and compliant an enterprise is to the privacy laws.

1.2.3.2 Anonymization and data protection

- K-anonymity, differential privacy, and homomorphic encryption techniques anonymize the CPS-generated data to prevent unauthorized identification of individuals. However, this approach can still cause the exposure of sensitive data and violation of privacy if incorrectly implemented.
- This is prompting the exploration of privacy—enhancing technologies to reduce risks, but there remain challenges between providing privacy and a data utility. Somehow, anonymizing them fully may result in losing the value these data hold for predictive analytics and AI-driven decision-making.

1.2.3.3 Consent and user awareness

- Users interact with DTs, often without understanding that they do, as such systems run "in the back end" and collect data without the users' consent. The data collection without the knowledge of the user leads to many ethical and legal issues in sectors like healthcare and finance.
- Organizations must use user-friendly consent management platforms, but to provide clear, transparent, and accessible privacy policies. This way, the users receive the information on how their data is used and are given the option to opt out if they wish.

1.2.3.4 Potential for data misuse

- Historical and real-time data stored in DTs make them coveted by cybercriminals who might gain access to this data with the intent of using it for espionage, surveillance, or fraud. The misuse in such critical sectors as national defense and financial services can be very costly for the economy and geopolitics.
- A necessary protection mechanism is to enforce strict access control policies, robust authentication, and encryption to make sure that unauthorized replication or

modification of DTs does not happen. Advanced frameworks for securing them, including zero-trust architectures, may help to mitigate these risks.

Since CPS and DTs become essential parts of the Metaverse, it is necessary to mitigate privacy and security risks, including their effects. Besides this, it will be highly important to offer a secure digital ecosystem where robust encryption can ensure data robustness, regulatory compliance must be observed, and ethical data handling practices accepted. To reduce the imminent risks, organizations have to adopt the zero-trust security model, AI-driven threat intelligence, and DID management.

Moreover, standard legal frameworks for the handling of CPS and DT data by the Metaverse also have to be defined by policymakers. If the door is left wide open, privacy breaches, cybersecurity threats, as well as ethical issues will continue to grow without clear regulations. The following sections will shed light on the possible cyber threats and their mitigation to security CPS and DTs in the Metaverse.

1.3 Threat landscape for cyber-physical systems and digital twins in the Metaverse

However, integration of CPS, and DTs into the Metaverse lead to a number of benefits, they also find themselves exposed to an ever-changing threat landscape [14]. The existing Metaverse has real-time interaction, interlinked digital environments, and can be relied on IoT, AI, and blockchain technologies, thus causing an increase in the potential attack surface of malicious actors [15]. CPS and DTs can be targeted by cyber threats that can corrupt data integrity, affect system availability, hide user privacy, and lower operational safety. Assessing the threat landscape is then critical to developing an appropriate cybersecurity strategy, which will enable the resilience of these technologies.

1.3.1 Cyber attacks on cyber-physical systems in the Metaverse

As the Metaverse becomes more embedded with CPS, it makes it more and more attractive to cybercriminals to target it. In such a digital environment, some of the common most cyber threats imposed on CPS are malware, ransomware, Distributed Denial of Service (DDoS) attacks, and access violations.

The greatest issue, as far as malware ransomware hits are concerned, is that smart infrastructure, industrial automation, and healthcare systems can be infiltrated by malware and ransomware [16]. Malware is deployed by cybercriminals to disrupt the operation, steal sensitive data, or ransom it in exchange for restoring access. For example, ransomware locking access to a necessary control system in a situated smart factory with interconnected CPS could cause production halts, defective manufacturing processes, or safety hazards, to name a few.

DDoS attacks are another important threat, where adversaries send the system with an excessively high number of requests, and as a result, the service becomes unavailable. In particular, the Metaverse that depends on data exchanges between CPS and DTs in real-time should be the most susceptible to latency-based attacks, causing network performance and user experience degradation. Literally, these attacks can short-circuit bulk critical services such as virtual health consultations, autonomous vehicle routing, and smart grid operations.

Growing concerns also exist for unauthorized access and system intrusion. It is known that cybercriminals take advantage of weak authentication mechanisms and software vulnerabilities to hack CPS and their DT networks. Data manipulation, operational sabotage, and espionage may result from this unauthorized access. They could cause disruption of critical infrastructure such as smart power grids and automated transportation systems, for which they gain control over them.

1.3.2 Data breaches and identity theft risks

The Metaverse hosts, processes, and produces great amounts of personal, industrial, and operational data [17]. However, due to the storage and transmission of these data between the CPS, DTs, and cloud-based environments, these data are deemed high value to cybercriminals. While there are many severe threats in this landscape, the biggest one is a data breach, when malicious actors exploit the security vulnerabilities to obtain unauthorized access to sensitive information.

A CPS and DT ecosystem data breach can be very costly. In a smart healthcare system, for example, a breach could result in exposure of patient records, medical history, and real-time biometric data, resulting in identity theft and financial fraud. Likewise, a compromised DT of a smart city may give away critical infrastructure data in order to plan a cyber-physical large-scale attack against urban systems.

The other big risk associated with the Metaverse is identity theft, since the Metaverse involves digital avatars, biometric authentication, and blockchain-based identities. Attackers can steal login credentials, cryptographic keys, or even biometric data to impersonate users to attack and gain access to protected systems. Such a condition may result in financial fraud, unauthorized asset transfers, and corporate espionage.

To exacerbate this issue, there are no stringent identity verification mechanisms within DTs and CPS. Traditional cybersecurity measures may not be enough to combat deepfake technology or synthetic identity and impersonation attacks perpetrated by AI. At the very core, organizations will not have control of any data or user identities if they do not have robust MFA and encryption protocols in place.

1.3.3 Threats to real-time process integrity and synchronization

A second experimental design engages the railway industries here in Germany and in Norway, and examines the socializing of CPS and DTs to synchronize and process real-time data with high accuracy [18]. Although cyber threats aimed at process integrity, data tampering, and time-sensitive threats are dangerous.

Tampering with data and process manipulation are two major concerns in which the attackers insert false data or change time-critical data to affect the system behavior. For example, these can be navigation errors, traffic accidents, and operational failures in the autonomous vehicle network, for example, GPS coordinates defacing or sensor data malware. Likewise, an attacker on smart power grids can mislead power demand data to cause the instability of the grid and blackouts.

The second important issue is latency-based attacks where DTs and CPS break the real-time communication between them. As these systems depend on low-latency data synchronization, even a little bit of delay can cause their malfunctioning ties or operational inefficiencies. As an example, network delays or other real-time feed alterations in a robot-assisted surgery would lead to surgical errors with potentially life-threatening consequences.

The other risk of algorithmic manipulation (manipulation of an AI-driven system by exploiting the underlying algorithms) and adversarial AI attacks (attacks on the AI that outperform it by learning algorithms) also comes in because of the growing use of AI-driven automation in the Metaverse. It is possible that malicious actors can exploit ML models in CPS and DT to cause them to produce incorrect predictions, false alarms, or to make biased decisions. This is very important in the case of finance, cybersecurity monitoring, and industrial automation, where data accuracy and decision integrity matter.

To prevent such threats, organizations should use real-time anomaly detection systems, secure time synchronization protocols, and AI-based cybersecurity solutions [19]. Use of encryption techniques, access control mechanisms, and continuous monitoring will help enhance reliability in real-time processes within the CPS and DT environment.

Threats for CPS and DTs in the Metaverse are complex in nature and transient in nature. Organizations have to consequently adopt proactive security methods to protect these interconnected systems from malware attacks, identity theft, process integrity manipulation, as well as AI-driven threats. To mitigate such risks, the solution lies in the development of robust authentication mechanisms, end-to-end encryption (E2EE), as well as utilizing AI-driven cybersecurity solutions. On top of this, collaboration between the industries, governments, and cybersecurity experts needs to be fostered to build a safe and secure a digital–physical ecosystem. The third part of this thesis will discuss technical solutions to increase the CPS and DT security in response to the evolving cyber threats.

1.4 Technical solutions for cyber-physical systems and digital twins security

With the advancement of the Metaverse, such CPS and DTs embed into it and need to be secured [20]. Due to these complex interconnected systems, the systems are susceptible to cyber threats and therefore need strong technical solutions. In this section, we study this subject to discover some key approaches (e.g., cryptographic techniques, secure communication protocols, and AI-exposed threat detection) that can be applied to reduce and, to some extent, eliminate the threat. In order to protect CPS–DT environments from data breaches, unauthorized access, or cyber-physical attacks, a combination of such approaches is needed.

1.4.1 Cryptographic approaches for data protection

Securing data in both CPS and DT environments requires the cryptographic mechanisms. For confidentiality and data integrity guarantees, encryption methods are made use of, like Advanced Encryption Standard (AES), Rivest Shamir Adleman, Elliptic Curve Cryptography, etc., for data transmission and storage [21]. These cryptographic techniques can be used to implement the authorization and to prevent sensitive information from the access of the unauthorized person and from cyber threats.

Homomorphic encryption is one such effective method. This technique allows computing on encrypted data without the need to decrypt it [22]. In the case of privacy-preserving analytics, this is particularly important because you are doing analytics on sensitive industrial or personal data that you don't want to be exposed. Furthermore, blockchain-enabled cryptographic technologies reinforce the authenticity, auditability, and tamper-resistance data of DT models to ensure that they are secured and unchanged. Data integrity is further enhanced with the use of cryptographic hashing functions like SHA-256 and SHA-3 that make the data representation irrevocable and detect any unauthorized changes to the data.

Lightweight cryptographic protocols are needed for real-time CPS applications because of their very low processing overhead at the cost of security. Other algorithms aimed at resource-constrained devices, like ChaCha20 and Lightweight AES, strive to cryptographically secure the system at end-to-end without decreasing the system performance.

1.4.2 Securing cyber-physical systems–digital twin communication channels

CPS continuously interacts with DTs in real-time; thus the required secure communication protocols are essential to avoid any unauthorized interceptions. To keep the data exchanges secure, the solutions should implement E2EE and secure authentication mechanisms [23]. CPS operations are assured to be secured from eavesdropping, tampering, and spoofing attacks through secure communication.

Key secure communication protocols used in CPS and DT environments are presented in Table 1.2.

In smart cities, CPS is provided 5 G secure slicing, which is an isolated, secure network segment that 5 G can provide. Using these communication security frameworks, organizations can shield CPS–DT ecosystems from the threats of MITM attacks, data eavesdropping, spoofing, etc. By implementing zero-trust security models, every interaction of DT and CPS is verified every time, so that it minimizes unauthorized access.

1.4.3 Artificial intelligence and machine learning-based threat detection

AI and ML are crucial to improve cybersecurity by reducing cases of threats and providing real-time mitigation of the threats [24]. Security frameworks of AI are of continuous analysis of the network traffic, identification of anomalies, and response to cyber incidents.

Intrusion detection systems (IDS)-based on deep learning are good at identifying zero-day attacks, malware propagation, and unauthorized access attempts. Likewise, behavioral analytics are also used by AI-powered threat detection systems that discern the normal operation and suspicious behaviors, enabling them to detect a cyber threat before it escalates.

An AI-driven cybersecurity process workflow diagram is provided in Fig. 1.3 in the form of a Cycle Diagram Smart Art that describes the workflow of an AI-driven cybersecurity framework for CPS and DTs.

The AI-driven security frameworks iteration, represented on the cycle diagram, is about a continuous feedback loop that enhances the threat detection accuracy and adaptation. Deploying an AI for cybersecurity measure brings organizations the ability

Table 1.2 Secure communication protocols for cyber-physical systems and digital twins.

Protocol	Functionality	Application
TLS (Transport Layer Security)	Encrypts data transmissions over networks	Secure web-based interactions, Lightweight messaging with encrypted security, communication of IoT device Message Queuing Telemetry Transport (MQTT) with TLS
Zero Trust Architecture (ZTA)	Verifies every access request for security	Network-wide protection

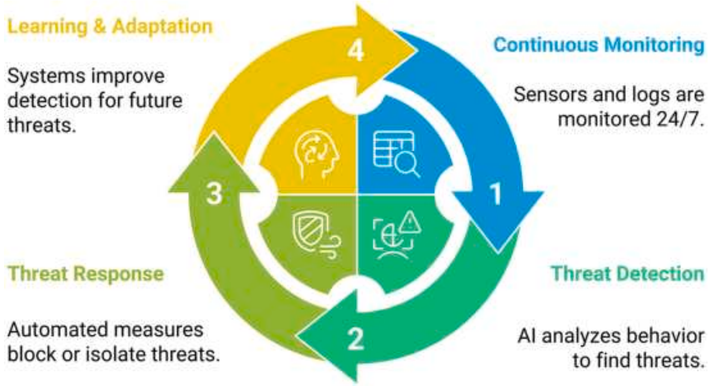

Figure 1.3 AI-driven cybersecurity cycle for cyber-physical systems and digital twins.

to quickly respond to incidents, gain proactive intelligence against threats, and automate defenses of their systems.

1.4.4 Future considerations for enhancing cyber-physical systems and digital twin security

Despite the significant measure of protection offered by current security measures, there is a need for future cybersecurity for CPS and DTs to protect from emerging threats, meet regulatory compliance, and be cross-platform interoperable [25]. The following suggestions may also be used to build long-term security resilience.

- Quantum-resistant cryptography: Due to advancements in quantum computing, sooner or later, traditional encryption algorithms can be attacked. Because postquantum cryptographic algorithms cannot be securely used in CPS–DT interactions, such algorithms will need to be researched, developed, and implemented based on the algorithms that have been suggested in the academic domain.
- Decentralized identity management: Blockchain identity verification systems based on blockchain help to reduce dependency on Centralized Authentication Mechanisms and bring down Identity fraud and access breaches.
- Regulatory compliance and standardization: In that sense, they should create global security standards for CPS–DT implementations in the Metaverse that comply with the GDPR, CCPA, and ISO/IEC 27001.
- Real-time autonomous cyber defense systems: Security mechanisms that employ AI to autonomously detect, counter, and recover from cyber threats.

Given that Metaverse is going to be the successor of the Internet and organizations out there are planning to onboard their CPS and DTs in Metaverse, it will become a culture to protect them from various security threats with layered security.

Cryptographic techniques and secure communication protocols are implemented, along with AI-driven threat detection, to improve system resilience.

Table 1.2 outlines the secure communication protocols that can be used to protect the exchanges of data, and Fig. 1.3. AI-driven cybersecurity mechanisms can measure amenity. The CPS DT ecosystems can be secured against further evolving cyber threats by the inclusion of the above-mentioned advanced security features. The second part of this paper will cover privacy mechanisms for preserving individual data, data protection, and regulatory compliance in CPS DT environments.

1.5 Privacy mechanisms for cyber-physical systems and digital twins in the Metaverse

With such an increase of CPS and DTs within the Metaverse, privacy concerns are now making themselves known [26]. Since these environments are interconnected, the vast amount of data generated and exchanged in these environments incurs the risk of unveiling the user's anonymity, infringing on data ownership, and regulatory compliance. How to implement robust privacy mechanisms on top of existing protocols to ensure the privacy of sensitive information as much as possible, without affecting the efficiency and being usable at the same time. The survey on this section discusses privacy mechanisms consisting of identity management frameworks, data anonymization techniques, and user-controlled data sharing [27].

1.5.1 Identity management in virtual–physical environments

Privacy in Metaverse's CPS and DT ecosystems is key and is factored through identity management [28]. Therefore digital identities of users and entities are needed for secure, verifiable, and privacy-preserving access to and control over the cyberphysical resources with many simultaneous interactions in real-time.

DID framework is one of the best ways to implement privacy-friendly identity management that leverages blockchain and a self-sovereign identity model. Through these systems, users can themselves control their personal data without handing the control to central identity providers, thus reducing the risk of identity and unauthorized tracking. Unlike the traditional model of identity verification, where the credentials of the users are stored and handled by third-party platforms, DID ensures that identities are under user control and the authentication can be done in a secure and privacy-respecting way.

Zero-knowledge proofs (ZKP) is another approach in which ZKP are a cryptographic method that enables to verify identity credentials without divulging personal details. This technique lets users in the Metaverse prove some of their attributes (e.g., age verification, access permission) without disclosure of PII [29]. Organizations can enhance privacy protection and smooth processes for identity verification by integrating ZKP-based authentication in the CPS–DT bi-directional communication.

Moreover, further mechanisms of identity security bolstering (like biometrics, cryptographic token-based authentication, etc.) can be introduced for more security without losing ease of access. Implementing strong authentication measures eliminates the risk of identity spoofing and accesses to critical CPS DT operation unauthorized.

1.5.2 Data anonymization and privacy-preserving techniques

Since there are large-scale data exchanges in CPS and DT networks, privacy-preserving data processing techniques are required to protect the individuals and the organizations from potential risks of unauthorized profiling, data mining, and surveillance. Anonymization and encryption are among several privacy-enhancing techniques, such as these, that can be implemented in the Metaverse to ensure secure data flows.

Differential privacy is one of the techniques widely used to introduce statistical noise into data sets so that personal or proprietary information is not extracted. Using this method, CPS DT systems can perform analytics on anonymized data such that the individual records are untraceable [30]. In smart city applications and industrial automation, for healthcare monitoring and other such use cases, we require real-time data insights, and, at the same time, we do not want sensitive information to leak. For such scenarios, differential privacy is of great use.

Another method is homomorphic encryption, which allows data to be processed in its encrypted state without having to decrypt it. While cloud-based DT applications require this technology for privacy-sensitive data processing in 3rd-party environments without compromising confidentiality. CPS DT systems using homomorphic encryption are guaranteed to maintain strong privacy guarantees, yet can still provide external platforms they interact with.

Another essential privacy mechanism that replaces the person's identifiers with unique but reversible pseudonyms is pseudonymization [30]. This helps organizations maintain the balance between the utility of data and privacy adherence in areas such as finance, healthcare, and IoT ecosystems with the need of auditability and traceability.

Federated learning has also started leveraging itself as a privacy-enhancing approach to use AI for CPS DT applications. Federated learning is a mechanism that trains multiple entities (decentralized) on models in a way that there is no need to centralize user data. This approach greatly minimizes the data exposure risks, as the analytical accuracy remains mostly intact.

1.5.3 Enhancing user control over data sharing

Giving more control to users and users' data is the fundamental aspect of privacy in CPS–DT interactions [31]. If user data is not collected, processed, and shared in an explicit and affirmative manner, then we have privacy violations and regulatory noncompliance by way of no proper governance mechanisms.

A way to solve this issue is to create user consent management platforms, which allow individuals to decide who gets to have access to and use their data. On these platforms, users will be able to determine what data to share and who to share it with, withdraw permissions, and track data transactions to the users' individual benefits and rights in the Metaverse.

Moreover, automated, transparent, and immutable consent agreements can be also enforced by smart contracts, that is, smart contracts that run on the blockchain. These are contracts that help keep to the privacy policies and reduce intermediary dependency. With blockchain-based data governance embedded into CPS–DT ecosystems, trust and compliance with performance to Data GDPR, CCPA and HIPPA solutions can be significantly increased [32].

In addition, by adopting privacy dashboards, users can have real-time understanding of how their data is processed, stored, and shared real-time. Such dashboards help with transparency in that they enable users to peruse data logs, set permissions, or be alerted of a possible privacy violation. Privacy dashboards provide the Metaverse with a means of facilitating greater visibility and user-enabled autonomy in the strengthening of its data protection practices.

Data minimization and purpose limitation principles are further crucial principles of user-controlled data sharing. Collecting and processing CPS DT data by organizations has only to be used for explicitly defined and agreed-upon purposes in order to reduce the risk of that data being used or repurposed without consent by those who collected the data.

1.5.4 Future perspectives on privacy in cyber-physical systems and digital twins

Privacy in CPS and DTs inside the Metaverse needs to be guaranteed through the use of a multilayered approach encompassing DID management for preserving personal privacy, privacy-preserving data processing techniques, and allowing users to have control over their own data to share with others [33]. With the help of ZKP, differential privacy, homomorphic encryption, and smart contracts, organizations can make sure that even in the case of a data breach, their data remains secure and ensures compliance with global standards in global privacy.

Future research should move in the direction of developing adaptive privacy frameworks to reinforce privacy measures, taking into account the security and usability issues and regulatory compliance. AI-driven privacy monitoring tools can be integrated into communications for purposes of detecting anomalous data access patterns (that indicate potential breaches) at an early stage. Also, industry cooperation on the development of a standardized privacy protocol for interaction between CPS–DT will be essential in the goals of creating a safer and user-centered Metaverse.

With the Metaverse rapidly continuing to grow, technology developers and implementers of CPS–DT will have to prioritize privacy-by-design technology frameworks and empowering users as they work toward establishing trust and facilitating sustainable adoption. The subsequent section looks at DTs as one of the main security concerns and the methods by which upcoming threats can be mitigated in the growing cyber-physical landscape.

1.6 Digital twins as a key security focus

DTs in CPS at Metaverse quickly get into function to provide better monitoring, prediction analytics, and productivity. Nevertheless, their integration brings with it significant security and privacy concerns, hence becoming a primary area of security to protect CPS environments [34]. In theory, there is no clear distinction between any physical system and its counterpart DT that is built from it. In this section, we investigate how DTs fit in CPS operations, how security challenges manifest themselves in their representations, and how to secure DT synchro with physical systems.

1.6.1 The role of digital twins in cyber-physical systems operations

DTs are a digital representation of real-life assets that are kept up to date in real time to help in making better decisions, optimizing operations, and for risk assessment. These simulate physical behavior and forecast system performance by making use of data from sensors, IoT devices, AI models, etc. [35]. Some key use cases of DTs in CPSs operations are:

- Predictive maintenance: DTs enable equipment failure prediction and scheduling of proactive maintenance to avoid downtimes and cost savings.
- It monitors it in the real-time system by continuously analyzing the sensor data and providing insights about the performance, efficiency, and vulnerabilities of the system.
- Simulation and optimization: DTs allow manufacturing, healthcare, and transportation industries to simulate and optimize their operational conditions.
- They can incorporate AI and make autonomous decision-making as the DTs can take real-time decisions to enhance security and efficiency without any human intervention.

However, as CPS harnesses the importance of DTs, these DTs need to be secured since, without, they can be subject to cyber threats, unauthorized manipulation, and operational disruption.

1.6.2 Privacy and security concerns in digital twin representations

Since DTs process huge volumes of real-time sensitive and operational data, they are the prime candidates for cyber-attacks [36]. Key security concerns with respect to DT representations include the following.

1. Unauthorized access, data breaches: If a DT's data repository is compromised, attackers gain knowledge of critical infrastructure, industrial processes, or personal information, and there is a possibility for breaches to happen.
2. Malicious users can manipulate DT models to send incorrect feedback to CPS and thereby misguide the decision processes and cause operational failures.
3. Consequently, a synchronization mechanism between a DT and its physical counterpart can be compromised and hence lead to outdated or falsified system states in real-time systems, which in turn can degrade the performance of the overall system.
4. DTs use simulations to run that are often based on user data, thereby providing the potential for inadvertent exposure of any sensitive personal or corporate data.
5. Attackers can inject malicious code into DT environment to disrupt CPS functionality and ask for ransom in order to restore it.

Therefore it becomes essential to carefully address these underlying security concerns through a multilayered security strategies that combine encryption, access control, AI-based anomaly detection, as well as robust synchronization protocols [37].

1.6.3 Securing digital twin synchronization with physical systems

To ensure the integrity of the system, as well as to prevent cyberthreats, it is critical to virtually guarantee digital synchronization of the DTs and their physical counterparts [38]. The synchronization processes of DT could be protected by the following measures:

- Integrity verification based on blockchain: Using the blockchain technology, any updates or alterations of a DT will be immutably recorded and can be verified to be sure whether they are authorized or not.
- AI real-time anomaly detection: AI-based monitoring systems are continually monitoring synchronization patterns, and if unusual patterns are discovered in the patterns, they indicate a cyberattack or data manipulation.

- End-to-end encryption: Encrypting data exchanged by DTs and physical systems so that, even if the data is attacked, this data is unintelligible for attackers.
- Zero trust security models: Deploying the zero trust architecture to DTs ensures that there is an ongoing authentication and validation of every interaction between the DT and its physical counterparts.
- Multifactor authentication to system access: DT platforms ought to put into use MFA mechanisms to block unauthorized access and heighten security.

Deploying these security mechanisms facilitates organizations assuring that DTs act as trusted digital counterparts of their physical systems and become resilient to cyber threats.

Real-time monitoring, predictive analytics, and operational automation are all pluses that come to us from DTs as they become so vitally important to optimizing CPSs within the Metaverse [39]. But they are increasingly reliant on real-time data synchronization, AI developed simulations and sensor networks, which places them at great risk of security breach. For operational resilience and preventing cyber threats, secure access to DTs, integrity protection, and encrypted communication between DTs and their physical counterparts are needed. Future directions and recommendations to enhance CPS and DT security in the changing Metaverse are elaborated in the next section.

1.7 Future directions and recommendations

Since Metaverse evolves as CPS and DT, it becomes essential to address emerging security challenges [40]. However, such combined systems require a prospective standpoint due to the extremely rapid advances in technology, to assure the security, privacy, and resiliency of these end-to-end networks. Then, this section describes improvements in the security frameworks of CPS, DT, and the corresponding regulatory and legal implications, as well as the emerging research areas and new opportunities to influence the future of CPS and DT security.

1.7.1 Enhancing security frameworks for cyber-physical systems in the Metaverse

Adaptive security frameworks are necessary in the cyber secure CPS and DT environments to mitigate the evolving cyber threats [41]. The enhancements in security need to encompass the application of high-level of cryptographic techniques, AI-based threat detection, and DID management. Several key approaches include:

1. Postqantum cryptography (PQC): If you aren't familiar with the advancements in quantum computing, quantum computing won't be entirely obsolete, but you can

no longer use conventional encryption methods. Lattice-based and hash-based cryptographic algorithms like PQC algorithms are resilient to quantum attacks in long-term.

2. ML algorithms can detect anomalies in real time, and they can provide predictive cybersecurity to preclude the potential cyber threats, before they cause damage.
3. Blockchain technology enables decentralized and blockchain-based models of data integrity, identity management, and decentralized access control within a CPS ecosystem, thereby minimizing the possibility of failures at a central point.
4. The first framework introduces zero trust security architecture where every user, device, and system interaction are continually authenticated and monitored to reduce attack vectors in DT environments.

Adding those advanced security mechanisms in Fig. 1.4, the organizations will be able to construct self-adaptive resilient infrastructures, which are immune to contemporary cyber threats.

1.7.2 Regulatory and legal implications

As CPS and DTs continue to be deeply embedded within the critical industry, the legal and regulatory aspects for protection of personal data and ethical development and deployment of technology become, therefore, very critical [42]. Innovation must find

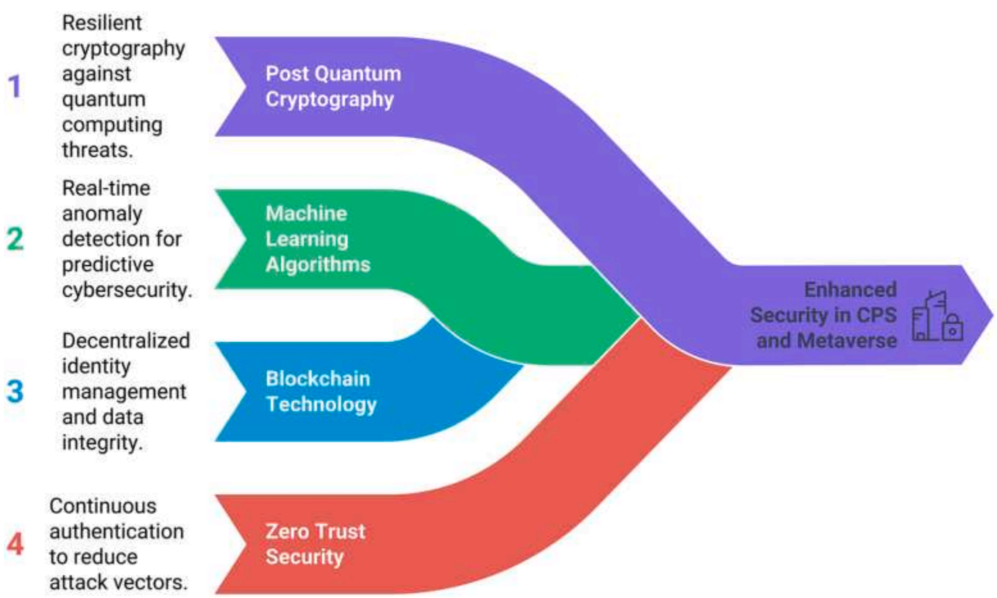

Figure 1.4 Unified security approaches for cyber-physical systems.

its balance with privacy and security of the user, and the government and regulatory bodies need clearly defined policies.

A couple of regulatory considerations are key, some of which include:

- Security Policies Global Standardization: Security policies such as GDPR, CCPA, and ISO/IEC 27001 have to be relocated into CPS and DT's environment to achieve the global conformity of secure implementation.
- Data sovereignty and cross border data transfers: Organizations must comply with regional data sovereignty laws, and it is relevant that all CPS and DT sensitive data is protected while being transferred over various jurisdictions.
- Transparency, explainability, and no bias in AI models powering DTs: there is a need to have transparent, explainable, and bias-free AI models powering DTs in order to prevent the use case of unintended consequences from algorithmic discrimination to unfair decision-making.
- Cybersecurity Liability and Risk Management: A legal framework that would articulate the liability of the institution above the breach, as well as the kind of compensation that will be allowed in the event of an incident, and laws on mandatory reporting of breaches.

When the Metaverse extends, governing bodies and firms must cooperate to frame far-ranging security cybersecurity strategies that should check possible misuse of CPS and DT technologies.

1.7.3 Emerging research areas in cyber-physical systems and digital twin security

Innovative technologies and risk mitigation strategies serve as future research in CPS and DT security, and more development will be done on the cross-domain security applications in DT security. Some promising research areas include [43]:

- Research is being done on AI-driven self-healing security systems where we would, in a way, have autonomous, self-repairing security models which would be able to detect, isolate, and preferably neutralize cyber threats in real time.
- Future DTs will have features that include proactive cybersecurity mechanisms integrated that allow the DTs to be protected from attacks and still safely operate.
- Privacy-preserving computation techniques: These comprise techniques including multiparty computation (MPC), homomorphic encryption, as well as federated learning, which enable secure data processing without compromising on privacy.
- Security improvements for 5 G and 6 G: Due to ultra-low latency and super high speed of next generation network, CPS and DT will have to be secured through next generation network to prevent new types of cyber physical threats.

- Future authentication would be based on continuous behavioral monitoring and biometric-based security to eliminate its dependency on password-based authentication.

Focusing on these cutting-edge research areas, organizations and researchers can manufacture next-generation security solutions for CPS and DT to keep them secure, privacy compliant, and resilient against evolving cyber threats [44].

It will depend on technological improvements, legal laws, and preventive investigation for shaping the future of CPS and DT security in the Metaverse. Through better security architectures, implementing legal requirements and cybersecurity investment in new emerging cybersecurity technologies, organizations may construct resilient and adaptive as well as privacy-preserving CPS environments. The ensuing section will narrate the pivotal takeaways from the work done above and suggest actions that can be taken toward a safe future for CPS and DTs in the Metaverse.

1.8 Securing the future of cyber-physical systems and digital twins in the Metaverse

CPS and DT have been implemented in Metaverse for the new changes in several industries that have been empowered to monitor, predict, as well as automate [45]. But, with this integration comes a lot of risks and threats that affect the security and privacy of users, which if not well addressed, poses a threat to the creation of a secured, reliable, and trustworthy digital environment. This paper covers various categories of CPS and DT security, including threat, technology, privacy, and future work. As for the final part, it is devoted to the ultimate insights and potential directions to develop for guaranteeing the further advancement of CPS and DTs in the Metaverse.

1.8.1 Key findings and insights

As is made clear throughout this paper, it will be possible to extract several key points concerning the security of CPS and DT [46].

1. New challenge: When Metaverse adopts CPS and DT as extensions of their environment, this will open another facet of attack that hackers can use to infiltrate and attack them, including data theft, identity theft, malware, and real-time control of processes. In this regard, it has been noted that as these technologies advance, the adversaries are not left behind in exploiting the vulnerabilities.
2. Privacy and security always go hand in hand. Whenever data is being processed, user and data must not be strange bedfellows as they call for identity management frameworks, data anonymisation approaches, and privacy-enhancing technologies to facilitate balancing of the conflicting roles of protecting data and at the same time

enhancing system functionality. For precise reasons, crucial individual and industrial information in the DTs can be leveraged with disastrous consequences on individual and organizational undertakings.

3. CPS and DT security is increased through: Technical solutions such as cryptography where several layers of protection are used; use of ML in threat detection; use of blocks for security and zero trust models; and these are the most effective measures that can be employed to reduce such vulnerabilities. Utilizing all these kinds of defenses on multiple layers, every single communication of a system is both verified and secure.
4. Legal systems of jurisdictions remain diverse: Consequently, the sovereignty, liability, and security enforcement of data within CPS ecosystems in Metaverse remain poor. It is important for countries and various organizations of the globe to set standard security and privacy measures so that deploying IoT becomes safe and compliant.
5. The future research will focus on the emerging risks, such as quantum-resistant cryptography and self-paced cybersecurity, preserving computation, and the AI cybersecurity framework will plan the newer variety of threats. Such a future resilient CPS and DTs therefore depends on how furthered these advancements will go in AI, quantum computing, and decentralized security.

1.8.2 Steps toward a secure future for cyber-physical systems and digital twins in the Metaverse

From the view of protective measures for the long-term CPS and DT sustainability, further actions should be taken by organizations, policymakers, and researchers. Among these are other recommended strategic actions [47].

- For establishing industry–wide standards, cybersecurity specialists alongside governments will have to speak with industry leaders to set them and ensure adherence by all CPS and all DTs. This means that there will be a creation of norms to ensure that a standard measure of security is used in the international organizations.
- Develop an AI-based security mechanism: The input on ML-based anomaly detection and intelligence response to attacks will enrich the contribution to threat detection and response in real-time. Like it is clearly indicated by the steady increase in the number of cyber-attacks, AI-based cyber security will help in a quick response to them and limit the effects of the cyber-attacks.
- Can use blockchain for secure identity management, Identity solutions that are decentralized, as well as blockchain-based access control that help to mitigate cases of identity theft and unauthorized access. Thus the use of blockchain technology

increases the ability to further confirm the idiosyncrasies of digital identity and their reliability in different Metaverse environments.

- This is by encouraging system architectures that consider privacy first, for instance, user-controlled privacy mechanisms, differential privacy approaches, and consent-driven information sharing, among others, which will help individuals and entities to protect their online footprints. It is therefore not very shocking to find that a privacy by design model will be required in order to achieve trust toward CPS and DT applications.
- Spend on cyber security awareness and training: Since the human intervention results into a greater number of errors in either the software or hardware products, it would be quite useful to invest in cyber security awareness and training of people involved in the development of the system, and the people who would operate this system. When training is strong, security measures will be provided and observed properly.

To sustain the relative position on threats that are emerging at the IT front, the following additional actions are required: Additional investments in the new security technologies, such as quantum encryption, self-healing networks, and AI-based automated security frameworks will be necessary [48].

1.9 Conclusion

The present and future of a large number of industries, ranging from healthcare, smart cities, industrial automation to virtual worlds DTs, and the Metaverse are inextricably linked to CPS. This brings together a set of emerging privacy and security issues that must be solved as the basis for safe and secure operation of the system. Being the foundation of CPS and DTs, the first class interactive and real-time systems that are constituents of Metaverse entail corresponding security and privacy concerns.

One of the concerns that is critically very important in CPS as well as DTs in the Metaverse is that of data security. The implemented systems use highly minimized, enormous, real-time data that is collected from the sensors, or the edge devices, or from any used connected structure, or local information in general. However, dissemination of such information leads to so many violations of individual and corporate privacy, industrial espionage, and even cyber-physical attacks that have the potential to cause physical harm or possibly, the deaths of individuals. These risks can, however, be prevented through the use of secure ciphering methods, generalization of the data, storage protocols, and so on. The method of sharing secrets could be used in a way as to construct a secret matrix which is large enough so as to accommodate rows of plaintext (e.g., 8 rows represent 1024 bits of plaintext) and use other such techniques like homomorphic encryption, ZKP to secure the matrix such that the algorithm could be effectively operated on the matrix to yield the correct result but none of the operations in the matrix as well as the matrix itself can be communicated between the two units.

The second great issue is—identity and access management to the Metaverse. For CPS and DT to function together, the methods of authentication and user verification have to be integrated into a single system so that the right actors engage the system. It is crucial to understand that a simple username and password system is not feasible in near-encapsulating environments, as it's too risky and has various weaknesses, where biometric data, behavior authentication with the help of AI, decentralized systems for identity management, among others, are in use. Assisted by blockchain-based decentralized identities, MFA can be a better mechanism to authenticate against identity theft and impersonation.

Other areas that fall under security threats pertain to the real-time process integrity and synchronization of CPS and DTs. Since these systems involve the exchange of data and synchronization continuously between the physical body and the virtual model, any form of interjection into these processes could be catastrophic. Interference during a feedback loop is possible either by injecting data poisons or by spoofing the information under the subject, or by a DoS. Thus guests can enhance CPS and DTs in Metaverse security with a fully secure cryptographic hash function, Trusted Execution Environments (TEEs), and real-time anomaly detection system employing an AI.

The other important factor, which needs to be addressed, is how AI and ML work as threats' detectors and preventers. One of the most important uses of an AI cybersecurity tool is to detect threats in the runtime, which enhances the security for the Metaverse application with CPS integration. However, this concept also has its downside: the weaknesses of having AI systems can be summed up in the fact that they themselves are prone to adversarial attacks, in which the attackers modify the training data or learn how to make AI models produce wrong results. Such an attack can be secured by strong adversarial defense mechanisms that also entail education of the model on training and real-time supervision of AI-infused security systems.

Related to the concept of the DTs, new issues regarding privacy are introduced with the help of DTs in the Metaverse. DTs create digital prognoses of real tagged items, including buildings, machines, and people. If not well protected, such replicas are usually the biggest bounty an attacker seeks if he or she desires to obtain personal information and or affect digital personalities. To maintain computation privacy, use privacy-preserving methods like federated learning, differential privacy, and secure MPC; make sure that the data of users involved in DT models are protected in a way that they cannot be accessed by unauthorized people.

The security of 5 G and edge computing again hit the bar high with an increased reliance on 5 G and edge computing supporting the real-time communication of CPS and DTs. These technologies are of high bandwidth and low latency, but are also instrumental in fueling up the cyberattack submarine. These include malware or physical tampering of malware on edge devices, which would also be specifically vulnerable. The above risk factors can be abated by applying secure firmware and hardware-based root of trust profiles that are enhanced by IDSs.

With reference to CPS and DTs in the Metaverse, there are some regulatory and legal considerations in regard to security as well. This declaration implies that the governments and the industry bodies must come up with overall cybersecurity for these technologies that are distinct from those technologies. Of course, there are present-day data protection laws such as GDPR and CCPA; however, CPS and the CPS-Metaverse environment require a set of practical privacy rules based on the (CPS)-Metaverse setting. Among the general measures that can further enhance the security environment, it is possible to note such measures as the security protocols standard and compliance requirements, together with industry cooperation.

However, other than that, the privacy and the security risks can only be avoided through; education and awareness among the users. It is due to a human factor, social engineering, and people are not aware of proper security measures. Having a training program to teach about the security risks for CPS or the security measures for DT application to all participants and developers will significantly reduce the threats and also manage to instill security-conscious participation.

Unfortunately, there remain more developments to be made in security technologies and in defending against threats before connected product systems and DTs in the Metaverse will become a reality for many organizations, or to state that, CPS and DTs will not be found in the Metaverse. As a result, to culminate the loop of the chain ecosystem, prospects like quantum cryptography, self-sovereign identity systems, and autonomous security orchestration would further extend the strength to the security pedestal of the interdependent ecosystems. It is recommended that continued work should now be done on research and innovation to enhance protection against such cyber threats, but this should be done while observing the core ethical issues and privacy.

Finally, although such an integration of CPS and DTs in the Metaverse is novel, such a potential has to come with the corresponding responsibility of putting great efforts in understanding the privacy and security implications of every process undertaken on their integration. To address these issues, a multiple approach is required where new levels of encryption, proper authentication measures, the incorporation of AI measures to identify threats, adherence to the standards and regulatory framework set by law, portions of teaching the users, and so on can be useful. Hence, Metaverse stakeholders that would offer safer and more trusted environments will ensure that cyberspace and DTs will continue to be developed toward growth with proper security and privacy in place. While such technologies are being developed, it will be very crucial for security experts, policymakers, engineers of security, scientists, and leaders of these specialists to come together in order to build a new, sustainable, and safe digital and physical environment of the future.

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CHAPTER 2

Artificial intelligence/machine learning for digital twins enabled metaverse

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2.1 Introduction

This section introduces digital twin (DT) technology and the supporting steps provided by software, hardware, machine learning, and artificial intelligence (AI). The roles of machine learning (ML) algorithms and AI are briefly discussed to clarify the chapter's efficiency and the subsequent details in the study. This part defines the research on ML and AI and also presents a communication platform for DT devices, enhancing this technology in the edge and sensor layers of IoT infrastructure.

DT has emerged as a groundbreaking technology aimed at simulating the possible conditions and behaviors of devices or systems, as well as mitigating risks associated with undefined states. This technology becomes particularly crucial in the context of modern advancements like Metaverse technology and smart cities, which aim to support the evolving demands of contemporary human lifestyles. DT bridges the physical and virtual environments, facilitating accurate simulations of system behavior and enabling real-time decision-making to address a variety of scenarios. The application of DT spans multiple domains, including industrial, medical, educational, economic, and management sectors, often integrated with Metaverse, Internet of Things (IoT) or Medical Things infrastructures. Its deployment depends on the specific characteristics of the components involved and the need to support both virtual and physical realities. In complex situations—such as the threat of fatal diseases or viral epidemics—the significance of technologies like DT becomes apparent. DT enhances product quality, mitigates risks in medical procedures, and improves decision-making in industrial and medical applications. For instance, in the healthcare sector, DT can support the development of intelligent treatment and care solutions for serious conditions like Alzheimer's and cancer. Augmented reality, combined with AI-driven drug recommendations, exemplifies this potential. The success of DT is heavily dependent on the precise implementation of its five layers: static, dynamic, operational, simulation, and predictive twins. These layers work together to ensure data accuracy, transmission, and analysis. While existing communication infrastructures are capable of supporting DT

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applications, ensuring a secure and reliable communication platform remains a significant challenge. Such platforms must not only manage the complex demands of DT but also accurately define various system states and connect the physical and virtual realms. Despite its promise, DT technology faces challenges in predicting energy consumption, reducing system delays, and recommending solutions for cost and energy savings. The complexity of data analysis and behavioral simulations adds to these difficulties. The application of machine learning algorithms and AI techniques in communication modeling and real-time operations is crucial. However, the models used must be optimized for the system in question to overcome these challenges.

DT's architecture is also designed to complement existing systems like computer-aided design (CAD) and building information modeling (BIM). It enhances dynamic design, simulation, and real-time adaptation, but this integration adds further complexity to its implementation. Fig. 2.1 illustrates the process flow of DT, encompassing data collection, analysis, simulation and prediction, optimization, decision-making, and virtualization. Various case studies have contributed to advancing one or more of these steps to improve the technology's efficiency.

Security provision is a critical requirement in many DT applications, and various case studies have sought to develop appropriate methods to address this demand. The type of DT plays a significant role in ensuring that reliable or available solutions are implemented to accurately represent and manage the physical, data-driven, or hybrid systems. When a DT system is designed to emulate the physical environment and expert laws, reliability and safety become the primary objectives, especially when there is no immediate demand for system access. On the other hand, availability becomes a key feature when the system follows a data-driven approach, emphasizing immediate access to ensure responsiveness. In hybrid systems that combine both physical and data-driven DT models, the characteristics of reliability and availability depend on the specific application and its requirements. To address these needs, machine learning algorithms, communication patterns between components, and the physical infrastructure of the communication system are key factors. Federated learning (FL) facilitates secure and reliable communication between devices in a DT-enabled system by preventing direct access to local training models and data [1]. Q-learning offers a framework for constructing reliable or available systems based on application priority and demand

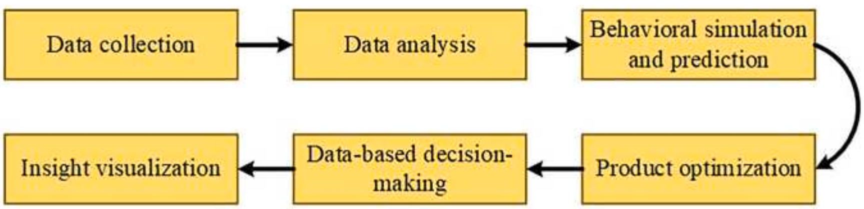


Figure 2.1 The steps of digital twins (DT) technology. *No permission required.*

[2]. Near-sensor processing reduces the time required for data access, minimizing the risk of delays in acquiring timely data, which is crucial for real-time decision-making in data-driven DT systems [3].

Timely pattern recognition and data analysis are fundamental in implementing DT, as accurate and efficient feature extraction from vast data sets directly impacts the effectiveness of DT-based approaches across diverse systems with varying demands and priorities. Many case studies in this field focus on the development of custom ML algorithms for feature extraction and model training in the context of big data analysis. Supervised and unsupervised learning techniques are widely used to meet the demands of DT technology, with deep learning models, particularly multilayer neural networks, being highly favored for their effectiveness [4]. Deep reinforcement learning has gained popularity for its ability to identify data dependencies and effectively guide the training process by defining expected conditions through actions and states in the Markov chain model [5]. AI-based techniques also play a crucial role in supporting the complex tasks of data collection, analysis, and simulation in data-driven DT systems. In these cases, intelligent models often serve as experts in discovering features and identifying unknown behaviors within a system, with evolutionary computing proving to be a practical solution [6]. However, the use of AI and ML techniques introduces additional costs related to memory, bandwidth, and computational delays, which can reduce the overall efficiency of DT systems. To mitigate these challenges, several partial techniques, such as bit reduction, quantization, vectorization, and task mapping, can be employed to reduce communication overhead and improve the performance of DT systems. These methods help minimize the extra costs associated with ML and AI-based approaches, enhancing the overall efficiency of DT technologies.

The IoT and Internet of Medical Things (IoMT) are often considered communication platforms that link nodes, with the data from these nodes used to simulate system behaviors through DT technology. These platforms also form the backbone of smart cities, powered by IoT and Metaverse technologies. However, the complex computations involved in these systems introduce overhead that can complicate the implementation of DT technology. Many studies have explored the use of DT technology for physical simulation and the testing of practical architectures for various processing units, such as neuromorphic processing units, to enhance system efficiency [7]. Hardware-based solutions play a crucial role in reducing the additional costs associated with utilizing data sources for DT. These solutions aim to improve communication performance between components of IoT, IoMT, and the Internet of Vehicles (IoV). Dataflow mapping methods are recognized as effective solutions for minimizing communication delays and reducing energy consumption [8–10]. This approach provides an inverse method for supporting DT technology, particularly when many studies focus on using DT to simulate the behaviors of structures or architectures in IoT, IoMT, and other communication infrastructures to address their challenges.

However, when DT technology is applied beyond infrastructure emulation and enhancement, it significantly improves data analysis and real-time decision-making. This is achieved by employing a suitable architecture and structure that supports efficient data transfer between nodes and data processing at the edge level.

This chapter aims to analyze various AI and ML-based approaches that have enhanced the efficiency of DT technology by reducing the additional costs associated with real-time decision-making. The research focuses on machine learning algorithms for both physical and data-driven types of DT, prioritizing the specific demands of the targeted applications. The chapter evaluates a variety of AI and ML techniques to improve data collection, feature extraction, data analysis, and model training, while also considering their potential positive and negative impacts on DT-based methods. Additionally, hardware-based (HW) solutions are explored for reducing latency and enhancing energy efficiency when implementing complex machine learning models and AI algorithms for feature extraction, thus ensuring accurate behavior simulations for both data-driven and hybrid models. The study seeks to present an effective combination of HW, ML, AI (ML-AI), and hardware-ML (HW-ML) techniques, analyzing their impact on the performance and cost of implementing DT-based systems. This chapter specifically examines the inference and training phases of AI and machine learning algorithms, analyzing various approaches that either improve or hinder the efficiency of DT in supporting different systems. The research defines three key concepts to guide the case study and the targeted approaches:

Artificial intelligence and machine learning algorithms for DT (AI/ML): Highlights the AI and machine learning algorithms that influence the efficiency of DT in solving various problems, particularly in terms of supporting reliability and availability.

The partial approach of AI and ML for DT (PAI-PML): Describes partial techniques for customizing AI and ML algorithms to support DT-based systems with minimal cost.

Hardware-based solution for DT (HWDT): Analyzes the efficiency of different hardware-based approaches in improving the inference phase of AI and ML models that affect DT technology.

The type of DT and the specific systems targeted have a significant impact on selecting the appropriate approaches to support the various steps of implementing DT with minimal cost. The priority of the application plays a critical role in this decision-making process. The chapter discusses four applications—medical, industrial, educational, and incident management—each with distinct priorities. It examines both physical and data-driven types of DT before introducing the concepts of AI/ML, PAI-PML, and HWDT in detail. Given the importance of application priorities and DT types, the chapter provides a comprehensive explanation of AI and ML approaches, their partial techniques, and hardware-based solutions, as applied to the four defined applications. The study includes a review of relevant research, an application definition, the presentation of techniques related to AI/ML, PAI-PML, and HWDT, as well as a discussion of feature aspects and conclusions. Fig. 2.2 illustrates the chapter plan, outlining the details of the subsections.

2.2 An overview of the related studies

In recent years, DT have emerged as a popular and advanced technology, surpassing traditional CAD and BIM simulations by enabling real-time decision-making based on predicted and detected system behaviors. Augmented reality and virtual reality devices highlight the significant role of DT technology, particularly through the deployment of Metaverse, AR, and VR, all of which demand accurate and comprehensive simulations of system behaviors. A growing body of research has focused on integrating DT technology into various applications to achieve high-performance outcomes, resulting in an extensive collection of related case studies in the field. This section reviews some

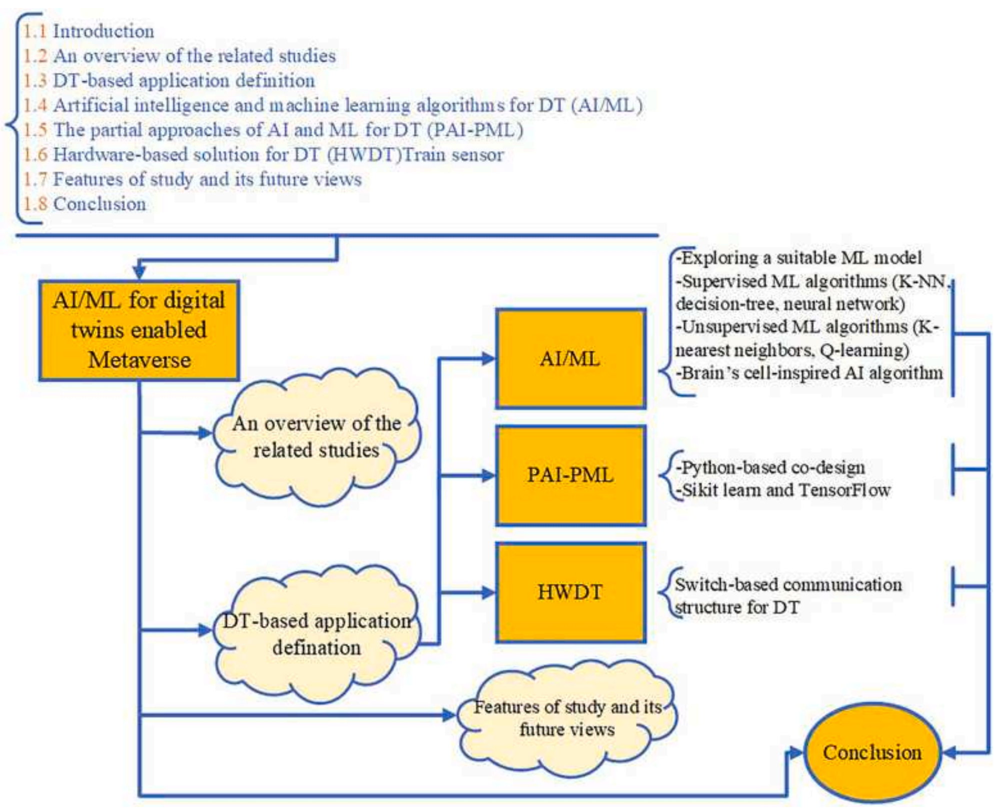


Figure 2.2 The plan of the chapter. *No permission required.*

of the most promising approaches involving AI and ML algorithms applied to support DT technology, as well as analyzing several efficient partial techniques aimed at enhancing the training phase of ML and deep learning models. Additionally, hardware-based techniques are explored, which target improvements in the inference phase of deep learning models and enhance the efficiency of communication infrastructures in IoT, IoMT, and Metaverse applications. These hardware solutions play a crucial role in supporting the data collection and monitoring phases of DT systems.

AI is an ideal choice to enhance the role of DT in supporting various applications across industrial, educational, medical, and management sectors. Its ability to analyze and infer data dependencies is crucial for extracting practical features of a system. Several case studies have explored AI-based approaches to amplify the capabilities of DT, especially in real-time decision-making tasks such as collision detection in robotics and scheduling in adaptive production. These studies typically employed traditional ML algorithms like K-Nearest Neighbors (K-NN), Long Short-Term Memory, and Gradient Boosting [11]. Research reviews have shown that advanced AI algorithms, such as Deep Q-Learning, Reinforcement Learning, Genetic Algorithms, and Convolutional Neural Networks (CNN), are particularly effective due to their ability to handle complex operations and large datasets. However, this study also highlights a gap in AI and ML applications for addressing the depth of DT challenges, especially in mapping virtual realities to physical systems. Most research has focused on mapping real-time data from the physical environment into virtual reality, while the reverse mapping process remains less explored. In the medical field, the role of DT in applications such as drug discovery and healthcare, particularly within IoT and IoMT environments, has been significant. Blockchain and 6G technologies support these applications by ensuring the security of patient records. AI and ML algorithms have been used to develop predictive models that integrate vast amounts of medical data, including online healthcare monitoring and vital sign data, to recommend suitable treatments based on simulations generated by machine learning outputs [12]. Bordukova et al. [13] emphasized the role of AI in DT development for drug discovery and clinical testing, demonstrating AI's effectiveness in speech recognition, anomaly detection, symptom analysis, and side effect clustering to aid in prediction and decision-making. This research also presents a promising future for AI-powered DTs in replacing traditional in silico simulations with computational models that emulate cellular behaviors at a human level, offering minimal-risk analysis and predictions for drug impact under various conditions. The ability of AI algorithms to analyze data and solve complex problems has enabled dynamic solutions for treating diseases, considering real-time data from patient-specific DT or laboratory conditions [14]. However, AI alone has limitations in handling individual characteristics for healthcare, treatment, and drug recommendations, as it heavily relies on previous experiments and observations. This challenge is addressed by integrating AI with DT techniques. In industrial applications, DT combined with AI and deep learning algorithms has shown promising results in critical areas such as urban water management. DT technology has been employed to address issues like waterstorm management, where AI and ML algorithms assist in data collection and analysis from weather sensors and other data sources to predict and manage waterstorm events [15]. D'Urso et al. [16] also focused on industrial applications, particularly in the steel industry, where DT was used to detect and predict damage and estimate the remaining useful life of components. In this application, the regression-based decision tree algorithm proved effective as an ML model for developing a predictive model using synthetic data generated by the DT, with calibration data playing a crucial role in optimizing the model when faced with variable standard quantities.

The partial techniques discussed here aim to optimize the performance of AI and machine learning algorithms during their training phase. These methods focus on reducing computation time and energy consumption while enhancing the accuracy of models in prediction, detection, and recommendation tasks. Among these, pruning techniques have proven to be effective by removing weak weights, neurons, and layers from multilayer neural networks [17]. This approach has been employed to enhance the efficiency of deep learning algorithms in both generalized and customized applications within IoT and IoMT infrastructures, particularly for medical image processing, where data sensitivity is a critical factor in the research area [18]. Vectorization methods play a significant role in improving the efficiency of multilayer neural networks by reducing computation delays and the complexity of multiplication operations, especially in implementing multiply-accumulation (MAC) operations [19]. These techniques can be seamlessly integrated into neural network simulations, particularly when using Python codesign within the TensorFlow ML framework [20]. Quantization, another practical technique, accelerates the training phase by applying a bit reduction mechanism to MAC operations, which also contributes to improvements during the inference phase [20]. The use of Tensor Processing Unitswith their systolic array structure offers an opportunity for 32-bit multiplication based on 16-bit and 8-bit operations, with Google Colab serving as a prominent example of this application [21,22]. In addition to these methods, several other partial and practical techniques have been developed to empower the three widely used ML-improvement methods: pruning, vectorization, and quantization. Together, these techniques help increase the efficiency of DT systems by reducing the additional costs associated with data collection and prediction phases.

Numerous case studies have demonstrated the critical role of hardware and communication platform structures in supporting ML and AI algorithms to meet the diverse demands of various systems. A large number of studies have focused on improving the efficiency of IoT, IoMT, and Metaverse infrastructures, aiming to enhance security, reliability, trust, and timely decision-making for various services and applications. Deep learning accelerators have emerged as prominent examples in this area of research [23,24]. Sánchez PM et al. [25] analyzed the efficiency of hardware in addressing system vulnerabilities when exposed to attacks and assessed the true positive ratio of different ML and AI algorithms. Their findings highlighted the importance of hardware characteristics in selecting suitable machine learning algorithms to support IoT devices. Specifically, the study used hardware behavior fingerprinting to evaluate the impact of ML algorithms on intrusion detection in IoT applications. This approach included three types of fingerprinting-based security: hardware, hardware behavior, and frequency ratio. Another case study focused on the role of hardware fingerprinting in the trust domain and intrusion detection for security in IoT applications, examining the efficiency of hardware behavior and frequency ratio fingerprinting in addressing security concerns [26]. The hardware components of IoT devices and their communication mechanisms significantly influence trust and security, as these elements are crucial for satisfying system demands. This communication can be considered a form of hardware access to data resources. A notable example is the use of an field-programmable gate array (FPGA)-based accelerator from the Xilinx PYNQ Z2 family, which successfully supported a random forest algorithm for intrusion detection in a system with minimal cost. This was achieved through ensemble feature selection, which reduced resource utilization, computational complexity, and delays while improving the accuracy of intrusion detection by pruning unstable features from the feature space [27]. The study also improved the performance of IoT systems by addressing the issue of resource utilization limitations. The improvement was made possible through a combination of software and hardware techniques, where the software component defined a lightweight random forest algorithm, more efficient than traditional neural networks. Most FPGA-based deep learning accelerators are customized for specific applications, particularly in healthcare. For instance, Ghani A et al. [28] applied an FPGA board with a CNN model to detect cytotoxicity in kidney cells, enhancing image processing accuracy. The implementation accelerated real-time patient cytotoxicity diagnosis by applying quantization techniques during the inference phase and using 8-bit computations for feature extraction. Overall, the reviewed studies on hardware-based IoT and IoMT improvements, along with related research, underscore the significant role of hardware optimization in enhancing the efficiency of ML and AI algorithms during both inference and training phases. These optimizations have proven to be essential for improving the performance of IoT applications.

When discussing DT in research, the concept of a digital representation plays a crucial role. It reflects any physical entity in the real world to facilitate the use of DT technology in creating a virtual model of a system or device. The physical representation includes components such as sensors, controllers, and manufacturing outputs, all of which are connected through technologies like IoT, IoMT, and Metaverse. The type of target components and their interconnections determine the features and communication infrastructure of the system. Metaverse supports AR and VR devices, alongside traditional components, whereas IoT and IoMT support a broader range of devices, excluding AR and VR. Additionally, in the context of DT technology, synthetic data is a critical concept that distinguishes between accessible real-world data (including previously recorded data and sensor outputs) and data generated from these real-world sources. To clarify these concepts, this chapter introduces the following definitions related to DT, which are further explored in subsequent sections:

IoT-based DT technology: Refers to DT technology where the components of the target system are connected through the IoT communication infrastructure.

IoMT DT technology: Describes DT technology applied to medical-based applications, where the components communicate via the IoMT.

Synthetic data: Reflects the concept of data generated by DT systems from real-world data, emulating the behavior of a system based on physical information received from the environment.

In silico: Explains the computer simulation of biological systems, which creates a virtual laboratory for drug discovery and design.

Fig. 2.3 illustrates an IoT-based DT technology designed for industrial applications, where the components are interconnected through IoT infrastructure.

Fig. 2.4 depicts a DTused to emulate the behavior of the hippocampal segment of the human brain, analyzing its behavior across different stages of Alzheimer's disease. This example is targeted at IoMT-based applications, where the DT technology utilizes IoMT infrastructure for data collection and analysis.

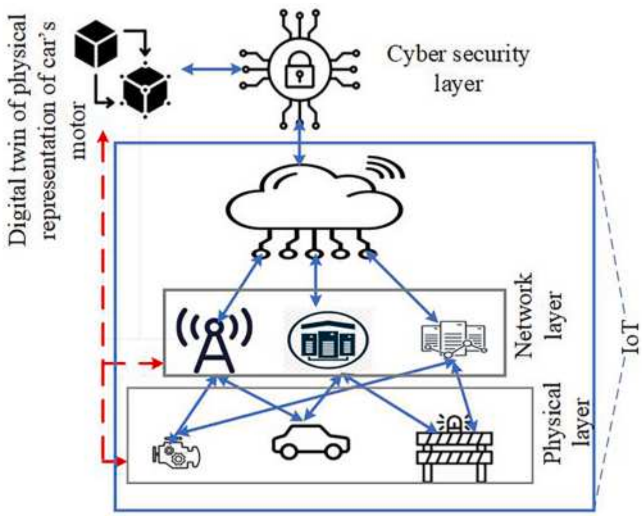


Figure 2.3 An industrial DT-based application connected to Internet of Things. *No permission required.*

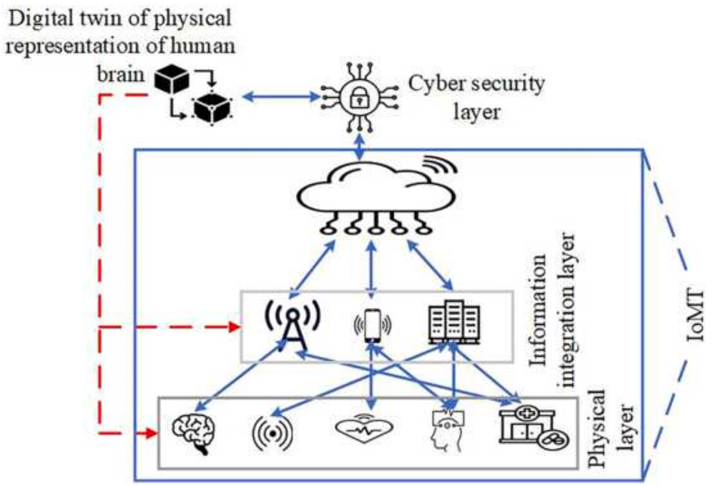


Figure 2.4 Medical DT-based application connected to Internet of Medical Things. *No permission required.*

2.3 Digital twins-based application definition

This section outlines four industrial, medical, educational, and incident management applications, each inspired by real-world scenarios that illustrate their tasks and operations. These applications are framed within AI/ML, PAI-PML, and HWDT contexts. A task graph visually represents the communication between the nodes of each application, with edges connecting the components identified as the graph's vertices.

2.3.1 Digital twins-based application 1

This application illustrates a practical example of a medical-based DT, represented by a task graph with V vertices and E edges. Digital twins-based application 1 (DT-APP1) showcases the nodes and their communication in a drug discovery application aimed at patients suffering from depression. It simulates the interactions of human brain cells in response to aggregated G proteins in the dendrites. The application integrates various sensors, including blood pressure monitors, pulse oximeters, heart rate monitors, and electroencephalograms (EEG), alongside neuromodulation, physical representation, and a virtual model of the human brain. The output from these sensors, along with neuromodulation feedback and physical representations, is transmitted to the virtual model. Additionally, key patient records are integrated into a centralized data center. DT-APP1 can be managed using three types of DT technology: physical, data-driven, and a hybrid approach, as indicated by the dashed line for experts in Fig. 2.5.

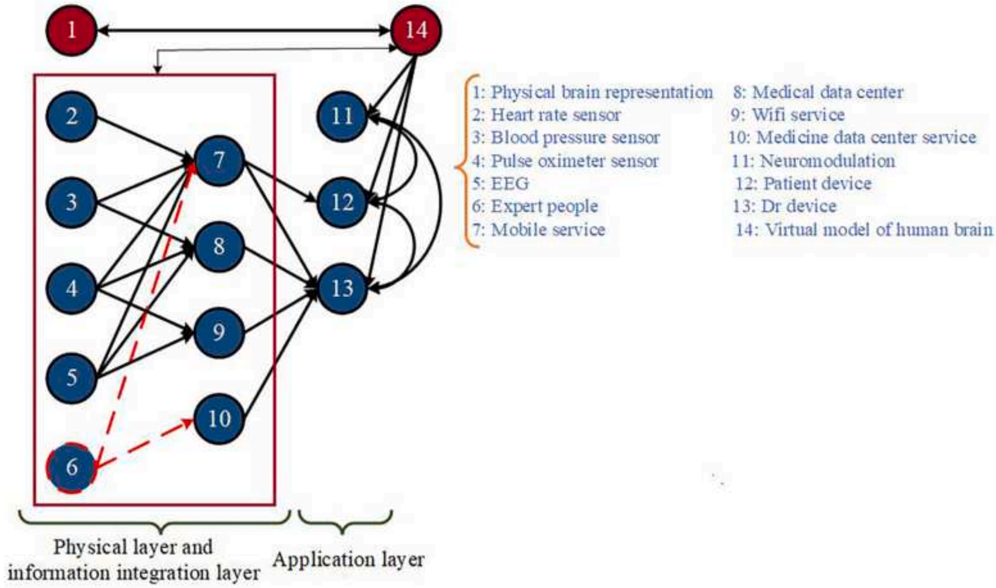


Figure 2.5 A task graph of DT-APP1. *No permission required.*

2.3.2 Scenario for digital twins-based application 1 (Scenario-APP1)

Outlines a plan for DT-APP1, detailing the communication between its nodes based on their defined connections. The scenario focuses on drug discovery operations and treatment recommendations for patients with depression. Three modes have been considered in designing this scenario: data-driven, physical, and a hybrid approach that combines both. In the physical mode, the application serves a straightforward purpose: it recommends a drug from a limited list of prescribed medications based on outputs from EEG sensors and monitors vital signs—such as heart rate, blood pressure, and oxygen levels—of affected individuals. The digital model is constructed from this physical representation, simulating human brain responses to various drugs to help prevent allergic reactions and side effects. In the data-driven mode, the digital model leverages historical patient records along with real-time sensor data to identify suitable medications from a broader range of existing drugs. This DT employs a neuromodulation device for treatment, utilizing both the sensing information and previously registered data to enhance drug recommendations. The combined data-driven and physical mode introduces an expert into the scenario, facilitating drug discovery and treatment recommendations through medicine prescriptions and the use of the neuromodulation device. This mode reflects more complex operations, as it supports in silico actions via the digital model for drug discovery. Table 2.1 illustrates the activation nodes of DT-APP1 based on Scenario-APP1 and the three defined modes of the DT.

Table 2.1 Scenario-APP1 that demonstrates the activation situation of the nodes of physical (Phy), information integration (Inf), and application (App) layers.

Physical layer's sensors	Information integration layer's services	Application layer's services	Physical-based mode			Data-driven mode			Combination mode		
			Phy	Inf	App	Phy	Inf	App	Phy	Inf	App
Heart rate	Mobile	Neuromodulation	√	√	×	√	√	√	√	√	√
Blood pressure	Medical data center	Mobile	√	×	√	√	√	√	√	√	×
Pulse oximeter	Wifi	Dr	√	√	√	√	√	×	√	×	√
EEG	Medicine data center	Patient	√	×	√	√	√	√	√	√	√
Expert			×			×			√		
Physical representation			√			√			√		

No permission required.

2.3.3 Digital twins-based application 2

resents an industrial application that leverages DT technology to analyze potential technical issues in vehicles. This application, referred to as digital twins-based application 2 (DT-APP2), is represented by a task graph where vertices correspond to the nodes of DT-APP2 and edges illustrate the communication pathways between its components. DT-APP2 comprises both a physical representation and a virtual model that includes elements such as a car, road traffic sensors, gas stations, parking facilities, and weather sensors. The output data from these sensors is transmitted to the virtual model after passing through a cybersecurity layer for data integration. Additionally, the outputs from the sensors and the DT are interconnected with mobile services, roadside emergency assistance, towing services, and other support systems. The primary function of the DT within this application is to enhance safety by preventing road accidents and addressing urgent issues for passengers through timely decision-making. This application employs a data-driven approach, utilizing various data sources alongside real-time information gathered from the sensors. DT-APP2 is specifically designed to predict potential obstacles that may hinder vehicle movement on urban roads, particularly in areas where access to repair shops is challenging. Fig. 2.6 illustrates the task graph of DT-APP2, showcasing the communication links represented by the edges of the graph.

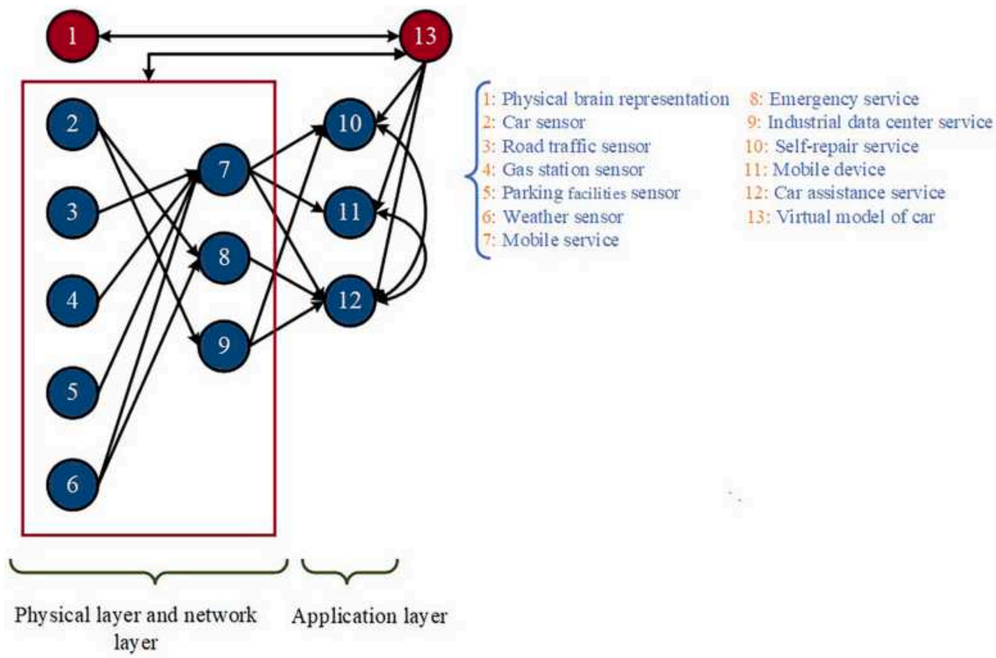


Figure 2.6 A task graph of DT-APP2. *No permission required.*

2.3.4 Scenario for digital twins-based application 2 (Scenario-APP2)

Clarifies the role of each node in DT-APP2, outlining a set of tasks and objectives designed to provide effective services to users through the application of DT technology. Scenario-APP2 serves as a framework for DT-APP2, featuring a task graph that emphasizes the timely detection of vehicle technical issues, the prediction of acute obstacles, and the prevention of potential road accidents. The DT simulates the behavior of a vehicle by incorporating a physical representation of its motor characteristics and other relevant details. It leverages real-time data from sensors to manage various potential scenarios. Specifically, the digital model anticipates technical problems with the vehicle's motor before they lead to failure, enabling proactive measures such as repairs or the deployment of spare modules. In cases where self-repair is unsuccessful, DT-APP2 alerts passengers to contact roadside assistance. Additionally, it can notify roadside assistance directly when issues arise that cannot be resolved through self-repair. The system is also designed to inform towing services and gas stations when problems occur, particularly in situations where roadside assistance may take longer to reach. This scenario is grounded in a data-driven DT approach that utilizes IoV technology to facilitate communication among devices, servers, and data resources. Details regarding Scenario-APP2, including its components and activation conditions, are illustrated in Table 2.2.

2.3.5 Digital twins-based application 3

Outlines the role of DT technology in educational applications, highlighting its significant impact through the development of a virtual science laboratory. This virtual environment allows students to engage in science experiments and assessments, enhancing their understanding of scientific concepts. Digital twins-based application 3 (DT-APP3) specifically focuses on creating a virtual chemical laboratory where students can simulate the process of making artificial blood. This application employs both expert and physics-based DT to replicate the behaviors of a real science laboratory, enabling students to successfully complete experiments based on their knowledge and choices regarding laboratory materials. A task graph representing DT-APP3 illustrates its nodes and the communication pathways between them, as depicted in Fig. 2.7. The system includes a physical representation model of a science laboratory, equipped with lab equipment and material sensors that are activated by student selections. The outputs from these sensors are transmitted to a virtual model of the laboratory after being integrated into a cybersecurity layer. To visualize the results, VR-based headsets and monitors are utilized, serving as interfaces between the virtual model and the user. Furthermore, Metaverse technology is employed as the communication infrastructure to facilitate connections between the application's nodes and support data analysis.

Table 2.2 Scenario-APP2 based on the data-driven pattern.

Physical layer's sensors	Activation situation	Network layer's services	Activation situation	Application layer's services	Activation situation
Physical representation	√	Mobile	√	Self–repairing	√
Car	√	Emergency	√	Mobile	√
Road traffic	√	Industrial data center	√	Car assistance	×
Gas station	√				
Parking facilitates	×				
Weather	×				

No permission required.

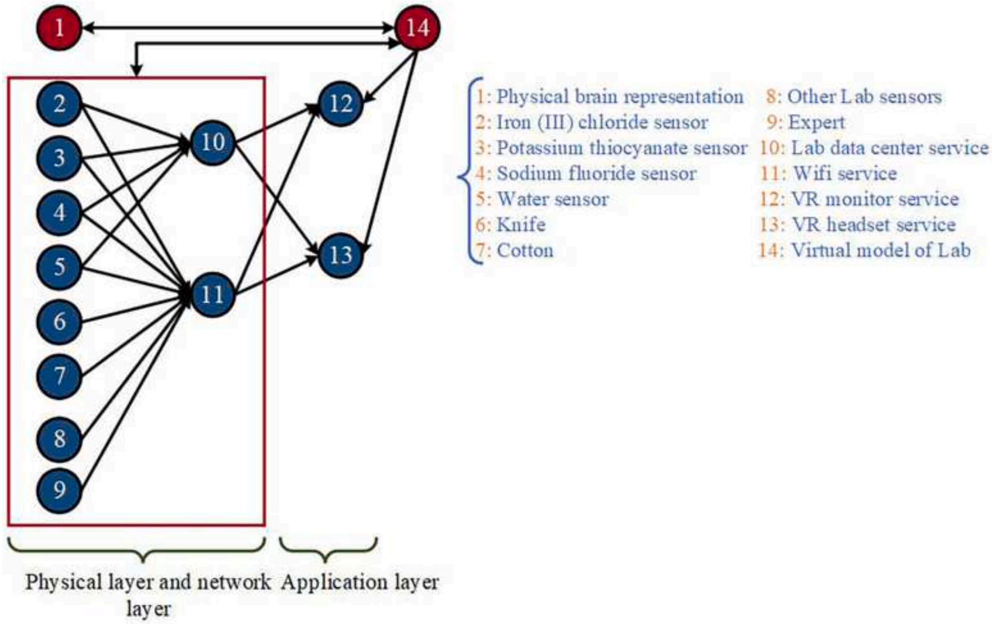


Figure 2.7 A task graph of DT-APP3. *No permission required.*

2.3.6 Scenario for digital twins-based application 3 (Scenario-APP3)

It aims to outline a specific plan for DT-APP3, clarifying its operations and tasks as defined by the communications represented in the edges of the task graph. This scenario illustrates how the sensors and server nodes are activated when a student conducts a laboratory test to create artificial blood using the appropriate lab materials and equipment. According to expert guidance within the application, the test requires Iron (III) chloride, Potassium thiocyanate, Sodium fluoride, and Water as the necessary lab materials, along with a knife and cotton as lab equipment. The corresponding sensors will transmit signals to indicate when these items are in use. DT-APP3 facilitates the execution of the science test based on the student's choices and knowledge. The results are then relayed to VR-based headsets and monitors, allowing students to observe their laboratory test outcomes. Table 2.3 outlines the role of each node in DT-APP3 as it relates to Scenario-APP3.

2.3.7 Digital twins-based application 4

Presents a sophisticated application of DT technology in incident management, specifically designed to address the challenges of managing high-risk situations that demand timely and accurate decision-making. Digital twins-based application 4 (DT-APP4) is tailored to meet the needs of urban fire management, emphasizing the critical

Table 2.3 Scenario-APP3 based on physical pattern.

Physical layer's sensors	Activation situation	Network layer's services	Activation situation	Application layer's services	Activation situation
Physical representation	√	Lab data center	×	VR headset	×
Iron (III) chloride	√	Wifi	√	VR monitor	√
Potassium thiocyanate	√				
Sodium fluoride	√				
Water	√				
Cotton	√				
Knife					
Other Lab's sensors	×				
Expert	√				

No permission required.

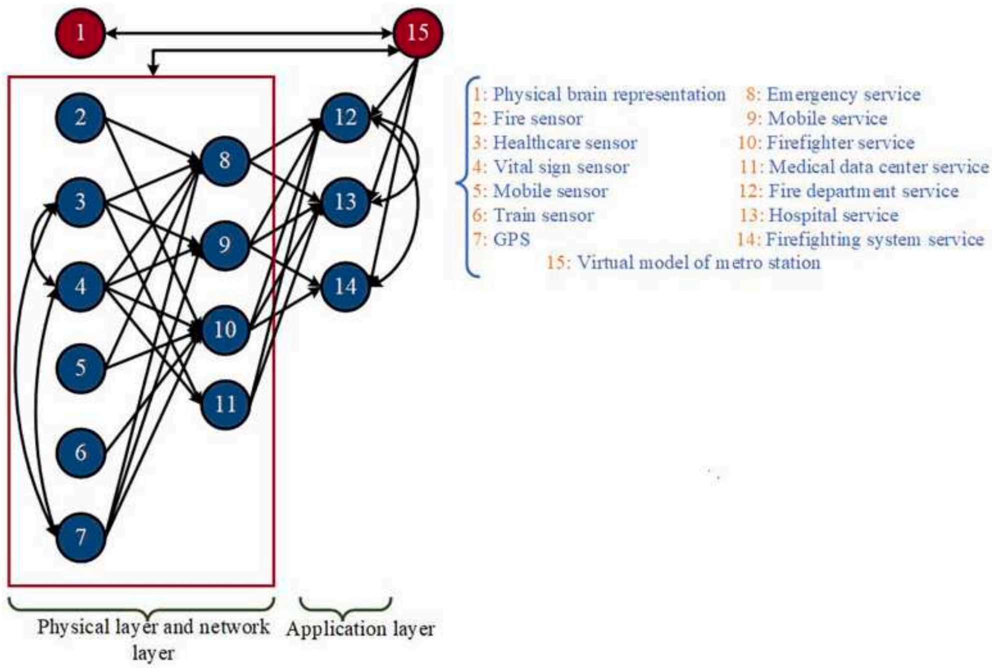


Figure 2.8 A task graph of DT-APP4. *No permission required.*

importance of prompt recommendations, obstacle detection, and potential problem prediction in such scenarios. The application leverages a data-driven, DT technology-supported IoT communication infrastructure to interconnect its components and facilitate data analysis. The architecture of DT-APP4 is represented by a task graph, consisting of vertices and edges, as illustrated in Fig. 2.8. Key sensor nodes include vital sign and healthcare sensors, mobile devices, a physical model of the target area, and fire alert sensors. Additionally, DT-APP4 features both physical representations and virtual models of the target area affected by fire, all linked to a cybersecurity layer that processes sensor outputs following data integration. The DT then transmits simulation results and system behavior analyses to the mobile devices, healthcare teams, and emergency response servers involved in fire management.

2.3.8 Scenario for digital twins-based application 4 (Scienario-APP4)

Follows a fire response plan for a metro station within the framework of DT-APP4, clarifying the tasks assigned to the application's nodes, their interdependencies, and connections. This scenario employs healthcare and vital sign sensors to identify emergency cases and facilitate timely service delivery. These sensors also help detect blind spots in areas affected by fire where global positioning system (GPS) signals may be

Table 2.4 Scenario-APP4 is based on the data-driven pattern.

Physical layer's sensors	Activation situation	Network layer's services	Activation situation	Application layer's services	Activation situation
Physical representation	√	Emergency	×	Fire department	√
Fire alert	√	Mobile	√	Hospital	√
Healthcare	√	Firefighter	√	Firefighting system	√
Vital sign	√	Medical data center	√		
Mobile	×				
Train sensor	×				
GPS	×				

No permission required.

unreliable. Scenario-APP4 incorporates a virtual model of the target metro station, derived from its physical representation, to simulate various situations and details. This data-driven DT technology allows for the prediction of critical conditions and locations. The DT utilizes outputs from healthcare sensors and relevant historical records to identify individuals with chronic diseases, prioritizing them for timely assistance. Additionally, the outputs from vital sign sensors enable the virtual model to identify injured individuals and determine the fastest and safest routes for their rescue. Cameras and other monitoring sensors on trains and at stations assist in predicting both risky and safe pathways, facilitating the blocking of hazardous areas and guiding firefighters and relief personnel in managing the emergency effectively. Table 2.4 details the situation and activation modes for each component of DT-APP4, based on the specifics of Scenario-APP4 (Table 2.5).

2.4 Artificial intelligence and machine learning algorithms for digital twins (artificial intelligence/machine learning)

ML and AI algorithms are crucial for data collection and analysis in various smart applications that rely on real-time decision-making. DT have emerged as powerful tools to enhance real-time decision-making and predict unknown states of a system, with data serving as their foundation. While ML and AI models can bolster system security, they also pose risks depending on how data is utilized and shared. This section examines various ML and AI algorithms that support DT technology, focusing on their effectiveness for specific applications. To provide clarity, we first define the following concepts related to ML and AI in the context of DT technology:

Supervised ML algorithms: Highlights supervised ML algorithms used for data collection, analysis, and decision-making in DT to support various applications.

Unsupervised ML algorithms: Discusses unsupervised learning algorithms and the techniques that empower them to enhance DT technologies across different applications.

AI algorithms: Covers intelligent techniques that emulate human behavior to support DT in recommendation and prediction tasks relevant to specific applications.

By analyzing these AI/ML techniques for DT, this chapter aims to provide insights into their roles in enhancing decision-making and operational efficiency.

2.5 Supervised machine learning algorithms

This subsection explores the selection of an appropriate machine learning algorithm based on application priorities, data dependencies, and the data generated by DT. The chosen algorithm will be applied to the four defined applications, allowing for an analysis of its effectiveness in enhancing the performance of DT technology.

Table 2.5 Parameter declaration.

ComplexityIndex: **Defines an index for the DT problem's complexity, whereas** $0 \leq ComplexityIndex \leq 1$	*Input*: **The input definition of a neural network based on the input features and their impact coefficient**
UpdateMood: *Determines the need to update model, whereas UpdateMood*⊏ *Binary*	$NewFeature_n$: *The new extracted feature with n index*
IG: *Information gain for the decision tree before new feature extraction, whereas* $0 \leq IG \leq 1$	$center_i$: *The certain of the cluster with i index, whereas* $certain_i$ ⊏*Integer*
Entropybeforesplitingnode: *Entropy a node of tree before splitting whereas* $0 \leq Entropybeforesplitingnode \leq 1$	*MaxED*: *The maximum Euclidean distance, whereas* $MaxED \geq 0$
Entropyaftersplitingnode: *Entropy a node of tree after splitting whereas* $0 \leq Entropyaftersplitingnode \leq 1$	*ED*: *The Euclidean distance whereas* $ED \geq 0$
$penalty_n$: *Penalty value of* $Drug_n$ *located on the leaf of the decision tree, whereas* $0 \leq penalty_n \leq 1$	k_{old}: *The old number of clusters before new feature extraction, whereas* $k_{old} \geq 0$
$Drug_n$: *The drug with n index*	k_{update}: *The updated number of clusters after new feature extraction whereas* $k_{update} \geq 0$
n: *The index number for drugs ,whereas* $n \geq 0$	$Penalty_t$: *The penalty value of a state of a Markov model at t time, whereas* $0 \leq Penalty_t \leq 1$
M: *The maximum number of the drugs, whereas* $M \geq 0$	r_t: *The reward value of a state of the Markov model at t time, whereas* $0 \leq r_t \leq 1$
N: *The maximum number of drugs, whereas* $N \geq 0$	*P*: *The probability of transmitting to the next state based on penalty and reward values, whereas* $0 \leq P_t \leq 1$
PIG: *The information gain value based on penalty, whereas* $0 \leq PIG \leq 1$	*p*: *The initial value of the probability of transmitting to the next state, whereas* $0 \leq P_t \leq 1$
θ_n: *The impact coefficient of the new feature with index, whereas* $n0 \leq \theta_n \leq 1$	G_A: *The A graph with E edges and V vertices*
totalNewfeature: *The total number of the new features, whereas* $totalNewfeature \geq 0$	*E*: *The number of edges of A graph, whereas* $E \geq 0$
k: *The number of classes in the K-NN algorithm, whereas* $k \geq 0$	*V*: *The number of vertices of A graph, whereas* $V \geq 0$
Updatedk: *The updated value of k, whereas* $Updatedk \geq 0$	$[A]_{i \times j}$: *The matrix A with i rows and j columns*
$\theta_{com1,2}$: *The common value of the impact coefficient between features 1 and 2, whereas* $0 \leq \theta_{com1,2} \leq 1$	*i*: *The number of rows of an A matrix, whereas* $i \geq 0$
$CC_{n,n+1}$: *The correlation coefficient between*	*j*: *The number of columns of A matrix, whereas* $j \geq 0$
$a_{i,j}$: *The located element of the A matrix on row i and column j, whereas* $0 \leq a_{i,j} \leq 1$	*Pattern*: *The pattern of relationship between the nodes of an application based on the brain's cell-inspired algorithm, whereas* $Pattern \geq 0$

(*Continued*)

Table 2.5 (Continued)

ComplexityIndex: **Defines an index for the DT problem's complexity, whereas** $0 \le ComplexityIndex \le 1$	*Input*: **The input definition of a neural network based on the input features and their impact coefficient**
Fault: *The pattern of faulty nodes based on the brain's cell-inspired algorithm, whereas Fault* ≥ 0	*AppPattern*: *Faulty node detection and identifying the relationship between nodes based on the human brain's cell-inspired algorithm*
$j_{\max}$: *The maximum number of columns of A matrix, whereas* $j_{\max} \ge 0$	*PC*: *A fixed value of an A matrix that describes the association between axon, dendrite, and neuron, whereas* $PC=47$
G_{AA}: *The graph A for DT-APP1 with EA and VA edges and vertices*	*EA*: *The number of edges of the AA Graph, whereas* $EA \ge 0$
VA: *The number of vertices of AA Graph, whereas* $VA \ge 0$	$[AA]_{ai \times aj}$: *The matrix AA with ai rows and aj columns*
$aa_{ai,aj}$: *The element of AA matrix located on row ai and column aj, whereas* $0 \le aa_{ai,aj} \le 1$	*ai*: *The number of rows of the AA matrix, whereas* $ai \ge 0$
aj: *Column index for AA matrix, whereas* $aj \ge 0$	$flow_{f_{c,c+1}}$: *The flow between* PE_c *and* PE_{c+1} *whereas* $flow_{f_{c,c+1}} \ge 0$
$flow_{f_{c,c-1}}$: *The flow between* PE_c *and* PE_{c-1} *whereas* $flow_{f_{c,c-1}} \ge 0$	$f_{\max}$: *The maximum flows, whereas* $f_{\max} \ge 0$
$TotalFlow_{c,c+1}$: *The total flows between* PE_c *and* PE_{c+1} *whereas* $TotalFlow_{f_{c,c+1}} \ge 0$	$TotalFlow_{c,c-1}$: *The total flows between* PE_c *and* PE_{c-1} *whereas* $TotalFlow_{f_{c,c-1}} \ge 0$
PE_{c+1}: *The processing element located on c+1 position of the network, whereas* $PE_{c+1} \sqsubset Binary$	PE_{c-1}: *The processing element located on c-1 position of the network, whereas* $PE_{c-1} \sqsubset Binary$
PE_c: *The processing element located on c position of the network, whereas* $PE_c \sqsubset Binary$	*Cluster*: *Clustering the PEs based on the flow between them*

No Permission Required.

2.5.1 Exploring a suitable supervised machine learning algorithm

DT technology employs machine learning algorithms in two steps before and after constructing synthetic data, which necessitates describing following two definitions for the issue:

2.5.2 Machine learning algorithm before synthetic data construction

Involves data analysis and pattern identification to emulate behavior within DT technology.

2.5.3 Machine learning algorithm after synthetic data construction

Focus on employing a machine learning algorithm for decision-making and prediction following behavior simulation and synthetic data generation by the DT.

The characteristics of the target play a critical role in selecting an appropriate ML algorithm to meet the application's requirements, starting with identifying the nature of the data, which includes both continuous and discrete types. When the target exhibits a continuous data pattern, regression algorithms can be a suitable choice for developing a predictive model. Classification ML models provide a great opportunity to support applications with discrete data patterns of the target. To predict the expected binary output, logistic regression is a proper choice as a supervised ML algorithm to meet the demands of a system in this category. Deep neural networks (DNNs) create a framework for both supervised and unsupervised purposes across various systems, supporting both classification and regression objectives.

The update of ML models is a crucial aspect of exploring DT, particularly in supporting virtual models across various applications. The effectiveness of these updates hinges on the roles played by updated data sources and the construction of synthetic data following behavior simulations conducted by DT. To mathematically assess the complexity of the target model after incorporating additional attributes and increasing feature counts through system emulation, we define the *ComplexityIndex*. This index is calculated based on the total number of features prior to synthetic data construction (*totalFeature*) and the newly extracted features (*feature*), weighted by their respective impact coefficients (θ) postsimulation. $feature_n$ and θ_n denote the *n-th* feature and its associated impact coefficient, respectively.

$$ComplexityIndex = \frac{totalFeature + \sum_{n=0}^{n=N} \theta_n \times feature_n}{totalFeature} \tag{2.1}$$

$$UpdateMood = \begin{cases} 0, & ComplexityIndex \simeq 1 \\ 1, & Others \end{cases} \tag{2.2}$$

The *ComplexityIndex* serves as a critical indicator for determining when to update an ML model. Eq. (2.2) provides a mathematical framework for identifying the update status, termed *UpdateMood*, represented as a binary value. When *UpdateMood=0*, it indicates that the number of extracted features or their impact efficiency is insufficient, prompting the retraining of the ML model. Conversely, when *UpdateMood=1*, it signifies an increase in the number of efficient features post-synthetic data construction, necessitating the replacement of the existing model with a more suitable algorithm.

This subsection further evaluates the performance of three prominent supervised ML algorithms of decision trees, neural networks, and K-NN, along with various strategies to enhance model performance in DT technology, both before and after synthetic data construction.

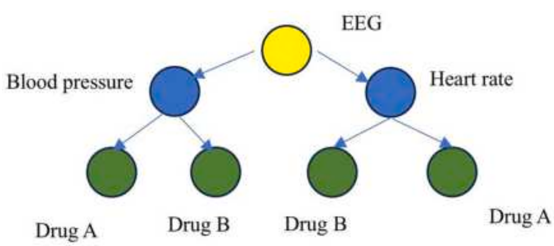
2.5.4 Decision tree machine learning model

The decision tree algorithm is a widely used machine learning model for addressing simple classification problems involving discrete target data. In this context, DT-APP1 represents a medical application focused on drug recommendation and discovery for patients with depression disorder. Scenario-APP1 outlines a situation characterized by three moods: physical, data-driven, and a combination of both, all aimed at creating a virtual model of the human brain's physical representation. For drug recommendation within this physics-based virtual model, the decision tree effectively meets the application's requirements both before and after the construction of synthetic data. The graph below illustrates the implementation of the decision tree for DT-APP1 in the physical mode of Scenario-APP1. This virtual model assists experts in predicting the most suitable medication, either Medicine A or Medicine B, for a patient. Notably, synthetic data has not yet been constructed to include additional features with high-impact coefficients on the target: (Graph 2.12).

The decision tree is built by calculating the information gain for each feature, starting from a random node or an expert's recommendation. The following equation describes how to estimate information gain (IG) for the decision tree:

$$IG = Entropybeforesplitingnode - Entropyaftersplitingnode \tag{2.3}$$

Scenario-APP1 outlines a plan for a data-driven, structure-based DTthat leverages real-time sensor outputs alongside historical patient information, including vital signs, symptoms, and medication allergies. The goal is to recommend medications with minimal side effects. This approach is more complex than the physics-based virtual model, as it relies entirely on data for drug recommendations. In this framework, synthetic data is used to construct additional features that influence the target outcomes.



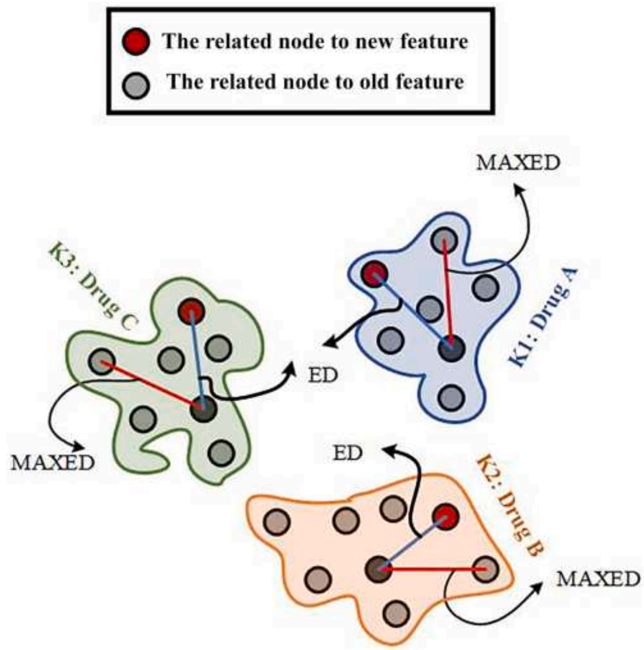
Graph 2.12 Decision tree for DT-APP1. *No permission required.*

The analysis of these additional features can also be integrated into the decision tree model by assessing their impact on existing features. Eq. (2.4) mathematically describes how to incorporate a penalty value from medications into the vital sign features, considering their side effects in the decision tree reconstruction. *PIG* estimates an updated value of the information gain after applying the penalty value ($penalty_n$) of a drug with n index ($Drug_n$).

$$PIG = \left(\sum_{n=0}^{n=M} penalty_n \times Drug_n \right) \times IG \tag{2.4}$$

The accompanying graph illustrates the construction of the decision tree supporting DT-APP1 based on Scenario-APP1 in a data-driven context. It shows how penalty values are applied to blood pressure and heart rate nodes, accounting for the effects of medications on these vital signs (Graph 2.13).

The Penalty-based Decision Tree (PDT) algorithm outlines the steps for implementing a decision tree by applying penalty values to the computation of information gain for target participant nodes, which are highlighted in green within the algorithm.



Graph 2.13 Penalty-based decision tree for DT-APP1. *No permission required.*

Algorithm The penalty-based decision tree (PDT)

Inputs: 1- OldF: old features' values of DT-APP1's densor nodes (BloodPressure, HeartRate, PulsOximeter, EEG) whereas OldF⊂ Integer
2- NewF: New features extracted whereas NewF ⊂ Integer
3- Drug: The type of A and B drugs whereas Drug ⊂ Binary number

Output: Re Drug: The recommended drug whereas Drug ⊂ Binary number

Parameter declaration:

$node_q$: Task graph's node with q index whereas $node_q$ ⊂ Binary number
PE_n: qNoC's PE with n index whereas PE_n ⊂ Binary number
$ap_{i,j}$: An array of application matrix whereas $ap_{i,j}$ ⊂ Binary number
i: $The\ index\ of\ drugs = \{0,1\}$
j: $The\ index\ of\ tree'sleaf\ whereas\ j \subset Natural\ number\ and\ j \geq 0$
f: $The\ index\ of\ old\ features\ = \{0, 1, 2,3\}$
nf: The index of new features whereas n ⊂ Natural number and n ≥ 0

Start
Procedure PDT(OldF, NewF, Drug)
  Start phase 1 *//Identify similar communication pattern with Astrocyte, neuron, and dendrite, and define task graph*
    Initializing the parameter of the tree in root and stem definition
    $Root \leftarrow OldF_f$
    $leaf_j \leftarrow Drug_i$
    Randomly arranging tree and initial setting the stems of the tree based on features
    for each feature in application do
      Estimating the entropy value of each internal node of the tree
    end for;
    for each branch in the decision tree do
      Estimating information gain value
      if ($IG_b > IG_{b-1}$) **do**
        priority assignment to the feature of IG_b
        Sorting the tree
        if (NewF!= Null) do
          Go to phase 2
        else
          ReDrug← $leaf_j$
          Exit for;
        end if;
    end for;
  end phase 1;
  Start phase 2 *// Identifying the minimal-cost PEs and predict the risky PEs based on the Aβ protein aggregation*
    Update HC graph with the node of Aβ protein and its relationship with Astrocyte, neuron, and dendrite
    Update the array of $[HC]_{q\times q}$ matrix based on the association between the nodes HC graph
      for each PE in TargetPEs do
        Analyzing the cost of PE based on $A\beta PE_{i,j}$ Equation
        $RiskySituation \leftarrow \sum_{i=0}^{i=2}\sum_{j=0}^{j=2}(i+1)\times\left((j+1)\times PE_{i,j}\right)$
        if (RiskySituation=51) do
          Identifying the risky PE based on Equation (1.13) and predicting the faulty area
        end if;
      end for;
    Updating initial parameters and specify RiskyPE
  end phase 2;
end procedure;

Algorithm 2.1 PDT

In Scenario-APP1, the combination of physical and data-driven structures addresses drug discovery through real-time data, historical patient information, and expert knowledge. This approach utilizes a virtual model to emulate the complex behaviors of the human brain, particularly in aggregating G proteins around dendrites. To support DT-APP1, an unsupervised learning algorithm is required following the construction of synthetic data by the DT.

As previously mentioned, the decision tree algorithm is well-suited for solving straightforward problems with minimal features. However, its complexity increases with the number of levels, which is dependent on the number of application nodes. This complexity can lead to costly computational operations, particularly when starting with a random node to build the decision tree.

2.5.5 K-nearest neighbor model

K-nearest neighbor (K-NN) is a widely used supervised ML algorithm that effectively handles both classification and regression tasks, accommodating data types that are continuous and discrete. DT-APP2 exemplifies an industrial application of DT technology, designed to enhance vehicle safety by monitoring the car and its passengers to prevent accidents. The Scenario-APP2 aims to create a virtual model that simulates the behavior of a car, analyzing potential obstacles and issues based on the car's characteristics and real-time technical defects of its motor. This application is tasked with meeting the demands for prediction and recommendation, making K-NN a suitable choice to fulfill these system requirements. The virtual model of the car's motor relies on a data-driven framework, generating synthetic data and additional features relevant to the target model. As such, updating the machine learning model is crucial for accurate predictions and classifications. The value of 'k' in K-NN will be adjusted based on the newly generated features for DT-APP2 after constructing synthetic data. Importantly, the type of machine learning model does not need to be changed before or after implementing the virtual model. However, certain techniques are necessary to develop a K-NN model with an updated value of 'k' at minimal cost for data classification. This includes feature selection and assessing the impact of each feature while taking into account their Hamming or Euclidean distances.

The K-NN model is updated to reflect a new value of k (denoted as *Updatedk*), which is determined by the nature of additional features generated after constructing synthetic data. This value is estimated using their impact coefficient (θ_n), as described in Eq. (2.5).

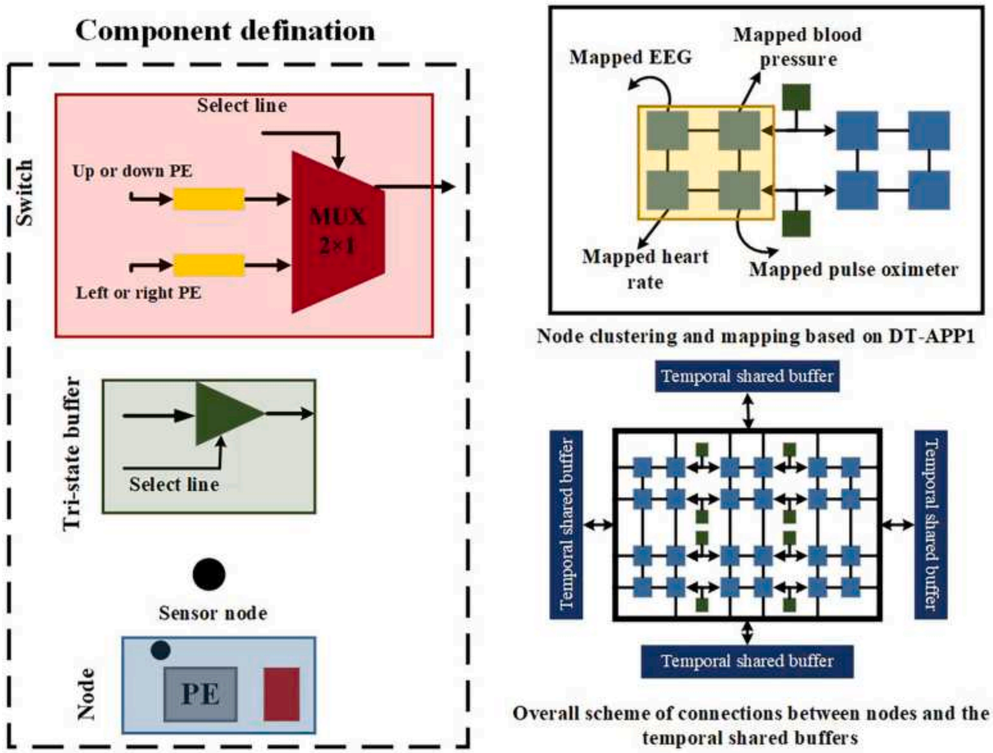
$$Updatedk = \left(\frac{\sum_{n=0}^{n=N} \theta_n}{totalNewfeature} \right) \times k \tag{2.5}$$

The following graph illustrates the K-NN algorithm's role in data classification and solution recommendation for DT-APP2, based on Scenario-APP2, following the behavior simulation of the virtual car model. Initially, the value of k was set to four before the virtual model simulation; it is subsequently updated to five upon the addition of new features after the DT simulation (Graph 2.14).

The K-NN algorithm begins with a randomly selected value of k, which can lead to overfitting or excessive generalization, potentially increasing computation time if the chosen value is not suitable for the dataset. The model's performance is evaluated using metrics such as the F1-score, log loss, and Jaccard index, with particular emphasis on the F1-score to assess the efficiency of DT-APP2.

2.5.6 Neural network model

DNN models are utilized for both supervised and unsupervised learning in systems well-suited for DT applications, particularly because they can generate synthetic data. This chapter introduces an educational application called DT-APP3, which features a virtual science laboratory model. This model allows students to conduct science experiments



Graph 2.14 K-Nearest Neighbors model for DT-APP2. *No permission required.*

and create artificial blood using a virtual selection of lab materials and equipment. In Scenario-APP3, the application adheres to a physical pattern for defining the virtual laboratory test, necessitating labeled data to predict observations through the DT. While extracting data dependencies within the system can be complex, DNNs can effectively predict outcomes. In contrast, utilizing K-NN and decision trees complicates the system and reduces efficiency, as these methods start with a random k value and feature nodes to meet the requirements of DT-APP3. To enhance data analysis and facilitate the extraction of data dependencies between inputs and expected observations for the target science laboratory test, this research employs statistics-based approaches. Statistical analysis is applied to identify relationships between input and output data, as well as to determine the type of data distribution for DT-APP3 based on Scenario-APP3. The Empirical Cumulative Distribution Function (ECDF) plot from the Seaborn library aids in identifying the data distribution type, using the command seaborn.ecdfplot(). This section emphasizes traditional statistics-based methods to uncover data associations, while Section 2.5 will delve into Python-based techniques designed to streamline operations and reduce implementation costs, including the use of ECDF plots. In this application, the system employs random variables tested by Kendall's rank correlation as a nonparametric statistical approach to estimate the τ value. Due to the expanded features resulting from simulating the behavior of lab materials in the science laboratory test for creating artificial blood, the neural network model must be updated by increasing its neurons, layers, and weights. Additionally, a node clustering method can simplify this process. Input neurons are clustered based on data dependencies between synthetic and real-time data, which are analyzed by computing correlation coefficients between the new and existing features.

Eq. (2.6) illustrates the significance of the correlation coefficient between inputs ($CC_{n,n+1}$) in the NN model, particularly in eliminating redundant features that are dependent on existing ones. When the correlation condition is satisfied, the impact coefficient of two dependent input features shares a common value, facilitating the pruning of unnecessary input neurons.

$$Input = \begin{cases} \theta_0 + \theta_{com1,2}(\theta_1 + \theta_2)(x_1 + x_2) + \cdots + \theta_{comn-2,n-1}(\theta_{n-2} + \theta_{n-1})(x_{n-2} + x_{n-1}), \; CC_{n,n+1} \neq 0 \\ \theta_0 + \theta_{com1,2}(x_1 + x_2) + \cdots + \theta_{comn-2,n-1}(x_{n-2} + x_{n-1}), \; (CC_{n,n+1} \neq 0) \wedge (\theta_n + \theta_{n+1}) \simeq 1 \\ \theta_0, \; (CC_{n,n+1} \neq 0) \wedge (\theta_n + \theta_{n+1}) \simeq 0 \\ \theta_0 + \theta_1 x_1 + \theta_2 x_2 + \cdots + \theta_{n-1} x_{n-1}, \; CC_{n,n+1} = 0 \end{cases} \tag{2.6}$$

The requirements of DT-APP3 are effectively addressed by a DNN, both before and after the behavior simulation and synthetic data generation processes, as illustrated in Fig. 2.9. This figure demonstrates the clustering and removal of neurons based on data dependencies among the inputs.

At first glance, classification and prediction may appear to be complex tasks within the model implementation and learning process when using a supervised DNN. However, the machine learning model can be optimized through various techniques, such as neuron and weight pruning, layer reduction, and weight and neuron clustering. These optimizations contribute to making DNNsa popular and effective choice for modern technologies, including DT.

2.6 Unsupervised machine learning algorithms

The deployment of state-of-the-art intelligent technologies, along with remote monitoring and device management demands, has resulted in vast amounts of unlabeled data. These resources are essential for applications that require feature extraction to support various tasks. Supervised ML models typically outperform unsupervised learning algorithms in simpler problems due to their reliance on labeled datasets. In contrast, unsupervised machine learning models effectively address the challenges posed by complex systems that operate with unlabeled datasets. Consequently, unsupervised ML algorithms can be particularly powerful for DT-based applications, as they are designed to tackle intricate problems and unknown scenarios. DT generate synthetic data following the behavior simulation of physical models, which can enhance the feature set and impact coefficients relevant to the target outcomes. This capability allows for the updating and retraining of ML models to incorporate synthetic data when new

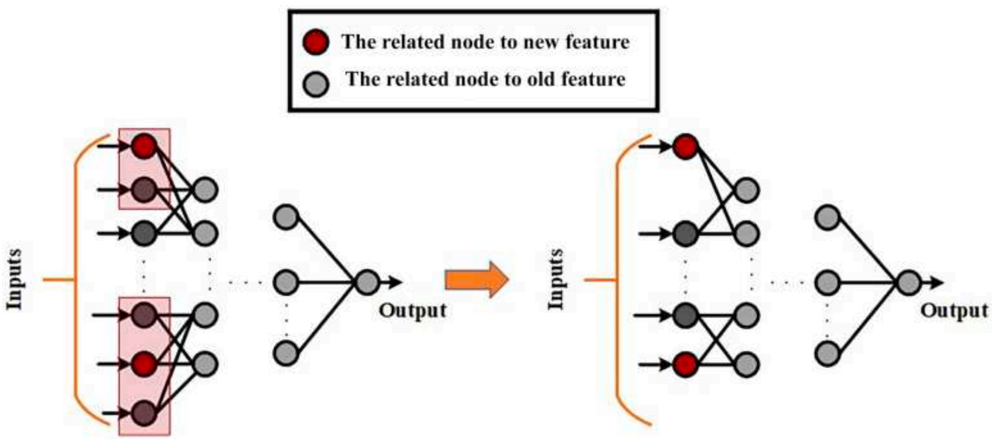


Figure 2.9 Neural network model before and after new feature extraction. *No permission required.*

features with significant impact coefficients emerge. This analysis examines two types of ML algorithms—before and after synthetic data construction—using Eqs. (2.1) and (2.2) as benchmarks for assessing their effectiveness, similar to the evaluation of supervised ML models. The focus of this subsection is on analyzing the efficiency of two widely used unsupervised ML algorithms: K-means clustering and Q-learning, applied within DT-based systems for the defined applications.

2.6.1 K-means clustering model

The ML algorithm employs a data clustering method to identify groups and subgroups for system recommendations. This process involves defining a random number k of clusters to establish their centers and computing the Euclidean distance between data points and these centers, which can be adjusted through averaging. DT-APP1 represents a medical application of DT technology, as outlined in Scenario-APP1, which describes three implementation plans: data-driven, physical, and a combination of both. Supervised machine learning models have demonstrated that decision trees can effectively support both data-driven and physical modes in constructing virtual models for medicine recommendations when prescribing drugs based on labeled data. In the combined mode, the virtual model identifies suitable drugs for depression treatment by leveraging real-time data, expert opinions, and registered information, necessitating the use of unlabeled data. The k-means clustering model plays a crucial role in fulfilling the requirements of DT-APP1 within Scenario-APP1 by categorizing various medicines, their potential side effects, and patient symptoms. The DT analyzes real-time data and simulates both defined and unknown behaviors within the drug discovery system, enabling the extraction of additional features and necessitating updates to the machine learning model. Given the resource-intensive nature of randomly selecting k values, new features are defined as new data points. Their Euclidean distance from the centers of existing clusters ($center_i$) is estimated to determine their inclusion based on the condition $ED \leq MaxED$, as described in Eq. (2.7).

$$ED_{NewFeature_n, center_i} = \sqrt{(NewFeature_n - center_i)^2}$$

$$ED = Min\,(NewFeature_n,\ center_i),\ (0 \leq n \leq N) \wedge (0 \leq i \leq I)$$

$$k = \begin{cases} k_{old}, & ED \leq MaxED \\ k_{update}, & ED \geq MaxED \end{cases} \tag{2.7}$$

A new feature is assigned to a cluster if its Euclidean distance is less than the maximum distance ($MaxED$) of existing data points, while k remains set to its previous value (k_{old}). Conversely, if this condition is not met, the number of clusters is updated to

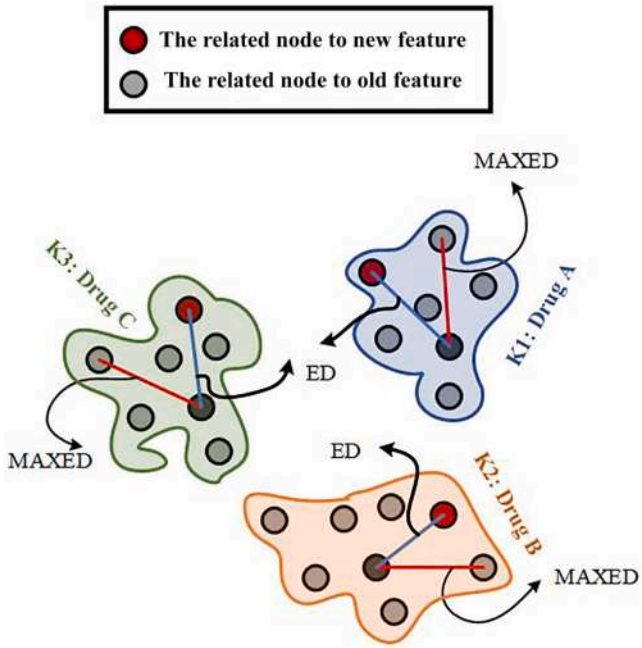


Figure 2.10 Data clustering using k-means neighbors before and after generating synthetic data. *No permission required.*

a new value (k_{update}). Fig. 2.10 illustrates the implementation of k-means clustering for DT-APP1, showing how additional features are positioned at the margins of existing clusters.

The k-means clustering algorithm effectively addresses pattern detection and solution recommendation challenges, making it suitable for medical recommendations, treatment classification, and drug discovery. However, it faces the challenge of the costly process associated with randomly assigning k values. This challenge can be alleviated in DT applications through decision-making processes that integrate features into existing clusters following synthetic data generation.

2.6.2 Q-learning model

Introduces a reinforcement learning approach that leverages the Q-learning algorithm and the Markov Decision Processto define various actions corresponding to each state. The Q-learning model has gained popularity as an unsupervised machine learning algorithm due to its ability to receive feedback from each state by evaluating the rewards associated with specific actions. This algorithm has proven effective in addressing complex learning challenges and meeting the intelligent demands of smart systems by establishing a dynamic structure of states and actions, where the system transitions between different states based on reward values. DT-APP4 exemplifies an incident management application, as outlined in Scenario-APP4, which specifies a data-driven plan for behavior simulation using a virtual model. This application aims to assist in managing fire incidents at a metro station by utilizing real-time data and historical information related to the environment, station, and individuals connected to the IoT communication infrastructure to monitor vital signs. The primary objective of DT-APP4 is to provide real-time and accurate services during incident management, as specified in Scenario-APP4. The virtual model of the metro station generates synthetic data by simulating unknown situations and analyzing them to prevent fires and ensure the safety of both people and firefighters. This process creates opportunities for extracting additional features with significant impact on decision-making, prediction, and solution recommendations, key tasks for DT-APP4. Consequently, updating the model is crucial to meet the application's demands after simulating system behaviors through the DT, where the Q-learning model can offer effective learning solutions for DT-APP4 based on Scenario-APP4. Before delving into the implementation of Q-learning for DT-APP4, it is essential to define several key concepts related to the machine learning model that supports DT in decision-making, prediction, and recommendation:

2.6.3 Discount factor

Represents a penalty applied to the reward, reflecting the effectiveness of each state's actions. A high discount factor indicates a tendency to revert to a previous state due to the low efficiency of new features in solving a problem.

2.6.4 Penalty

Signifies unnecessary transitions between states, leading to returns to previous states for retries, which impacts the discount factor.

2.6.5 Reward (r)

It is calculated based on successful actions taken in a state and their positive influence on subsequent states. The reward value aids in computing both the discount factor and probability.

2.6.6 Probability (P)

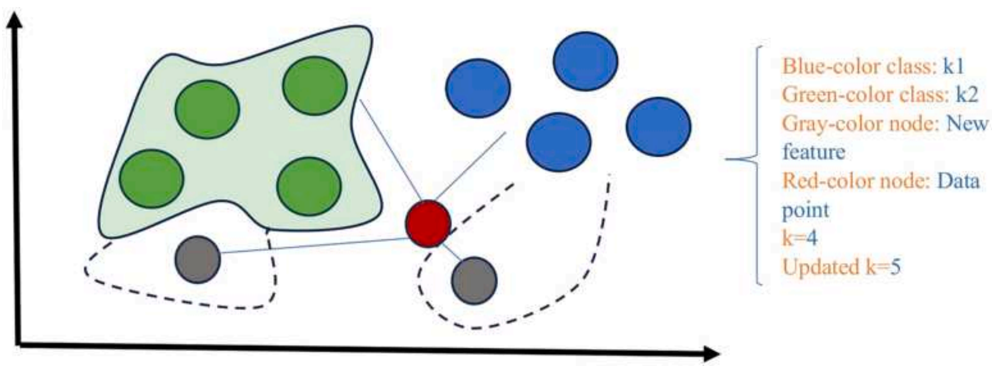
Determines the likelihood of transitioning to the next state, influenced by both reward and penalty values.

Equations (2.8) and (2.9) provide a mathematical framework for estimating probability (P) and discount factor (DF)based on penalty, reward, and initial probability values related to feedback from the current state during action execution. These models facilitate the identification of features with low efficiency in problem-solving, allowing for necessary updates to continue refining the model. The following graph illustrates the communication between states in Q-learning based on the Markov chain model for DT-APP4, highlighting how the virtual model constructs synthetic data and additional features. Click or tap here to enter text (Graph 2.15).

$$DF = \frac{Penalty_t}{r_t}, \; t \geq 0 \tag{2.8}$$

$$P = (r \times p) - Penalty \tag{2.9}$$

The Penalty-Rewards-Based Q-Learning (PRQ) algorithm outlines the steps for implementing the Q-learning model to meet the objectives of DT-APP4. By applying penalty and reward values, the PRQ algorithm effectively minimizes the additional costs associated with model updates. The red lines in the PRQ framework illustrate the detection of low-efficiency features, allowing for their elimination and facilitating ongoing data updates.



Graph 2.15 Q-learning model for DT-APP4. *No permission required.*

Algorithm Penalty-reward-based Q-learning (PRQ)

Inputs: 1- feature: features including new and old features whereas $s \geq 0$
2- Q: Learning rate whereas $Q_1 \geq 0$
Output: PValue: The predictive target in cognitive network
whereas $0 \leq$ PValue ≤ 1

Parameter declaration:
t: *time to represent state* whereas $0 \leq t \leq 1$
$state_n^a$: *state n of feature a at time t*
act_n^a: *Physical sensor = action*
$reward_{n+1}^a$: *Rewards for action act_n^a at time n and $(n+1)$*
$penalty_{n+1}^a$: *Penalty for action act_n^a at time n and $(n+1)$*
Q: *Learning rate*

```
Start
  Procedure PRQ (feature, Q)
    Start phase 1 // Initialize Q based on primary lookup table
      state_n^a ← feature_i //State definition based on the old and new features and the actions of their related sensor nodes
      for each episode in episodes do
        do in iteration
          Initialize primary cognitive network with Q
          Target cognitive network with Q
          Defining next state based on the new feature
          Update actions and data dependency between the nodes of the application
        end iteration;
      end for;
    end phase 1;
    Start phase 2 // Initializing the primary states and actions, and predicting a risky location
      for each episode in episodes do
        do in iteration
          for each action of state do
            Analyze the successfully and unnecessary operations of the action and scoring them
            reward_n^a ← R_w(state_n^a, act_n) // Reward value assignment
            penalty_n^a ← R_w(state_n^a, act_n) // Penalty value assignment
            Estimating the value of discount factor (DF_n) for state n based on penalty and reward values
            Updating the value of probability (p_{n-1}) for state n-1 based on penalty and reward values
            if (DF_n ≃ 0) do
              Remove state_n^a // Removing low-efficiency new feature
              Update network
            end if;
            Pvalue← WinnerLocation //Predict target in cognitive network based on Q
            Updating the parameters of cognitive network
          end for;
        end iteration;
      end for;
    end phase 2;
  end procedure;
```

Algorithm 2.2 PRQ

By identifying features with minimal impact on the actions of related states, the cost of retraining the model is reduced, especially when behavior simulations lead to the extraction of new features in DT applications. The Q-learning model proves to be an effective ML algorithm for supporting DT-based applications, particularly in scenarios involving complex tasks that require real-time service delivery. Its capability to create a secure platform for data transfer further enhances its suitability for such applications.

2.7 Artificial intelligence algorithms

Recent intelligent technologies require advanced AI-based techniques to meet the demands of smart devices, given the complex data patterns and communication among nodes. These technologies necessitate real-time services and data analysis to support immediate user needs, which is particularly relevant for DT in real-time tasks and decision-making. This subsection evaluates the efficiency of an AI algorithm inspired by the patterns of human brain cells within the context of DT technology. The assessment focuses on defined DT-based applications. This algorithm can be adapted for detecting faults, disorders, and risky situations across various intelligent applications where DT are deployed to fulfill at least one specific purpose.

2.7.1 Brain cell-inspired artificial intelligence algorithm

The hierarchical structure of human brain cells creates efficient patterns that support the implementation of modern intelligence systems and complex devices. The behavior of these brain cells provides valuable insights for developing intelligent algorithms that enhance IoT and IoMT applications. By drawing inspiration from protein aggregation patterns associated with conditions such as Alzheimer’s, Parkinson’s, and depression , we can better address these health challenges. The relationships among neurons, axons, and dendrites establish a framework for identifying data dependencies and detecting faulty devices. This enables the utilization of spare or alternative components to maintain service continuity for malfunctioning nodes. Such an approach can significantly improve virtual modeling for real-time data analysis, prompt decision-making, and the prediction of risky situations by emulating system behaviors and generating synthetic data that offers insights into unknown states. DT-APP4 effectively connects a network of sensor and server nodes to manage incidents through the application of DT technology. This application follows the strategy outlined in Scenario-APP4, which addresses fire incidents in metro stations by identifying and predicting risky situations and hazardous locations to prevent the spread of fire and ensure the safety of individuals. An intelligent algorithm has demonstrated its effectiveness in fulfilling the requirements of DT-APP4 by modeling the association patterns among neurons, axons, dendrites, and protein aggregation. The graph G_A illustrates the relationships among human brain cells, characterized by E edges and V vertices, as α, β, and G proteins aggregate in response to Alzheimer's, Parkinson's, and depression. A corresponding matrix represents the associations between neurons, axons, dendrites, and protein aggregation, consisting of I columns and J rows, where $a_{i,j}$denotes the element located at the i row and j

column. The subgraph analysis technique aims to identify similar patterns of data dependency and associations between the nodes of DT-APP4, based on the relationships among neurons, axons, and dendrites as described in Eq. (2.12)(Graph 2.16.

$$G_A = (E, V), E = 6$$

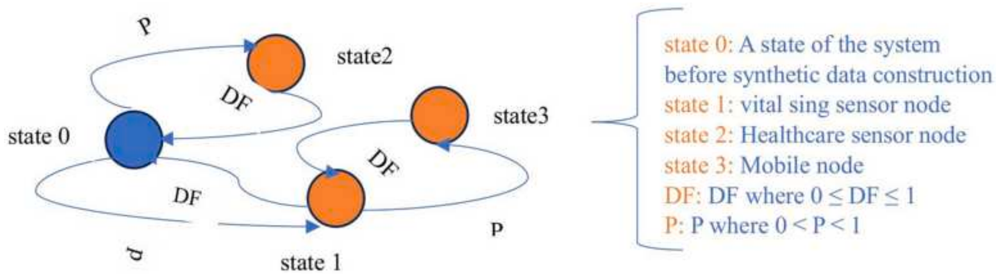
$$A = \begin{bmatrix} a_{0,0} & \cdots & a_{0,j} \\ \vdots & \vdots & \vdots \\ a_{i,0} & \cdots & a_{i,j} \end{bmatrix}$$

$$[A]_{i\times j} = \begin{cases} i = E \\ j = i \end{cases} A = \begin{matrix} Ne \\ Ax \\ De \\ \alpha \\ \beta \\ G \end{matrix} \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

Equations (2.10) and (2.11) estimate two margin values, *Pattern* and *Fault* used for subgraph detection and pattern recognition in a DT-based application. These parameters define the conditions for Eq. (2.12). The algorithm identifies a pattern that corresponds to the associations among human brain cells and assigns a value to *AppPattern* when the condition $Pattern = PC$ is satisfied. If this condition is not met, *AppPattern* is set to zero. Furthermore, Eq. (2.12) can also be utilized to identify faulty nodes by analyzing the *Fault* condition instead of evaluating the *Pattern* value.

$$Pattern = \sum_{i=0}^{i=2} \sum_{j=0}^{j=j_{max}} ((j_{max} \times i) + 1) \times a_{i,j} \tag{2.10}$$

$$Fault = \sum_{i=3}^{i=i_{max}} \sum_{j=0}^{j=j_{max}} ((j_{max} \times i) + 1) \times a_{i,j} \tag{2.11}$$



Graph 2.16 The graph of the brain cell-inspired model. *No permission required.*

$$AppPattern = \begin{cases} 1, & Pattern = PC \\ 0, & others \end{cases} \tag{2.12}$$

Before delving into the specifics of the algorithm supporting DT-APP4, we establish the following assumption to facilitate a clearer analysis of the problem and its solution:

Assumption:
The GPS at the metro station is unable to provide validated data. Consequently, the system requires an understanding of the faulty GPS's target location. The algorithm leverages output from vital sign monitoring sensors to gather relevant information.

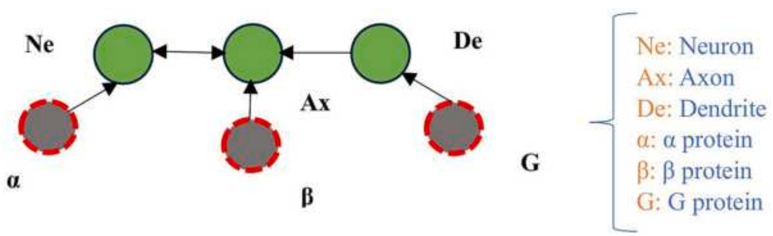
Based on this assumption for DT-APP4, the corresponding matrix of its graph is defined with *ri* rows and *rj* columns, represented as $aa_{\mathrm{ai},\ \mathrm{aj}}$. Additionally, the AA graph illustrates the relationships among the three key nodes of DT-APP4, reflecting both the assumption and the connections between the application components (Graph 2.17).

$$G_{AA} = (EA,\ VA)$$

$$AA = \begin{bmatrix} a_{0,0} & \cdots & a_{0,aj} \\ \vdots & \vdots & \vdots \\ a_{ai,0} & \cdots & a_{ai,aj} \end{bmatrix}$$

$$[AA]_{ai \times aj} = \begin{cases} ai = EV \\ aj = ai \end{cases} AA = \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{matrix} \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

This algorithm, along with other advanced AI models, is built on a flexible structure that supports various applications. It adapts to different contexts and employs diverse techniques to enhance the model's performance.



Graph 2.17 Brain cell-inspired model for DT-APP4 based on the assumption. *No permission required.*

2.8 The partial approaches of artificial intelligence and machine learning for digital twins (PAI-PML)

This section explores partial approaches to implementing ML and AI aimed at enhancing the efficiency of models that support DT technology. These techniques focus on optimizing computation time and memory usage during the training of ML and AI models, specifically through Python-based codesign, Scikit-learn libraries, and TensorFlow for algorithm development. DT plays a crucial role in addressing challenges such as communication delays and energy consumption across various fields of computer engineering. By emulating and predicting system behavior and critical data paths, DT can propose solutions to mitigate these issues. The effectiveness of this technology relies on robust data analysis techniques and real-time data access, while also necessitating additional memory for data storage when generating synthetic data. Ultimately, reducing the training costs of ML and AI models enhances the performance of DT applications, enabling them to deliver timely and efficient services.

2.8.1 Python-based codesign

The definition and dominance of the system within the instructions of a codesign language significantly influence the performance of model implementation. Python codesign is a widely adopted high-level system description language, primarily because it defines the operations of ML and AI algorithms. The dictionary data type in Python is commonly utilized for data labeling and organizing information from lists. However, sorting processes can be resource-intensive, both in terms of storage space and computation time, particularly when analyzing large datasets targeted by ML and AI systems. To address these challenges, efficient sorting methods such as heapq and quicksort can be employed. By importing the heapq library in Python and utilizing its partitioning method, we can enhance sorting efficiency. The heapq approach reduces time complexity, enabling effective data exploration by focusing on specific quantities of the smallest and largest elements within a list. This method serves not only as a data structure but also as a sorting technique, offering flexibility to meet diverse data exploration needs while minimizing time complexity and delays. The following pseudocode demonstrates how to use the heapq library to find the five largest and smallest elements in a list using Python.

```
import heapq
heapq.heapify(TargetList) #Rising sorting a target list (TragetList)
maximum = heapq.nlargest(n,TargetList) #Return n largest value of a list (TargetList)
minimum = heapq.nsmallest(n,TargetList) # Return n smallest values of a list (TargetList)
```

Pseudo code 1.1 HEAPQ

Quicksort is a widely used sorting algorithm that employs a partitioning approach based on a pivot value, dividing the list into lower and higher partitions. This method generally requires less storage space compared to other sorting techniques. However, its worst-case time complexity is greater than that of heapq-based sorting. To mitigate this issue, a hybrid approach that combines quicksort and heapq can be employed. This method leverages quicksort for the sorting process while utilizing heapq for efficient value retrieval, as exemplified by the Quicksort-Heapq-based sorting (QHS) algorithm.

```
Algorithm Quicksort-Heapq-based sorting (QHS)

Inputs: 1- List: dataset list with n members whereas m ≥ 0
Output: 1- SL: Return the list as a sorted list with m members whereas m ≥ 0
        2-V: Return a value of the sorted list whereas V⊏ Integer

Parameter declaration:
pivot: pivot value for quicksort whereas whereas pivot ⊏ Integer

Start
  Procedure QHS (list)
    Start // Initialize Q based on primary lookup table
      if (demand = 0) do // Checking the demand of algorithm to sorting process
        pivot ← list [high] // starting quicksort algorithm for the demand of the sorting list for the target algorithm
        Starting quicksort algorithm with pivot's value
        if (list[i] ≤ pivot) do
          Add list [i] into the class of the low values
        else
          Add list [i] into the class of the high value
        end if;
        SL←quicksort (list, low, high)
      else // Checking the condition of demand = 1 when the algorithm demands return the specific values
        V←heapq.nlargest (n, SL) // Return n largest value of the sorted list (SL) with m members
      end if;
    end;
  end procedure;
```

Algorithm 2.3 QHS

The QHS algorithm significantly enhances the performance of AI and ML applications by reducing data exploration costs and improving the efficiency of decision tree-based applications both before and after the generation of synthetic data.

2.8.2 Sikit-learn libraries and TensorFlow

This section elucidates the efficient characteristics of the scikit-learn and TensorFlow libraries in supporting various ML and AI algorithms, particularly in optimizing their training phases to minimize energy consumption and latency costs. K-means clustering is recognized as one of the most popular unsupervised machine learning algorithms and serves as a suitable model for synthetic data analysis within a virtual framework. A critical aspect of the K-means algorithm is determining the optimal value of K, which can significantly impact the model's performance. The validation of K can be approached through two methods: internal and external. The external method involves expert analysis, where specialists compare the number of clusters with actual categorizations relevant to the target problem. However, this approach may not be ideal for DT applications. In contrast, the internal method assesses the efficiency of different K values in clustering features by employing the elbow method. The inertia parameter plays a key role in this evaluation, as it estimates the sum of squared distances between data points and their respective centroids within each cluster. This process can be demonstrated using Python, specifically by importing the KMeans library from "sklearn.cluster" and executing the command "kmn.inertia_".

The deployment of deep learning models through fully connected neural networks presents significant challenges regarding weight storage, which can strain memory capacity and increase costs for ML and AI algorithms across various applications. This issue is particularly relevant for DT technology, as it relies heavily on DNN models for decision-making, detection, and prediction tasks. Fortunately, several effective approaches exist to tackle this challenge. One notable solution is offered by TensorFlow, which has partnered with Arm to implement a toolkit-based method for weight clustering on smartphones. This method utilizes weight pruning techniques to replace similar weights within a layer by applying clustering algorithms that explore weight similarity in DNN models. When this weight clustering solution is combined with quantization techniques—allowing for multiply-accumulate operations using 16 or 8 bits—the demands on memory capacity can be significantly mitigated for DT addressing complex problems.

As these techniques demonstrate, a detailed focus on ML and AI algorithms can substantially reduce the additional costs associated with model training and learning, which remains a major challenge for DT-based applications.

2.9 Hardware-based solution for digital twins

The costs associated with data processing present significant challenges for DT technology, primarily due to its requirement for real-time data analysis to facilitate timely decision-making. This includes considerations for energy efficiency and communication delays. While ML and AI techniques, along with partial system descriptions, have proven effective in enhancing the training phase of ML and AI models, the inference phase introduces additional costs related to energy consumption, delays, memory usage, and bandwidth capacity. Various hardware solutions have been identified to mitigate these overheads during the inference phase, including node clustering, in-memory processing, near-memory processing, and optimized transistor and gate-level structures. Furthermore, the communication infrastructure plays a critical role in establishing connections between nodes in a DT-based application. This section evaluates a low-cost switch-based communication infrastructure as a potential hardware solution to accelerate the inference phase of ML and AI models.

2.9.1 Switch-based communication structure for digital twins

A virtual model connected to IoT, IoMT, or Metaverse communication infrastructures is designed to fulfill a specific purpose within a particular application. It relies on output data from designated sensor nodes and data sources, which are determined by the established connections among the application's components. These nodes can also function as target devices for other applications integrated into the IoT, IoMT, or Metaverse, thereby increasing the complexity of service and node allocation across multiple applications. Data processing in a DT-based application faces significant challenges due to the high volume of data transactions between nodes and memory, coupled with a rapid influx of requests for memory access and data storage. To address these issues, task mapping and node clustering techniques can reduce communication latency during data transfers between nodes, while temporal buffers can help manage memory capacity demands for real-time data processing. This chapter examines the architecture of a communication infrastructure that includes a set of processing elements (PEs) and shared and temporal buffers interconnected via simple switches, as illustrated in Fig. 2.11.

The task mapping method is implemented prior to applying the node clustering technique, which is organized based on the interrelationships among the components of the application across the set of PEs linked through the switches. The figure illustrates the task mapping for DT-APP1 and categorizes the PEs according to the application's connections.

As illustrated in Fig. 2.11, the tri-state buffers play a crucial role in determining the phase of the categorized nodes, distinguishing their functions within the proposed DT-based application or for sharing with other applications. These simple buffers help minimize delays in dedicating nodes to real-time data processing for DT, thereby facilitating timely decision-making, prediction, and detection. In the context of node clustering, we initiate a cluster with the processing element PE_c as the primary target node, incorporating adjacent PEs based on the total flows (*TotalFlow*) between them at time t. Eq. (2.13) mathematically describes the node clustering process by evaluating the total flow between the target node and its neighboring PEs. The condition of each cluster is updated by substituting the target processing element when an adjacent node (PE_{c-1}, PE_{c+1}, or both) joins the cluster.

$$TotalFlow_{c,c+1} = \sum_{f=0}^{f=f_{\max}} flow_{f_{c,c+1}}$$

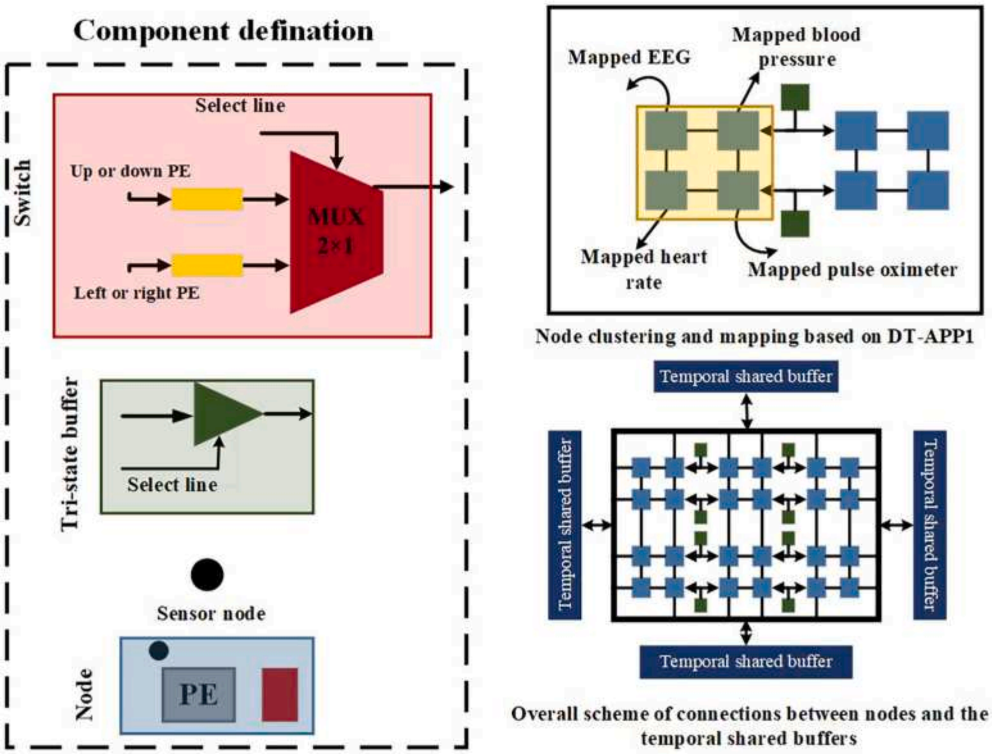


Figure 2.11 Communication infrastructure for sensor nodes as a hardware-based solution to the costs of DT technology. *No permission required.*

$$TotalFlow_{c,c-1} = \sum_{f=0}^{f=f_{\max}} flow_{f_{c,c-1}}$$

$$Cluster = \begin{cases} PE_{c+1}, \ TotalFlow_{c,c+1} \geq 1 \\ PE_{c-1}, \ TotalFlow_{c,c-1} \geq 1 \\ PE_c, \ Others \end{cases} \tag{2.13}$$

The PEs are directly linked to temporal buffers, enabling temporary real-time data storage without the need for registration in the main memory. This approach reduces memory access requirements and storage demands while also mitigating delays in data processing. The task mapping and node clustering strategies effectively decrease communication latency and enhance energy efficiency by eliminating unnecessary hop counts during data transfer between nodes. When clustering the nodes of IoT or IoMT as contributors to the application, these extra hop counts between source and destination nodes are removed, resulting in improved energy consumption and reduced delays. This clustering also accelerates memory access and the inference phase of ML and AI algorithms, thereby enhancing the efficiency of DT-based applications in data analysis and solution recommendations. Furthermore, hardware-based techniques significantly influence the performance of DT applications. The architecture of the communication infrastructure and the data transfer methods between source and destination nodes play a crucial role in addressing cost challenges associated with DT technology.

2.10 Features of the study and its future views

The DT technology represents modern techniques and creates opportunities to support state-of-the-art intelligent AR and VR-based devices in emulating and simulating unknown behaviors of a system. This enables informed exploration of solutions based on the synthetic data constructed by the virtual model of a physical representation. This technology has successfully emerged to meet the demands of various applications in industrial, medical, educational, incident management, and economic sectors by predicting possible situations and conditions for solution recommendations. The performance of ML and AI algorithms plays a crucial role in enhancing or hindering the efficiency of the virtual model in decision-making and insight virtualization. This study focuses on ML and AI models that can support the processes of data collection and analysis, as well as model retraining after creating synthetic data through DT. To identify suitable AI/ML algorithms, the research centers on models that require only data updates after constructing synthetic data with minimal variations. The energy consumption and delay in DT-based applications define another important purpose of the study, which is to analyze machine learning and AI models. The features and future aspects of the chapter are as follows:

2.10.1 The update of machine learning and artificial intelligence algorithms after synthetic data creation

DT technology utilizes machine learning and AI algorithms in two stages: before and after synthetic data generation. The virtual model, which represents the physical system, is developed through the analysis of data collected from real-time and recorded sources by using ML and AI algorithms. The models must be updated when the virtual model generates synthetic data for decision-making, prediction, and solution recommendation. It is essential to propose flexible ML and AI algorithms that require minimal updates due to the costs associated with exploring a different model and undergoing the entire model re-training process. This study provides an opportunity to explore suitable machine learning and AI algorithms based on the application's priority and the data dependency among its nodes, thereby enhancing the efficiency of DT technology.

2.10.2 Energy consumption and communication delay

The virtual model creation of DT technology involves complex operations that lead to increased energy consumption and delays. This issue negatively impacts the performance and efficiency of DT technology in supporting various applications with differing demands, even as this technique aims to address the challenges of modern technologies in the Metaverse. ML and AI algorithms play a crucial role in DT, aiding in the perception of the initial physical representation of a system and informing decision-making after synthetic data generation. This chapter examines hardware and software-based approaches that can enhance energy efficiency and reduce communication delays, creating opportunities for further research in the field to improve the quality of service provided by DT technology by eliminating its cost burdens. It focuses on Python-based codesign, Scikit-learn, and TensorFlow methods that effectively reduce memory capacity requirements and latency, alongside implementing a simple switch-based structure, near-memory processing, and hardware-based solutions for clustering and mapping to enhance the performance of DT-based applications.

2.11 Conclusion

Metaverse technology has emerged to meet the advanced demands of modern humans across various sectors, including industrial, educational, economic, medical, and management. Augmented and virtual realities constitute the majority of these sectors. The DT technique has been used to address the unknown behaviors of different systems, incorporating virtual and augmented reality by constructing a virtual definition and image of a system. DT face challenges such as increased costs and data processing difficulties when attempting to solve complex problems that involve intricate computations. ML and AI algorithms are employed for data analysis and virtual model definition, and they are also used to meet the needs of a DT-based application after generating synthetic data. This chapter focuses on the effectiveness of supervised and unsupervised ML algorithms and AI models in supporting DT-based applications while minimizing the need for model updates. ML and AI models were analyzed to identify suitable algorithms for applications, prioritizing minimal costs related to delays and energy consumption. This investigation explores the partial approaches of Python-based codesign and Scikit-learn for defining algorithms that require minimal memory capacity and computation time. The research also addresses hardware-based solutions to reduce communication delays and enhance the energy efficiency of implementing ML and AI models, thereby improving the performance of DT technology while analyzing algorithmic details. This chapter provides an opportunity to identify suitable MLand AI models for deploying a DT-based application with minimal cost overheads, supported by an efficient communication infrastructure for the connections and data processing of sensor nodes.

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CHAPTER 3

Digital twins in healthcare development of an accurate machine learning model for health monitoring through digital twins

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3.1 Introduction

Digital twins in healthcare are revolutionizing the comprehension and administration of patient care and medical procedures. A digital twin is a virtual representation of a tangible physical entity, which in healthcare may refer to a patient, organ, or healthcare system. This idea facilitates real-time monitoring, simulation, and predictive modeling, which are essential for personalized medicine, enhancing diagnostics, and optimizing patient outcomes. In contrast to conventional static models, digital twins undergo continuous evolution by assimilating real-time data from many sources, including sensors, medical records, and wearable devices. This ongoing data stream guarantees that the twin remains current, offering relevant insights for doctors [1].

A significant application of digital twins in healthcare is personalized treatment. Digital twins can amalgamate extensive individualized data, encompassing genomes, lifestyle variables, and real-time physiological metrics, to customize treatment according to a patient's exact requirements. By simulating the effects of various treatments on a patient's physiology, healthcare providers can anticipate responses to drugs and therapies without prior physical administration. In cancer treatment, a digital twin of a tumor can assist clinicians in evaluating several chemotherapy regimens to identify the most effective option for a specific patient. This signifies a substantial transition from the "one-size-fits-all" care model to a more tailored, individualized strategy that can enhance patient outcomes and reduce adverse effects [2].

Besides personalized medicine, digital twins have significant promise in surgical planning. Surgeons can utilize computerized representations of organs or systems to rehearse surgeries and mimic various techniques before executing them on real patients. For example, intricate cardiac procedures can be simulated electronically, enabling physicians to detect possible difficulties and enhance their skills before the actual

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procedure. This enhances the accuracy of surgical procedures while diminishing the probability of errors and problems. Virtual rehearsals can reduce patient recovery duration and hospitalizations, enhancing the safety and efficiency of surgical procedures. The capacity to replicate a patient's distinct anatomy in real-time facilitates highly tailored surgical approaches that improve the success rates of intricate procedures [3].

In addition to specific patient care, digital twins can enhance hospital management and operations. Healthcare facilities can develop digital duplicates of their actual infrastructures to simulate patient flow, resource distribution, and personnel requirements. This is particularly advantageous at times of elevated demand, such as pandemics or natural disasters, when hospitals must function at optimal efficiency. Through predictive analytics, digital twins can anticipate bed occupancy rates, forecast equipment utilization, and ascertain that personnel levels are sufficient to address patient requirements. Digital twins can model the impact of infectious disease proliferation on hospital capacity, enabling administrators to optimize resource planning and allocation. This skill can markedly enhance the overall efficiency of healthcare systems, lowering costs and augmenting patient care [4].

In medical research and pharmaceutical development, digital twins provide the capability to enhance the efficiency of new therapy evaluations. Traditionally, clinical trials are protracted and costly; however, digital twins can model patient populations to forecast the responses of various groups to a novel medication. This can expedite the medication development process by detecting potential adverse effects and efficacy concerns prior to the commencement of human trials. Moreover, digital twins might simulate rare diseases or syndromes that are challenging to investigate in extensive clinical trials due to the limited patient population. Researchers can enhance the design of clinical trials by simulating diverse scenarios and responses, thereby increasing efficiency and reducing costs while maintaining patient safety and efficacy [5].

The management of chronic diseases is another domain where digital twins could exert considerable influence. Chronic ailments such as diabetes, cardiovascular diseases, and respiratory disorders necessitate ongoing monitoring and prompt therapies. Digital twins can monitor real-time data from wearable devices and other assessment tools to model the advancement of various disorders and notify healthcare providers of probable complications before they escalate. This can facilitate more proactive and preventive care, hence decreasing hospital admissions and emergency visits. A digital twin of a diabetic patient might monitor glucose levels, anticipate increases, and recommend insulin modifications in real-time, facilitating a more tailored approach to disease treatment.

Digital twins in healthcare hold significant promise, but their extensive implementation requires the resolution of certain hurdles. A major challenge is data privacy and security. Digital twins necessitate access to extensive sensitive patient data, prompting issues around the storage, sharing, and protection of this information.

Adherence to healthcare regulations is essential to safeguard patient data from misuse or compromise. The amalgamation of various data sources, such as electronic health records (EHRs), Internet of Things (IoT) devices, and wearable technology, poses interoperability issues. Harmonizing data from many sources into a unified digital twin necessitates a strong technological infrastructure and coordination among various stakeholders [6,7].

3.2 Case studies of digital twin applications in healthcare

3.2.1 Tailored medicine

Personalized medicine is transforming healthcare by customizing therapies to the specific characteristics of each patient. Digital twins are essential in this methodology, generating dynamic models informed by a patient's genetic, environmental, and lifestyle variables. These models enable healthcare providers to predict patient responses to specific medications, resulting in personalized therapy programs that improve efficacy and reduce unpleasant reactions. This technology is especially advantageous in cancer, as digital twins assist clinicians in determining the most suitable chemotherapy regimens according to the distinct genetic makeup of each tumor. As personalized medicine advances, standard clinical treatment now incorporates digital twins. They enable individuals to actively participate in their healthcare journeys by visualizing their health data and treatment alternatives. This participation enhances patient comprehension of their diseases and promotes adherence to treatment regimens. The incorporation of digital twins into personalized medicine is establishing a new benchmark in healthcare, thereby enhancing patient outcomes and the overall quality of care. The capacity for personalized medicine to revolutionize chronic illness management is substantial. Ongoing breakthroughs in genetics and data analytics will position digital twins as pivotal in formulating customized treatment programs that cater to the intricate demands of individual patients [8,9].

3.2.2 Management of chronic diseases

Chronic diseases present persistent issues in healthcare, requiring novel solutions for efficient management. Digital twins enable proactive monitoring by amalgamating real-time data from diverse sources, such as wearable devices and EHRs. This ongoing data stream allows healthcare providers to retain a holistic perspective of a patient's health, facilitating prompt interventions that can markedly enhance outcomes. In diabetes care, digital twins can replicate blood glucose variations influenced by diet, physical activity, and medication. Through the analysis of these simulations, healthcare providers can customize treatment programs to address individual patient requirements, resulting in improved glycaemic control and diminished consequences. As digital twins advance, they will become progressively essential for the proper management of chronic diseases [10].

3.2.3 Surgical planning and simulation

Surgical treatments inherently involve risks, necessitating rigorous planning for optimal outcomes. Digital twins enable surgeons to recreate a patient's anatomy by generating intricate 3D models that support pre-operative simulations. Practicing intricate procedures in a virtual setting enables doctors to refine their skills and bolster their confidence, resulting in enhanced surgical precision. Recent improvements in imaging technology, including MRI and CT scans, facilitate the development of highly precise digital twin models. These models facilitate surgical planning and enhance communication among surgical teams. When all team members can visualize the patient's distinct anatomy, collaborative talks can foster more effective methods and mitigate risks during actual surgeries. Furthermore, digital twins can offer significant insights into surgical healing. Through the analysis of data from analogous treatments, healthcare providers can foresee probable difficulties and institute preventive measures. This proactive strategy is especially advantageous in high-risk operations, as comprehending prospective outcomes can greatly influence patient safety [11].

3.2.4 Operational efficiency in healthcare institutions

Healthcare institutions continually encounter demands to enhance operational efficiency while providing superior patient care. Digital twins offer an effective solution by simulating hospital operations to pinpoint bottlenecks and enhance resource allocation. Through the simulation of several situations, hospitals can acquire insights into patient flow, personnel utilization, and equipment requirements, resulting in enhanced operational efficiency. Hospitals can employ digital twins to examine patient admission trends and modify staffing levels accordingly. This data-driven methodology enables healthcare facilities to predict high-demand periods, assuring preparedness to address patient demands. By proactively mitigating possible issues, hospitals may improve the patient experience and decrease waiting times.

Besides enhancing resource allocation, digital twins provide real-time surveillance of hospital activities. By consistently integrating data from diverse sources, healthcare administrators can make educated decisions that enhance operational efficiency. For instance, in the event of an unforeseen surge of patients, digital twins can facilitate the redistribution of resources to regions necessitating urgent intervention. Moreover, the use of digital twins can result in substantial cost reductions. By minimizing inefficiencies and optimizing procedures, healthcare facilities can distribute resources more efficiently, eventually benefiting both patients and providers. As the healthcare sector evolves, employing digital twins for operational efficiency will become increasingly vital [12].

3.2.5 Predictive analytics and decision-making assistance

When combined with digital twins, predictive analytics provides healthcare providers with critical insights into patient outcomes. Through the analysis of historical and real-time data, digital twins can predict patient health trajectories, enabling physicians to make informed decisions that improve care quality. This proactive strategy allows healthcare personnel to foresee probable difficulties and respond preemptively, thereby enhancing patient safety. Predictive analytics can identify patients at elevated risk for readmission, enabling healthcare professionals to establish customized follow-up programs. By analyzing diverse patient attributes and post-discharge variables, doctors may cater to individual requirements, thereby markedly diminishing the probability of readmission. This strategy not only improves patient care but also aids in managing healthcare expenses related to preventable hospital admissions. Moreover, digital twins enhance decision-making by amalgamating several data sources, offering clinicians a comprehensive perspective on patient health. This holistic viewpoint allows healthcare providers to account for all pertinent elements when formulating treatment regimens, resulting in improved outcomes. With the progression of predictive analytics, the incorporation of digital twins into clinical workflows will be essential for providing high-quality, evidence-based care [13].

3.2.6 Effects of artificial intelligence and machine learning

The incorporation of artificial intelligence (AI) and machine learning (ML) into digital twins signifies a substantial progression in healthcare technology. These technologies augment the analytical skills of digital twins by facilitating more advanced modeling and simulation of patient reactions to therapies. AI systems can evaluate extensive datasets from many sources, enabling digital twins to produce precise forecasts on medical outcomes based on real-time data. This data-centric methodology enables customized treatment strategies and enhances overall healthcare provision. AI and ML algorithms can enhance the operational facets of healthcare systems. Predictive modeling can uncover patterns in patient admissions and resource utilization, enabling healthcare facilities to deploy resources more efficiently. By anticipating patient demands, hospitals can maintain sufficient staffing levels, handle inventory efficiently, and optimize patient flow, boosting the overall patient experience.

Furthermore, the collaboration of AI, ML, and digital twins creates novel opportunities for study and innovation. As these technologies mature, they can aid in formulating sophisticated treatment protocols and clinical standards grounded in a thorough comprehension of patient health dynamics. This advancement will enhance patient outcomes and enable healthcare providers to make informed decisions utilizing real-time data and predictive insights.

3.2.7 Challenges of interoperability and data integration

The effective execution of digital twins in healthcare depends significantly on the capacity to amalgamate data from diverse sources, such as EHRs, IoT devices, and additional health information systems. Nonetheless, attaining interoperability continues to pose a substantial difficulty. Diverse data formats and systems can obstruct the fluid interchange of information, complicating the development of precise digital twin models. Healthcare organizations must prioritize the establishment of standardized data protocols and frameworks to facilitate data sharing and overcome these challenges. Initiatives that advocate for interoperability, such as the Fast Healthcare Interoperability Resources standard, seek to establish uniform interfaces for the interchange of health data. Healthcare practitioners can ensure the construction of their digital twin models on comprehensive and up-to-date patient data by adopting these criteria. Moreover, promoting collaboration among stakeholders—such as healthcare providers, technology developers, and regulatory agencies—is essential for addressing interoperability concerns. When these people work together, they can come up with new ways to make data integration easier and the use of digital twins more effective in clinical settings [14].

3.2.8 Regulatory and ethical considerations

The increasing utilization of digital twins in healthcare presents significant regulatory and ethical implications. As digital twin technology advances, regulatory authorities must formulate standards to guarantee patient safety, data privacy, and the ethical application of AI algorithms. Concerns around data consent, openness, and accountability are critical, particularly when digital twins depend on vast quantities of sensitive patient data. Healthcare providers must prioritize data security and privacy in the implementation of digital twins. This entails acquiring informed consent from patients for data gathering and ensuring the responsible and ethical use of patient information. Furthermore, as AI algorithms progressively influence clinical decision-making, it is essential to confront any biases inherent in these systems. Training algorithms on varied datasets helps decrease care inequities and enhance the fairness of digital twin applications [15]. Regulatory frameworks must adapt in tandem with technological changes. As digital twins increasingly integrate into clinical practice, it is imperative for regulatory authorities to regularly evaluate the safety and efficacy of new technologies. Healthcare organizations can effectively manage the intricacies of digital twin adoption by instituting explicit guidelines, hence upholding superior levels of patient care and safety [16].

3.2.9 Analysis of digital twin deployments

Case studies demonstrating effective digital twin applications in healthcare offer significant insights into optimal practices and acquired knowledge. A prominent example is the application of digital twins in hospitals for surgical planning and simulation. Surgeons can boost surgical precision and mitigate risks by developing intricate 3D models of patients' anatomies for the practice of complex procedures. Hospitals implementing this strategy observed enhanced patient outcomes and heightened surgeon confidence. A healthcare practitioner employed digital twins for the management of chronic disorders. By incorporating real-time patient data from wearable devices, the provider created virtual models that facilitated ongoing monitoring of patients' health conditions. This proactive strategy enabled healthcare practitioners to foresee difficulties and modify treatment strategies accordingly, leading to enhanced disease control and increased patient satisfaction. Additionally, a hospital system used a digital twin approach to enhance its operational efficiency. Through the simulation of patient flow and resource allocation, the institution pinpointed inefficiencies in its processes and executed data-informed modifications that improved patient care. This method enhanced operational KPIs and resulted in substantial cost reductions [17].

3.2.10 Prospective trajectories and advancements

As technology advances, there will be significant innovation in the use of digital twins in healthcare. A viable avenue is the enhanced integration of future technologies, including augmented reality (AR) and virtual reality (VR). These technologies will augment the visualization and interaction capabilities of digital twins, enabling healthcare practitioners to interact with patient data in immersive environments. These innovations could transform medical training and surgical planning, resulting in enhanced outcomes. We anticipate that the emphasis on patient-centered treatment will propel the advancement of more individualized digital twin applications. Future improvements may encompass interactive patient interfaces that allow patients to visualize their health data, treatment alternatives, and prospective results. This transition towards patient empowerment will not only improve their comprehension of health concerns but also promote adherence to treatment regimens. Moreover, as healthcare becomes progressively data-centric, the significance of cybersecurity in safeguarding patient information will intensify. The incorporation of blockchain technology could provide solutions for secure data sharing, safeguarding patient information while facilitating comprehensive digital twin models. This novel methodology may facilitate the widespread use of digital twins in diverse healthcare environments [18,19].

3.2.11 Digital twins for better patient engagement

Patients can take a more active role in their healthcare with the help of digital twins. Patients can see the potential effects of therapies, drugs, or lifestyle changes on their health by building virtual models of their bodies. People are able to make better decisions and stick to their treatment plans because of an interactive experience that simplifies complicated medical facts. Patients with long-term conditions, such as diabetes, can monitor their blood sugar levels in real-time and observe the effects of dietary, exercise, and pharmaceutical changes. Their therapy becomes more personalized as a result of these realizations, which in turn encourages individuals to take an active role in managing their health. Patients can also monitor their development over time with digital twins, which gives them concrete information about how well their treatment strategies are working. With the growing importance of patient participation in modern healthcare, digital twins provide a means to connect patients and practitioners. Better outcomes and greater happiness are the benefits of people using these tools to actively participate in their healthcare journey and ask educated questions [20].

3.2.12 Early diagnosis and real-time monitoring

By combining information from several sources, such as wearable devices and EHRs, digital twins make it possible to track a patient's vitals in real time. With this constant stream of information, doctors can see the big picture of a patient's health and identify problems before they become noticeable. For patients with cardiac issues, for instance, the digital twin might notify healthcare personnel of any serious changes in the patient's vital signs, allowing for continuous monitoring. Chronic condition management benefits greatly from the real-time capabilities of digital twins. Healthcare professionals can intervene and prevent issues by collecting data on important metrics, including blood pressure, heart rate, and glucose levels. This preventative method greatly enhances patient outcomes by lowering the frequency of hospital visits and the likelihood of emergency events. Furthermore, digital twins substantially improve early detection. These models can discover patterns and trends that indicate the start of a disease with the help of predictive analytics, even before conventional diagnostic methods can pick them up. For diseases like cancer, where prompt diagnosis is key to effective therapy, this paves the way for early intervention, which improves prognosis.

3.2.13 Digital twins for oncology precision medicine

Digital twins are revolutionizing the field of oncology by developing individualized cancer treatments. By simulating a patient's tumor growth in response to their unique genetic profile and environmental variables, these models enable physicians to personalize treatment plans for each patient's unique malignancy. Better, less intrusive methods of treating tumors are possible with the use of digital twins, which show how different treatments, such as radiation, immunotherapy, and chemotherapy, would react to a tumor. Digital twins can lessen the need for cancer therapy trial and error, which is one of their main advantages in oncology. Finding the optimal course of treatment for a patient often requires oncologists to try out different approaches. Digital twins remove a significant amount of uncertainty by providing simulations that illustrate the most effective treatments. This leads to fewer adverse effects for the patient and faster therapy modifications. Researchers can also use digital twins to model the virtual interactions between cancer cells and prospective treatments, which opens up new avenues for drug development. This advances precision medicine in oncology by hastening the development of game-changing treatments and guaranteeing the highly personalized testing of novel medications.

3.2.14 Utilizing virtual twins to enhance rehabilitation and recovery

When it comes to rehabilitation and recovery, digital twins play an even bigger role than they do in diagnosis and treatment. Digital twins can optimize recovery time by replicating the patient's anatomy and condition postsurgery or injury, allowing for the implementation of personalized rehabilitation programs. Take orthopedic surgery as an example. With the use of a digital twin of the patient's joint, therapists may see how various physical therapy exercises affect recovery and make adjustments to the routines to speed up the healing process. In addition, digital twins can provide continuous feedback on how well a patient is doing. Wearable sensors record motion and muscle activity data, which therapists can compare with the digital twin to ensure the recovery is proceeding as planned. By tailoring the program to meet individual needs, therapists can expedite patients' return to function and reduce the likelihood of problems if recovery is slower than anticipated. Digital twins encourage and support patients by enabling them to visualize their own progress toward their recovery goals. People are more likely to remain in their rehabilitation programs and achieve better results when they can see progress over time. Additionally, this technology promotes recuperation at home, resulting in fewer clinic visits while still closely monitoring the patient's progress.

3.2.15 Digital twin model integration with genomic data

Integrating genomic data into digital twin models increases the possibility for highly individualized treatment. Healthcare providers might anticipate a patient's response to therapies by incorporating their distinct genetic composition into the virtual twin. This method excels in predicting the likelihood of pharmaceutical side effects or the risk of developing specific diseases. To better understand which people have a higher risk of developing cardiovascular disease or a particular kind of cancer, for instance, digital twin models that incorporate genetics could be useful. In order to lessen the chances of illness starting, healthcare providers can use this information to create preventative care plans. These plans may include lifestyle changes and early interventions. This potential signifies a major departure from reactive treatment and toward preventative care. Pharmacogenomics uses digital twins enhanced with genetic data to choose the best medications for each patient. This level of accuracy enhances therapeutic results while reducing the likelihood of negative effects. The integration of genetic data with digital twins will greatly influence the future of personalized medicine. This will allow for unprecedented degrees of customization in patient treatment, thanks to the advancements in genomic technologies.

3.3 Devices in digital twin scenarios

3.3.1 Internet of Things sensors and devices

IoT sensors are crucial in digital twin technology, delivering real-time data on diverse aspects such as temperature, pressure, humidity, motion, and others. Temperature sensors are essential for monitoring climate control systems and industrial activities that necessitate accurate temperature regulation. Pressure sensors monitor system performance in manufacturing and avert failures. Accelerometers and gyroscopes are essential for monitoring movement and direction in automotive and robotics applications, whereas proximity sensors facilitate object recognition, hence enhancing operational efficiency on manufacturing lines. Environmental sensors can quantify parameters such as air quality and humidity, which are essential for assessing environmental impact and maintaining comfort in smart buildings. Energy meters play a crucial role in optimizing smart grid and building operations by providing data on power usage and efficiency. These IoT sensors enhance the fundamental operation of digital twins by providing detailed, real-time data on physical systems, allowing digital twins to precisely replicate real-world conditions. By collecting the data, IoT sensors assist digital twin systems in detecting anomalies, forecasting problems, and enhancing operations. In predictive maintenance applications, sensors can notify operators of anticipated equipment failures prior to their occurrence. The incorporation of IoT devices into digital twin technology connects the physical and digital realms, enabling the monitoring, control, and optimization of system performance with exceptional accuracy.

3.3.2 Edge devices

Digital twins utilize edge devices such as microcontrollers and microprocessors (e.g., Arduino, Raspberry Pi, NVIDIA Jetson) for real-time data processing at the network's periphery. These devices minimize latency by processing data locally, which is crucial for applications requiring instantaneous reactions, such as autonomous driving or industrial automation. Edge gateways are crucial for aggregating data from several sensors and conducting preliminary analysis prior to transmitting the processed information to the cloud or central servers. This method reduces bandwidth consumption and facilitates expedited decision-making, enhancing the efficacy of digital twin applications. Edge devices play a crucial role in enabling distributed processing, making them essential for extensive digital twin implementations. Edge devices can sustain system responsiveness by processing data near the source, even in remote areas with restricted internet connectivity. In situations where real-time management is essential, such as in manufacturing or health monitoring, edge computing guarantees that digital twins remain operational and precise, irrespective of network issues. The edge processing capability enables digital twins to manage extensive data volumes while alleviating the burden on cloud resources, hence enhancing operational cost-effectiveness and resilience.

3.3.3 Cameras and machine vision systems

Cameras and machine vision systems play a crucial role in digital twin setups, offering visual insights that facilitate real-time monitoring and analysis. CCTV cameras play a crucial role in maintaining security by continuously monitoring and detecting any unauthorized entry in buildings. Advanced machine vision systems like 3D scanners and LIDAR collect spatial data in three dimensions, giving detailed representations of physical objects and environments. Construction, automotive, and robotics fields often utilize these technologies, as high-resolution spatial data aids in tasks such as quality control, mapping, and navigation. Infrared cameras, a type of machine vision, capture thermal data. They play a significant role in predictive maintenance and enhance energy efficiency. These cameras can spot heat patterns, which helps in finding equipment that is overheating or not insulated well, allowing for proactive maintenance. By using both visual and thermal data, machine vision systems help create digital twins that offer a complete understanding of their surroundings. This leads to improved predictions and a better grasp of the state of physical assets.

3.3.4 Actuators and control devices

Actuators and control devices, like servo motors and robotic arms, play a crucial role in digital twin implementations. They enable the digital twin to affect or mimic actions in the real world. Servo motors allow for accurate movement and positioning, and they're often used in robotics and automated manufacturing processes. Actuators take control signals and turn them into actual movement, which allows digital twins to manage machines from afar and change settings instantly. Robotic arms are commonly found in assembly lines and can replicate programmed actions from digital twin simulations, which helps keep physical and digital operations in sync. Programmable logic controllers (PLCs) play an important role in industrial automation by handling inputs from sensors and controlling different machines. These devices are strong and dependable, made to endure tough industrial settings and manage complicated control tasks. Integrating with digital twins allows PLCs to adjust machinery in real-time based on predictive insights, which helps in achieving optimal performance. Actuators and control devices act as the physical link for digital twins, connecting digital simulations with real-world actions.

3.3.5 Network and communication devices

Network and communication devices, such as 5 G and LTE modems, Wi-Fi, and Ethernet connections, facilitate data transmission between physical devices and digital twin systems. High-speed cellular modems, including 5 G and LTE, offer low-latency connectivity, which is crucial for applications that depend on real-time data, such as autonomous vehicles and industrial automation. Wi-Fi and Ethernet serve as prevalent connectivity solutions that facilitate communication between IoT devices and cloud platforms or centralized databases, thereby ensuring a smooth data flow within digital twin systems. Bluetooth and Zigbee find extensive application in digital twins, particularly for short-range communications within smart buildings and residences. Wireless protocols are frequently utilized in IoT networks that require close-range, low-power communication. The success of digital twin applications is significantly dependent on strong and efficient network connections, as seamless communication guarantees that the digital twin stays current with the status of its physical counterpart. Dependable networking devices are essential for successful digital twin implementations.

3.3.6 Wearable devices

Wearable devices, including smartwatches and fitness trackers, are becoming more integrated into digital twins, particularly in the fields of healthcare and workforce management. These devices track health metrics such as heart rate, activity levels, and stress, delivering real-time data to digital representations of patients or workers. Integrating wearable data allows digital twins in healthcare to provide tailored insights, proactive alerts, and predictive analytics for effective health management. In industrial settings, wearables have the capability to monitor worker safety and productivity, delivering crucial insights for ensuring optimal working conditions. AR and VR headsets serve as important instruments in digital twin applications, enabling users to experience digital twin models within immersive 3D environments. For instance, professionals can utilize AR glasses to superimpose digital twin information onto actual machinery, enhancing the precision and effectiveness of maintenance tasks. These devices improve the interactivity of digital twins by allowing users to interact directly with virtual models, offering a practical method for comprehending complex systems and enhancing training and operational efficiency.

3.3.7 Cloud computing and storage

Cloud platforms like AWS, Microsoft Azure, and Google Cloud offer the necessary computing and storage resources to effectively process, store, and analyze the substantial amounts of data produced by digital twins. Cloud computing facilitates scalable and high-performance data processing, which is crucial for simulations and real-time analytics. Utilizing cloud resources allows digital twins to perform intricate calculations and extract insights from historical data, supporting informed decision-making across multiple sectors. Cloud-based data lakes and warehouses serve as repositories for extensive historical data derived from digital twin applications. This data serves as the basis for predictive modeling and trend analysis, enabling digital twins to deliver important insights into system performance and future results. Cloud computing enhances the scalability, accessibility, and analytical capabilities of digital twins, facilitating their application across various fields, including healthcare and smart cities.

3.3.8 Computational devices

High-performance computers (HPCs) play a vital role in digital twin simulations that demand significant processing capabilities, particularly in sectors like aerospace, manufacturing, and healthcare. High-performance computing systems are capable of managing intricate models and substantial data flow, facilitating precise simulations of real-world scenarios. Graphics processing units (GPUs) play a vital role in digital twin technology by delivering the necessary processing power to execute ML algorithms, particularly in data-heavy fields such as automotive, healthcare, and energy. The application of high-performance computing and GPUs allows digital twins to execute intricate simulations and process data in real-time, yielding insights that traditional computing capabilities cannot achieve. In applications such as virtual prototyping and predictive maintenance, these computational devices enable precise modeling and swift analysis, improving the accuracy and dependability of digital twin technology.

3.3.9 Artificial intelligence and machine learning software

AI and ML technologies, such as TensorFlow and PyTorch, are crucial for analyzing data from digital twins, facilitating predictive insights and automated decision-making. ML algorithms can evaluate trends, identify anomalies, and forecast future events utilizing real-time and historical data. This feature is particularly advantageous in intricate systems like as manufacturing or energy grids, where AI can detect inefficiencies and propose optimizations. Specialized digital twin platforms, including Siemens Mindsphere and GE Predix, offer specific environments for the creation, management, and analysis of digital twins. These platforms amalgamate IoT data, AI algorithms, and visualization tools to provide intricate and dynamic digital representations of physical systems. Utilizing AI and ML, digital twins may offer enhanced insights and adjust to evolving situations, rendering them an invaluable resource for predictive maintenance, resource management, and operational efficiency.

HPCs are essential for digital twin simulations, necessitating significant processing capacity, particularly in aerospace, industrial, and healthcare sectors. HPCs can manage intricate models and substantial data throughput, facilitating precise simulations of real-world situations. GPUs are essential in digital twin technology, as they deliver the computational capacity required for executing ML algorithms, particularly in data-intensive sectors such as automotive, healthcare, and energy. The utilization of HPCs and GPUs allows digital twins to conduct intricate simulations and real-time data processing, yielding insights unattainable with traditional computing capabilities. In applications like virtual prototyping and predictive maintenance, these computational devices provide precise modeling and swift analysis, hence improving the accuracy and dependability of digital twin technology.

3.3.10 Data integration and management tools

Data integration technologies, such as Apache Kafka and Apache NiFi, facilitate uninterrupted data transfer among sensors, edge devices, and digital twin applications. These instruments consolidate and analyze data from multiple sources, guaranteeing that digital twins obtain precise and prompt information. Data integration platforms are essential for large-scale digital twin implementations, requiring real-time synchronization and analysis of data from several devices and locations. APIs and middleware serve as middlemen, enabling communication between various systems and software in digital twin applications. These tools facilitate interoperability through common interfaces, enabling digital twins to extract data from various sources and consolidate it into a cohesive model. Data integration and management solutions make it easier for digital twins to work together smoothly. They keep the flow of information going and allow for expansion in complex, data-heavy places like smart cities, healthcare, and manufacturing. The applications of advanced technologies in healthcare as shown in Table3.1.

Table 3.1 Applications of advanced technologies in healthcare.

Medical application	Focus area	Data/ inputs used	Key benefits	Challenges	Current adoption	Patient outcomes
Surgical planning	Pre-surgery simulation	Imaging data, patient history	Reduced surgical errors, personalized planning	Integration with hospital systems	Growing adoption in advanced hospitals	Shorter recovery times, fewer post-surgical complications
Rehabilitation	Physical therapy optimization	Wearable sensors, patient feedback	Faster recovery, customized exercise plans	Lack of interoperability between devices	Limited to specialized rehab centers	Enhanced patient adherence, faster progress
Oncology	Personalized cancer treatment	Genomic data, imaging	Precision medicine, fewer side effects	Ethical concerns about genetic data use	Early-stage adoption	Increased treatment success, minimized trial-and-error
Preventative care	Early disease detection	Genomic data, wearable data	Early intervention, reduced healthcare costs	High initial setup cost	Growing in wellness clinics	Fewer heart attack cases, reduced emergency admissions
Cardiology	Remote heart monitoring	Wearable ECG, heart rate monitors	Early detection of abnormalities, continuous monitoring	Data privacy concerns	Common in cardiology clinics	Reduced cardiac events, lower readmission rates
Diabetes management	Continuous glucose monitoring	Glucose sensors, insulin data	Improved glycemic control, reduced complications	Device cost, limited insurance coverage	Moderate adoption in diabetes care	Fewer hypoglycemic events, better quality of life
Neurology	Epilepsy seizure prediction	EEG data, wearable sensors	Reduced seizure frequency, early alerts	High false-positive rates in prediction	Limited to research settings	Improved safety, reduced injury risk

(*Continued*)

Table 3.1 (Continued)

Medical application	Focus area	Data/ inputs used	Key benefits	Challenges	Current adoption	Patient outcomes
Respiratory care	Asthma management	Spirometry, wearable sensors	Personalized treatment, fewer asthma attacks	Device accuracy, limited interoperability	Slowly growing in respiratory clinics	Reduced ER visits, better asthma control
Mental health	Depression and anxiety monitoring	Mobile app data, wearable stress indicators	Early intervention, personalized care	Data security and privacy concerns	Emerging telehealth and wellness apps	Reduced severity of symptoms, better daily functioning

3.4 Application of deep learning

3.4.1 Convolutional neural networks

Mostly used to interpret pictures and other grid-like input, convolutional neural networks (CNNs) are specialized deep learning architectures. They are especially useful for jobs involving object detection and image classification because they automatically learn spatial hierarchies of features using convolutional layers. CNNs are essential for medical image analysis in the field of healthcare because they provide quick and precise evaluations of problems like tumors or fractures. In the context of digital twins, CNNs can generate real-time models of a patient's anatomy from continuous imaging data. For instance, oncologists can track tumor growth or treatment response by updating a patient's digital twin with regular scans. Better patient outcomes result from more informed healthcare decisions made possible by the ability to see these changes over time. The detection of lung cancer using chest X-rays is a noteworthy use of CNNs in healthcare. Large collections of labeled photos can train a CNN to recognize cancerous tumors. When incorporated into a digital twin structure, this technique can enable continuous monitoring and send out notifications in the event of new lesions, guaranteeing prompt response [21,22].

3.4.2 Recurrent neural networks

Recurrent neural networks' (RNNs) capacity to process sequential data is ideal for time-series analysis. RNNs store knowledge about prior inputs in their hidden states while processing input data in succession. They are appropriate for applications like speech recognition and natural language processing, where the sequence of data points is crucial because of their capacity to retain context. RNNs can be used in healthcare digital twin models to assess patient data over time, such as test results or vital signs. RNNs can forecast future states by identifying the temporal connections in a patient's medical data, allowing for proactive therapies. For example, using previous data, an RNN could assist in predicting changes in a diabetic patient's blood sugar levels. Predicting cardiac events is a useful use of RNNs in health monitoring. An RNN can be trained on heart rate data sequences obtained from wearables to identify patterns linked to arrhythmias. When combined with a digital twin, this device might keep an eye on the patient's health and notify medical professionals of any problems, allowing for prompt treatment [23,24].

3.4.3 Long short-term memory networks

To overcome some of the shortcomings of conventional RNNs, particularly the vanishing gradient issue, researchers created a specific type of RNN known as long short-term memory networks (LSTMs). To efficiently learn long-term dependencies, LSTMs employ unique gating techniques to regulate the input flow. Because of this, LSTMs are especially well-suited for applications involving lengthy data sequences. By simulating patient health trajectories across time, LSTMs can be extremely helpful in the creation of digital twins. LSTMs can produce predictions about future health conditions by analyzing past patient data, allowing medical professionals to adjust treatment regimens appropriately. An LSTM, for example, might assist in anticipating the course of chronic illnesses, facilitating prompt interventions. Heart failure patients use LSTMs to forecast hospital readmission rates. By training on a patient's past medical records, including admissions, discharges, and treatment outcomes, an LSTM can identify trends that indicate a high risk of readmission. Individualized care plans can decrease readmission risks by incorporating this data into a digital twin [25,26].

3.4.4 Gated recurrent units

Gated recurrent units (GRUs), a condensed form of LSTMs, also aim to identify temporal connections in sequential input. Compared to LSTMs, GRUs use fewer parameters, allowing for faster training without compromising performance in various applications. When computational resources are scarce, people frequently use GRUs due to their effectiveness. GRUs can be used in digital twins to track and forecast patient health using time-series data, like blood pressure or heart rate. GRUs can give healthcare professionals real-time insights and alarms by utilizing their capacity to handle sequential data, enabling more rapid patient care. Wearable medical devices can use GRUs to monitor vital signs and physical activity. For instance, a digital twin that integrates information from a smartwatch can use a GRU to examine daily activity patterns and forecast any health hazards. This predictive capacity may encourage patients to adopt lifestyle modifications that reduce their risk of developing chronic illnesses [27,28].

3.4.5 Autoencoders

Autoencoders are neural networks designed to create effective data representations through unsupervised learning. A decoder reconstructs the original data, while an encoder compresses incoming data into a lower-dimensional space. Autoencoders are especially useful for applications like dimensionality reduction and anomaly detection because of this structure. The healthcare industry can use autoencoders to construct digital twins that identify and scrutinize patterns in complex patient data. Autoencoders can assist in identifying abnormalities that can point to new health problems by learning a condensed representation of patient health parameters. Proactive health monitoring and early intervention depend on this competence. Identifying irregularities in EHRs is one real-world use for autoencoders. The algorithm can detect anomalous patterns that might point to mistakes or other health hazards by using past patient data to train an encoder. When integrated into a digital twin architecture, this technology enhances patient safety by promptly notifying medical professionals of any irregularities [29,30].

3.4.6 Generative adversarial networks

Two neural networks—a discriminator and a generator—compete with one another in generative adversarial networks (GANs). The discriminator assesses the legitimacy of the generated data, whereas the generator produces artificial data. Thanks to this adversarial training process, GANs can generate high-quality synthetic data that closely mimics real data, making them useful in situations where data is scarce. The healthcare industry can use GANs to supplement current datasets with artificial patient data, particularly for uncommon illnesses. By ensuring they have adequate data to produce precise predictions and evaluations, this can improve the training of ML models used in digital twins. The production of artificial medical images for training is a noteworthy use of GANs. For example, radiologists may train on a wider range of datasets thanks to GANs' ability to produce realistic MRI that mimic different clinical states. This feature can increase the training of AI models used for image analysis and enhance diagnostic accuracy when incorporated into a digital twin environment [31–33].

3.5 Machine learning algorithm

The produced synthetic patient dataset comprises diverse health-related variables for 1000 individuals. Each patient receives a unique "Patient ID," and their "age" ranges from 18 to 90 years. The dataset includes "heart rate" (ranging from 60 to 100 bpm), "systolic BP" and "diastolic BP" values indicative of standard blood pressure ranges, and "oxygen saturation" levels between 95% and 100%. Additionally, the dataset specifies "body temperature" within a range of 36.1°C–37.2°C. We simulate a binary "Diabetes" variable, which indicates whether a patient has diabetes (1) or not (0). This dataset is applicable for health monitoring and digital twin simulations.

The dataset of patient health variables was used to construct and assess ML models for diabetes prediction. The program first produces random patient data, encompassing age, heart rate, blood pressure, oxygen saturation, body temperature, and a binary diabetes result. We then organize the dataset into a Pandas dataframe and store it as a CSV file. Upon loading the dataset, the code distinguishes the features from the target variable (diabetes) and partitions the data into training and testing sets. We normalize the features to ensure that all variables contribute uniformly to the model training.

This application implements three ML models: logistic regression, random forest, and a stacking classifier that integrates the former two models with gradient boosting. We train each model using the training dataset and generate predictions on the test set.

We compute and display the accuracy metrics for each model, providing a definitive comparison of their efficacy. Furthermore, we produce comprehensive categorization reports that include parameters like precision, recall, and F1-score for each model.

A classification algorithm's precision is a metric that shows how well its positive predictions work. It is calculated as the ratio of true positives, or cases that were accurately predicted to be positive, to the total of false positives, or instances that were mistakenly categorized as positive. When the cost of false positives is significant, precision is especially crucial. Precision is essential in medical diagnostics, for instance, as a false positive could result in needless therapies or additional tests. Precision in spam detection reduces the number of valid emails incorrectly classified as spam. In situations where inaccurate positive predictions might have serious repercussions or cause customer discontent, high precision indicates that the classifier is making fewer mistakes when identifying something as positive.

Recall, also known as sensitivity or true positive rate, indicates the effectiveness of the classification system in identifying genuine positive cases. We find recall by adding up the number of true positives to the number of false negatives, which are real positive cases that the model missed. Recall is crucial when capturing all the positive cases, even if some of the negative ones are misclassified. For instance, a high recall ensures the detection of most fraudulent transactions, even if it necessitates the reexamination of a few valid transactions. Similarly, high memory ensures the detection of most disease cases during disease screening, thereby reducing the risk of incorrect diagnosis. When missing accurate cases is very dangerous, you need a model with a high recall, even if it means giving up some precision.***

The F1-score is the average of precision and recall, and it gives us a single measure that is fair for both. If there are different numbers for each class or if both false positives and false negatives cost something, the F1-Score is very useful. The F1-score gives a more complete picture of a model's performance by balancing precision and recall. This is especially useful when you need to find all positive cases while reducing the number of false positives. When datasets lack balance, relying solely on accuracy would be incorrect. For instance, in a dataset consisting of 95% negative cases and 5% positive cases, a model that consistently guesses negatively will yield a high accuracy rate, but a low F1-score. This shows how important it is to have a balanced measure like the F1-Score.

Support is the number of real instances of each name in the dataset. This number shows how many samples are in each class. It is not a performance measure by itself; it just gives the metrics some background by showing how many examples there are for each class. On the other hand, in a classification report, if a class has low support, the small sample size could make the precision, recall, and F1-score for that class less accurate.

Determining the reliability of performance metrics is crucial, particularly when dealing with imbalanced datasets and underrepresented classes. If a classifier performs well in a class with high support but poorly in a class with low support, it may indicate that the model requires modification or additional data in the poorly represented class. Support information assists stakeholders in determining whether the success metrics apply to all classes or if the model requires additional work for classes with lower support.

The program incorporates visualizations for confusion matrices, receiver operating characteristic (ROC) curves, and feature importance to enhance the assessment of model performance. The confusion matrices demonstrate the predictive accuracy of each model for diabetes by displaying true positives, false positives, true negatives, and false negatives. The ROC curves elucidate the balance between sensitivity and specificity, with the area under the curve (AUC) serving as a comprehensive metric of model efficacy. Finally, the feature importance plot for the Random Forest model elucidates the contributions of several health indicators to diabetes prediction, facilitating a clearer comprehension of the most relevant aspects in the model's decision-making process.

3.5.1 Result and discussion

Table 3.2 provides a summary of the models' performance, detailing the accuracy results for Logistic Regression, Random Forest, and Stacking Classifier. The Logistic Regression model attained an accuracy of 0.5733, suggesting a satisfactory level of predictive performance. Conversely, the Random Forest and Stacking Classifier models exhibited accuracies of 0.5133 and 0.4900, respectively, which are lower than expected. This indicates that the Logistic Regression model demonstrated greater effectiveness in classifying the data within this specific context.

The classification report for the Logistic Regression model is detailed in Table 3.3. The precision values for Class 0 (0.57) and Class 1 (0.59) reflect a well-calibrated capacity to reduce false positives in both categories. The model demonstrates a recall score of 0.80 for Class 0, indicating a robust ability to accurately identify the majority class. However, the recall for Class 1 shows a notable decline to 0.32. This disparity

Table 3.2 Accuracy results.

Model	Accuracy
Logistic Regression	0.5733
Random Forest	0.5133
Stacking Classifier	0.49

Table 3.3 Logistic regression classification report.

Metric	Class 0	Class 1	Macro Avg	Weighted Avg
Precision	0.57	0.59	0.58	0.58
Recall	0.8	0.32	0.56	0.57
F1-Score	0.66	0.42	0.54	0.55
Support	158	142	300	300

suggests a possible concern regarding class imbalance, as the model appears to struggle with accurately identifying instances of the minority class (Class 1). The F1-score of 0.66 for Class 0 and 0.42 for Class 1 highlights the existing imbalance, indicating that the model demonstrates strong performance for Class 0, yet encounters difficulties with Class 1.

The performance metrics of the Random Forest model presented in Table 3.4 indicate comparable trends. The precision for Class 0 stands at 0.53, which is marginally lower than Class 1, recorded at 0.48. The recall scores of 0.63 for Class 0 and 0.39 for Class 1 indicate that, similar to the Logistic Regression model, the Random Forest model also struggles with accurately identifying the minority class. The F1-Score, representing a harmonic mean of precision and recall, shows that the Random Forest model exhibits similar performance to Logistic Regression for Class 0 (0.58), while demonstrating reduced effectiveness for Class 1 (0.43).

The outcomes for the Stacking Classifier, as shown in Table 3.5, highlight the difficulties associated with class imbalance. The precision and recall metrics are the least favorable among the three models, especially for Class 1, which exhibits a recall of merely 0.25. The data indicate that the Stacking Classifier demonstrates the lowest efficacy in identifying the minority class, yielding an F1 score of 0.31. The observed decrease in performance across all metrics for the Stacking Classifier suggests that the integration of the individual models failed to enhance predictive capability in this instance.

The overall performance underscores a prevalent issue in classification tasks: the possible effects of class imbalance. Logistic Regression demonstrates effectiveness as a

Table 3.4 Random forest classification report.

Metric	Class 0	Class 1	Macro Avg	Weighted Avg
Precision	0.53	0.48	0.51	0.51
Recall	0.63	0.39	0.51	0.51
F1-Score	0.58	0.43	0.5	0.51
Support	158	142	300	300

Table 3.5 Stacking classifier classification report.

Metric	Class 0	Class 1	Macro avg	Weighted avg
Precision	0.51	0.43	0.47	0.47
Recall	0.71	0.25	0.48	0.49
F1-Score	0.59	0.31	0.45	0.46
Support	158	142	300	300

model; however, its inadequate performance on Class 1 prompts questions regarding its suitability in contexts where the identification of minority classes is essential. Future work may include investigating methods like oversampling the minority class, under-sampling the majority class, or utilizing sophisticated algorithms aimed at tackling class imbalance, including Synthetic Minority Over-sampling Technique (SMOTE) or ensemble techniques that concentrate on enhancing predictions for the minority class.

The logistic regression model demonstrates a notable capacity for accurately classifying instances of Class 0, achieving 126 true positives and merely 32 false negatives. This demonstrates a significant recall for the majority class, as illustrated in Fig. 3.1. The model exhibits challenges with Class 1, accurately identifying only 46 instances, which leads to 96 false positives. This discrepancy underscores the model's inclination towards Class 0, as evidenced by its overall performance metrics. Because of the strong results in Class 0 and the big mistakes seen in Class 1, it is clear that future model improvements need to address class imbalance. The Random Forest model illustrates a somewhat distinct situation. The model accurately identifies 91 instances of Class 0; however, it misclassifies 67 instances as Class 1, resulting in a recall of 0.57 for Class 0. Fig. 3.2 illustrates that the model accurately identifies 53 instances in Class 1, but misclassifies 59 instances as Class 0.

This model demonstrates superior performance compared to logistic regression in minimizing false negatives for Class 1; however, it continues to show a considerable level of misclassification across both classes. The performance analysis reveals that the Random Forest model exhibits more balanced precision and recall scores compared to

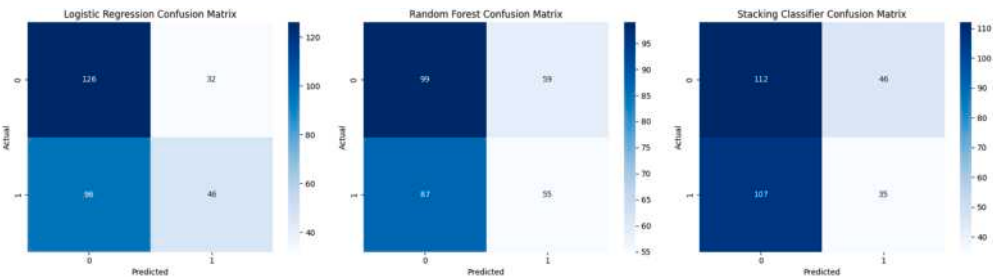

Figure 3.1 Logistic regression confusion matrix.

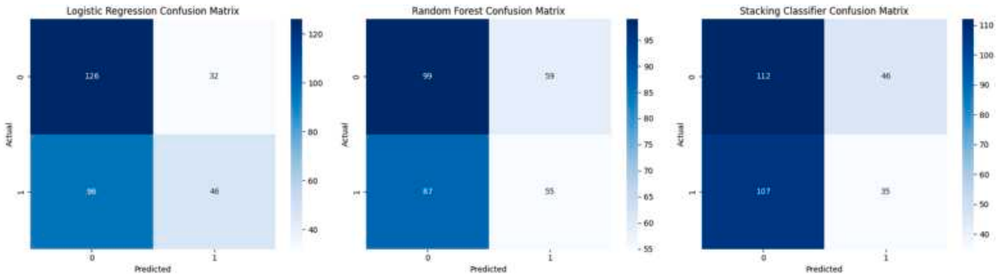

Figure 3.2 Stacking classifier confusion matrix.

the Logistic Regression model; however, it continues to face challenges in effectively identifying the minority class.

The Stacking Classifier demonstrates the lowest level of effectiveness when compared to the other two models. Fig. 3.3 illustrates the analysis, which accurately identifies only 112 instances of Class 0, while misclassifying 46 instances as Class 1. In Class 1, there is a notable misclassification of 207 instances as Class 0, leading to a considerably low recall score. The subpar performance highlights the difficulties associated with the Stacking Classifier in this scenario, as it merges the limitations of its individual models rather than leveraging their advantages. The confusion matrix reveals an opportunity for enhanced optimization and tuning to elevate performance, particularly in the accurate identification of the minority class.

The confusion matrices collectively illustrate the challenges faced in accurately classifying the minority class across all models. The logistic regression model exhibits superior overall accuracy and recall for Class 0; however, its performance for Class 1 is insufficient. The Random Forest model demonstrates a marginally improved balance; however, it remains inadequate in effectively tackling the class imbalance problem. The Stacking Classifier, although theoretically appealing, fails to achieve the anticipated performance improvements and underscores the need for further efforts in model optimization and possible rebalancing of the training dataset. In the future, researchers may look into ways to improve classification performance, especially when it comes to

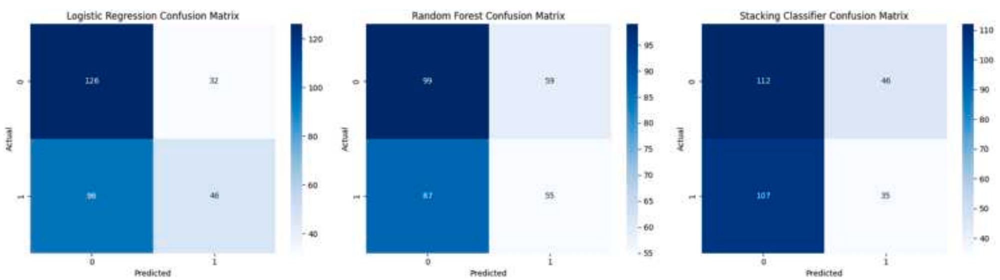

Figure 3.3 Random forest confusion matrix.

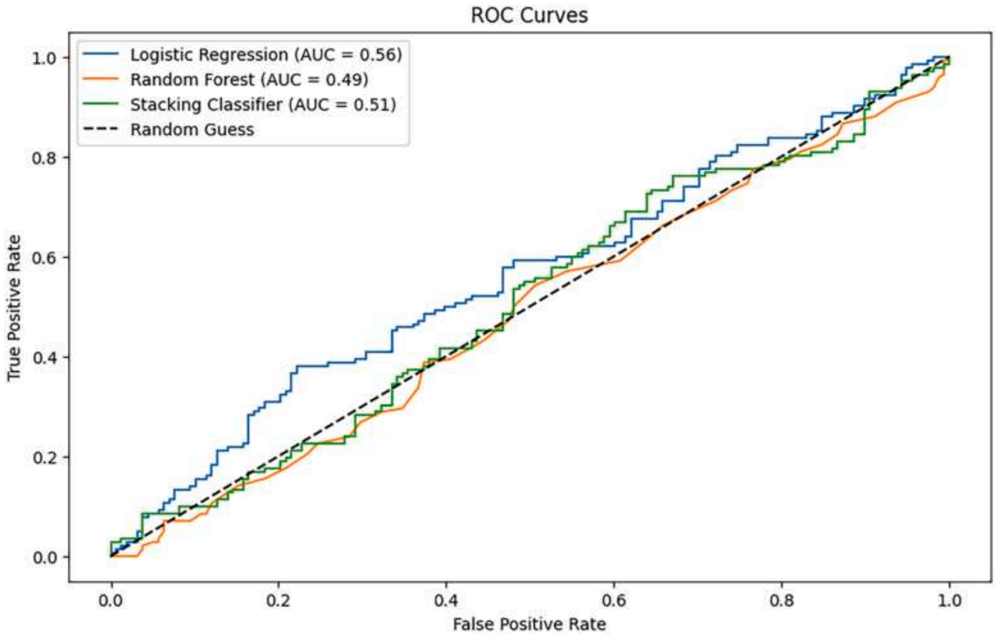

Figure 3.4 ROC curves comparative analysis. *ROC*, receiver operating characteristic

the minority class. These methods could include resampling strategies, algorithm changes, or the use of cost-sensitive learning. Adding more performance metrics, like the ROC curves shown in Fig. 3.4 and AUC, could also give us more information about how well the model is working and help find the best classifier for the given dataset.

The study looked at how well Logistic Regression, Random Forest, and Stacking Classifier models worked. It found that Logistic Regression had the best accuracy, at 0.5733, which shows how well it can predict the future. Nonetheless, it demonstrated a notable class imbalance, achieving a recall of 0.80 for Class 0 while only attaining a recall of 0.32 for Class 1, which suggests a preference for the majority class. Random Forest demonstrated a marginally improved balance; however, it continued to face challenges with Class 1, attaining a recall of 0.39. The Stacking Classifier exhibited the lowest performance, achieving a recall of merely 0.25 for Class 1, indicating that the integration of models did not enhance overall effectiveness. The results show how complicated class imbalance is and how more research needs to be done on improving the identification of minority classes using techniques like oversampling, undersampling, or complex algorithms like SMOTE. In summary, although Logistic Regression yielded the highest performance, the significant misclassification of Class 1 indicates a need for additional model optimization and a concentrated effort on mitigating class imbalance to enhance classification efficacy in imbalanced datasets.

3.6 Conclusion

This study found that logistic regression was the most effective model, attaining an accuracy of 0.5733; nevertheless, it faced challenges with class imbalance, recording a high recall of 0.80 for the majority class (Class 0) and a significantly lower recall of 0.32 for the minority class (Class 1). The Random Forest exhibited a somewhat improved balance but continued to struggle with Class 1, whereas the Stacking Classifier underperformed, achieving a recall of merely 0.25 for Class 1. The results show that even though logistic regression was the most accurate, all of the models had a challenging time reliably identifying the minority class. This demonstrates the need for more advanced methods, such as SMOTE or cost-sensitive learning, to enhance performance in imbalanced datasets.

AI disclosure

During the preparation of this chapter, the author(s) used Quillbot in order to make the content more readable, improve the quality of the sentences, and check the grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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CHAPTER 4

Revolutionizing health care: the role of digital twins in personalized medicine

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4.1 Introduction to digital twin health system

The sharing of medical data using technology methods between medical teams from distinct organizations takes place as part of Health Information Exchange (HIE). Healthcare Information Exchange serves to boost healthcare delivery safety alongside efficiency by providing secure, fast access to clinical data for healthcare providers. Through this system, interoperable healthcare platforms can exchange and cooperate with each other, thereby enabling patient-centered care delivery. HIE remains in a state of continuous advancement because national and state, and local entities execute initiatives to change healthcare delivery. The power of modern technology enables Healthcare Interoperability to deliver essential improvements throughout all aspects of contemporary healthcare delivery. The healthcare industry benefits from HIE through both nurse administrative process optimization and emergency patient data accessibility, which drive important improvements in overall healthcare efficiency. Medical facilities use HIE technology to provide urgent access to essential medical records, which both reduces errors and leads to better outcomes [1].

As a broader concept, eHealth builds upon advanced information and communication technologiesto provide healthcare services for patients and providers together with professionals and those responsible for making health policy decisions. Health information technology gathers medical applications such as electronic health records (EHRs), telemedicine services, wearable health monitoring devices and health information portals, and mobile health apps under its umbrella. The technology provides simplified medical services together with individual-driven healthcare control systems. Through telemedicine, patients in distant locations can use video conferences to receive specialist medical help, which eliminates travel needs and helps save costs of time and financial resources. Wearable fitness trackers generate live health information, which healthcare professionals can use to adjust their treatment strategies for patients.

Metaconstructs
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части von eHealth automatizes healthcare provider workloads by simplifying administrative work and streamlining data workflow processes.

When the term eHealth emerged during the late 1990s, researchers adapted it from similar terms like eCommerce and eBusiness to showcase technology's disruptive power in their domains. Business and marketing experts first introduced the term before healthcare professionals secured its use as they demonstrated the digital technology and internet potential to reshape healthcare infrastructure. The collaborative effort combining healthcare and technological leadership defines eHealth, as Intel Corporation observes. This partnership works to maximize internet-based health services delivery. The healthcare industry now relies heavily on eHealth technologies, which help solve major healthcare problems. Patients access healthcare providers directly through online services, including appointment scheduling and viewing test results, and healthcare institutions connect data efficiently, and patients create digital communities to exchange information with each other. The illustrations show the structure of the e-health system in Fig. 4.1 [2].

The effects of eHealth transcend technology because it completes a core transformation of both healthcare culture and operational structure. Through digital connectivity of health records, eHealth enhances care quality so medical practitioners can prevent duplicate assessments that betray documentation from previous providers.

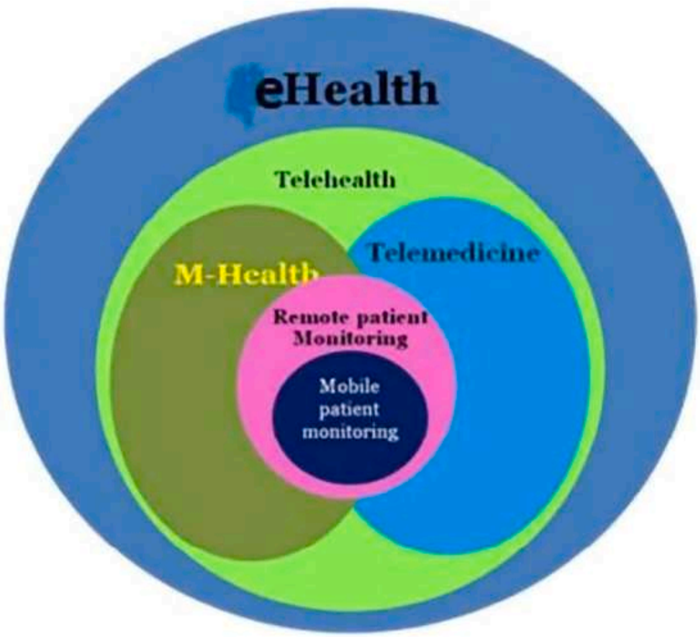

Figure 4.1 Health view system.

Through data and health record accessibility to patients, eHealth functions as an empowerment tool, building joint patient-care provider partnerships. E-Health faces multiple difficulties, including how to bridge digital disparities while protecting health data against unauthorized access, alongside safeguarding patient confidentiality.

4.2 Health view system

The visualization in Fig. 4.2 shows eHealth at the intersection of Public Informatics, Medical Informatics, Medical Imaging Bioinformatics data. Each of these disciplines focuses on distinct areas of health and science: population health stands as the primary focus of Public Informatics, while Medical Informatics focuses on clinical processes and patient care, and Medical Imaging interprets body tissues through visual display, and Bioinformatics researches cellular and molecular genetic information. The various connections show how eHealth functions as an interdisciplinary domain that unites technological aspects and healthcare concepts [3].

The academic world has an ongoing discussion about defining eHealth precisely. A few academic scholars contend that eHealth functions more effectively as a business marketing concept than it does in scientific communication. One Journal of Medical Internet Research (JMIR) Editorial Board member suggests eHealth finds stronger expression in commercial and promotional contexts, which implies a lack of scientific clarity in medical terminology.

Following varied scholarly hesitance regarding the definition of eHealth, this term nevertheless finds widespread endorsement in scientific discussions. The medical research community recognizes the growing importance of "eHealth" through the usage of this term in at least 76 Medline-indexed articles that appear in titles or abstracts.

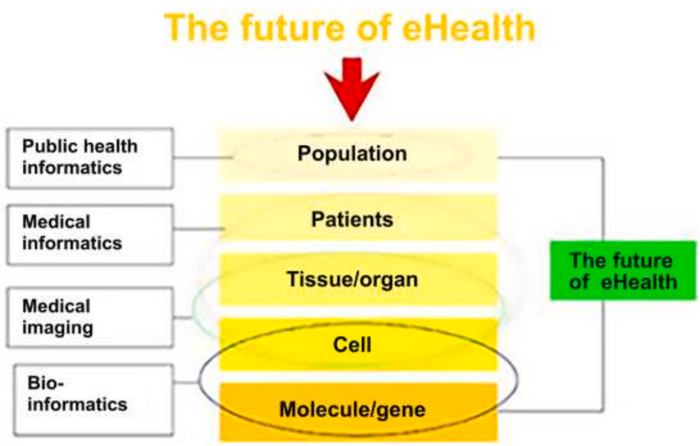

Figure 4.2 Knowledge level in system.

Academic experts must establish a unified definition for eHealth within the scholarly domain since current efforts have not reached full agreement. Others emphasize eHealth remains a fluid concept because it continues to evolve, thus making definition tasks challenging. In a comparison of defining eHealth to defining the Internet, one JMIR Editorial Board member underscored both concepts' dynamic nature and their development as shaped by their applications. The scholarly community needs constant efforts for adapting and refining the eHealth definition to capture its mutable dimensions as it advances, Fig. 4.3 [4].

4.3 Convergence of health system

Technology advances beyond its operational role because eHealth connects medical informatics to public health while integrating business applications. eHealth incorporates online healthcare service provision and information advancement through Internet-enabled technologies, as shown in Fig. 4.3. The management of healthcare by information and communication technology serves both as a framework for global interconnected thinking and as a commitment to improve medical services at local and regional, and worldwide levels. The "e" in eHealth both represents electronic technology while enforcing multiple essential standards.

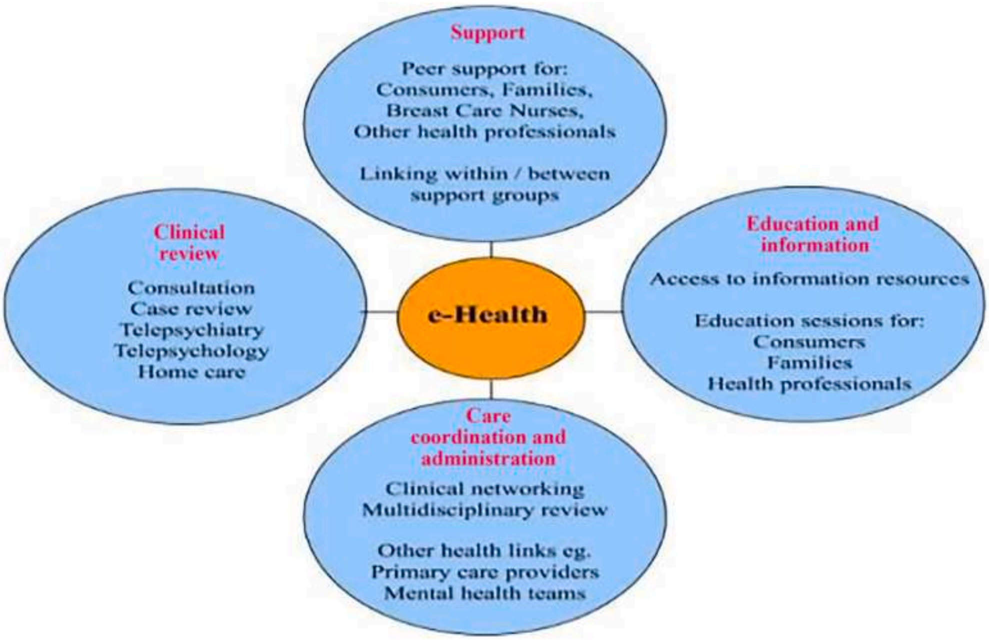

Figure 4.3 Convergence of digital twin eHealth.

Academic journals like the Journal of Medical Internet Research frequently explore objectives and potential of eHealth through their articles.

One essential purpose of eHealth systems involves making healthcare more efficient while creating cost reductions. Effective eHealth implementation leads to reduced healthcare expenses while streamlining clinical diagnostics and delivering better interinstitutional teamwork and promoting patient-oriented medical strategies. The quality of care gets improved through eHealth by letting patients check provider services, along with enhancing quality assessments and leading patients toward optimal healthcare selections.

The foundational principle of eHealth depends on evidence-based practice standards because all implementation initiatives require strict scientific reviews to show measurable performance metrics. Through eHealth, patients gain both medical information and control over their health records online, which supports active patient participation in healthcare decisions.

Through eHealth platforms, patients create strong working alliances with medical professionals who participate in shared decision-making. Through its digital platforms, eHealth enables provider education through continuing medical educationwhile supplying customized preventive information and health education to consumers. Through eHealth, healthcare professionals achieve standardized communication and enhanced information exchange, which enhances both coordination and integration across healthcare systems.

The global reach of eHealth eliminates geographic obstacles and conceptual limitations to provide patients access to health services rendered by professionals located throughout the worldwide healthcare market. The digital healthcare revolution faces specific moral challenges because providers must implement procedures to safeguard patient disclosure rights and maintain protected data confidentiality, and achieve fairness in medical interactions with their clients [5].

The promise of eHealth to bring fairer healthcare to everyone remains a central issue for this field. The expansion of eHealth technologies creates the potential to widen disparities between IT users and nonusers of technology. Digital tools remain out of reach for disadvantaged populations because of socioeconomic factors that include income level and education level, as well as geographic location. To make eHealth technologies usable by everyone, it is essential for political forces to bridge the existing gap between population segments, especially between urban and rural regions, and between rich and poor layers of society, and between different age groups and genders.

The complex concept of eHealth initiatives pairs advanced technology systems with the mission of healthcare evolution to solve various medical problems, including process efficiencies and treatment excellence standards, together with evidence-based learning methods, as well as patient power gains and system ethics standards and service distribution equity goals. The delivery of eHealth will achieve success by surpassing

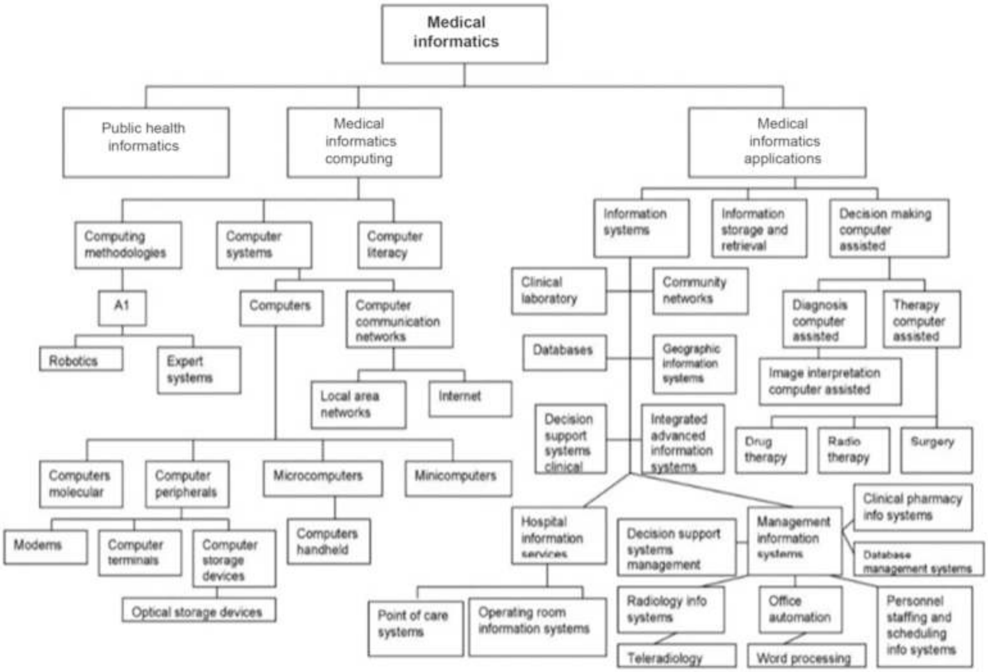

Figure 4.4 Tree Diagram of Medical Informatics.

existing barriers while making sure every person accesses its advantages [6]. Fig. 4.4 demonstrates the structural arrangement of medical informatics shown above.

4.4 Medical Information

Medical Informatics exists as an interdisciplinary area that utilizes advanced computing technology to work in support of clinical work, as well as biomedical pursuits and medical education activities. The purpose of this area of research is to establish a full understanding of platform applications, followed by discussions on present and upcoming developments. As demonstrated in Fig. 4.5, the fundamental capabilities for information management remain essential for achieving medical success. Like how physiology connects to the "logic of life" and pathology understands the "logic of diseases," medical informatics operates as healthcare's "logic." Medical informatics connects healthcare professionals' approaches to patient treatment while enabling treatment selection through refinement and fostering medicinal knowledge generation and institutional management within healthcare organizations Fig. 4.5 [7].

Fig. 4.6 illustrates the interconnected design of eHealth and eGovernment systems as well as their essential priorities. Strong data management models remain crucial for supporting digital medical data exchanges, which need to include all departmental

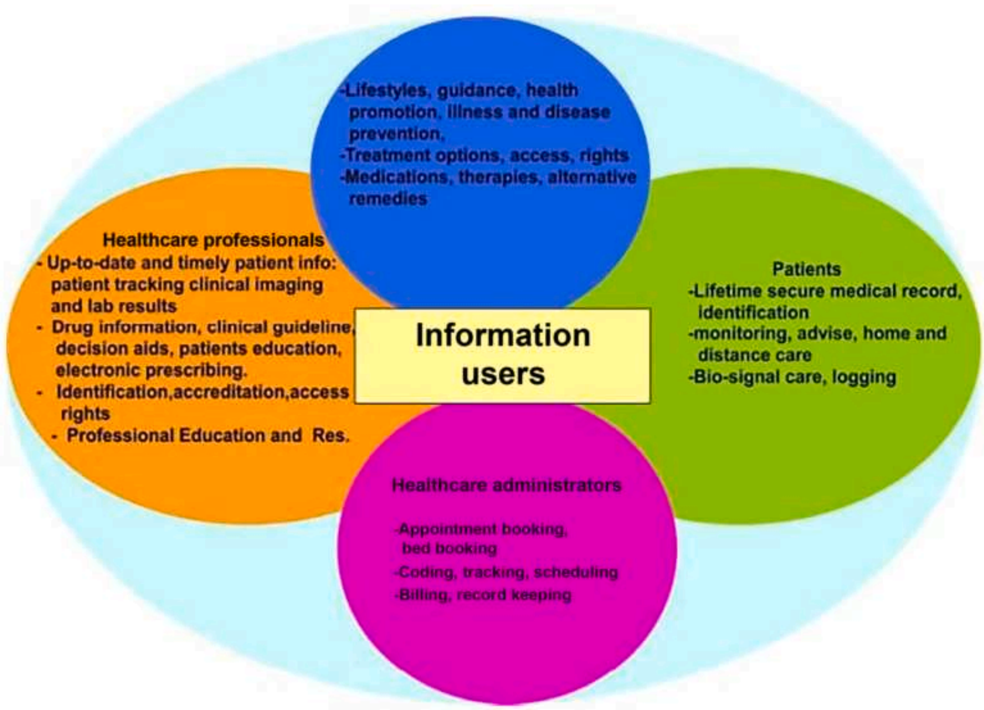

Figure 4.5 User and eHealth.

systems and patient files, medical images, bio signal processing, and clinical decision support systems. Computers strengthen human cognition through their expertise in data storage, along with fast retrieval and accurate results, and advanced computational capabilities [8].

Several key principles guide the documentation of patient data in digital systems:

The data collection process should happen as directly as possible from where these data originate. Data documentation requires compliance with precise standardization protocols. Received data should be saved in full for future use, yet human review interpretations require preservation of their underlying source data for validation purposes. The use of data coding is allowed only after exhausting all other presentation techniques, while the information entry should occur directly from the observation's primary recorder. The data entry system functions best by giving users instant error alerts.

Data entry personnel receive a positive impact from their data processing due to immediate utilization or enhanced workflow quality. When data authentication involves coder identification and signature alongside time-stamping the event, it leads to enhanced data quality while also extending ownership rights.

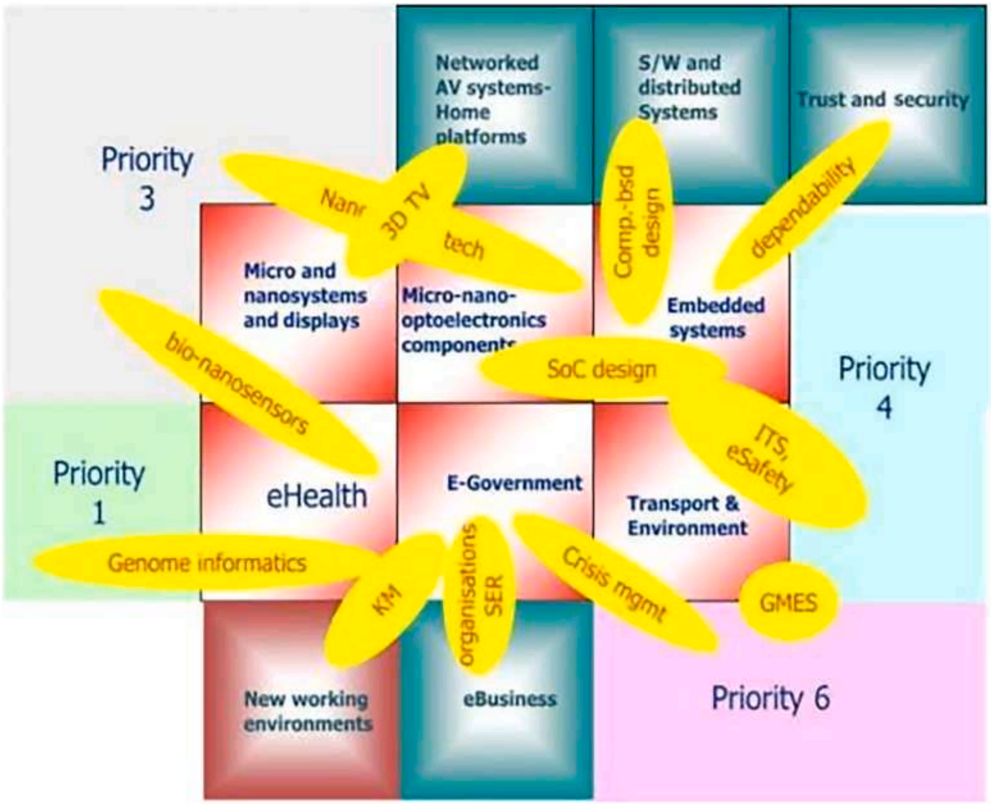

Figure 4.6 Digital twin basic technologies and application areas.

Core technologies working in partnership with their applications have generated essential improvements for managing healthcare systems, as presented in Fig. 4.6. Medical Informatics governs healthcare information management together with information organization and analysis, and information utilization tasks. Both Figs. 4.6 and 4.7 demonstrate the shared goals between medical informatics and other healthcare disciplines, though its own distinct methods of management differentiate it. The core principle of medical informatics depends on technology through its use for information organization and management techniques.

The Fig. 4.7 demonstrates the structural links between the Computer Grid and Data Grid, and Knowledge Grid, and their connection to population data and Electronic Medical Records, in addition to tissue data and pathological information, and molecular data.

Future healthcare depends on the fundamental implementation of both HIE and eHealth technologies. These tools, together with internet access, create a health system designed to provide effective access to care and support efficiency with patient-centered

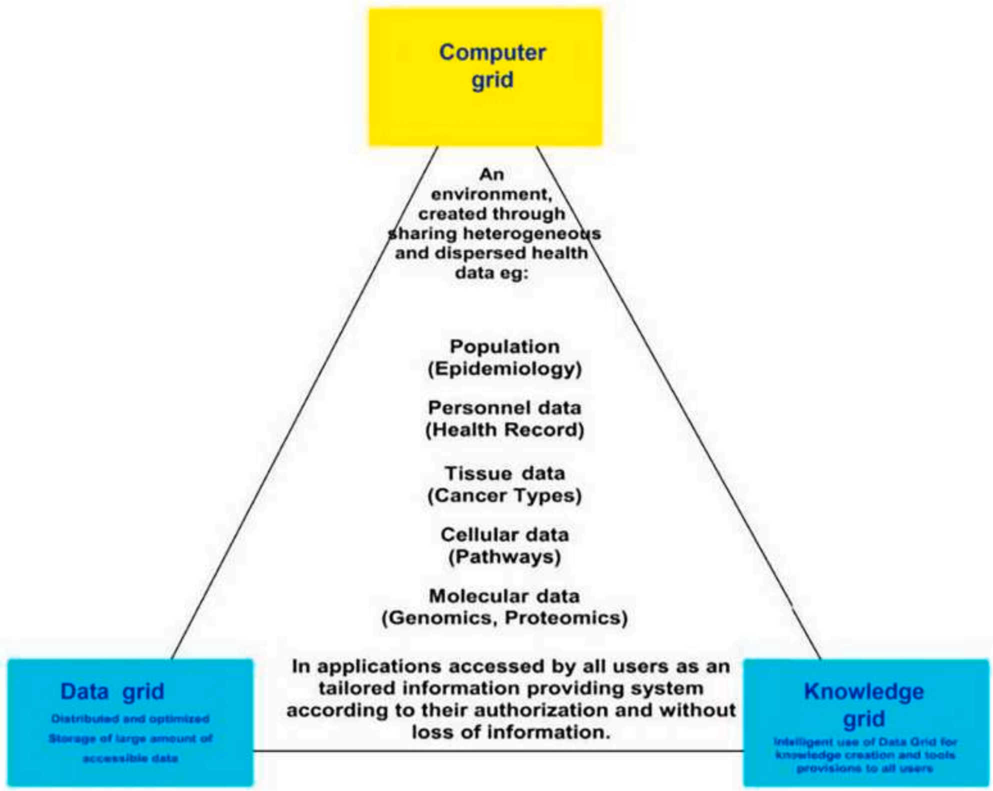

Figure 4.7 Computer Grid, Data Grid, and Knowledge Grid.

services. These systems represent a groundbreaking medical operations approach that creates better outcomes through smarter, integrated, faster treatment protocols [9].

4.5 Digital twin system screening EPR screen design and performance (response times)

1. When incorporating usability into an Electronic Patient Recordapplication, several factors must be carefully considered to enhance user experience and system efficiency.
2. Critical nature of data: The system should decide when to show messages or create warnings based on how important the handled data points are. Users need immediate feedback systems when performing critical tasks that involve medication entry.
3. Work environment: Physical workspaces that reflect end-user needs emerge from time-motion studies, which form the basis for design considerations. The interface design follows functional requirements derived from actual use conditions [10].

4. User activities: Repetitive data input operations require continuous access to this page, so the interface design should persistently display the same screen. Maintenance workflow disruptions are minimized through the system, which enables operational time conservation.
5. Efficient screen usage: Interface design should display essential information without any interruptions on a single screen while executing tasks to help users stay away from switching displays. A single integrated display of vital information enables partners to reach decisions more swiftly while managing lower cognitive stress levels [11].
6. Automated dialog boxes: The system should present essential dialog windows having critical medical alerts when appropriate situations occur. The system uses automated methods to deliver alerts about potential problems so users remain uninformed by human intervention. Detailed user help tools form an integral part of the system through tooltips, together with wizards and F1 help functionality, and interactive error messages, data entry tasks. The system reduces workflow disturbances and uses this to save operational time.
7. Understanding user profiles: The system requires detailed user help tools, which consist of tooltips together with wizards, F1 help functionality, and interactive error messages. Applications become usable to different user groups because of user-friendly feature development methods. Designs should match each task type for step-wise user interactions. Users need repeated access to this page because they perform repeated data entry tasks. The system reduces workflow disturbances and uses this to save operational time [3].
8. Task profiles: Step-wise user interactions need designs that match each task's characteristics. The data entry tasks for specialized users performing registration clerk work require keyboard priority, while medical professionals' functions are best with mouse input.
9. Consistency: Users remain loyal to systems that display consistent behavior and exhibit simpler navigation as their ongoing use becomes simpler.
10. System performance: System acceptance by users primarily relies on the efficient performance capability of the system. Operating dialog systems need improved response time development to achieve maximum system performance levels. User devices use response time recording capabilities, which begin measurements at action initiation by users, then finish measuring after the first data displays become action-ready [13]. Task completion duration must extend through the moment when the earliest available set of records starts operable as users access multiple displays. Completing requires user interaction. The researchers applying timeline analysis found that single-window patient registration and session scheduling systems should handle requests at a rate under 2.5 minutes. This precise operational specification enables validation of the system's defined performance objective [12].

4.6 Conclusion

The implementation of digital twins throughout healthcare creates a revolutionary advancement for optimized patient treatment delivery, combined with optimized operational results from customized medical interventions. Healthcare providers implement patient-level digital twins to evaluate real-time clinical data, which generates predictions that support improved healthcare decisions and individualized therapy plans. The advanced approach enables healthcare staff to better guide medical treatment by using scenario prediction abilities to optimize clinical practices and resource management within today's complex healthcare system. The combination of healthcare data from wearables and EHRs generated by digital twins, enables continuous clinic improvements for practice development. Healthcare organizations implementing digital methodologies can make digital twins able to transform preventive care and continued disease management, and surgical evolution. Achieving complete benefits from digital healthcare solutions depends on the progress of data privacy standards and interoperability improvements with precise algorithm implementations. Stakeholder protection of ethical deployment systems allows full digital twin technology potential to be unlocked, resulting in enhanced health outcomes along with optimized infrastructure resources.

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CHAPTER 5

Digital twin and education: a revolutionary pathway to learning

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5.1 Introduction

Technology perpetually challenges education by incessantly offering resources, tools, and software alongside the current democratization of diverse Artificial Intelligence (AI) in daily operations. Academia and other participants in the educational process must engage in this discourse, spearheading exploration, articulating needs, and leveraging these resources [1]. It is essential to devise, implement, and assess the potential of novel technologies, particularly for this research, which pertains to the use of immersive virtual worlds or the metaverse. One should regard the teaching and learning process comprehensively, including curriculum design, pedagogical activities and tactics, content generation, and student performance assessment. Moreover, technology should facilitate enhanced inclusiveness and access to education and knowledge generation.

These technological advancements have brought forth a virtual environment merged with mixed reality that exists alongside the real world. It enables the interaction between subjects through three dimensuional (3D) virtual experience capabilities. Such online digital environments offer a wide variety of shared human experiences, and with such potential, they are destined to become part of our future lives [2]. The Metaverse will bring substantial innovations to other industries, including education. The Metaverse concept is derived from the words "meta," meaning transcendent, and "universe." It was a science fiction concept first introduced in the novel Snow Crash [3]. As Lee [4] stated, the metaverse is an open three-dimensional virtual space that exists parallel to the real world. That would imply that virtual reality belongs to an advanced stage of technology. Metaverses are virtual spaces that allow users to interact as custom-set avatars, a reflection of realities that may be feasible around the real world, with release from time and space constraints [5]. The notion of virtual worlds or metaverses should move beyond mere commerce or entertainment regarding the making of a real virtual civilization. In this context, digital users or avatars serve as virtual representatives of our alter egos, signaling a tendency toward creating artificial

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communities within the digital world and, thus, furthering the development of artificial life there [6].

The Metaverse is a three-dimensional virtual world, especially noted for its multiuser aspect. Computer technologies like personified agents and simulations facilitate social and economic interactions among people without geographic constraints. In this description, Metaverse is characterized as a virtual world to be explored, where users can interact through an avatar while experiencing many circumstances and lifestyles. Metaverse has various definitions, and it needs a particular interpretation. It represents conceptualizing the third wave of the Internet revolution, influenced by emerging technologies. This encompasses extended reality (XR), 5G, AI, data processing, and an expanding array of technological innovations. These technologies are the cornerstone of the Metaverse, a sophisticated combination of functionalities for changing digital interaction and virtual experience. The new teaching methodologies accompanying the growth of the Metaverse support students' critical thinking in changing the educational system. The Metaverse has four significant hypotheses: embedded Internet, social ecology, virtual space and time, and combined virtual reality [7]. The Metaverse is an extended reality virtual space made possible with the help of human-computer interaction and other tools. These technologies meet several needs: immersion, sharing, and creation, as well as the possibilities of application in very diverse domains.

Personalized education, put into the student's context, may be enabled by the intervention of a teacher, technical resources, and the didactic-pedagogical approach [8]. In considering content production and pedagogical techniques, games allow the development of new interactions for students to interact with their context. Simulation is an important asset to developing methodologies in teaching and learning because the students can see and act [9]. The fidelity to reality in using these educational settings spans several levels, from primary school to tertiary education and vocational training. During the Industry 4.0 revolution, digital twin (DT) technologies transformed engineering, architecture, and health. These advanced technologies enable the creation of real-time digital reproductions of any physical item, offering a potent instrument for simulation, analysis, and decision-making. The growth in technology, with its heightened use of DTs, is becoming ever more widespread in numerous industries, providing deeper information and awareness about complex structures. DTs can have numerous applications in educational institutions, including providing students with virtual simulations of actual laboratory equipment, campus planning and development, curriculum development and testing, and teacher training. Digital technology, specifically as it relates to education, is very exciting and yet still relatively new. An effective strategy to enhance learner agency involves establishing learner-centered teams focused on specific educational objectives, including customizing learning experiences, identifying adaptable feedback mechanisms, fostering career preparedness, and promoting learners' academic and personal well-being [10]. The use of digital technologies in higher education is a nascent subject, with some published research so far. This study investigates the capacity of DT technologies to enhance and augment education and learning. Due to the absence of consensus regarding the description of a DT in higher education, we formulate a concept that captures the critical elements in educational settings. Furthermore, we assess the applicability of insights from DT design in other businesses to the field of education. Our approach includes three main categories of DTs for education: a DT as an item (such as a campus or laboratory equipment), a DT as a person (like a student or instructor), and a DT as a process (such as administrative processes related to the learner experience or learning design). Despite the potential offered by DTs, their implementation encounters some challenges. A perpetually evolving DT faces the challenge of perpetual incompletion. The volume of data required for the DT to function in real-time and receive updates presents many challenges for data governance and technological infrastructure [11].

The authors delineate and discuss these and many other difficulties. The current work proves the feasibility of developing a DT of a person, in a concrete case, an educational one, that is, a student one. Considering cases of such a DT in specific educational environments, the complexity of such an activity has hindered its development in students' cases to date [12]. The latest advances in learning analytics (LA) and educational data mining (EDM) have enriched the understanding of utilizing learner information to enrich educational experiences, with future developments in the use of data in view. The application of DT technology might improve the use of data. Digital technologies may be used in higher education to enhance student experiences and results. This discourse fosters prospective concepts for their implementation, with the obstacles that must be overcome. This research examines the educational dimensions of the metaverse, seeking to assess its contributions and the obstacles associated with its growth in an educational framework. It examines the metaverse's fundamental principles and relevance in education, considering the benefits and drawbacks of these technologies in pedagogical practice. This chapter delineates the forthcoming problems of the metaverse within the educational environment, emphasizing new pathways for scholarly inquiry.

5.2 Understanding the Digital Twin

A general description of the idea of a DT still needs to be discovered, despite other definitions from different disciplines that have been suggested historically. Based on an analysis of many studies of DT technology use, five principal dimensions of a DT have been established to include: (1) object and process, (2) integration, (3) digital form, (4) form or scale, and (5) information. Not many definitions present examples of DTs' function, but with increasing many types of DT applications, it is possible to present several feasible examples. Definitions often start with a summary of the DT's representation. The types of DTs vary between a collection of virtual information structures [13], an object model [14], a virtual/analogous software, a software analog, or a virtual twin replicate. Having a virtual or digital model replicate an item or a process under replicate forms part of our working definition of digital representation. For real-time information to pass between a DT and actual items or processes under digitization, an information channel must be developed, and an integration feature. With such a feature, DTs can then differentiate between "Digital Shadows" and "Digital Models," both of which pass information in a unidirectional [15].

The model may be dynamically updated to reflect changes in the object or process during its existence, facilitated by bidirectional communication [16]. Some definitions of the required synchronization frequency assert that it must be live and dynamic, while others [17] argue that a specific frequency and quality may be achieved. The likelihood of live integration is increasing as the technology for DTs progresses. Consequently, we have specified that DTs must include a dynamic mechanism facilitating bidirectional communication among the paired things. Historically, a DT denotes a physical object. Over time, the possible uses of DTs have expanded to include systems and individuals. Specific articles explicitly identify the physical characteristics of the item, while others include phrases such as "real-world entities and processes" and "living or nonliving organisms." The authors have extensively defined "object or process" to include individuals, tangible objects, and procedures. A decision tree's size or configuration signifies the extent of model applicability. This feature is included in only two surveyed definitions, described as "micro atomic level to the macro geometric level" or state and structure. This function recognizes many settings for magnification that can be leveraged with DTs. IBM arranges four scales in an ascending manner: asset twins, system/unit twins, process twins, and component/part twins. Considering DT's range and diversity, the level was valuable for a full description. Several sources can provide information that DT technology can utilize to build and adapt in real-time. Past definitions involved references to behavior and operational information [18] and information regarding past, present, and future times. This work incorporates current, past, and future data definitions as part of our definition to enable scenario forecasting and real-time decision-making. These five descriptors describe a DT as a "multitiered digital model of a living or inanimate entity or process updated in real-time with information about the respective object/process in terms of past, present, and future." This concept encompasses elements of DT technology that have emerged lately due to developments in technology and computer processes. It includes the capacity of digital technologies to be designed for and by learners, educators, institutions, and processes, so it may also be used in the educational setting. Fig. 5.1 shows the prominent applications of DTs in recent education systems.

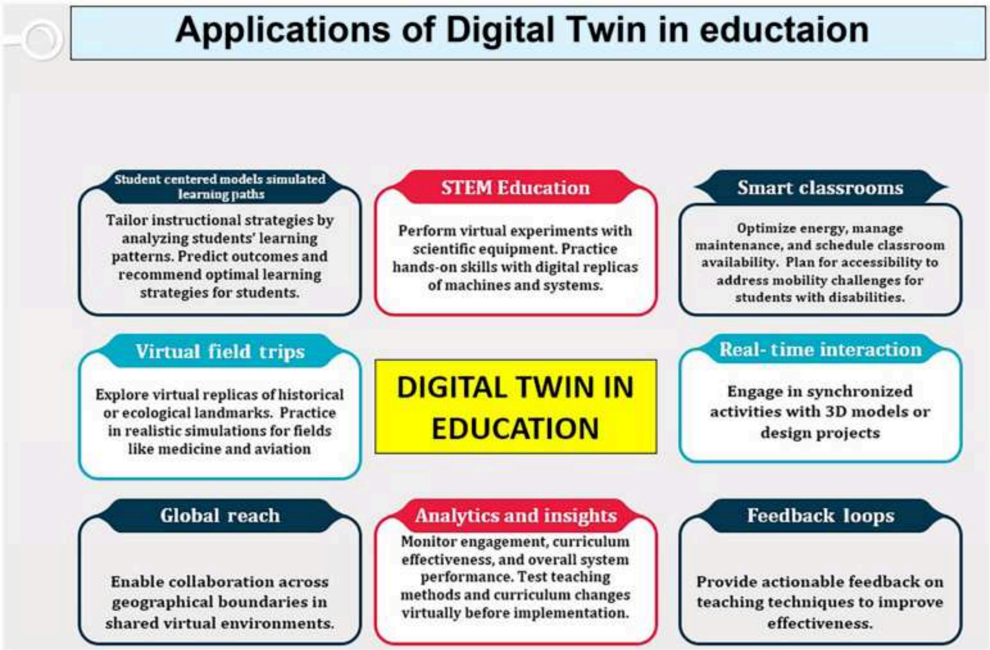

Figure 5.1 Applications of DT in education. Recent applications of DT in the education system. *DT*, digital twin.

5.3 Metaverse and education

The onset of the COVID-19 epidemic has profoundly impacted every aspect of daily life. Integrating Information Communication Technologies and digital gadgets into education has become essential [19]. The domain of educational technology, which integrates computer software and hardware with educational theories and methodologies to promote technology-enhanced learning and increase teaching and learning activities, is also gaining traction [20]. Furthermore, as students mature in increasingly diverse and globalized contexts, with continuous access to digital devices and personalized, rapidly evolving information, their perceptions of effective learning and educational needs have transformed. Consequently, students pursue more engaging, stimulating, and relevant learning experiences that allow them to have an active role rather than remain passive spectators. Hence scrutinizing and understanding the potential effects of innovative technology-enhanced student-centered learning experiences on the teaching and learning process is crucial.

Moreover, learning is more organic, significant, and influential when it centers on student inquiry, fosters the development of 21st-century skills, tackles social concerns, and is integrated with information and communication technology. Digital technologies and resources may enhance student motivation since they are inherently integrated with technology. Consequently, when cutting-edge technologies are optimally used in a student-centered approach, they may effectively resolve these challenges by facilitating more profound learning experiences. Furthermore, the swift integration of digital devices and emerging technologies in educational activities supplants outdated and ineffective teaching tools, enhances existing educational processes, and introduces novel methods and approaches to learning.

Immersive virtual learning environments (VLEs) are increasingly sought-after tools in education, as they have the potential to enrich individualized and engaging learning experiences. In these settings, which may be enhanced by XR technology, students can safely engage with virtual material and gain practical experience. Virtual Learning Environments are structured informational and social places that may intersect with actual settings, facilitating educational interactions via the amalgamation of diverse technology and several pedagogical methodologies. Such an environment goes beyond online education; rather, it enhances traditional classroom activities, enabling learners to become actively and collaboratively involved in the educational process. It also provides an important mechanism for creating educational virtual communities of belonging. Furthermore, VLEs provide rich educational content, enhance the critical thinking and problem-solving abilities of learners, foster collaborative learning and communication, enable monitoring and assessment of academic performance, and provide convenient access to interactive learning resources and materials. The use of Metaverse across different industries within the context of VLEs is gaining momentum due to the potential benefits it offers. The Metaverse is a virtual, three-dimensional constructed environment through which one can have real-time communications with others and with virtual contents and goods, simulating real-life experiences but transcending distance and temporality restrictions. That one's virtual and real selves merge in cyberspace is that in the Metaverse, virtual and real worlds will coexist in a manner such that one will have a variety of experiences with one's virtual presence and yet will have a real-life presence with one's fellow humans through avatars.

XR technologies are used in conjunction to provide people with a virtual presence inside a completely digital world. The foundational elements of the virtual worlds inside the Metaverse, akin to those in virtual reality, are persistence, interaction, and embodiment. Consequently, the Metaverse is a realistic digital extension of the physical realm that immerses people in collective and concurrent virtual environments via telepresence. Moreover, Metaverse allows users to network and engage while sharing feelings, experiences, and culture. Consequently, Metaverse facilitates the establishment of virtual communities and social identities, offering users a feeling of belonging and enhanced social presence.

Furthermore, the Metaverse represents the amalgamation of "virtually enhanced physical reality" and "physically persistent virtual space," facilitating the transition of everyday interactions and duties into the virtual realm, hence possessing the capacity to transform human communities and culture. The development highlights the improvements in virtual worlds, augmented reality, mirror worlds, and life logging, employing its axes, which are based on a spectrum that spreads from the inner space to the outer space and from the augmentation to the simulation, emphasizing applications and technologies. Metaverse is getting more and more popular with educational institutions at various levels. In environments that are immersive and virtual with game elements, students can have a more engaging, fun, and interactive learning experience while boosting their creativity, individual and collective intelligence, and short-term memory. Additionally, Metaverse allows educators to create an atmosphere for emotional learning and erase barriers of social and identity boundaries. Offering a scalable, dynamic, flexible, and diverse environment for learning, the Metaverse enhances student motivation and engages them in the learning process because it offers interactive and immersive experiences while promoting active communication and collaborative activities, which enable asynchronous and synchronous learning and teaching processes. Moreover, when utilized in a student-centered approach, the Metaverse can enhance students' problem-solving abilities and critical thinking, improve their learning outcomes, academic performance, and augment their understanding of a subject, fostering high-quality, dynamic learning environments.

5.4 School curriculum & metaverse

Incorporating the metaverse into the educational curriculum is crucial for cultivating new connections and promoting an innovative learning environment. "In curricular subjects, software significantly enhances the learning process, allowing for a more creative and functional content exploration." Integrating the metaverse into the educational curriculum signifies a substantial broadening of conventional learning limits beyond the physical constraints of the classroom. Integrating the metaverse into the curriculum affords instructors multiple ways to improve the educational experience for students. Again, it is important to point out that integration of the metaverse into the school curriculum will require some detailed planning regarding technology access, educator training, and student safety and privacy protection. Educators should be equipped to explore possibilities in the metaverse and adopt instructional strategies in relation to learners' needs and characteristics. "To fully attain this educational dimension, educators must liberate themselves from the confines of their institutions and adopt novel perspectives on their practice [21]". Incorporating the metaverse into the school curriculum introduces a new dimension of learning, allowing students to engage in unique, interactive, and tailored educational experiences. By exploring metaverse possibilities, educational institutions may equip their students to confront modern issues, fostering creativity, cooperation, critical thinking, and adaptation.

5.5 Virtual environment of augmented reality

Educators are using the metaverse to enhance students' educational experiences. In this new context, students explore digital worlds that enhance and augment traditional curricular material. For example, in classes about animal life, students are encouraged to participate in a virtual environment where they may interact with life-sized representations of several species. This engagement transcends simple observation, enabling students to investigate the cultural and ecological dimensions inherently associated with each species. Engagement in the metaverse exceeds conventional pedagogical approaches by deepening students' comprehension and invigorating their interest. This technique enables the exploration of biodiversity and the intricate cultural aspects of the animals examined in depth. In this context, the early childhood education instructor partners with the educational technology educator to facilitate students' engagement with an augmented reality experience offered by Google. Students see life-sized creatures projected onto the table's surface. This pedagogical method engages students' imagination and familiarizes them with essential scientific principles.

5.5.1 Interactive stimulations, collaborations, and team projects

The metaverse is a framework for interactive simulations, enabling students to safely and systematically engage with real-world scenarios. In scientific classrooms, students may participate in a simulation of a complicated experiment, manipulating virtual components, gathering data, and assessing outcomes. This practical methodology fosters scientific reasoning, problem-solving abilities, and informed decision-making. Furthermore, via immersive and tailored experiences, students were prompted to investigate and design 3D objects on the Makers Empire 3D platform, accessible at www.makersempire.com. This endeavor enhances the educational experience and substantially fosters the development of technical and artistic competencies. Students cultivated their creativity, improved their spatial thinking, and acquired practical knowledge of fundamental design and engineering principles through modeling and animating their 3D creations. Integrating technology, art, and science within an interactive and stimulating educational setting equips students to meet future needs and problems, cultivating a spirit of invention and a problem-solving orientation.

One of the most important advantages of the metaverse is that it can enable student collaboration even at a distance. Educators have encouraged collaborative projects when students work online to achieve shared goals. Students can collaboratively build and design a virtual city on this platform, considering urban planning, sustainability, and economics. This virtual collaboration enhances communication, teamwork, and dispute resolution skills. Geographical studies also involve learners interacting with a virtual environment that takes the form of a simulation of their city to discover and link with the cultural components of history, find historical landmarks, and understand where they reside. In this way, virtual reality increases the learners' level of understanding and inspires eagerness towards learning.

Most importantly, the metaverse opens up doors for participatory and instructive research in subjects such as geography. Students can move around and interact with virtual models of their city, touching the cultural aspect, discovering historical monuments, and perceiving the spirit of urban spaces. This helps students understand the material much better, and interestingly, builds curiosity and eagerness among them to make education cool and important. The immersive experience that the metaverse offers enables students to engage more interactively than traditional learning methods, whereby students can virtually explore and interact with aspects of the environment and thus become active participants in their learning. Also, reproducing their towns or other places virtually allows students to contextualize their study, making the subject more relevant and concrete, and improving understanding and retention of information since pupils can relate it to their surroundings. The capacity to explore many environmental facets, uncover new knowledge, and establish connections among diverse ideas helps enhance pupils' inherent curiosity.

5.6 Incorporating digital twin technology into education

DT technologies are relevant across many contexts, sectors, and industries. The objective of utilizing DTs in industries is to conduct validation, optimization simulation, and evaluation, and provide recommendations, predictions, and controls for the actual entity, enabling informed decision-making, enhancing performance, and extending the lifecycle of a physical entity. For example, DT technology may assist in urban landscape design within the civil engineering and construction sectors. DTs have been used in the manufacturing sector to identify design flaws and evaluate performance capabilities to optimize production by creating virtual product representations. Digital technologies are used in the agricultural industry to manage, monitor, and predict the future of livestock and crops. Utilizing human DTs to formulate intelligent diagnoses, DTs are already facilitating novel opportunities for the medical sector to offer tailored healthcare. Given the many intriguing applications of technology, attention is increasingly transitioning to the potential uses of digital technologies in educational contexts. Higher education institutions must enhance their instructional offerings, environments, and processes in a more competitive landscape to cultivate interest in education and retain students. DTs may be used in several ways to improve educational settings and results, aiding institutions in overcoming this challenge. The benefits of digital technologies include:

1. The capability to improve the adaptation of learning settings,
2. The customization of education according to individual needs,

3. Sustainability, and
4. Optimization within higher education.

The efficacy of digital technologies in higher education is primarily contingent upon these four components, which also provide a basis for exploring future uses of digital technologies.

5.6.1 Applications of digital twins in education

The educational use of DTs is numerous and widespread. Some of its most prevalent use cases in education include:

1. ***Virtual classrooms***: With DTs, virtual classrooms can be designed, and students can access information, collaborate, and work collaboratively on assignments anywhere on the planet.
2. ***Virtual labs***: Virtual Labs enable students can run experiments and interpret information in a virtual environment.
3. ***Personalized learning***: DTs can facilitate the development of customized educational experiences for learners. DTs enable students to access materials customized to their requirements and learning preferences, facilitating accelerated growth.
4. ***Assessment and evaluation***: DTs can facilitate a more precise evaluation of pupils' development. DTs enable educators to assess students' comprehension of ideas and examine their advancement over time.
5. ***Gamification***: DTs can facilitate immersive and captivating educational experiences. DTs enable instructors to use game aspects, such as prizes and challenges, to incentivize pupils and promote learning.

5.6.2 Teaching assistant & digital twin technology

The concept of a "Digital Twin" is still very much in its beginning in Higher Education; however, several applications have emerged recently with some powerful opportunities for how DTs might be utilized as pedagogic tools inside Academic Institutions. Thus students will be able to work on the DT in class and outside of class. This could improve the integration between theory and practice by making a virtual version of laboratory equipment for students. Allowing students to be given this virtual apparatus for their test and experimentation with different situations should enhance their experience in learning and increase situation awareness by allowing them to learn from all of their mistakes. The tests of use for a DT for the aircraft flight simulation system demonstrated that the test subjects had highly positive reactions towards the technology of DTs, with increased interest in using such functionality in the future.

Students appreciated the autonomy to play with and adjust the system's parameters via the DT to see the impact of these modifications on the system's overall behavior.

The DT virtual learning experience enhances sustainability by enabling learners to interact with large machinery, such as excavators, therefore conserving time and financial resources related to equipment and transportation. To tackle equality concerns and environmental objectives, DTs provide students with access to inaccessible technology in their present location. The technology of DT individualizes learning through accommodation to learner level and expertise, opening access to new platforms and tools, and providing students with an opportunity for practice and investigation during off-class times. Learning experiences in terms of DT can be designed for individual learners and in terms of individual learners' requirements and interests, offering them formative work and specific tools. In a study researching the use of DTs in mechatronics training, a high-tech platform with a foundation in a DT was constructed. With such a platform, students could monitor development and administer individualized lesson planning regarding individual aptitude and progression.

5.6.3 Campus infrastructure using digital twin

Developing a DT of a physical campus enables the execution of simulations to examine diverse scenarios that may impact the campus, such as the implications of increased enrollment on available space, the introduction of new courses on overall activities, and the effects of a natural disaster on buildings and services. Utilizing Internet of Things (IoT) sensors, environmental parameters related to thermal, auditory, visual, and indoor air quality may be regulated and enhanced on smart campuses produced by DT technology [22]. The University of Bologna in Italy uses IoT sensors inside DTs to monitor student movements and classroom occupancy rates, aiming to detect and guide those with impairments to accessible pathways between sessions. In terms of resilience, digital technologies may assist academic institutions in managing situations such as the COVID-19 pandemic, which necessitated the transition to online learning during lockdowns and the enforcement of social distancing protocols. Universities may use digital technologies to track occupancy and pedestrian movement to promote social separation, facilitated by Internet of Things devices and thermographic cameras [23]. In the event of further pandemics or natural catastrophes, DT simulations of online course capacity may enhance the effectiveness of online and hybrid learning delivery.

The technology of a DT can even be blended with augmented reality, virtual reality, and the technology of the Metaverse to develop a virtual campus for any educational institution. In April 2023, the University of Iowa initiated "Metaversity," a virtual twin campus. University operations can even have DT replicas to improve student experiences. One such improvement can include administration processes that streamline learner recruitment and career guidance, providing learners with personalized and flexible options. Details about a learner's past experiences and future academic objectives could be leveraged to suggest the most suitable courses and study path options through automation in a DT.

5.6.4 Digital twin technologies for learners

In the early days of DT technology, development in almost all sectors concentrated initially and predominantly on actual items and processes. Advances in 3D printing and VR/AR technology make building a high-fidelity human DT easier. Constructing a humanlike DT is now possible through technological advancement and capabilities for storing and processing high volumes of information sets. Research is being done in a range of industries in order to specify future use of this technology [24]. For example, the medical [25,26], sports science [27], and product development [28] sectors use human-DTs nowadays. To monitor a patient's state of body and counteract disease progression, medical professionals use DTs, acting as the correct DT of an individual, including ideal replicas of all life-supporting organs and organ systems. It assists medical professionals in tracking students' medical information and medical devices in real time. Because of rapid development in LA and EDM, information about students and educational environments can be utilized in educational environments. Employing LA and students' data mining output makes it feasible to build learner decision trees to boost students' capabilities in studying. Microlevel information about students could be utilized to provide real-time feedback about students' ongoing studies with current courses. On the other hand, through students' behavior analysis, a teacher could modify instruction techniques to maximize students' motivation.

Shengli [23] pointed out that to reduce the complexity of DTs in humans, the intended function of any design should be identified. As expected, the learner's behavior could often be subjective and unexpected, adding to DT complexity [29]. Strategies toward framework development for recommendation systems inside digital teaching-learning environments are proposed to control the complexity [30]. Agrawal et al. [31] suggested Levels of DT as one way of addressing this complexity by clearly demarcating the roles that people and their corresponding DTs perform. Other forms of improvement in the learning environment and support can also be done innovatively through context-sensitive development of a learner environment through data mining analysis of personal and social data. Students facing challenges due to employment obligations, familial duties, and impairments might benefit from the real-time analysis of their data using DTs [32]. Delivering learners prompt, tailored alerts on time management strategies, such as reminders for lectures and tests, together with recommended reading lists, may represent a prospective use of digital technologies. Martynov asserts that the development of an educator's digital toolkit may facilitate the analysis and refinement of instructional methodologies and the identification of professional competencies to improve academic practices. To facilitate simulations and decision-making on prospective learning scenarios, an instructor's DT might include data on the educator's characteristics, curriculum design, research competencies, and expertise.

5.7 Essential elements for developing learner's digital twin

The Digital Twin Consortium, a worldwide group consisting of government, academia, and industry, developed the DT Capabilities Periodic Table (CPT) to build a common platform for defining a common frame for DT technology. CPT lists technological and architectural requirements for developing a DT and describes six important capabilities in developing an effective DT [33].

1. ***Data:*** It may derive from several educational systems and methodologies and is crucial for developing a learner's DT. Some examples of such information include students' electronic trails in a learning management system, evaluation scores, statistics for enrollments, and academic skill support and use of a library. Compiling such rich sources of information, such as audio and sensor information (e.g., eye tracking), is becoming increasingly feasible in an attempt to assess learners' affect and state of attention.
2. ***Intelligence:*** The intelligence component is the regulations, frameworks, evaluations, and documentation that underpin DT's functionality. The pedagogical perspective is crucial in developing models and determining the most appropriate framework for designing digital technologies in an educational setting. Creating effective learner interventions requires comprehension of the learning design of activities and assessments while evaluating the outcomes of diagnostic tests.
3. ***Management:*** In an educational institution, it is important that technology and technology design comply with legislation regulating other educational structures, and that planning for sustaining the technology and design program is formulated. In such a scenario, management entails device management, activity tracking, system administration, and management of information.
4. ***UI/UX:*** It describes how learners and instructors interact with digital technology through dashboards, augmented reality/virtual reality, visualizations, and interfaces. Integrating these interfaces with other learning systems should be explored to create a coherent experience for instructors and students for better engagement and participation.
5. ***Integration:*** A structure for integration is needed to allow data collection, processing, and storage to create a DT. Tools like Twin Builder or application programming interfaces can allow data integration across multiple learning platforms, enabling communication across various systems.

5.8 Optimal strategies for creating and employing digital twins

DTs are practical tools, but must be designed and implemented correctly to function at their full potential [34]. Optimum methodologies for creating and leveraging DTs in education involve:

1. ***Comprehend your aims:*** Before developing a DT, you need to understand your goals. What do you want to achieve with the DT? What data do you need to capture? What challenges do you expect to encounter? Understanding your goals will help you develop an effective DT.
2. ***Formulate a plan:*** A Digital Twin is a multifaceted entity. You need to plan how to create it. Thus, the hashtag strategy shall involve a timeline, budget, and test/evaluate framework for the creation of the DT.
3. ***Select appropriate technology:*** The DT may be shaped using a variety of technologies, including sensors, simulation software, and machine learning algorithms. The kind of technology to be used for your DT is important regarding its effectiveness and reliability.
4. ***Utilize data:*** Since data is the strength of any DT, it must be utilized more effectively. Collect data from the physical entity to develop models and simulations that are as close to reality as possible.
5. ***Assess and analyze:*** After the development of the DT, it must be tested and analyzed to be accurate and reliable.

5.9 Digital twin and education in the global world

DT technology has evolved into the advanced integration of physical systems with their virtual counterpart, which has found a place in education in many countries. They are virtual replicas of any object, system, or process-anything physical, and they connect the physical to its virtual self in real-time data synchronization [35,36]. Technology helps personalize learning in education, enhances infrastructure management, and closes the gap between theory and practice. The adoption and implementation of DT technology vary across the United States, Britain, India, China, and Japan, reflecting unique priorities, challenges, and innovations in each country.

5.9.1 United States

The United States is at the forefront of adopting DT technology for education because it already has superior technological infrastructure and a culture of innovation. Areas of key focus: Personalized learning through the use of DTs on simulations of student behaviors in order to improve individualized education, smart campuses by applying optimization to energy efficiency, safety, and resource management, and STEM education through hands-on virtual labs in engineering and sciences. Some universities, such as MIT and Stanford, have joined hands with IT giants like Microsoft, IBM, and NVIDIA to integrate DTs into research and teaching [37]. However, drawbacks persist, for instance, student data may be a vulnerable concern for K-12 setups, and school education has to bear several costs associated with its implementation in schools. However, the United States views DTs as a transformative tool to enhance education and facilitate individual achievement.

5.9.2 Britain

Britain is potentially integrating DT technology into education, improving learning and institutional efficiency. The key themes are innovative learning environments with optimization of classrooms, digital apprenticeships, simulating workplace scenarios, and infrastructure management for resource optimization and sustainability. Universities like Imperial College London and the University of Cambridge apply DTs in their architecture and engineering, while government initiatives also support using innovative technologies in schools. Various challenges are unequal opportunities for digital resources and balancing innovation against traditional teaching [38]. The UK considers DTs the key to future-proofingits education system.

5.9.3 China

The high priority given to technological innovation and educational reform in China has accelerated the DT technology for schools and universities. Among these focus areas, AI-based learning that delivers personalized education, smart classrooms powered by IoT, and workforce training in industries related to robotics and AI are at the forefront. Scale implementation has been motivated by partnerships with technology giants like Alibaba and Tencent to improve resource utilization at scale and the output of the students. These include a few unique challenges: balancing privacy concerns against use and over-reliance on technology. China's proactive approach underpins commitments to leveraging the benefits of DTs in scalable and efficient education [39].

5.9.4 Japan

Japan uses DT technologies to solve challenges such as disaster preparedness and the aging population. DTs help schools simulate evacuations, virtual labs enhance STEM instruction, and demographic adaptation maximizes school resources in shrinking student populations [40]. The University of Tokyo uses DTs in urban planning, and government programs aimed at lifelong learning for the aging population exist;

however, this also brings about challenges, such as high costs and resistance to moving away from traditional methods. Extending DTs in Japan's IT strategy epitomizes the ability to adapt technology to the needs of its student body and society.

5.9.5 Canada

Canada is a forerunner in AI-facilitated learning and brilliant campus creation. The University of Toronto and the University of British Columbia, amongst other prestigious universities, have embraced DT technology to create real-time simulations for training and increase student engagement. AI-facilitated analysis and immersive platforms have been encouraged and developed in Canada, with educational institutes able to use virtual replicas of students for personalized training [41]. There is even a creation of a DT for use in sustainability, with reduced consumption of energy and operational efficiency in campus operations being facilitated through it.

5.9.6 Australia

Australia is utilizing DT models in its educational field to enhance student success prediction, innovative infrastructure, and distance learning. AI-enabled DT technology is being implemented in universities such as the University of Sydney and Monash University for student tracking, virtual labs, and innovative campus technology. Government programs have facilitated work toward leveraging IoT-enabled DTs for educational space maximization, renewable energy-efficient use, and campus security enhancement [42]. DT simulations have supported Medical and engineering programs, with students practicing in real-time, simulation-environment settings with no geographical boundary restrictions.

5.9.7 India

While highly promising, the adoption of DT technology for educational purposes is still in its infancy in India. From a perspective focused on digital transformation and skill development, some important areas of intervention will involve vocational training in industries related to manufacturing and healthcare, the integration of EdTech to ensure interactive learning, and the optimization of infrastructure in overcrowded schools. Companies like BYJU and Vedantu use AR- and AI-based simulations, while initiatives by the government under "Digital India" promote innovative technologies in public schools. The digital divide and strained budgets are the challenges. With its large population and focus on technology-driven education, India has a good chance of scaling up the use of DTs for broader access [43].

5.9.8 Comparative insights of global powerhouses

The United States and China have been leading in deploying DTs in education, supported by strong technological ecosystems and government-industry collaborations. Britain and Japan focus on integrating DTs with existing systems to modernize education while preserving traditional methods. Canada and Australia have placed high value on smart and sustainable campuses, student success analysis, and IoT-enriched infrastructure. Toronto, UBC, and Monash University employ predictive AI frameworks. In India, the nascent EdTech sector has a vast potential for adoption, both through the government and other initiatives. However, some general challenges that cut across regions include privacy issues, unequal access to technology, and balancing innovation with affordability and traditional teaching. DT technology has the potential to transform education through personalized learning, smart campuses, workforce training, and disaster preparedness. International collaboration and shared best practices could drive more equitable, efficient, and engaging educational systems as global adoption expands.

5.10 Challenges in the real world

A range of barriers must be resolved for DT applications in universities. First, information that will have to be accumulated and regularly updated for DT creation and maintenance is involved in the first part. Widespread application of DT can be hindered by the massive amount of information that will have to be regularly accumulated, stored, and processed without sufficient software and hardware infrastructure. Although tiny data sets of items and processes may pose little obstacles, the collection of comprehensive information for DTs of instructors and students is crucial for facilitating accurate prediction and simulation. Acquiring thorough information on a student requires significant effort, particularly in offline courses, including any models or strategies for learner use. DT must also consider the ramifications of "missing" data. The digital literacy of educators, especially those who need more technical expertise, presents a significant barrier to the adoption and use of digital technology in higher education. The design of digital technologies incorporates several fields, such as psychology, mathematics, computer science, and statistics. Although a user does not need competence in all these areas, using DTs in educational settings will be enhanced by a basic understanding of some essential concepts. Comprehending the management strategy for the sustainability of DT is essential. The maintenance of DT involves the cost of continuous development and processing, and distributing accountability for its maintenance. Sustaining DT integrity and security involves considering various additional factors, depending on its range, particularly when sensitive information is involved. Sustaining proper and moral use of computer technology in tertiary-level studies is an important matter closely intertwined with information governance. Utmost care must be taken in collecting, storing, and using information under DT technology to safeguard children. The data supporting the DT must be accessible to learners, and if possible, the designers and managers of DTs should provide means to empower learners to control their data [34,44].

5.10.1 Recommendations

Collaborations between educational institutions, technological businesses, and government agencies should be established to facilitate the sharing of resources, knowledge, and money among these entities. The government must give educators continual training and assistance in order for them to properly use DT technology in their classrooms. It is also crucial that technology businesses and developers implement rigid data privacy and security measures for the protection of sensitive information about educators and scholars. The teachers/educators should, therefore, implement programs that bridge the digital divide to ensure all students, irrespective of their socioeconomic background, have access to DT technology.

5.11 Conclusion & future scope

The transition of DTs from mere computer representations of processes and machines in a simple parametric form to complex marriages of human and physical factors has helped the use of DT technology in experiential learning improvement. Despite the limited availability of technology and technological capabilities, the educational application of DT technology is still in its infancy. In terms of academic output, in terms of the use of DT technology at the tertiary level, it was observed that between 2018 and 2023, the publication grew consistently, with 94.57% of all manuscripts under consideration concentrated in 2020 and thereafter. This signifies that during and after the COVID-19 pandemic, scientific productivity surpassed that of prior years.

Several critical factors must be considered before using the DTs in educational procedures.

- *What degree can multidimensional data be gathered, saved, and evaluated to provide feedback to the learner and assist the decision-maker in making informed choices?*
- *If DT delivers erroneous input to learners, how will it be rectified?*
- *What should the standards and regulations for data interoperability across various institutions be?*

Additional study is necessary to comprehensively comprehend components highlighted as crucial digital transformation building blocks, their integration within the educational context, and the impact of digital technologies on students' learning outcomes.

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CHAPTER 6

Bridging real and virtual worlds through digital twins and the metaverse in cultural heritage preservation

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6.1 Introduction to digital transformation in cultural heritage

Heritage is the collective memory and identity of societies, holding in place that recounts their glorious achievement in history, art, and architecture that have provided great influence on human civilizations. For centuries, preserving this legacy has revolved around physical conservation, documentation through records, and education. But while such valuable means were in place, they have been much too often exposed to environmental degradation, natural disasters, conflict, and neglect. The advent of digital technologies, especially digital twins and the metaverse, has overturned the square into which cultural heritage had been boxed with regard to how it is documented, protected, and shared globally.

Digital twins are high-fidelity virtual models based on physical objects or environments that enable real-time interaction and monitoring, as well as the preservation of the tangible and intangible aspects of cultural heritage [1]. The metaverse builds on this by providing a standard VR ecosystem that expands into other immersive environments, where audiences can immerse themselves, explore them, and contribute to their preservation. The two in conjunction provide not just protection for cultural artifacts, but democratize access to history for people right across the globe so that they can experience and appreciate cultural sites and artifacts on a lower tier. It is to a great extent that the history of technology in heritage preservation can be traced back to the end of the 20th century, with developments related to Geographic Information System and early computer-based modeling. The emergence of the 1990s brought fine tools for accomplishing accurate digital reconstruction using 3D scanning and photogrammetry, liberating so many applications alongside virtual museums and interactive educational. It was in 2020 that AI, in tandem with blockchain, came in handy in allowing dynamic interactive digital twins and secure management of metadata, thus raising the whole affair a notch on the ladder [2].

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This chapter offers further examination into how digital twins and the metaverse are changing the heritage preservation space. It presents aspects relating to theory, application, enabling technology, challenges, and future directions in detail about how these technologies create new ways of thinking when it comes to the preservation space. Through multiple real-world examples and from the case studies, this chapter highlights the transformative potential of these technologies and their implications for researchers, practitioners, and policymakers.

6.2 Theoretical foundations

The flowcharts of the theoretical models of combining digital twins and preserving cultural heritage are shown in Fig. 6.1, which comprises steps involving data discovery

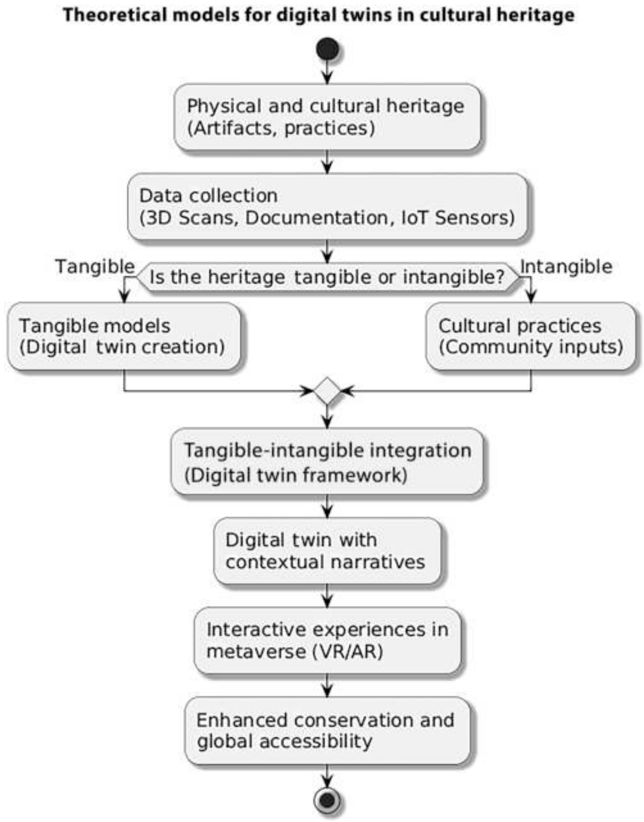

Figure 6.1 Digital Twins: Theoretical Models for the Cultural Heritage. In this flowchart, steps are sequentially presented through the integration of tangible and intangible in the digital twinning of the cultural heritages. Stages may range from collecting data through the creation of an interaction experience in metaverse, with resultant superior conservation compared to the universally accessible final product.

from sources relevant to physical heritage and cultural heritage such as artifacts, structures, and architectural traditional practices. From intangible, tangible, such as constructing or artifacts against the traditions or practices. This stage will further lead to both streams, in which it integrates the features of heritage digitally under a digital twin framework.

The digital twin enshrines contextual stories, which include histories and multimedia material, for all-around heritage interpretation. Design improves in interactive experiences of the metaverse, such as immersive explorations in virtual reality (VR) and augmented reality (AR), where audiences connect with and experience heritage through the new interfaces. What emerges in the open is no longer just heritability, but also the protection and openness to the people around the world; the cultural heritage gets conserved and celebrated at all times.

The flowchart explains the framework, which combines the digital twin and the metaverse for cultural heritage conservation. It begins with identification, whether they be tangible heritage-like relics and built structures, or intangible heritage-like traditions and oral histories. These will serve as the input for the creation of digital twins. With the digital twin integration, this turns into the former being reflected in a dynamic, high-fidelity virtual model of the heritage elements-breathing life into cultural heritage as real-time living, symbolic paradigms. The digital twins provide a representation of all things, either tangible or intangible, in real-time, providing continuously changing information for purposes of monitoring, analysis, and conservation planning. It is in this realm that the modern preservation effort works, ensuring that nothing less than the essence of the heritage elements will be safely stored digitally for posterity. The incarnated metaverse representation engages with the mechanisms through which these digital twins enable audiences to have their immersive and interactive experiences. In the metaverse, audiences have the opportunity to virtually experience the reconstructions of cultural sites, engage in storytelling, and culturally share knowledge in ways that transcend geography. This stage again reiterates the prospect of technology in making accessible culture and heritage to wider audiences beyond continental or geographical boundaries, which in turn nurtures intercultural interest and understanding.

Interaction and collaboration further shine on the collegial aspect of these technologies in which researchers, technologists, and local communities are collaborating to give life to the digital twin and the metaverse experiences, ensuring they will be culturally sensitive and inclusive. This type of collaboration boosts the authenticity of the digital representations while empowering the communities to share their heritage with their own voice. The intended results include preservation, high-level global access, and education about cultural heritage. These were a few plenitudes of possibilities in the digital twin purview and the metaverse that could bear preserving and sharing cultural heritage. This has made digital technologies cross the threshold between the physical and virtual worlds-proposing another means for humankind to relate to its past to remain real and accessible to the next generations.

6.2.1 Definition and concepts of digital twins

Digital twins are the virtual counterparts of physical entities, including attributes of the visual and structural, as well as their functioning and environmental dynamics. Although originating from the manufacturing and aerospace industries, digital twins have primarily been designed with the purpose of enhancing operational efficiency using real-time data integration with predictive analytics [3]. The application of digital twins in cultural heritage preservation is indeed a concept that extends further into the creation of a high-resolution digital model replica of an artifact, monument, or historical site. For example, in the case of the Great Wall of China, a digital twin can embed structural integrity, environmental conditions, and historical context that allow stakeholders to watch its condition remotely, predict deteriorating trajectories, and simulate restoration interventions. These replicas bridge the gap between static documentation and dynamic, interactive preservation by alluding to sustainability and cultural stewardship in their very workings.

6.2.2 Overview of the metaverse

This is an immensely vast, interlinked digital universe where users interact as avatars in immersive environments. The term took on a more visible standing in early 2020 with the birth of technologies such as VR, AR, and blockchain [4]. The application of the metaverse to cultural heritage is a shift that offers an interactive space to witness past historical cultural sites and artifacts in ways that transcend physical limitations. For instance, a metaverse-based representation of ancient Rome enables users to walk through reconstructed streets, interact with historically representative characters, and look at the socio-political dynamics in the era (2022). This interactive experience promotes greater engagement, learning, and overall accessibility to cultural heritage on a global scale.

6.2.3 Theoretical models linking digital twins and cultural heritage

The relationship existing between the digital twin and metaverse springs from the ability of the two to connect space in the physical and virtual sense of Heritage management. Previous theoretical models by the Cultural Heritage Digital Ecosystem (CHDE) demonstrated that data interoperability, participatory engagement, and multidimensional analytics were the key aspects that required a better understanding. Digital twins were described as a basis for heritage data within CHDE, while the metaverse would serve as an experiential level that embodies interaction and storytelling. The CHDE is a comprehensive framework attempting to graphically express the interaction between physical heritage and its digital counterparts [5]. Digital twins are conceived to be layers on which all physical attributes, structural conditions, and environmental data are captured for heritage assets. Further layers embedded into CHDE are:

Interpretive layer: Offers context, historical background, and socio-cultural significance.

Interactive layer: User engagement from virtual tours, simulations, and educational tools.

Analytical layer: Use AI and data analytics to provide predictions about degradation patterns and conservation strategies.

In this ecosystem, data interoperability is deemed to be the fundamental pillar. It allows seamless interaction between internet of things (IoT) devices, heritage management systems, and digital twins, within the CHDE, to engage in informing, monitoring, conserving, and experiencing buildings in an all-encompassing manner (Fig. 6.2).

6.2.3.1 Tangible-intangible integration model

Cultural heritage can include both tangible and intangible heritage. Tangible refers to the more physical components of cultural heritage: things you can touch: artifacts and architecture. The Tangible-Intangible Integration Model aims to build a bridge in this context, it helps to communicate the intangible dimension of heritage with the digital twin [6]. For example, a digital twin representation of a building rightly represents not only architectural detail but also multimedia artifacts like oral history, folk music, or rites associated with the site. It is an ideal representation of cultural sensitivity in the attempt

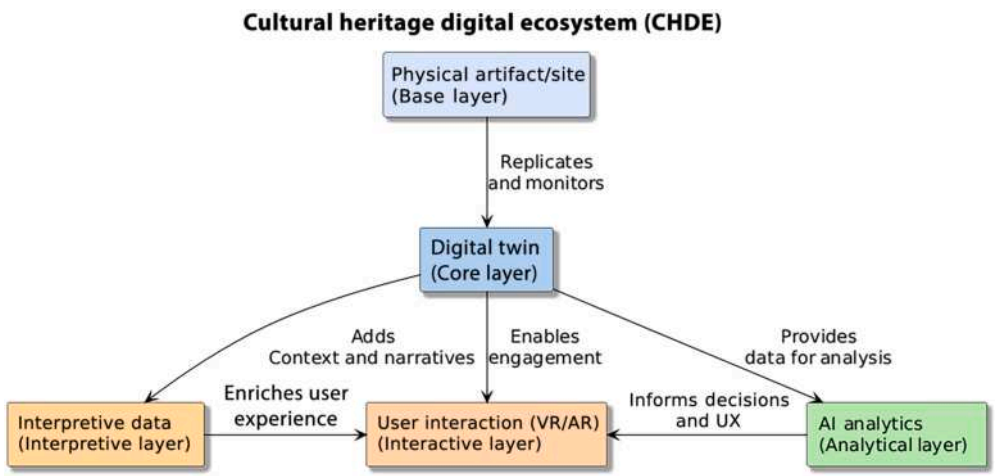

Figure 6.2 The cultural heritage digital ecosystemillustrates through a clear hierarchy, the integration of physical and digital layers in cultural heritage preservation and how data and functionality flow between the physical artifacts, digital twins, and interactive and analysis systems.

to design digital twins, as this would require input from local communities, historians, and anthropologists to ensure that the intangible aspects are presented in the correct form (Fig. 6.3).

6.2.3.2 Real-virtual continuum

The Real-Virtual Continuum of the digital twins in Fig. 6.4 stems from a spectrum extending from purely physical/real heritage to virtual reconstructions. This continuum recognizes the varying levels of virtuality in heritage preservation ventures:

Physical-digital hybrid: This refers to basically combining physical artifacts and their digital twin to provide an enriched information arena for inspection and update.

Virtual-only representation: This model uses digital twins to recreate lost or inaccessible heritage structures, like excavated sites, Palmyra, or submerged archeological sites.

6.2.3.3 Participatory digital heritage model

Participatory digital heritage model; part of Fig. 6.5—At the heart of this is participation and inclusiveness, being a model for community-led preservation and education, digital heritage can be actively, constructively developed, managed, and interpreted by various stakeholders, researchers, and the public themselves under decentralized governance aided by collaborative tools. Using blockchain technology within this model tends to ensure transparency and shared ownership of digital twins [7]. Examples include community-led initiatives for preserving indigenous artifacts, a common scenario where blockchain is resorted to in tracking the contribution and ascribing rights.

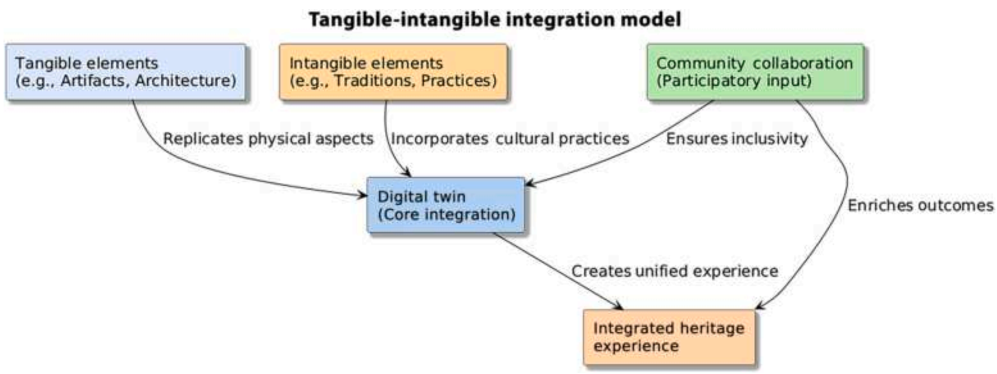

Figure 6.3 Tangible-Intangible Integration Model. This is an abstract representation of various heritage elements, combining the physical and the nonphysical, augmented by community collaborations, and incorporated into the digital twin model to generate a unified heritage experience.

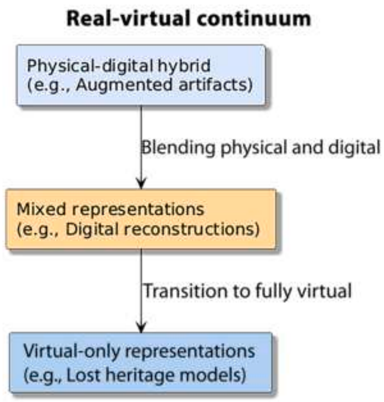

Figure 6.4 Real-Virtual Continuum A continuum: from the physical-digital hybrid models, through the mixed representation, toward the fully virtual reconstruction, illustrating the range of options available for preserving heritage.

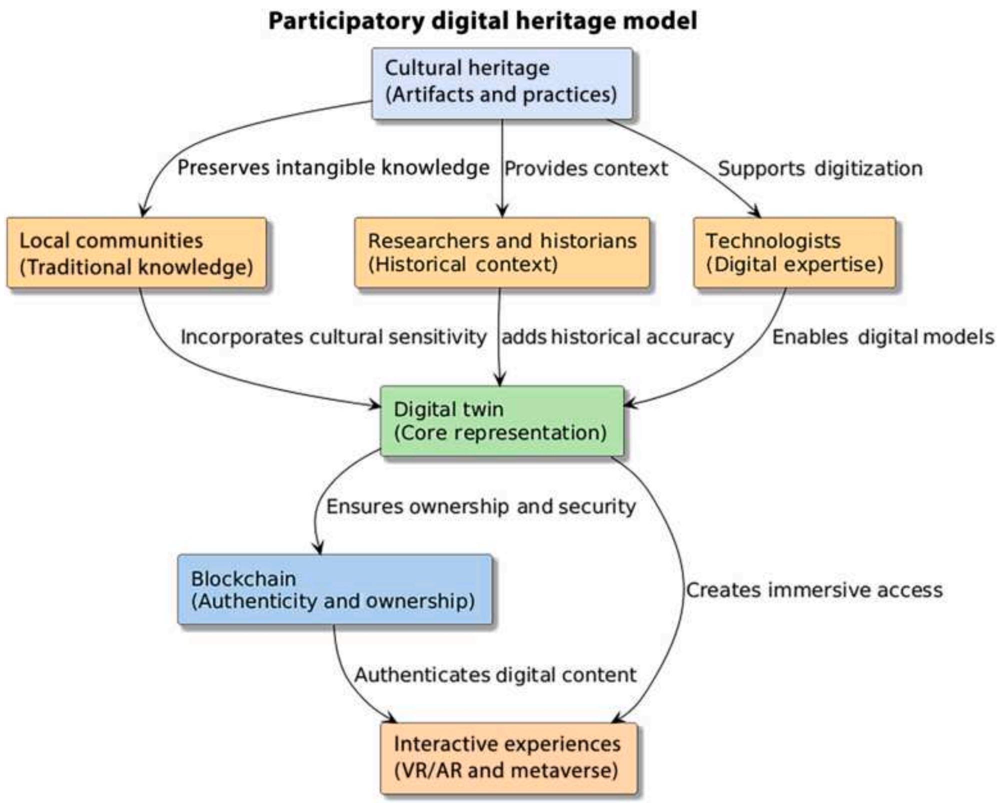

Figure 6.5 Participatory digital heritage model, this model demonstrates the collaborative roles of local communities, researchers, and technologists to create digital twins of cultural heritage, ensuring authenticity with blockchain and enhancing user engagement with immersive experiences.

6.2.3.4 Conservation-driven predictive models

Predictive models work by the use of digital twins in respect to preventive conservation. Mitigating risks by simulating environmental conditions, visitor impacts, and structural stresses provides actionable insights [8]. For example, a digital twin of the Taj Mahal in Agra, India, measures pollution and simulates long-term effects on its marble facade.

In Pompei, predictive analytics allows estimates on the effects of foot traffic on sites, guiding tourism policies for their preservation.

These models, depicted in Fig. 6.6, depend on real-time information from IoT sensors and advanced machine learning algorithms to anticipate and tackle potential threats before they develop.

6.2.3.5 Interaction-centric models in the metaverse

Interaction-Centric Models for the Metaverse. Fig. 6.7 shows how interaction-centric models are brought to life using the metaverse with digital twins. The models are interaction-oriented, with development focusing on the facilitation of user engagement

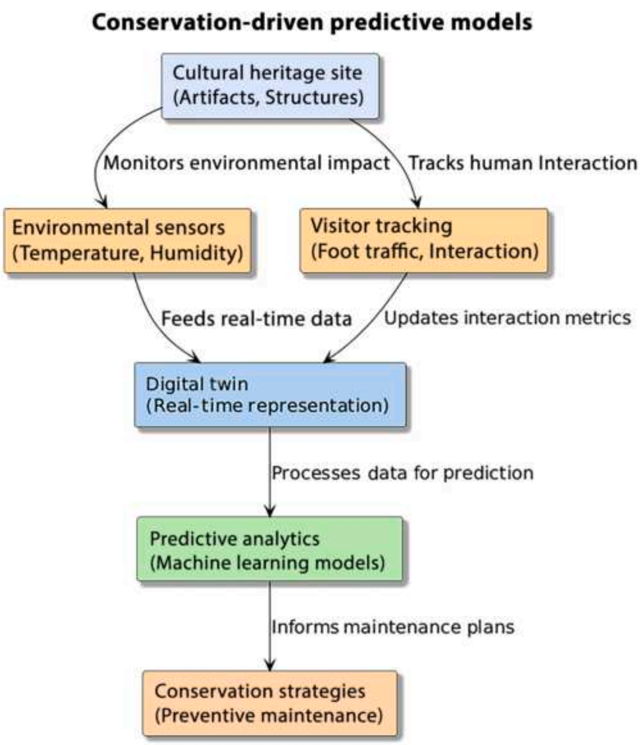

Figure 6.6 Conservation-Driven Predictive Models: This model illustrates datalogging from environmental sensors as well as visitor tracking with digital twins, where predictive analytics aids in formulating effective strategies for conservation.

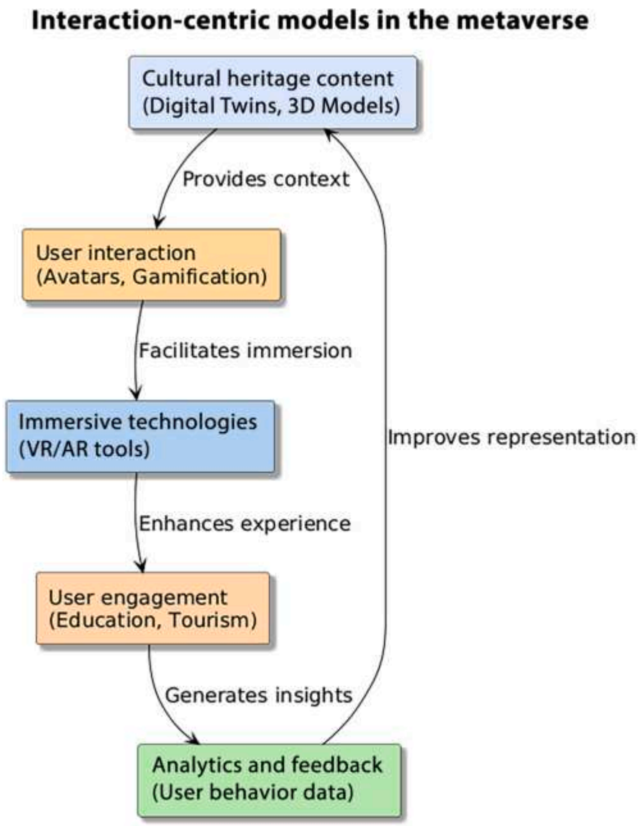

Figure 6.7 Interaction-Centric Models in the Metaverse. This showcases the role of cultural heritage content and immersive technologies in user engagement through interaction and analytics within the metaverse.

and experience. It makes its audience reach out to cultural heritage through storytelling, gamification, and immersion technologies. For instance, the reconstruction of medieval Europe via a metaverse enables the interaction of users with historical personalities as they engage in festivals reconstituted together with the examination of original architectural use [9]. Accessibility is also addressed in interaction-based models for ethnical heritage with the intention of keeping refuge experiences to meet different audiences, including people with disability.

6.2.3.6 Ethical and governance models

Production Note: In the below paragraph, we have changed Fig. 6.7, which is duplicate twice so Fig. 6.7 change to Fig. 6.8 to maintain the sequence. (Delete the note after incorporating)

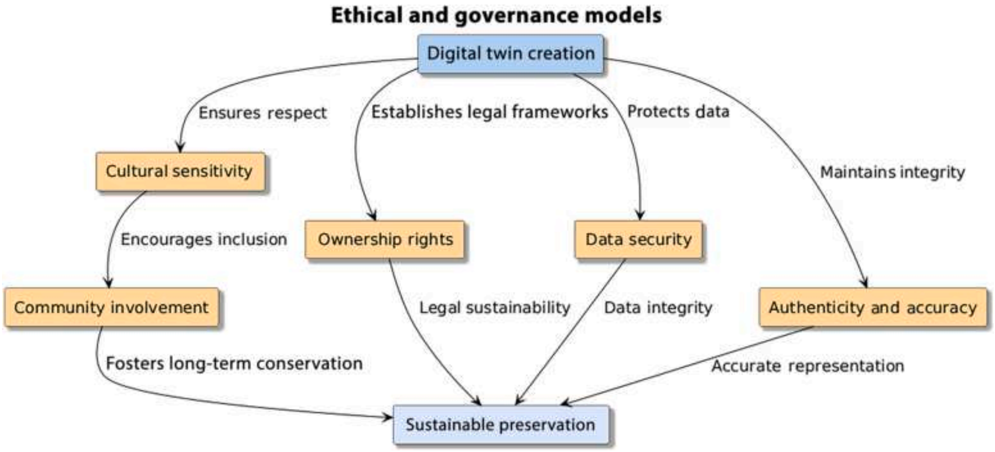

Figure 6.8 Ethical and governance models. This framework showcases considerations of cultural sensitivity, ownership rights, and data security during digital twin production, thus ensuring ongoing sustainability in applications of cultural heritage.

Illustrated in Fig. 6.8 are theoretical frameworks that deal with key ethical considerations and governance mechanisms for the sustainable implementation of digital twins for cultural heritage.

This includes frameworks for accuracy and authenticity of digital representation. Respect for the rights and interests of communities from whose heritage resources and assets are produced. Prevent family exploitation for commercial purposes while in the digital space.

6.2.3.6.1 Applications and relevance

These theoretical frameworks offer practical guidance in the application of digital twins in cultural heritage preservation. It brings together the dimensions of physical, cultural, and technological, and allows for a more encompassing and inclusive approach toward the safeguarding of humanity's legacy. Thus while developing these frameworks, their future developments would expand the means to integrate other emerging technologies like quantum computing and advanced haptics to further enrich their applicability ([10]; no date).

6.2.4 AI's role in bridging real and virtual heritage

Artificial intelligence acts as an axis around which digital twin and metaverse technologies revolve. Logically, it enables the replication, analysis, and augmentation of cultural heritage. AI-powered tools merge neural networks and natural language processing, resulting in an automatic reconstruction of imperfect artifacts, immersive storytelling, and instantaneous translations of historical texts. For example, artificial intelligence algorithms helped in the recreation of the ancient city of Palmyra after its destruction, where archival images, aided by 3D modeling, furnished the digital twin as shown in Fig. 6.9.

As illustrated in the layered flow diagram in Fig. 6.9, AI acts as a bridge between real-world cultural heritage and its virtual representation. The very base is the Real-World Cultural Heritage level, which encompasses physical artifacts, traditions, and historical sites. This layer is considered a layer of input sources, with respect to digitization and analysis: 3D scans, photographs, and environmental data are such sources. The second layer engages processes empowered by AI that support transforming this energy into meaningful outputs. Some prominent AI-enabled applications include digitizing physical properties, providing a comprehensive context to historical narratives, restoring damaged or missing artifacts, conducting predictive analysis for conservation, and enhancing accessibility through translation. Finally, the top layer is Virtual Representation, a layer where this processed data gets converted into digital twins, VR/AR experiences, and interactive virtual heritage models, which allow users to engage with cultural heritage present and future in an immersive and innovative fashion that fosters preservation and accessibility for coming generations. This diagram shows clearly the vital role AI plays within the mediated layers connecting real to virtual heritage.

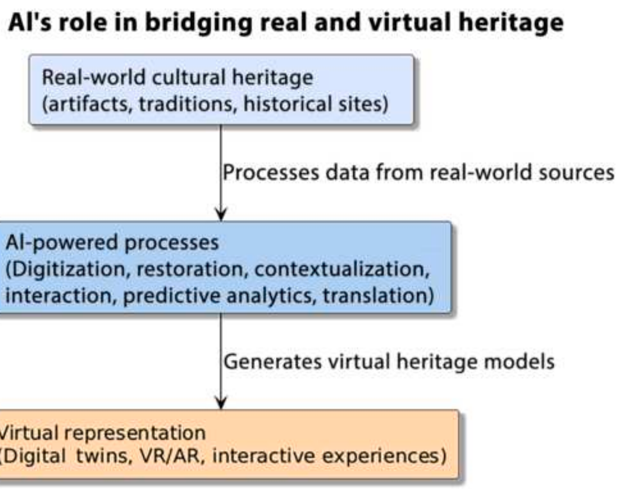

Figure 6.9 AI's Role in Bridging Real and Virtual Heritage: This diagram illustrates the central role of AI in linking real-world cultural heritage to its virtual counterparts, enabling digitization, contextualization, interaction, predictive analytics, restoration, and translation.

6.3 Key applications in cultural heritage preservation

6.3.1 Documentation and digitization of artifacts and sites

An archeological object or site can be accurately documented and digitized by the digital twin, of which one prime example is in heritage. Through 3D scanning and photogrammetry, heritage professionals are putting recorded high-definition details that traditional photography would never achieve [11]. The end product, the replica, can thus be made with the help of such digital data, which will act as the safe guardian for heritage in case physical artifacts vanish or are damaged. For instance, the Smithsonian Institution has digitized over 3 million artifacts, including the Apollo 11 command module, allowing people from every corner of the globe to explore these treasures in digital formats [12].

6.3.2 Interactive virtual museums and education

Integration of digital twins with IoT devices allows for real-time monitoring of Heritage sites. Temperature, humidity, and structural stability are some of the parameters monitored. This becomes paramount to any preventive intervention to go ahead, as it gives many stakeholders a chance to react before irreversible damage happens [13]. The merger of real-time monitoring and restoration technologies with digital twins signifies a paradigm shift in cultural heritage preservation. Digital twins, in this case, are high-end virtual duplicates of physical structures that nowadays serve in a dynamic nature for continual inputs and manipulations of upkeep efforts for conservation and restoration actions.

6.3.3 Real-time monitoring and restoration with digital twins

Real-time monitoring uses digital twins integrated with IoT devices to obtain data about temperature, humidity, and structural stability-related aspects in heritage sites. This data are essential for preventive conservation since it enables stakeholders to address the unknown but inevitable occurrence of threats before their irreversible damage [14]. Therefore the integration of real-time monitoring and restoration technologies with digital twins represents the basic paradigm change in the preservation of cultural heritage. Digital twins are high-fidelity virtual replicas of physical structures serving as dynamic tools able to receive constant updates from real-world data, thus allowing proactive conservation and accurate restoration.

6.3.3.1 Real-time monitoring

Real-time monitoring using digital twins will include embedding IoT sensors and other data collection devices into heritage sites. These sensors continuously capture environmental and structural parameters such as:

Temperature and humidity: Material preservation factors like stone, wood, and frescoes are significantly impacted.

Vibrations: Indicators of structural stress, often caused by earthquakes, heavy foot traffic, or nearby construction activities.

Air quality and pollution levels: Important for monitoring the impacts that urbanization has on heritage sites.

For example, in the Tower of Pisa, tilt sensors and strain gauges have been installed to feed real-time data into its digital twin, allowing engineers to monitor the inclination and detect any possible risk of structural instability [15]. Similarly, in Venice, digital twins integrate data from water level sensors to evaluate the effects of rising sea levels on historic structures.

6.3.3.2 Predictive analytics in monitoring

The real-time data is fed into AI-powered predictive analytics models integrated with digital twins. Predictive analytics identifies the probable risks based on historical and real-time data using machine learning algorithms. For instance, time series analyses predict how changing humidity levels, over a decade, would impact frescoes, enabling the implementation of other preventive measures, such as restricting climate conditions within the site [16].

6.3.3.3 Restoration using digital twins

In restorations, digital twins give an elaborate and data-driven platform for decision-making. Core applications entail:

Damage assessment: By matching the old models with real-time information, digital twins give indications of degradation or loss in some areas. An instance is after the fire incident at notre-dame which used the digital twin as leverage for identifying weaknesses within the structure and consequently laying down restoration plans aligned to that site's original architecture.

Simulation of restoration techniques: Engineers and conservators test the various possible restoration scenarios in the virtual world. Finite element analysis (FEA) and AI simulations test the structural performance of the suggested restoration materials under different environmental conditions.

Guidance for the reconstruction of the physical form: The masons and conservators are guided by digital-twin-generated high-resolution 3D models to restore delicate details like carvings or frescoes. Overlay through Augmented Reality shows the final outcome that could be expected after carrying out the restoration work.

6.3.3.4 Collaboration and accessibility

Collaboration and accessibility digital twins make it possible to collaborate among teams distributed across various geographies in restoring heritage. Even though the groups are distributed over several geographies, they will be able to access real-time data and restoration simulations from cloud-based platforms [17]. Because of digital twins, it is possible for multidisciplinary efforts among architects, historians, and engineers to give access to interactively explore restoration progress to the public.

6.3.3.5 Challenges and future trends

Though tremendous opportunities seem to exist in terms of digital twins for real-time monitoring and restoration-several challenges continue to prevail.

Data integration: Other than the historical archives and the environmental datasets, IoT sensors do not happen to integrate well.

Capital cost and expertise: Creating and operating digital twins requires substantial capital investment and a considerable workforce with appropriate skills.

Cybersecurity: It insists much on heritage data protection against possible cyberattacks.

Future innovations will include the use of edge computing, which will enable data processing closer to cultural sites, thus reducing latency and restoration in real-time. Blockchain technology may help authenticate and secure digital twin data.

6.3.4 Case studies

Case Study 1
: Notre-Dame Cathedral Restoration

This Project reveals the success story of how digital twins and AI appear to open possibilities for the future of cultural heritage preservation while trying to restore Notre-Dame Cathedral after its devastating fire in April 2019. Prior to the fire, historian Andrew Tallon performed detailed 3D scans of Notre-Dame Cathedral using light detection and ranging (LiDAR) technology. These scans constituted an almost complete digital twin of the cathedral, capturing the most minute detail of its architectural structure and dimensions. After the fire damage, most of the work to analyze and clean the scans for restoring the structure was done by AI-based methods; for instance, a machine learning algorithm identified specific areas of damage by comparing the digital twin with postfire imagery captured by drones. Finite Element Analysis, in conjunction with AI simulations, probed the structural integrity of proposed restoration materials for extreme environmental conditions like humidity and temperature gradients. Consequently, the digital twin allowed designers and engineers to make decisions with consideration of the preservation of the original design of the cathedral [18]. The project also demonstrated the necessity of preexisting digital documentation as a basis for understanding future disaster recovery measures and, therefore served as a model for future work in conservation.

Case Study 2

: Angkor Wat's Virtual Preservation

Angkor Wat digital preservation initiative has sought to showcase the combination of 3D modeling, AR, and AI to create an immersive virtual experience of one of Cambodia's most iconic cultural heritage sites. Environmental degradation and the constraints of physical tourism have imposed huge barriers to preservation. A high-resolution 3D laser scanning and photogrammetry campaign recorded the very fine detail of the temple, and reconstruction algorithms applied more knowledge to restore erosion sites, structural degradation, and erosion that could not be surveyed directly due to restricted access. Such a model involved photographs of restoration performed on many of the destroyed statues and other architectural elements. The digital twin was introduced into the metaverse with an immersive tour of Angkor Wat, which should eventually include an interactive, audio-guided narrative supported by natural language processing or natural language processing (NLP). Such extent broadened the global appeal for its historic and cultural significance for the Angkor Wat site while relieving physical tourism's pressure from an already delicate monument. The project defined heritage preservation in the digital age with a combination of technology and cultural sensitivity [19].

Case Study 3

: Pompeii's Predictive Modeling

The long-ago buried nightmarish city of ancient Roman Pompeii, with volcanic ash, became an embodiment of both endurance and sensitivity. The locality is impacted by yet unknown ambient threats to moisture, variation in temperatures, and visitor influences. To tackle these issues, IoT sensors and AI-driven predictive models were applied by the researchers. Real-time data from temperature, humidity, and vibration sensors were integrated into a print of twins of the site, providing constant monitoring over structural integrity. Machine learning algorithms acted on this data to predict upcoming risks under changing environmental conditions, for example, fresco deterioration, wall collapse. A reinforcement learning model of visitors' movements enabled the appropriate design of routes that minimize damage to fragile areas while still allowing foot traffic. Such visualization tools, with GIS-based risk maps, guided conservation teams to prioritize intervention of the most vulnerable sections of

Pompeii. This has enabled a further approach through AI that has vastly prolonged its lifespan while balancing preservation and public access [20].

6.4 Technological enablers

3D scanning and photogrammetry have emerged as cornerstones for the implementation of digital twins for cultural heritage. The collection of millions of data points allows for an accurate, high-resolution 3D representation of tangible objects and sites. Photogrammetry constructs an accurate 3D model through overlapping photographic images, while laser scanning detects intricate surface geometries [21].

For example, the Acropolis of Athens has been scanned with terrestrial laser scanners, resulting in a detailed 3D model that would help in monitoring time-dependent changes in structural condition and guide conservation efforts accordingly.

6.4.1 AI and machine learning in heritage analytics

AI complements digital twins by enabling predictive analysis, anomaly detection, and automated reconstruction of damaged or missing elements. Machine learning algorithms analyze vast datasets to predict very complex patterns of deterioration over time, while neural networks simulate environmental impacts on heritage sites such as temperature, humidity, and other weather considerations. One area where historical photographs and 3D modeling programs were used in the reconstruction of the Bamiyan Buddhas in Afghanistan which were destroyed in 2001.

6.4.2 Blockchain for authenticity and ownership

Blockchain technology addresses some of the greatest fears concerning the authenticity and ownership of the cultural heritage digital assets. The blockchain creates an irrefutable record of the metadata of certain cultural assets so that provenance is ensured and unauthorized alterations or reproductions are made impossible. Example: The British Museum is implementing blockchain technology to authenticate digital reproductions of the exhibits, allowing for the security of transactions when it comes to digital collectibles [22].

6.4.3 Immersive tools: VR, AR, and MR

VR, AR, Mixed Reality in the realms of technology create culture in their immersive-sided ways, where VR is the entirety of a digitally created environment, AR gives its viewers a digital tap on physical surroundings, and MR merges the two into interactive experiences. Example: At the Roman Colosseum, AR technology recreates historical occurrences, allowing visitors to see gladiatorial combat and architectural grandeur with their smartphone or headset.

6.4.4 IoT and edge computing in real-time monitoring

The IoT integrates sensors into heritage sites in order to collect data related to environmental factors, visitor traffic, and structural integrity. This information is utilized in real-time updates of the digital twin. Edge computing carries out rapid data processing at the source of its collection, thereby reducing latency and allowing for rapid responses to possible threats. Example: IoT sensors placed inside the Tower of Pisa measure tilt and strain; engineers rely on their output for a digital twin to assess mitigation strategies [23].

6.5 Challenges and ethical considerations

6.5.1 Technological limitations

Digital twins and the metaverse face technological challenges on multiple fronts, including scalability, computational requirements, and cost. Bringing a digital model up to fidelity requires intensive human and hardware resources. Furthermore, large-scale deployments require robust cloud infrastructures. Example: Digital preservation of Petra, Jordan, was delayed due to the high costs associated with deploying drone-based photogrammetry and data processing technologies.

6.5.2 Data privacy and security risks

The use of IoT and other blockchain systems in the preservation of digital items gives room for severe concerns regarding data privacy and cybersecurity. By unauthorized access to digital twins, there may be a possibility for misuse or falsification of heritage data. Critical questions arise concerning the ownership and representation of cultural heritage. For example, who owns the digital twin of a historical monument? Do indigenous communities have the right to decide how their culture will be displayed in the metaverse? The ethical politics here are complex. Example: Digital twins of native cultural objects populating the metaverse have led to frenzied debate over cultural appropriation and, in some cases, the need for community consent.

6.5.3 Balancing accessibility with cultural sensitivity

During the actual construction of digital twins, the areas of accessibility into cultural heritage, be it facilitated by either digital twins or the metaverse, shouldn't contravene cultural sensitivity guidelines. Certain cultural artifacts, traditions, and sites are highly sacred and might contradict the values of the communities protecting them when openly represented in the metaverse. Such rituals or ceremonies, were ordinary people meant to do in private, had they been uploaded to the metaverse and made publicly accessible, their sanctity would have been taken away. Developers must keep open discussions within communities to mark cultural boundaries in the presence of cultural sensitivity or keep out sensitive material in a manner in agreement with the values of various communities.

6.5.4 Recommendations for ethical practices

To ensure that the digital twins and metaverse are used in culturally sensitive ways, the following measures are suggested.

Codevelopment: Create cocreation models where local communities, historians, and technologists work in concert from the inception to the end of the project.

Transparency and accountability: Use technologies like blockchain to document decision-making processes, ensuring the community retains rights over cultural data.

Education and sensitization: Prepare training for developers, designers, and stakeholders to instill insights around cultural sensitivity and ethical frameworks to ensure no misrepresentation nor exploitation arises.

Long-term partnership: The establishment of continuous relations should be the empirical give and take to adapt and improve digital representations through evolving technologies.

6.6 Future trends

6.6.1 AI-driven simulations for historical reconstruction

The next advancements in AI will facilitate dynamic simulations of historical events, environments, and daily life. Such simulations would not merely preserve history but also reveal brand new insights regarding the past contexts of the same through immersive storytelling. Hypothetical scenario: A digital twin of ancient Egypt could simulate seasonal flooding of the Nile and its impacts on agriculture, trade, and daily life.

Decentralized platforms will empower communities to create and manage their digital heritage. With blockchain governance models, all participants will enjoy fair participation in decision-making. Innovations that enable Haptic Technology, such as Haptic feedback, will enhance the immersive experience of cultural heritage in the metaverse, allowing users to "feel" the texture of old artifacts or architectural features. Embedding Heritage into Web 3.0. A merging or better interaction between cultural heritage and Web 3.0 technologies opens up new avenues for interaction.

6.6.2 Practical recommendations

The stakeholders in digital twin and metaverse development for cultural heritage preservation,such as politicians, cultural institutions, technologists, and local communities-need collaborative, structured economies. These should generate strong research recommendations for the development of comprehensive ethical frameworks and regulations pertinent to the most pressing issues of data ownership, cultural authenticity, and informed consent of communities, which will fast-track a more technologically driven approach to digital heritage through grants and partnerships aimed at promoting innovative research and development. Diversity and equitable access need to be promoted to ensure the marginal communities can access these technologies, and digital literacy programs need to be put in place to enable the local population to empower themselves. In various cultural institutions, those with the required technical skills must appropriately be trained in the management and maintenance of digital twin and metaverse environments. They should consult communities and indigenous groups as stakeholders and ensure the accurate representation of their cultural assets. Sustainable practices such as energy-saving technologies should be encouraged to minimize the environmental impact of such digital initiatives while ensuring the viability of digital heritage models. Technologists and developers have to put significantly more emphasis on user-centered design when creating platforms that offer intuitive and matching experiences for a broader range of users. Implementing a securely managed data system, such as a blockchain, should protect ownership and transparency. For the systems to integrate seamlessly with tools already in place and practical grow as technology advances, interoperability and scalability of solution sets should be improved. On the other hand, the active cocreation of digital heritage projects could be left to the local and indigenous communities, whose traditional culture and stories will then become authentically represented. Such communities may make good use of technology in promoting cultural tourism and income generation while enabling the preservation of their knowledge for prosperity.

Collaboration of all stakeholders is compulsory. It could consist of setting up teams of historians, archeologists, technologists, and community leaders to share knowledge and inspire innovation. Through open-access transdisciplinary repositories with minimal risk, digital twin models can unleash worldwide research and education, while strong monitoring and evaluation frameworks ensure that these technologies will be ethical, efficient, and responsive to user needs. Stakeholders that follow these recommendations will confront challenges while fully unlocking digital twin and metaverse, culminating in celebrating and preserving global cultural heritage (Fig. 6.10).

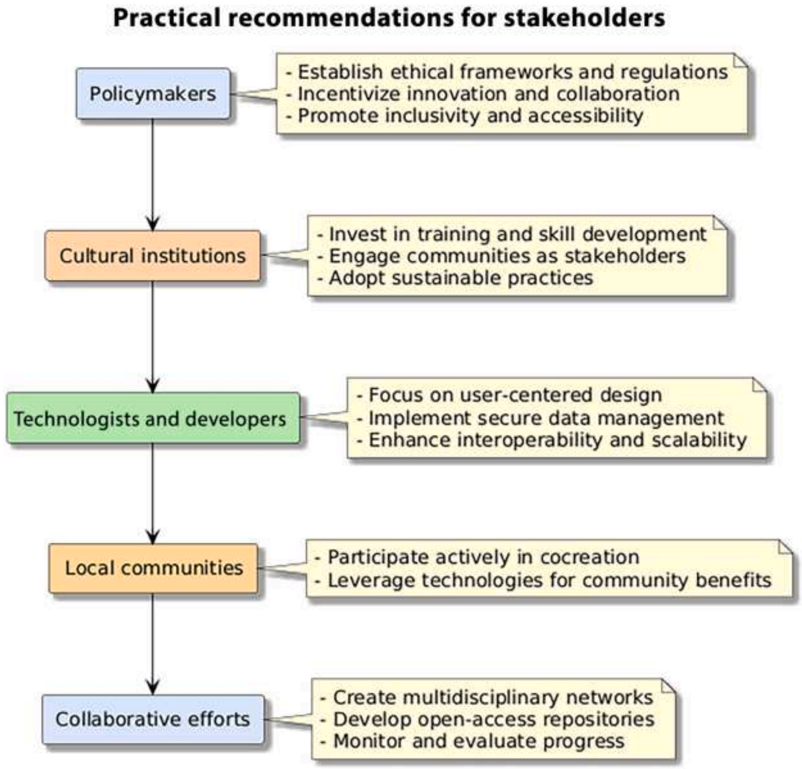

Figure 6.10 Practical Recommendations for Stakeholders: This compact diagram outlines actionable steps for each stakeholder category to ensure the effective adoption of digital twins and the metaverse in cultural heritage preservation.

6.7 Discussion and implications

6.7.1 Impacts on global accessibility

In order to establish contact worldwide, digital twins and the metaverse have redefined how cultural heritage is accessed and appreciated. Creative immersive interactive realism of historical sites, artifacts, and traditions by these technologies closes geographical and economic barriers for global audiences to experience cultural heritage from anywhere. This democratization enables more inclusive access to cultural heritage, greatly widening the educational reach to students, researchers, and enthusiasts for the study of world treasures without the constraint of physical barriers.

Moreover, virtual experiences provide a forum for cross-cultural understanding by presenting heritage within the context of its history, social practices, and embedded meanings. AI-driven immersive storytelling, AR, and VR are ways for individuals this would allow rich and emotional engagement with diverse cultures. In the metaverse, for instance, users witness a virtual recreation of traditional ceremonies, rituals, or even the architectural splendor of sites eroded by time and disaster, further enhancing empathy and cultural appreciation.

Over time, local communities will use their heritage more effectively to symbolize it on a global scale. In the metaverse, such communities assimilate in their context their history, art, and tradition, ensuring authenticity on that count and enkindling the pride in their cultural identity that has largely died out. Digital twins mitigate the environmental and structural impact of tourism and provide a sustainable alternative to cultural engagement. Virtual access reduces the physical strain on fragile heritage sites while encouraging responsible tourism practices. The challenges remain. These include creating equal, equitable access for the satisfaction of individual needs, digital literacy gaps, and safeguarding cultural data from misuse or misrepresentation. To better address these challenges, all parties must come together, including governments, cultural institutions, and technology developers, to create inclusive, ethical, and secure platforms. As they succeed, so grows the promise of providing instantaneous access to everything and promoting cultural appreciation through digital twins and the metaverse.

6.8 Conclusion

Digital twins and the Metaverse can spur a transformative point of intersection between technological innovation and cultural heritage preservation. Digitization of tangible and intangible heritage marks a new direction in restoration and conservation as well as universal accessibility. Real-time monitoring and predictive analytics will enable heritage sites to proactively intervene through digital twins. The metaverse expands this, offering immersive, interactive experiences by democratizing access that would allow the public to explore, engage, and learn about cultural treasures from anywhere. Such innovations would also support sustainability by reducing stress on vulnerable sites from physical tourism and providing a more environmentally friendly, culturally enriching virtual alternative. The indigenous and marginalized communities can now express their cultural heritage authentically and foster understanding and pride through cross-cultural relations. However, there are still some challenges that exist, such as ethical concerns in terms of cultural representation, digital divide, and data security. Their resolution depends on government, cultural institutions, and technologists working collaboratively to develop fair, secure, and inclusive frameworks.

With increasing adaptations, digital twins and the metaverse are steering their dominions in future cultural heritage. Not only do these technologies preserve the past, but they also build bridges between cultures, communities, and generations so that humanity's common legacy is treasured, appreciated, and transmitted to safe hands to be cared for by generations to come.

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Further reading

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CHAPTER 7

Enhancing battery safety through digital twinning in electric vehicles and storage systems

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7.1 Introduction

7.1.1 Background

Digital twins (DT) and the Metaverse offer transformative potential for energy systems. They produce virtual representations of actual energy assets [1], which facilitate real-time monitoring, modeling, and optimization. Numerous facets of energy systems, including grid management systems [2], energy storage, and power-generating facilities [3], can benefit from this technology. Operators employ DT [4] to identify abnormal behavior in renewable energy systems, improve grid management, and forecast energy demand, all of which improve maintenance and operating efficiency.

Improvements in data processing, socioeconomic considerations, and the reciprocal integration of digital and physical entities are among the present and future advantages that are described in the study [5]. It also draws attention to issues like data standardization, model correctness, and the integration of nonphysical systems [6–8]. This places a strong emphasis on enhancing data collection and processing, promoting socioeconomic integration, and cultivating reciprocal integration in order to build a comprehensive municipal DT.

By providing interactive dashboards and simulations, Metaverse's immersive virtual environments can enhance the application of DT even further. In order to forecast energy output and demand, conduct what-if analyses, and remotely regulate physical assets to optimize performance, users can observe and interact with an energy system's DT. Enhancement of asset management [9], operational reliability, and environmental sustainability can result from the integration of DT with the Metaverse. The study [10] emphasizes two scenarios: the long-term impacts of Connected Autonomous Carsand Hybrid Electric Vehicles, as well as the immediate advantages of real-time eco-routing

Metaconstructs
DOI: https://doi.org/10.1016/B978-0-443-40678-2.00008-8

based on emission-optimal algorithms. By enabling stakeholders to visualize and interact with the DT, virtual realityin the Metaverse facilitates the implementation and assessment of emission reduction measures.

Article [11] examines DT modeling, focusing on the fundamental ideas, techniques, and supporting technologies. By emphasizing their role in monitoring, simulation, prediction, and optimization, it draws attention to the significance of DT models in intelligent upgrades and digital transformation. Additionally, it classifies DT models according to their discipline, universality, dimension, hierarchy, functionality, and application sectors. The six components of DT modeling are also covered, including building, assembling, combining, verifying, modifying, and maintaining models. The article's conclusion highlights the necessity of a methodical approach to DT modeling and the creation of integrated software platforms to support the complete modeling process, in addition to remarks and suggestions for further research.

Through the use of IoT and cloud computing [12], the study demonstrates how DT and smart materials have the ability to completely transform the Indian Electric Vehicle (EV) market by enhancing maintenance procedures, cutting expenses, and enhancing vehicle performance. By building a virtual model of actual EVs, DT makes it possible to share and analyze data in real time for problem finding, predictive maintenance, and performance enhancement. Shape memory metals and polymers are examples of smart materials that can self-heal or alter shape, which lowers the cost of EV maintenance.

A thorough analysis of mind maps in EV design from multiple angles [13] through a review of 12 years of scholarly works identifies important EV-related elements, including renewable energy, e-mobility, battery charging, and sustainable transportation (2008–20). Consumer expectations, government planning, energy management, economic perspectives, and EV variations are the five facets of EV design that are covered by the study's creative mind map. The findings are meant to provide information and guidance for EV initiatives to a range of stakeholders.

The authors of [14] focus on using cloud data and cutting-edge algorithms to improve EV battery management systems (BMS). The first study introduces a cloud-based BMS that builds a DT of battery systems for State-Of-Charge (SOC) and State-Of-Health (SOH) monitoring and real-time diagnostics. It employs a particle swarm optimization technique for SOH estimation and an adaptive extended H-infinity filter for SOC estimation.

However, when evaluating battery life using cloud data, [15] suggests an approach that gives internal resistance and capacity prediction priority. It computes capacity using the ampere-hour integral method and predicts internal resistance using the Fuzzy Logic Optimized Kalman Filteralgorithm. Although solid oxide electrolytes are renowned for their exceptional stability and pure Li-ion conductivity, their electrochemical performance is constrained by their high boundary resistance and poor interfacial contact [16]. The study elucidates the inherent limits of solid oxide electrolytes by employing a 3D DT technique to observe and quantify interfacial flaws in solid-state lithium batteries.

Batteries have become the silent but essential engines that drive our contemporary lives in an environment of rapidly advancing technology. Batteries quietly weave a tapestry of comfort, sustainability, and development into everything from the smartphones we carry to the EVs revolutionizing our roadways and the renewable energy systems lighting up our houses. However, the need to maintain batteries' safety and resilience grows with their size and pervasiveness in our daily lives.

The widespread use of batteries, especially lithium-ion batteries, has exposed weaknesses while creating new opportunities. Over the years, we have seen news stories exposing battery-related mishaps, stressing the urgent need to improve their safety. These incidents, which range from cellphones catching fire to thermal runaway electric cars, serve as forceful reminders that securing human lives and preserving the environment must go hand in hand with the advancement of technology.

Establishing a reliable battery model is the first step in implementing battery DT. Battery models are now necessary tools for battery-powered applications that are important for performance and safety[17]. Depending on the way the inputs are fed into the model , battery models can be classified as empirical, semiempirical, or physically based on their related outputs. Moreover, data-driven, with the many battery models [18]. A battery's Equivalent Circuit Model (ECM) is frequently utilized in BMS algorithms and is comparatively simple to scale to the module or pack level. They originate from the empirical measurements of the cell's exterior properties. However, the internal electrochemical dynamics of the battery cannot be fully captured by looking at its exterior behavior alone, and it is challenging to offer insights into the electrochemical processes that take place inside the battery.

Furthermore, because ECMs are designed using data from target battery operating parameters, their accuracy sharply declines when calculating under different circumstances or when a battery needs to be changed. The work carried out in [19] is estimating the SOH of lithium-ion batteries using virtual experiments and machine learning techniques is presented by SOH estimation through virtual experiments lithium-ion digital battery twins trained on unstructured battery data. The article emphasizes the significance of maximizing the longevity of EV batteries. It presents the notion of the digital battery twin, a battery model that relies solely on data. The digital battery twin is trained using a unique recurrent encoder-decoder battery model and exclusively depends on the regularly recorded BMS data to estimate the remaining capacity (SOH) autonomously without any predetermined ageing information. The simulation framework that utilizes virtual experiments to evaluate lithium-ion batteries' SOH by assessing their remaining capacity. The model is unconstrained in terms of low current, requires only driving profiles to parameterize the battery's digital model, and can be used on a variety of datasets with charging and discharging profiles. The framework is especially well-suited for automotive applications and considers the battery model's validation requirements.

Additionally, an evaluation is conducted to determine the appropriateness of these methods for practical implementation in real-world scenarios. Two primary classifications of DT specifically model-based and data-driven DT, are compared. This study also examines the possible impacts of distributed ledger technology (DT) platforms on EV and assesses obstacles that hinder their implementation.

The study finishes by providing suggestions for prospective investigations within this domain, which [20] analysis suggests that DT technology can assume a progressively significant function within the automotive sector, necessitating additional investigation in this domain. The DT is mentioned in [21], a thorough electrochemical model for each battery cell, including models for the power electronic converters and thermal management system. The authors can gain important insights into how various design choices and control strategies affect the long-term deterioration and efficiency of the battery system by using simulations to study the behavior of the DT under various operating conditions.

Based on the findings elucidated in the [22], With a minimal Mean Absolute Errorof 0.4%, it has been found that the DT model can accurately predict battery capacity deterioration. The results indicate that the primary cause of the capacity decrease and resistance increase is the growth of the Solid Electrolyte Interphaselayer. When compared to a typical continuous charging approach, the model study shows that one of the suggested multistep charging processes can lessen the degradation of Nickel Manganese Cobalt (NMC)-based lithium-ion batteries. This work offers a solid theoretical framework for upcoming advancements in machine learning based on physics.

The development and use of DT technology in relation to Battery Energy Storage System (BESS) across the production process are examined in a study [23]. A number of suggestions are provided in this chapter for creating a DT model that accurately captures the traits and behaviors of BESS.

7.1.2 Challenges and opportunities

The following are some of the main challenges to enhancing the layout and operation of big battery systems: One strategy that is seen as promising is DT technology.

- Data trustworthiness: Accurate information about the battery's performance and properties is necessary to create an accurate DT [24].
- Complexity: Accurately simulating battery activity digitally is challenging. The more accurate the model, the more computationally intensive it becomes, posing a problem for computer power

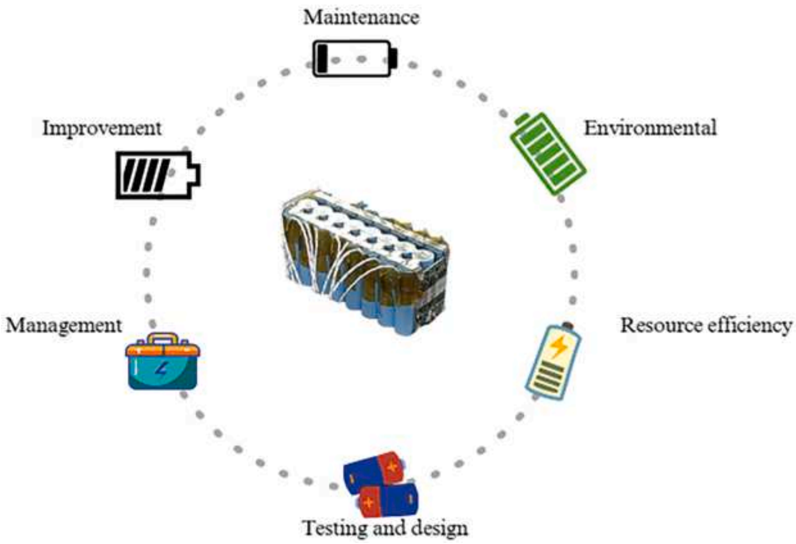

Figure 7.1 Opportunities for battery digital twinning. Battery life cycle.

- Real-time integration: Due to various circumstances, battery performance might alter over time, and it can be challenging to include real-time data into DT models. It is essential to keep the DT correct and current.
- Safety: The security and privacy of sensitive data must be protected since DT technology includes gathering and analyzing data from batteries in applications like EVs, and grid energy storage.

Improved performance, design testing, resource efficiency, and close-up monitoring of resilience and cycle life's end are all made possible with the help of DT of modeling [25]. By adjusting while data are recorded and analyzed in real-time, resource efficiency can be achieved by reducing time and money [26] with the possibilities for predictive maintenance. Further, storing energy usage can be optimized by integrating DTinto energy management systems [20] for applications both generation and energy storage. Improved battery management made possible by DT can promote sustainability [27] and lessen environmental impact [19,28]. Fig. 7.1 shows the opportunities in battery twining toward safety resilience.

7.2 Approach in the digital twin for battery modeling

7.2.1 Online estimation of parameters

A critical component of BMS for applications ranging, from electric automobiles to renewable energy storage, is the online estimation of battery parameters from real-world circumstances. This approach entails continuously monitoring and analyzing data to identify critical variables influencing battery performance and health. Several of the crucial variables considered in this investigation were:

1 **State of Charge (SOC)**: SOC is a percentage that indicates how much energy is still in the battery. Voltage, current, and capacity information are used in the estimation methods to calculate SOC [29].
2 **State of Health (SOH)**: SOH represents a battery's general health and degree of deterioration [30]. The expected lifespan and reliability of the battery are determined by looking at how its capacity degrades over time.
3 **Depth of Discharge (DOD)**: To avoid deep discharges that could endanger the battery's health, DOD, or the proportion of the battery's capacity discharged in a single cycle, is crucial.
4 **Open-Circuit Voltage (OCV)**: OCV is a battery's unused or charged voltage. An estimation of OCV is essential to ascertain the battery's actual voltage and charge/discharge behavior.
5 **Temperature**: Measuring and predicting battery temperature is crucial for safety and performance. Online temperature estimation can be utilized in thermal management systems to reduce overheating [31].
6 **Internal resistance**: The efficiency and power delivery of the battery are impacted by internal resistance. Hence, the voltage and current response analysis during operation can be used to estimate internal resistance in real-time [31].

7.2.2 Plant model upgradation and optimization

A critical step in raising the effectiveness and performance of industrial processes is upgrading the plant model following the physical systems for future plant model optimization. By simulating and forecasting how batteries will behave in various applications, a battery model is a mathematical representation that more accurately reflects the actual physical properties and operation of batteries. This alignment requires making informed choices, maximizing battery life, and enhancing safety. With a longer battery life, this is done to match the physical system for improved precision, safety, and efficiency. Using real-time data from sensors and monitoring devices to update battery models is normal practice. With this information, the model can adjust to shifting circumstances and increase the accuracy of its predictions regarding battery performance and health. Updating the battery model is often an iterative process that requires refinement as new information becomes available or the battery system changes.

7.2.3 Quantitative and qualitative analysis

Based on a battery's current condition and usage patterns, quantitative analysis forecasts when it will most likely reach the end of its usable life. Remaining Useful Life (RUL) is an important statistic for determining how long a battery will continue to function effectively. Machine learning, data-driven modeling, and physics-based modeling are used to estimate RUL. These models also assess battery ageing over time by taking into account variables including chemical deterioration, internal resistance growth, and capacity loss.

It can qualitatively evaluate how well the model reflects real behavior by contrasting the DTs simulation findings with the battery's actual performance. Differences between expected and actual results can reveal areas for development. The complete life cycle of the battery system, including its sustainability and environmental impact, may be evaluated using qualitative analysis. Analyzing variables like recycling and disposal alternatives can obtain a qualitative view of the system's durability.

7.3 Methodology

The initial step in the strategy is to demonstrate linear development for the features provided in the preceding section, like in the case of battery twining. However, when twining takes place, everything is done simultaneously. The thermal deterioration of a single cell and a group of cells is carried out in a modeling environment and is implemented into physical systems, as seen in Fig. 7.2.

The software environment receives the physical system's parameters as input. The thermal distribution can be optimized by choosing between rapid and gradual charges based on the characteristics described in earlier Section. Cells from various manufacturers can be instantaneously conducted using Electrochemical Impedance Spectroscopic (EIS), such as galvanostatic cycling. In galvanostatic cycling in batteries, it is common practice to quantify the charge and discharge current using a C-rate (measure of the charging or discharging speed of a battery). This rate is determined by dividing the current by the battery's nominal capacity, which represents its capacity when fully charged.

The C-rate is a metric used to quantify the speed of battery charged or drained about its nominal capacity. As an illustration, a C-rate of 1 C denotes the application of a current sufficient for a complete charge or discharge within 1 hour. C-rate multiples of 1 C are also employed. In battery research, it is customary to employ a C-rate of 0.1 C for charging and discharging a battery for a duration of 10 hours. The battery's nominal capacity, which is 2.6 Ah, was divided by a duration of one hour, resulting in a current of 2.6 A.

In contrast, a current with a magnitude of -2.6 A must fully deplete the battery within one hour, commencing from a state of full charge. The battery cycled at a rate of 0.1 C (or C/10, equivalent to 260 mA for10 hours). 0.2 C (or C/5, 520 milliamperes, 5 hours), 1 C (2.6 amperes, one hour), and 2 C. The experiment was conducted using a current of 5.2 Amperes and a duration of 30 minutes. The galvanostatic charge and discharge procedure was conducted using the potential range from 3.0 V to 4.2 V. Based on the cycle, the AC frequency sweep was conducted from 0.01 Hz to 100 kHz.

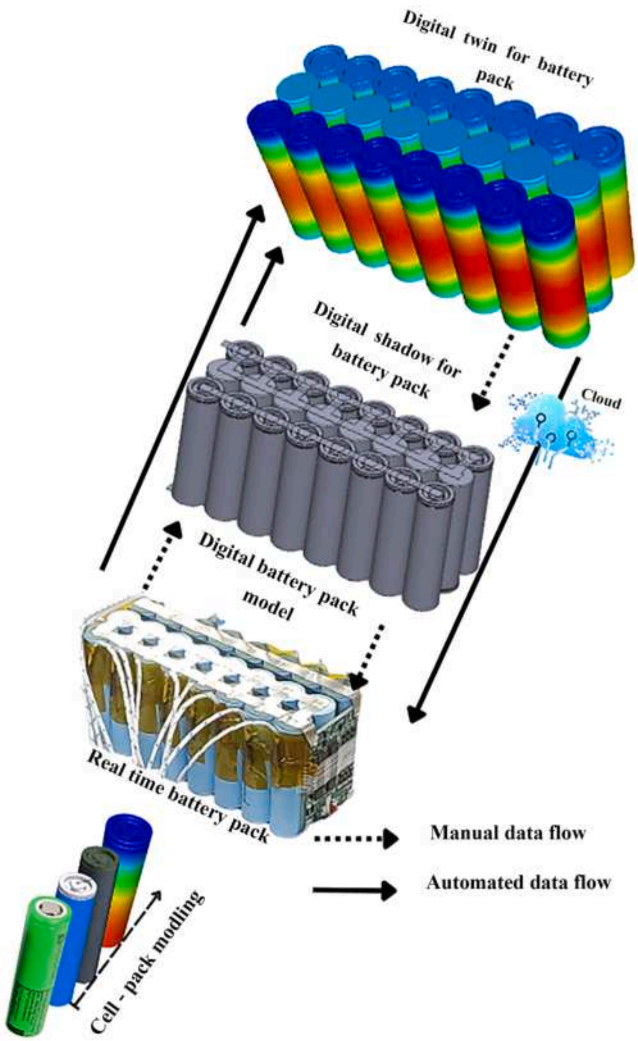

Figure 7.2 Systematic representation of digital twin. From cell to pack—Battery.

The frequency response of the single cell is analyzed using the R and C network's known parameters, leading to 3RC time constants. The ECM was developed for digital modeling based on the time constants, as shown in Fig. 7.3.

The initial modeling single cell is extended to the battery pack shown in Fig. 7.3 and Fig. 7.4, which has the required size and dimensions to emulate the EV battery pack. The multiscale multidomain (MSMD) model is created in ANSYS as table-based parameters, shown in Fig. 7.5, to analyze and discuss what-if case scenarios and extreme thermal scenarios resulting as output from driving on the ramp, accelerating at the

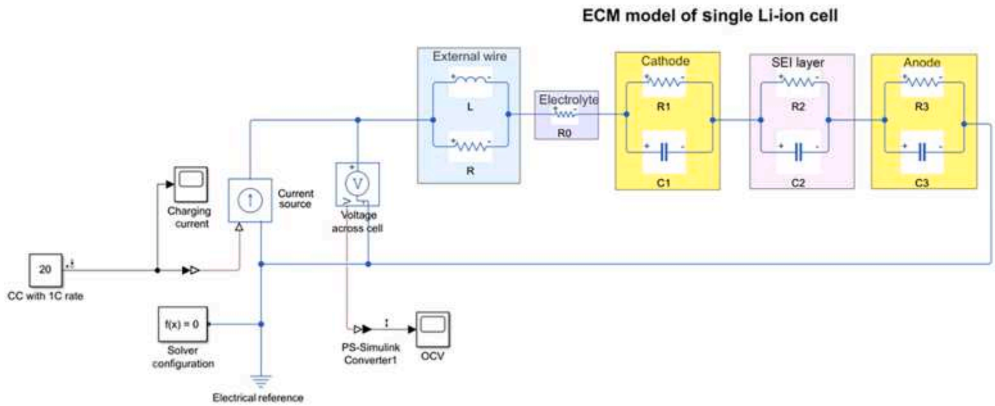

Figure 7.3 Implementation of the 3RC model in MATLAB. 3RC Model.

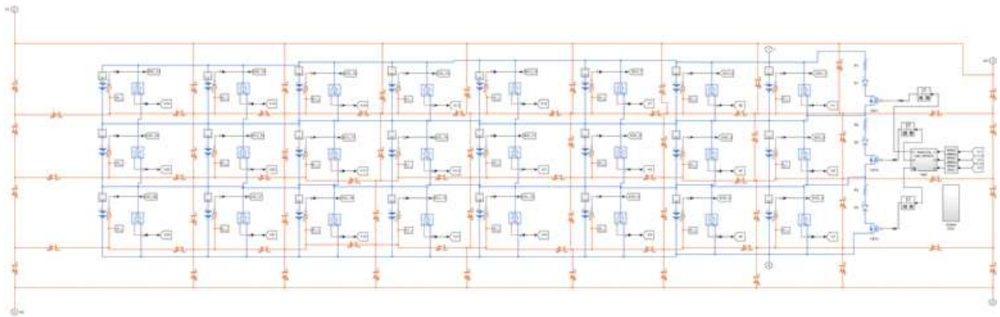

Figure 7.4 Implementation of the 3S8P battery pack in MATLAB. Battery pack modeling.

corners, and continuous driving in rough terrain can be studied using the real-time charging and discharging current profiles.

A suitable controller to enhance the safety and resilience of the BMS based on the estimated parameters from ECM using high-end computing software like MATLAB is approached. All the results estimated and analyzed from the model can be integrated into an actual vehicle over cloud computing. The real-time vehicle onboard controller can become cautious about extreme conditions and provide protective measures during possible extreme thermal conditions. However, the real-time parameters are still logged using the onboard computer and uploaded into the cloud to update the digital model. Which in turn forms the efficient DT.

7.4 Results and discussion

The results obtained by combining digital simulation and real-time scenarios lead to the development of the metadata for the battery packs in the cloud, providing various

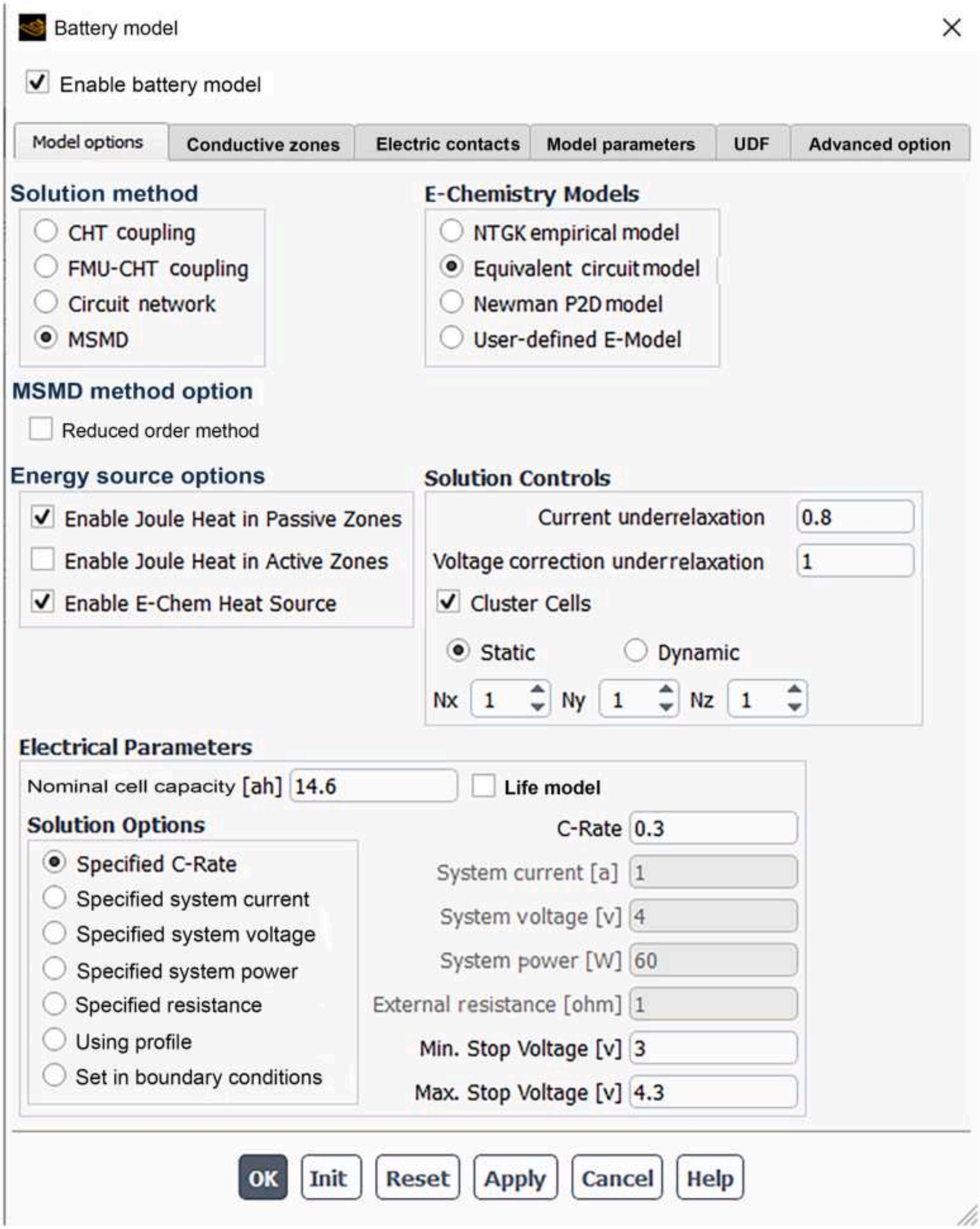

Figure 7.5 Multiscale multidomain (MSMD) model method to create a battery cell and pack. MSMD in modeling.

insights about the battery pack's behavior. The typical results from each stage of the process are listed as follows. Fig. 7.6 shows the typical frequency response of an individual cell carried out in the galvanostatic studies. Fig. 7.6 shows the frequency at which the charge transfer occurs in a cell. As it proceeds, the cell's internal resistance tends to vary concerning SOC. Overall, it can understand the minimal internal resistance region to employ charging.

Fig. 7.7 shows a typical Nyquist response elaborating the different regions of a cell's charge transfer, diffusion region, and inductive region. With the combination of Bode and Nyquist plots from galvanostatic studies, one can understand the design of the battery pack and fit the curves concerning suitable time constants. Higher time

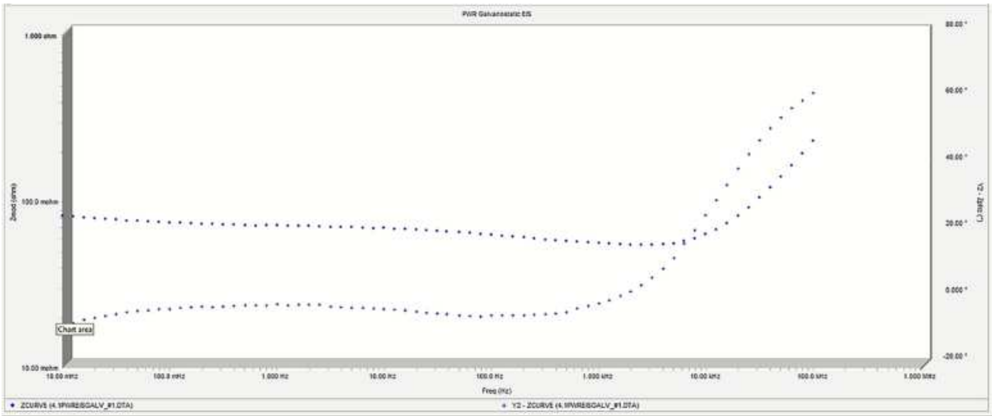

Figure 7.6 Bode plot representing AC sweep analysis of a single cell to estimate the parameters of the equivalent circuit model (ECM). Sweep analysis.

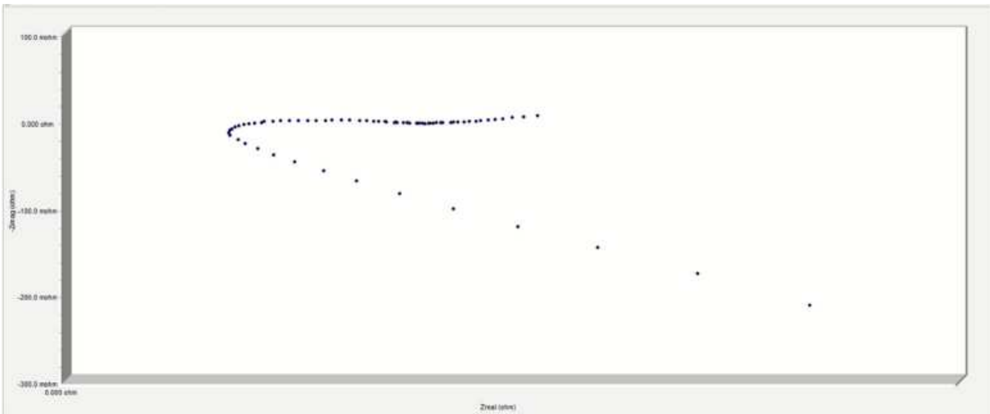

Figure 7.7 Nyquist plot representing AC sweep analysis of a single cell to estimate the parameters of the ECM. *ECM*, Equivalent circuit modeling.

constants, like 3RC to 5RC models, are generally provided with a good fit for a high-voltage battery. Typical 3RC fit residuals data for R_0, L, R_1, R_2, C_1, C_2, and C_3 are provided in Table 7.1.

Thermal abuse poses a significant safety concern and is considered the most hazardous scenario due to factors such as inadequate manufacturing quality control or suboptimal thermal management design in both standard and abnormal operating situations. Lithium-ion Batterysafety testing does not adequately elucidate the mechanism of thermal runaway propagation during internal shorting in the electro-chemical/thermal system due to its inherent complexity. Hence, a robust numerical model is crucial for comprehending thermal runaway propagation and determining the primary factors contributing to its mitigation in a battery module or pack. The MSMD model of 3RC time constants is best utilized to understand the effect of various thermal analyses of various extremes. A comparison of the simulated model and experimental model is given in Fig. 7.8.

The Battery (Table-Based) model in MATLAB employs the same circuit modeling methodology. Various physical phenomena of a cell can be effectively captured by utilizing a series connection of several resistor-capacitor (RC) pairs. Within the table-based model, there is an option to choose a number of RC pairs, whereas this model opts for 3RC pairs. The values of the resistance and time constant parameters can be derived. The successful prediction of cell voltage and continuous cell impedance is achieved by applying numerous frequency signals to the cell operating DC bias.

Furthermore, the model effectively predicts the impedance of cell continuity as it is discharged at varying initial SOC. This model considers the impact of cell SoC in Fig. 7.9, SoH and temperature in Fig. 7.10, and voltage and current waveforms representing the transition from CC to CV shown in Fig. 7.11. Furthermore, empirical evidence demonstrates that the model is employed to optimize the parameters on the status of the cell using a monitoring method. This combination of ANSYS and

Table 7.1 Estimated parameters

Parameter	Value	Units
R1	7.187e-3	Ohm
R0	56.86e-3	Ohm
C1	110.9	Farad
R2	13.89e-3	Ohm
C2	109.5e-3	Farad
R3	40.11e-3	Ohm
C3	1.442e3	Farad
L	394.1e-9	Henry
R	763.2e-3	Ohm

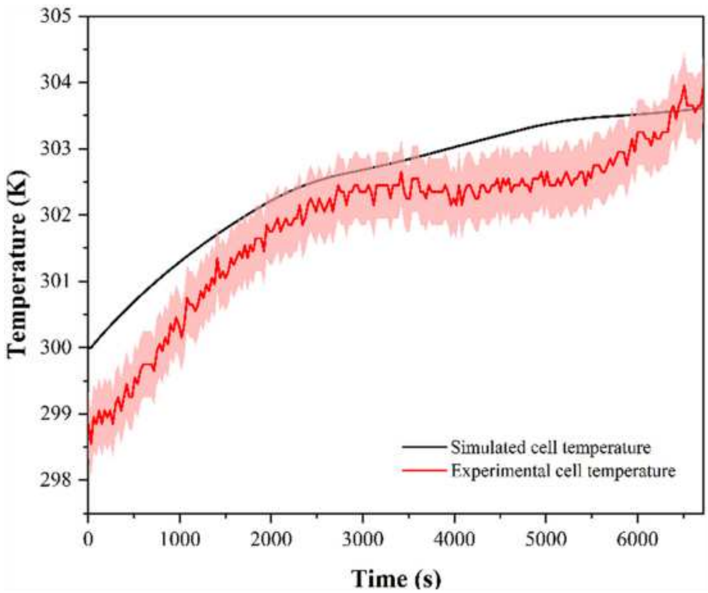

Figure 7.8 Comparison of the ECM model and experimental data under 1 A discharging condition. 1 A discharge. *ECM*, Equivalent circuit modeling.

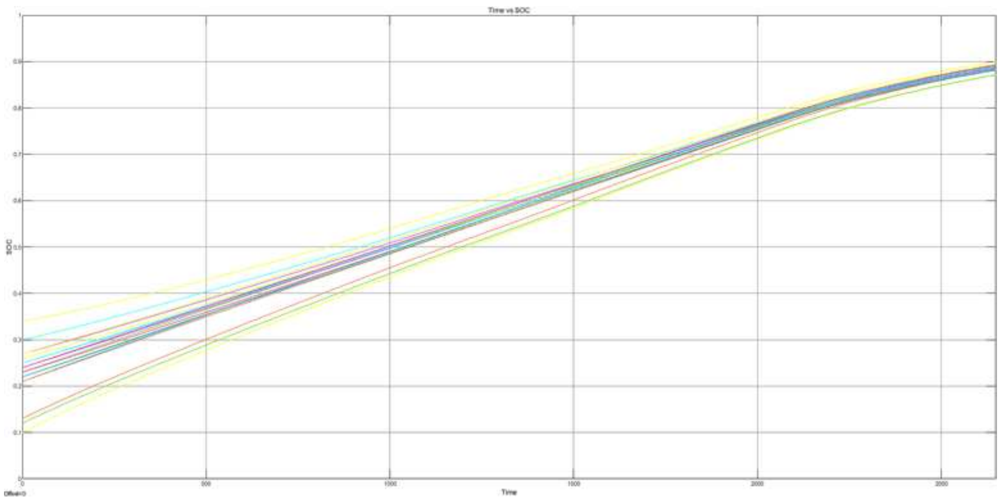

Figure 7.9 State of Charge of 24 cells in MALAB during charging at 1 C rate - 20 A reaching 0.9. 1 C rate.

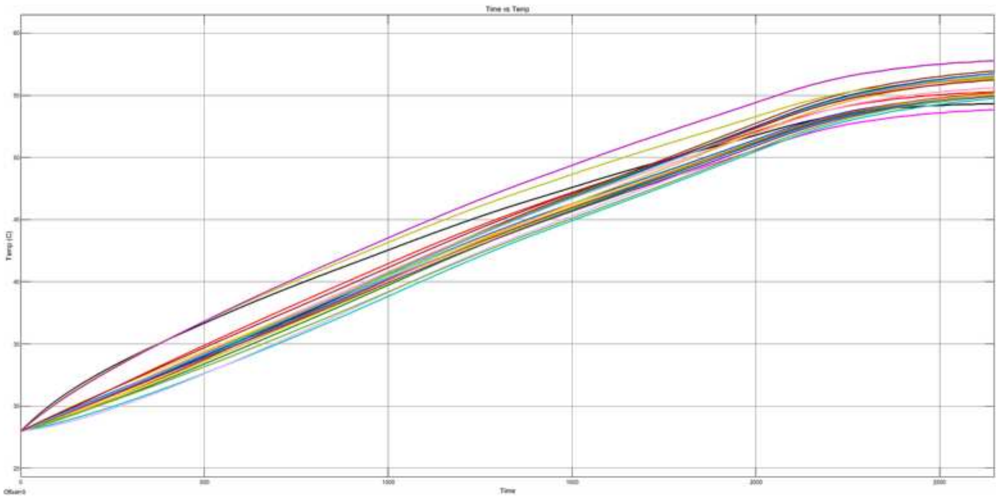

Figure 7.10 Temperature of 24 cells in MALAB during charging at 1Crate-20A. 1 C.

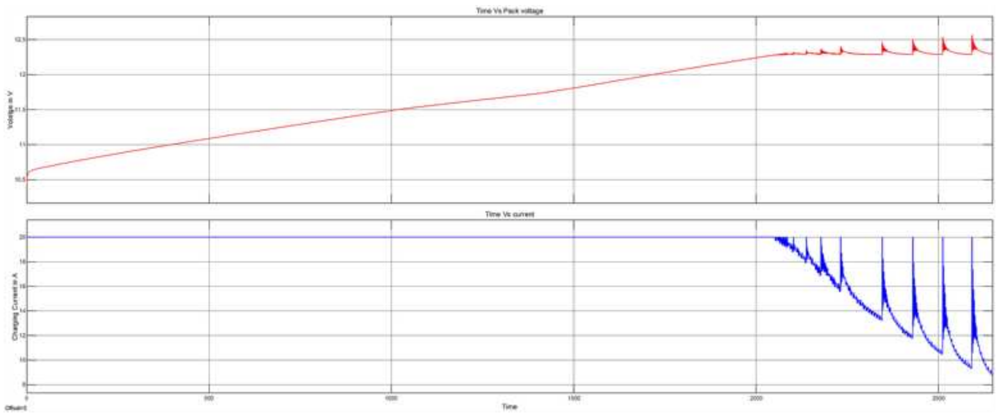

Figure 7.11 Pack voltage and charging current at 1 C–20 A representing a transition from CC to CV mode. 1 C.

MATLAB models derived from ECM modeling by utilizing EIS studies has proven to be a fundamental approach for digital twinning.

7.5 Conclusion

A digital model based on ECM and a data-driven technique to identify critical characteristics from a single cell using electrochemical impedance spectroscopy were used to illustrate the application of digital twinning towards the resilience of the battery used in applications like electric vehicles and photovoltaic systems. Critical parameters are used in the creation of the ECM in MATLAB and ANSYS. The ANSYS model is further developed to examine the battery pack's high thermal conditions, and battery pack controllers are built using MATLAB models. These two ECM and data-driven models are combined to produce accurate digital battery twin modeling.

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CHAPTER 8

Convergence of Metaverse and digital twins: evolution, integration, and future challenges in virtual-physical systems

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8.1 Introduction

Metaverse and digital twins (DTs) are two of the future evolutionary technologies that are going to help in a great way in how people will interact digitally and physically in the future. In the Metaverse, virtual presence will be able to work, socialize, and buy things. This system combines artificial intelligence (AI) with virtual reality (VR) and augmented reality (AR) technology for its operations. DTs, on the other hand, are the DTs of real-time physical objects. The technologies it uses are Internet of Things (IoT), cloud computing, and even AI. It has different applications in manufacturing and healthcare for performance tracking and assessment. When conjoined, these technologies will elevate effectiveness and boost experience regarding many applications. In the Metaverse and DTs, influence is the integral effect on interaction concerning the human being with virtual and actual environments, more than how the modern world lives their whole digital lives. The change takes place with socialization, entertainment, education, and commerce through the Metaverse. On the contrary, DT simulations [1] help industries carry out real-time simulations in sectors such as manufacturing, healthcare, and urban planning. Matters such as optimization, improved decision-making, and cost reduction are to importance. Enhanced virtual collaboration, predictive analytics, and personalized experiences are among these technologies, giving the limelight to consider them key drivers towards the new wave of digital innovation and economic growth. As evolution rounds these technologies evolve, a promise of possibilities is shared between the Metaverse and DTs. Future applications are more likely to change industries and everyday life. Prediction: DTs, for example, would create accurate real-time city models for urban planning that planners and policymakers can use to simulate and optimize everything from traffic flow to energy consumption. In the Metaverse, real-time models can be visualized and interacted with to allow

Metaconstructs
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data-driven decision-making in an immersive environment. DTs of patients and medical devices enable real-time monitoring, predictive diagnostics, and personalized treatment plans, while the Metaverse could facilitate virtual consultations, medical training, and rehabilitation. Joining DTs' predictive savvy with the immersive, social powers of the Metaverse creates an unprecedented opportunity for reshaping the future of work, communication, entertainment, or even governance: new engines of engagement, cooperation, and innovation will be created for individuals and organizations in the digital realm. This nexus is indeed a major leap towards more dynamic, interconnected, and efficient systems across all sectors.

Such methodologies put a thesis toward how modern appliances and innovation change the different interactions that human beings and organizations have in virtual and physical domains. The Metaverse and DTs are perhaps two progressing breakthroughs that can turn around different sectors of the economy into systems that possess remarkable potential. Such outcomes are paving the way to the next digital revolution by connecting immersive virtual worlds that are rich in experience right into the worlds that they are programming simulations against. Implementation within the industries of such technologies further pushes the change to digital transformation, making it an avenue for numerous opportunities for innovative methods, highly effective operations, and advanced team links through these developments. Both the Metaverse and DTs create an interconnected system that brings a world of virtuality to alter physical spaces while changing the way people will experience human interaction and the businesses they will operate and develop socially around the globe.

8.2 Basic foundation of Metaverse

8.2.1 Definition and core features

Through the Metaverse [2], people can actively engage with virtual spaces together with digital elements and other individuals in real time in this continuous collective virtual environment. Over several platforms and devices, the integrated concept uses VR [3], AR [4], and internet elements to deliver an immersive connected experience [5]. The virtual entity operates autonomously with advancement during user absence because of the persistence mechanism, which acts under the Metaverse philosophy. During times when users are not present, the system operates independently to support uninterrupted communication and activities in a manner similar to physical universes. Users benefit from seamless platform transition because different virtual environments integrate interoperability standards that unite with applications and platforms. Metaverse supports unrestricted movement of digital assets from avatars to virtual currencies and virtual items through all environments without facing any technical barriers. The Metaverse offers authentic interactive encounters featuring VR and AR convergence with three-dimensional technologies, which provides users with the experience of actually being in virtual spaces for gaming pleasure and work-related or social gatherings, and worldwide travel. According to Park and Kim [6], the achievement of Metaverse consists of hardware together with software and content elements. The foundational concept of the Metaverse structure relies on decentralization because it stops every governing authority from attaining complete control. The decentralization based on blockchain technology lets users hold digital assets and keeps them self-sufficient. People can interact in real time through avatars as the fundamental nature of the Metaverse emphasizes social connections for both relaxation and work, collaboratively or for entertainment purposes. The Metaverse project aims to develop an online realm that duplicates the real-world interactivity while maintaining diversity and complexity for work functions, along with social activities and entertainment venues, and more.

8.2.2 Historical background

The concept of the Metaverse has been under development for several decades, beginning as science fiction and progressing toward building an actual technology. Neal Stephenson introduced the term Metaverse in his 1992 novel Snow Crash, in which Metaverse is used to describe a successor to the internet, founded on virtual environments that one can literally enter, particularly as avatars. Late precursors to the Metaverse are so-called three-dimensional (3D) virtual worlds like Second Life, released in 2003, representing a definite user-generated virtual environment that features a certain step towards immersion within the internet. But then we were not able to realize all the elements mentioned in Sci-fi because of the technology shortage. The emergence of cutting-edge technologies such as VR, AR, blockchain, and cloud computing has led to the convergence of the concept of Metaverse into a real web of human, business, and technical systems. Internet, mobile computing, and social networking may be quoted as the key technologies that served as the core of modern Metaverse solutions. With AI on hand, real-time rendering, and decentralized digital economies through blockchain, what the modern Metaverse delivers is persistent, interconnected environments that simulate, represent, or extend physical world experiences. Today, there is a huge capital investment by leading technology companies to create environments where people can communicate, work, and play in realistic ways. The spread of devices such as VR headsets and AR glasses and the development of 5G networks have made the type of virtual interaction depicted as feasible here more efficient. These innovations have shifted the Metaverse from being a science fiction notion back to reality as a focused aspect of strategic planning across multiple industries that brings together the physical and virtual worlds.

8.2.3 Purpose and objectives

The main goal and objective of a Metaverse is to create a jointly experienced virtual space that affords deeper communication, interaction, and connectivity beyond the previously conceived space-time reality. Using technologies such as VR, AR, and AI, the Metaverse offers a chance for people to interact, perform business, attend events, and access information in the form of digital media applications in virtually simulated realities. In the idea of Metaverse, work conferences can be held in real-life board rooms, students can virtually visit some landmarks to even visually observe the graffiti, or sometimes entertainment can be very much indistinguishable from a video game. This enriches the experience, strengthened by a blending of personal and work, and promotes new and better ways of interacting and working. As a part of its economic transformation agenda, the Metaverse establishes virtual E-Commerce and new marketplaces that allow users to exchange new digital assets. The ownership of unique digital assets gets verified through blockchain-based nonfungible tokenization because of distributed ledger technology features that drive virtual economy growth. Virtual process modeling within the Metaverse allows commercial users to achieve remote control and improvement of real-world systems through virtual replication of physical spaces. Metaverse ideology describes the replacement of existing two-dimensional internet usage with 3D, multidimensional interactions that modernize how people communicate and learn while also transforming their playing and purchasing experiences.

8.2.4 Principle of operation

The Metaverse works by building a simulated, connected 3D virtual world that enables users to engage with other users and virtual objects in real time. The use of VR and AR makes the Metaverse a rich experience that can either fully immerse people or superimpose digital features over the physical world. Blockchain technology provides secure ownership and transfers of virtual property, while AI increases interactivity with smart avatars and customized experiences. Cloud computing enables the Metaverse by offering a scalable architecture for real-time, worldwide access. This virtual world allows users to socialize, work, play, and create in a persistent, dynamic world [7].

8.2.5 Core technologies behind Metaverse

8.2.5.1 Virtual reality and augmented reality

VR and AR are core technologies that support building and living in the Metaverse, a digital universe that integrates virtual spaces and real-world content.

VR provides fully immersive environments that transport users into completely digital realms. In the Metaverse, VR enables users to engage with a totally virtual world using hardware such as VR headsets, gloves, or motion sensors. These devices make it possible for users to perceive and interact with digital objects, individuals, and spaces in 3D, providing a feeling of presence as if they were physically within the virtual world. VR is essential for gaming, online meetings, social networking, and even virtual travel within the Metaverse, where the user can visit new places, go to events, or co-work in offices, all in a completely immersive experience.

AR, in contrast, places virtual elements over the real world, merging the virtual and the physical. AR increases the user's experience of the real world by incorporating computer-generated images, sound, or information. In the Metaverse, AR offers users the opportunity to engage with virtual objects that are embedded into their physical environments using devices such as smartphones, AR glasses, or tablets. For instance, AR is applied in the Metaverse to position virtual objects within the actual world for interactive purposes, including seeing and engaging with 3D holograms, playing location-based games, or engaging in mixed-reality shopping experiences.

Through effective partnerships, VR and AR form a powerful combined force in the Metaverse. While VR immerses the user entirely in a purely imaginary environment, AR serves to give an immediate, real-world experience a digital component, thus merging the real and virtual worlds. Participating in this new set of social interaction and entertainment, education, and commerce using these technologies, users are creating rich, interactive experiences that fuel the growth of the Metaverse.

8.2.5.2 Blockchain for ownership and transactions (nonfungible tokens, cryptocurrencies)

With its wide-ranging security features, decentralization, and transparency, Blockchain technology has provided the important Metaverse with an additional front of safety for its ownership systems and transaction modalities. NFTs and cryptocurrencies work as undercurrents of Blockchain technology to run virtual–economical interactions and ownership management for the Metaverse. The Blockchain system thereby works to verify nonfungible token (NFT) digital assets, which helps keep a record of not only their ownership but also of the authenticity verification step. The trading of virtual assets such as digital art and real estate, as well as in-game items, avatars, and clothing, is made available through NFTs in the Metaverse. Every NFT functions independently as it represents unique ownership of distinct digital items or pieces of content beyond the replicability that applies to standard cryptocurrencies. With social and economic advantages stemming from virtual properties, the verification of ownership of digital items becomes cardinal, for users seek provable evidence of ownership. Whenever a Metaverse buyer purchases their virtual land, such a purchase is validated through NFT means on the blockchain, which ensures that the buyer has ownership rights over the land. In the Metaverse, users transact through cryptocurrencies that serve as the main medium of exchange due to the confirmed acquisition of such currencies. The Metaverse economy relies on such crypto tokens as Bitcoin and Ethereum, and tokens specific to decentralized platforms such as MANA and SAND that belong to Decentraland and Sandbox, respectively, for users' transactions. Via these blockchain-operable transactions, there is no necessity for banks, with traditional peer-to-peer transfers being the secure way in which cryptocurrencies operate. The Metaverse needs a decentralized grip due to its transactional system that interfaces security, low-cost, and is easy to use for global businesses. The interplay of NFTs and cryptocurrencies establishes an economy for the Metaverse, which creates room for free trading among users on account of secure, transparent transactions guaranteed by blockchain technology. With trust in the digital system, contracts are enforced in a global market situation. The digital ownership is verifiably supported, thus promoting trust, while economic engagement is facilitated by the blockchain underlying the Metaverse infrastructure.

8.2.5.3 The Internet of Things

It occupies a central position as one of the technologies that will take the Metaverse into the future. Here's how: Embedded sensors and connectivity systems in nonspecific devices like home appliances and wearables connect the world of Bitcoin with the real world and become more than just a currency in today's tech-enabled society. Networked devices within the Metaverse shape real-time footage of the physical world, which in turn holds advantages for the users in a better interaction with virtual environments. "Smart Environment Interaction" becomes possible through IoT technology because it enables virtual spaces to interact with physical environmental conditions within the Metaverse. Smart homes and cities in the real world would establish real-time connections with virtual representations of the Metaverse so users could watch and operate their physical equipment through virtual environments. Rolling real-time data found across IoT devices results in VR/AR system enhancement in the Metaverse through continuous feedback and live environment management. Virtual fitness environments become more immersive through IoT-enabled wearables, which track your actual body movements in real-time. Web interfaces use IoT platforms to collect information regarding users' behavioral patterns, together with their preference choices and system operations. Metaverse users can benefit from personalized experiences when IoT gathers their health information and adjusts virtual environments, as well as customizes virtual avatars and settings. The integration of smart transactions and supply chain operations becomes possible when Metaverse users implement devices enabled by IoT, where they automate and simplify their business processes with smart contracts and blockchain protocols. IoT enables the integration of physical logistics components with virtual inventory management functions and other elements that facilitate smooth virtual and physical economic interactions. As a result, IoT establishes interconnections between the Metaverse and real-world economies.

8.2.5.4 Three-dimensional modeling and rendering tools

Digital environments, as well as virtual characters and their objects, require 3D modeling and rendering tools to develop and present Metaverse content. Through these tools, developers, along with artists and users, can develop interactive immersive experiences as basic components of Metaverse design. The development of the Metaverse depends on these tools as they provide capabilities to build virtual structures in addition to digital environments and characters [8] and virtual assets. Specialized software enables creators to build virtual objects through model manipulation, where they can modify geometry together with textures and lighting effects, along with different virtual object elements. The Metaverse implements various 3D modeling tools, which are outlined in the following list.

Users can download Blender free of charge as an open-source tool for developing 3D models together with animations and textures. The tool provides a complete feature set for modeling, along with rigging functions and digital sculpting capabilities, and texturing abilities necessary for virtual world asset development.

1. The professional software Autodesk Maya enables users to build detailed 3D models along with animations, as well as digital simulations. The entertainment industry, alongside gaming, utilizes this software to generate digital resources that can exist in VR environments.
2. Using SketchUp, one could create their really beautiful and functional models in three spaces. This is intended to create areas for architecture in the Metaverse. Users build environments, buildings, and real-world objects on this digital platform.
3. ZBrush specializes in making detailed organic models like characters or creatures. The Metaverse entirely exploits this software to create more detailed digital avatars and sculpted elements. At the end of constructing 3D models, one should use 3D rendering tools to make their work complete. Rendering transforms models made on computers to 2D visual representations by applying simulation programs that simulate visual effects like light patterns, shadow reflections, and texture highlights aimed at producing realistic or artistic visualizations. The Metaverse employs the use of 3D rendering tools like Unity 3D and V-ray, among others, for process operations.
4. This is a powerful gaming engine specialized in generating interactive 3D worlds and real-time visualizations. The Unity platform is used extensively today to build virtual worlds and games in Metaverse development. The rendering engine of Unity provides high-definition visuals coupled with automatic performance optimization on various types of hardware.

5. Unreal Engine is the leading platform for developing advanced virtual worlds rendered with immersive reality-like visuals. The Metaverse uses this solution in developing its high-fidelity environments and immersive experiences, especially through virtual games, simulations, and other applications.
6. V-Ray operates as a rendering plugin that combines with SketchUp and Autodesk Maya, and Blender to generate photorealistic digital images. The rendering software V-Ray functions across architecture and Metaverse virtual environment development to produce highly realistic, lifelike image outputs.
7. Octane Render uses GPUs to deliver efficient real-time rendering results through its GPU-based rendering engine. High-quality visuals of realistic virtual environments, along with objects in the Metaverse, can be developed effectively through this particular tool.

8.2.5.5 Artificial intelligence

Metaverse experiences are enhanced with AI by adding a more interactive, smarter, and more customized environment. AI can modify the Metaverse as per individual preferences, behavior, and past experiences, and can deliver more accurate content with recommendations such as various shopping lists, various activities to do, etc. Due to this modification, AI can do for personalization of the Metaverse, to make the virtual experiences by users more relevant and dynamic. Many virtual assistants and chatbots supported by AI also provide instant support, guide users in their virtual presence, and facilitate social interaction with real-time suggestions and improvements. Natural-Language Processing grants an unusual capacity for user communication, allowing interaction by voice or text, not driven by rigid command structure, which gives a more virtual-real feel to the experiences. AI heightens immersion by allowing a virtual environment to react to user activity by changing settings such as lighting effects or weather instances, acting along with NPC responses. An AI can track user activity to slowly refine the digital experience depending on how people interact with the content. This culminates in increasingly intelligent avatars; fluid interaction; ever-pleasant interfaces that, over time, feel natural to use. From content creation onward, AI can make real-time suggestions about how the user can customize every detail of their avatars, virtual spaces, and digital artwork, allowing for heightened levels of creativity and self-expression. Cutting-edge systems for emotion detection can read emotional cues and adjust their responses accordingly, leading to a much more genuine and empathetic interaction in the virtual environment. On that note, another feature of AI is prediction: It predicts the user's needs and serves relevant content while establishing dynamic virtual experiences in conformity with personal preferences—making all interactions a flow in the Metaverse, engaging, and fun.

8.2.6 Applications

8.2.6.1 Virtual reality socialization

The Metaverse is radically changing the way people bond by providing a truly immersive space within which social interaction can happen. Rather than simply sending messages out and posting stuff, users can enter a world of virtual living, making it possible for them to engage with friends, co-workers, or even strangers represented by the avatars of their choice. It is more immersive than any conventional social media. Picture going to a virtual concert, chilling at a digital party, or virtually celebrating milestones alongside loved ones—yet from the comfort of your own couch. It breaks down the physical barriers and bridges a digital and physical experience in ways we once never thought were possible. As the Metaverse is changing, so are its opportunities for co-creating and collaborating. Virtual workspaces bring together teams around the globe in shared digital environments to inspire innovation through interactive and immersive brainstorming sessions. There is a venue for artists, musicians, and other creative types to present their work, but in entirely new formats toward a planetary audience, and not just from inside the physical venues. Hence, this is an exciting new frontier for society, in which social and professional networks are reinforced, and the individual is given a voice in new and boundary-defying forms of self-expression, redefining modern community and creativity.

8.2.6.2 Business and remote work

The Metaverse is also transforming the way businesses operate and how remote teams stay connected. Virtual offices and 3D collaborative spaces allow teams to work together in real time, no matter where they are in the world. Instead of staring at a screen during another video call, employees can meet as avatars in a shared virtual space, making teamwork feel more natural and engaging. IP virtual communication reduces work-related social isolation and enhances meeting engagement for remote workers. The virtual environment enables companies to host digital networking events and trade shows combined with conferences, which build opportunities for worldwide connections and new career advancement options. Through the Metaverse, businesses get to experience better collaboration methods while simultaneously conducting immersive training programs. The Metaverse provides businesses with a risk-free space to build realistic training environments for employee simulations that range from customer service drills to industrial machine operation practice. Such training techniques build engagement levels while it is strengthening skill retention along with decreasing facility maintenance costs of physical training spaces. Organizations gain performance monitoring capabilities through analytics data collected in these virtual environments to improve their training scheme effectiveness.

8.2.6.3 Virtual commerce and shopping

The Metaverse is helping to change the face of retail by bringing those shopping for an immersive ambiance to their stores. The shopping goes through a process of the customers browsing products, virtually trying them on, and then making the payment via digital currency or NFTs. These allow retailers to construct an entire virtual shopping mall or customized special storefronts in which purchasers can mingle with products in a 3D environment. This is presently being given a more interactive experience than any traditional e-commerce website can provide. The marketplace is also for selling and trading nontangible items like digital fashion, art, and NFTs within the Metaverse, thus serving as one potential avenue into a new form of digital economy. On top of that, brands have an opportunity to provide personalized experiences by learning about users through their actions in the Metaverse. For instance, users can be engaged better through AI recommendations and personal virtual stores. Those "cool" marketing companies can also host events, limited-edition launches, and competitive promotions in the Metaverse to create different engagement levels, thus providing inducements to develop loyalty and sales. It allows for creating a deeper emotional bond between the company and its customers, creating a memorable experience with the brand.

8.2.6.4 Smart cities

The Metaverse has the potential to support smart cities through environmental, economic, and social sustainability goals [9]. Technologies like AI, Big Data, IoT, and DTs make platforms to reimagine urban design and service delivery and can enhance urban efficiency, accountability, and quality of life. DTs within the Metaverse will recreate digital replicas of physical entities, allowing simulation to optimize their real-world performance. The Metaverse can also provide influence over resource management and urban governance by providing a platform for virtual services and assets. Challenges remain, nonetheless, including the environmental impact of high computing demands, equitable access, and ethical considerations. Metaverse can be a useful tool for urban planners, where they can visualize infrastructure development projects before building them and identify problem areas, improving them using real-time data. Citizens can practically participate in these virtual cityscapes for a much more inclusive and participatory urban engagement on proposed changes. Likewise, these very virtualized environments will help enhance emergency response simulations, traffic flow optimizations, and predictive maintenance for public utilities - thus making cities safer, efficient, and sustainable.

8.3 Basic foundation of digital twins

8.3.1 Definitions and features of digital twins

DTs [10] can be said to be a digital representation of an entity [11], which can be an object, a system, or even a process. This technology encompasses an array of areas like real-time monitoring, simulation, and optimization, as it creates a digital model of a real-life entity, for which tangible and intangible aspects, as well as social relations, should be considered [12]. It is commonly used across sectors such as healthcare, construction, manufacturing, smart cities, and many more to be used for data processing, scenario simulation, making insights, and predictions, or enhancing them. A Digital Twin Network (DTN) is an emerging framework that leverages DT technology to create virtual replicas of physical objects. It enables the co-evolution of physical and virtual spaces through advanced modeling, communication, computing, and data processing technologies [13]

Some of the features of DTs are:

1. Data Integration: A DT is built with the data from its physical counterpart with the use of AI bots or sensors, which provide the model with real-time updates.
2. Simulation and Analysis: These give the user the ability to iterate different possibilities, predetermine secondary actions, and even forecast how the item in question will behave in the future without physically operating the object.
3. Feedback Loop: There is thorough interconnectivity as all the alterations made by the DT are incorporated into the physical object, and this leads to enhanced performance of the asset.

For example, there can be a DT of a wind turbine that forecasts its output under multiple conditions and even measures how much energy it produces and operates on before it needs maintenance.

8.3.2 Historical background

The use of replicas for real surfaces in engineering and particularly in space programs marked the beginning of DTs in the 1970s. NASA was one of the first organizations to use virtual models to mirror the behavior of the space vehicle systems during the Apollo mission. The principal advantage of this system was its ability to provide engineers with a virtual replica of a physical spacecraft on Earth that allowed for the identification of issues and the formulation of remedial actions without requiring physical access to the spacecraft. This early application showed the potential of using virtual replicas of such systems for analytical purposes, particularly when it comes to comparing current and desired performance characteristics [14]. When computing capability and the volume of data storage assets increased over the decades, the simple concepts of DTs developed into detailed models capable of a constant flow of information exchange with the actual objects. This progression led to the contemporary advances that made the DT technology paramount to industrial and technological situations.

Complex technology initiatives like IoT, cloud, and AI have subsidized the growth of DTs and made it one of the leading technologies of Industry 4.0. IoT devices include sensors that offer real-time data feeds for the operation of real-time DTss and cloud computing provides scalability. AI & Machine learning comparatively develop the prognostic & analytical capability of these virtual models to imitate & decide independently. Today industries such as manufacturing, and healthcare sectors among others have adopted the use of DTs as they consider aspects such as equipment performance, design, and prophetic maintenance requirements. DTs are of similar strain as connected, wise systems that expand the boundary between actual and virtual worlds and bring benefit to productivity, invention, and operation.

8.3.3 Purpose and objectives

The ultimate goal of DT technology is to enhance performance, availability, and productivity in multiple fields as a result of monitoring and analytical methods. It is the simulation of an asset, system or process in which real-time data is available enabling the stakeholders to evaluate the current and future functioning of the physical asset, system or process. This data exchange between the physical and the computer-based models continues to enhance business and organizational operations by preventing or reducing risks of collapse or general system failure. DTs make it possible to test simply and meticulously based on scenarios, giving the engineer insight into potential advancements so that they make the best decisions in which they enhance the overall performance of a system. In sectors such as aerospace, automotive or smart city, they probably increase efficiency, reduce cost and improve the usage of resources.

Also, DTs help to bring more innovation on the way as one can experiment and develop various concepts virtually before integration into the physical world. This attenuated the time required and the cost together with the amount of material used in the conventional stages of product development. In healthcare, digital replicas of specific patients can be created for use in the planning of subsequent treatments, which will result in the optimization of treatment plans for the individuals in question. In civil engineering, building and transport structures' replicas enable the calculation of when they require repairs and enhance their environmentally friendly designs. Through offering a detailed and accurate model of the systems, DTs enables industries to better use data and make decisions quicker and with higher accuracy.

8.4 Standardization process

Development Timeline: The standardization of DTs began gaining traction in recent years, with key standards established by organizations like ISO and IEEE. Notable milestones include the ISO 23247 series for manufacturing-oriented DT systems, which was approved in 2021 [11]

Key Standards:

1. ISO/TR 24464: Focuses on visualization components in DTs.
2. IEEE P2806: Aims to standardize architecture for smart factories.
3. ITU-T Y.3090: Details requirements for building DTs of physical networks

The architecture is typically structured in four layers [11]

Physical Layer: Involves real-world objects that can be modeled digitally.
Communication Layer: Ensures real-time data exchange between the digital model and physical entities.
Model Layer: Involves creating digital representations using various modeling languages and tools.
Function Layer: Handles the operational aspects such as diagnosis, prediction, and decision-making based on the data collected

8.4.1 Core technologies behind digital twins

The core technologies behind DTs play a crucial role in creating accurate, real-time virtual replicas of physical systems. Technologies required are shown in Fig. 8.1. It has the following technologies:

8.4.1.1 Internet of Things

The very first thing is the incorporation of IoT sensors in what they call "live data collection," which gives the experience into the DT and then allows real-time updates while keeping them aligned with the digital representation of the physical systems themselves. The continuous and consistent gathering of data types as temperature, pressure, vibration, or energy consumption, for different physical objects like machines, vehicles, and even buildings. The communication of these data takes place with the cloud or by edge computing systems. This is a way of carrying out dynamic DT models that purport to reflect the real-time status of physical assets. Updating data in real time gives room for continuous monitoring, predictive maintenance, and optimization, for example, when changes in production parameters can be made to improve the efficiency of production or failures detected, like an indication of potential equipment failure. IoT-enabled insights complement and enhance decision-making as they keep

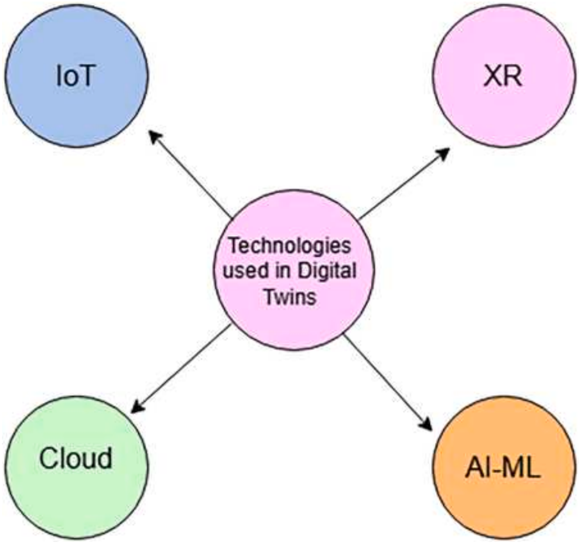

Figure 8.1 Technologies used in digital twins.

the operators up to speed with respect to what is actually going on in the system's health and performance, thus making informed choices.

Incorporating IoT sensors into DT infrastructures beyond real-time monitoring and predictive maintenance allows for the application of advanced analytics and machine learning applications. This vast amount of continuously collected data can enable organizations to discover patterns, detect anomalies, and even predict future occurrences with much better accuracy. For instance, predictive algorithms in machinery analyze vibration patterns and use them to predict possible breakdowns much earlier, which minimizes downtime and maintenance costs. AI-enabled insights can also be used to further optimize energy consumption so as to facilitate more sustainable operations and cost savings. As a result, this really close relationship between physical assets and their digital counterparts not only stands for operational efficiency but also for the strategic management of decision-critical points, providing actionable insights, thereby enabling companies to respond flexibly to changing conditions and remain ahead of the competition.

8.4.1.2 Cloud computing and big data

DT technology has its backbone in cloud computing and big data, which provide the infrastructure and analytical tools essential for effective implementation in any organization. Cloud platforms such as AWS, Microsoft Azure, and Google Cloud provide flexibility and scalability for expanding a company's DT models. It simulates a complex physical object or process and requires data storage and a lot of computational power. Moreover, cloud computing makes real-time monitoring and control accessible from anywhere, an especially valuable asset for industries such as manufacturing, transportation, and smart cities. Besides, cloud platforms provide the means to integrate real-time data from IoT sensors, machines, and devices into an up-to-date condition for timely decision-making. Cloud-based platforms also promote collaboration in multiple-stakeholder scenarios, making everyone involved informed with their share of updated information. Big data complements DT technology by processing, managing, and hosting the massive amounts of information necessary for accurate simulations. Big data tools allow the collection of data from a multitude of sources, such as IoT devices, sensors, and external databases, providing temperature, pressure, and speed information, among others, necessary to create precise models. Big data algorithms enable data analysis on behavioral patterns, performance, and failures within the systems, thus aiding applications such as predictive maintenance and process optimization. At the same time, real-time analytics using big data technologies not only ensures timely updates of the DT models but also provides instantaneous insights into detected changes and optimization of operations. Further to this, big data platforms integrated into the machine learning (ML) and AI paradigm will enhance DTs to be flexible to changing conditions, simulate different scenarios, and automate optimization processes. Cloud computing, combined with big data, currently stands as a pillar in the deployment and continued improvement of the twin technologies. Coupled with cloud computing, big data will generally improve the performance, cost efficiency, and innovation of big data technologies within all possible industries for years. Computational power plus scalable infrastructure could be harnessed from cloud computing to run highly complex simulations, while the huge datasets expected for real-time analysis and actionable insights would all be handled by big data. It reduces a customer's cost and does away with expensive on-site infrastructure, making DTs more accessible. It benefits smart cities, manufacturing, and automotive, in particular, as smart cities have DTs powered into them, enabling future predictions of traffic and energy, while manufacturers model equipment performance to optimize maintenance and operations. The automotive sector models and simulates vehicle performance and maintenance needs, supplemented with real-time data analytics. Together, cloud computing and big data drive innovation in optimizing design, maintenance, and future outcomes across sectors.

8.4.1.3 Artificial intelligence and machine learning

They will also make localization real-time, enable predictive modeling, and analyze advanced deep learning on much broader data. DTs represent the virtual models of an actual physical system or object. With AI and ML, these twins can process and analyze vast amounts of incoming data from sensors, detect patterns, and forecast future behaviors. These technologies enable DTs to conduct simulations and optimize the processes or automate the controls that develop better efficiencies with reduced downtime and predictive maintenance. After simulation, AI can be coupled with DTs towards real-replicating conditions possible in the world, input and output by finding optimal settings through simulation in performance. Continuous model improvability over time is made possible with ML, utilizing updated and newer data to improve prediction. The digital patients would have personal-independent patient-care plans, where care plans are modified in real-time with the needs of the patients as they happen. Through the inclusion of AI technologies in IoT devices, DTs are made even more intelligent in the surveillance of environments, event-deciding in making calls, and permitting more detection of anomalies autonomously without any human interference. This will help create an even better system reliability and optimization. Finally, AI and ML make DTs more adaptable, intelligent, and capable of offering accurate insights toward driving innovation and operational efficiency across different sectors such as manufacturing, healthcare, and energy, as well as urban planning. The two technologies thus form DTs into a grand for dynamic, real-time changing simulators monitoring and optimizing the progress of physical systems in a network across many industries.

8.4.1.4 Extended reality

It makes immersive visualization, real-time interaction, and simulation with DTs more effective by means of VR, AR, and Mixed reality (MR). VR offers completely immersive experiences of DTs to users; AR helps in adding real-time information on physical things that act much better for maintenance support and monitoring; and MR allows for live immersion in the digital-physical axis. XR also allows remote collaboration, immersive continuous training, predictive maintenance, and design validation, thus enhancing the use of DT technology to improve a company's performance while cutting costs and improving decision-making.

Moreover, these XR technologies actually improve the models of data visualization and analytics within DT ecosystems. Combining AI-driven insights with XR platforms would make interacting with complex datasets far more intuitive and meaningful. Engineers and decision-makers alike can visualize their operational data in real-time; simulate scenarios for predicting various outcomes; and finally, reach process optimization and risk management goals. XR brings into its fold through more interactive presentations and demonstrations of DTs; therefore, the overall communication of technical information is smoother between teams. This significantly opens up collaboration opportunities, speeds up solving problems, and helps with informed strategic planning, ultimately leading toward innovation and competitive advantage.

8.4.2 Applications

Applications of DTs exist in smart factories, medicine, smart cities, aerospace [15], and many use cases in IoT scenarios [16]

8.4.2.1 Manufacturing

DTs are used in manufacturing to create virtual models of manufacturing factories or production lines, which are employed for Process Optimization, Predictive Maintenance, and Factory Simulation [14]. On the other hand, these are the models that enable manufacturers to try operations, spot weaknesses, and maximize workflows. Real-time data from the sensors predicts that if this equipment has to be fixed or replaced early, then proactive maintenance can reduce downtime and cost. Factory simulations also help in trying out different scenarios to better the production processes before making any actual change. DTs are a further advantage for these technologists in improving decision-making making utilizing actionable insights through advanced data analytics and machine learning algorithms. Therefore, the real-time data and historical trends can be captured and merged by manufacturers to enable a holistic view of their operations for better forecasts in strategic planning. Production that digitally connects an organization helps an organization introduce more customized strategies in the production process, where a business can readjust to respond to fluctuating markets or be able to adapt and respond to supply chain disturbances. Continuous production parameters can also be measured using DTs to ensure that every product is produced with exacting quality standards throughout the production phase. Such translates into consistent products, smaller wastage, and better overall efficiency in manufacturing operations.

8.4.2.2 Urban planning and smart cities

Better Manage City [17] Infrastructures in Simulations and Decision Making. The DT concept in implementing Smart Cities or Urban Planning realizes real-time virtual copies of entire cities, as well as infrastructures, including transport and utility systems. This is in keeping with the idea of a Metaverse as a spatial internet and its parallel development in urban innovation through DTs and smart cities [18]. Such models help city planners simulate various conditions like traffic flow, energy usage, and so on, all to optimize their infrastructure and resource management. By testing different urban scenarios, city officials can make informed decisions, like enhancing traffic management or extending energy efficiency, to achieve the general aim of building a more sustainable and efficient city. In addition to better decisions, DTs can create interactive public engagement portals where residents themselves are able to visualize proposed changes and comment on them. Such forms of participatory engagement will enable communities to realize their responsibility as active contributors to the shaping of urban development and, as such, present more representative solutions about the real needs of the population. AI and machine learning that would be linked to such DT technologies would do predictive analytics, such that cities are ready for damage to their infrastructure, traffic snarls, or sudden cuts in energy supply before the occurrence. Proactive management not only improves the quality of urban life but also reduces operational costs in the pursuit of a sustainable future.

The DTs are making clear progress toward a smart-cities paradigm. In the context of the intelligent city, the DTs environment replicates real-virtual interactions through software definitions and gives intelligent feedback. Possessing a solid, ever-strengthening foundation of data and technology grounded in IoT, cloud, big data, AI, and then 5G—the digital model itself under which a twin city will sit. The Smart City Operating Brain (SCOB) [14], which exists more in terms of collecting operations over the smart dual-reality city but almost exactly makes that observation in terms of both virtual and real environments through which the DT city operates, will really be a critical cog here in how it manages urban activities more efficiently and improves coordination and responses to emergencies. Finally, DTs will connect the physical and the digital worlds in a smart city context to give the citizens enhanced perception, control, and intelligent services.

8.4.2.3 Healthcare

- Real-Time Patient Monitoring [19], Device simulation and diagnostics. The first application of DTs in medicine is real-time patient monitoring from virtual models that can be created using all data that medical sensors and wearables acquire from the individual. These models continuously observe the most important health parameters, which may predict the occurrence of future disease, to provide more personalized diagnosis and treatment. A second area of application of DTs will be to simulate the medical devices to ensure their correct performance, forecast future possible failures, and thus improve advanced diagnostics and optimal treatment plans, making healthcare more efficient. Along with these applications, DTs can significantly aid treatment planning and surgical simulation. Healthcare professionals can safely "test drive" treatment approaches and surgical procedures with a highly accurate virtual representation of a patient's anatomy before applying them in real life. Clinicians can anticipate complications, optimize surgical outcomes, and tailor interventions to the specific requirements of each patient. Furthermore, clinical analytics driven by AI and DTs would greatly enhance clinical decision-making toward faster diagnosis, improved patient outcomes, and lower healthcare costs.

8.5 Integration of Metaverse and Digital Twins

Combining these two technologies imitates the realization of a cyber-physical bridge, operating in two ways such that the virtual world data impacts the physical world, and the physical data from real-world sensors affects the virtual environment. This union opens major doors to the development of new, innovative methods in the future: A three-layer architecture approach to merging DTs with Metaverse, as given in [20]

8.5.1 Synergies between the two technologies

DTs have been recognized as the first building blocks for futurization into the Metaverse [21]. DTs can be defined as the creation of replicas in virtual environments of large-scale, high-fidelity digital models, having properties corresponding to their physical counterparts. The synergy of DT and Metaverse, therefore, has immense promise as it combines both the physical and virtual worlds, thus improving their functions. DT technology is the essence of Metaverse realization since it goes as far as providing the infrastructure for accurate virtual representations of real-world objects and their meaningful interaction in the real and virtual realms [22]. As such, incorporating DTs within the Metaverse allows the real-time replication of physical objects, systems, or environments to exist in reality. For example, a DT of a factory may be included in the Metaverse, so that its users can monitor, control, or interact remotely with it whilst bringing real-world data and simulations into immersive virtual environments. This also brings to the table enriched simulations and user interaction, as DTs provide detailed, data-driven models of physical assets, while the Metaverse enables users to interact with these models in fully immersive, 3D making complex systems accessible and intuitive for analysis and decision-making. DTs can be applied in the Metaverse for cost minimization, planning optimization, and better resource allocation [23]. Moreover, both technologies enable multiple users to engage simultaneously with DTs in the Metaverse from any location contributions being of tremendous meaning in particular fields such as healthcare, urban planning, and manufacturing.

It will form feedback loops to optimize the aforementioned technologies in such a way that real-time DT data can be visualized and experimented with in the Metaverse to provide insights for improving real systems. For instance, changes made to a DT of a smart building within the Metaverse hold the potential for improving energy efficiency and predicting maintenance needs. Moreover, the combination of these technologies allows immersive learning and training, where people can practice operations and troubleshooting in this realistic virtual environment well before approaching real physical machines. DTs and the Metaverse come together to build intelligent, connected systems; for example, smart cities, in which traffic, energy use, and infrastructure can all be managed and optimized in real-time. Essentially, DTs provide real-time data concerning and simulation of physical assets; the Metaverse, on the other hand, provides the capacity to make those models immerse with these assets, thus opening up new possibilities for visualization, optimization, and innovation across many industries. Feedback optimization for these technologies will be enhanced in that real-time data can be visualized and experimented upon in the Metaverse on DTs to gain insights that would be valuable additions to real systems. For example, changes in the DT of a smart building in the Metaverse may lead to better energy efficiency and predictive maintenance requirements. Also, immersive learning and training will be made possible through using these technologies in the field experience before engaging physical machines by practicing operations and troubleshooting in this realistic virtual environment. DTs and Metaverse will give rise to a connected, intelligent system like a smart city, where traffic, energy consumption, and infrastructure are managed and optimized in real-time. DTs provide the real-time simulation and data of physical assets, while the Metaverse is the immersive platform where models can be interacted with - thus forging new frontiers in visualization, optimization, and innovation across industries.

8.5.2 Practical use cases

The study presented in [24] expounded the purviews as well as applications of DTs in the Metaverse, as 15 applications ranging from simulation and training to emergency preparedness.

8.5.2.1 Urban planning and smart cities

DTs and the Metaverse mark a radical change in urban planning and smart city development. Digital reproductions of whole cities allow urban planners and architects to design, test, and optimize infrastructure in a simulated environment before making changes in the physical world. Thus, a city's DT encompasses virtual models of everything from buildings and roads to utilities and even social behaviors. These replicas are constantly updated through real-time data from sensors, cameras, and other IoT devices to ensure they represent a dynamic city. Within the Metaverse, you would navigate and interact with this DT through an engaging and immersive 3D environment, where city planners, government authorities, and the public can tour the city, simulate several potential urban developments, and observe how their decisions could immediately affect results. For instance, scenarios can be run with respect to placing new roads, public transport systems, or green spaces while absorbing data about traffic, energy usage, environmental factors, etc. This virtual interaction essentially helps to optimize different designs for urbanization and management, which benefits stakeholders in better decision-making, saving costs, and enhanced collaboration. Moreover, a city model in the Metaverse will provide real-time monitoring [25] of various systems in the city, such as traffic management, energy grids, and waste management. Planners would use the real-time data going into the DT to predict potential problems in areas such as traffic congestion, energy shortage, or a system breakdown that can now be preemptively handled. Digital models can solicit engagement from citizens, thereby providing them a platform to express their concerns or give input by participating in more stakeholder-oriented processes of urban decision-making development.

8.5.2.2 Manufacturing

The manufacturing sector promises to benefit immensely from the synergy between DTs and the Metaverse [26]. In this field, DTs symbolize physical assets, machines, or entire production lines, serving as a vehicle to transport real-time data of their performance. Metaverse immersion allows manufacturers to create a virtual factory in which every machine, conveyor, or assembly line has its avatar in space.

Training programs can be designed in this virtual space where manufacturers can simulate operators' work on handling equipment or troubleshooting problems using machine DTs. Such an experience would be enhanced in the Metaverse due to immersion and interactivity, allowing workers to experience lifelike scenarios, aka training, where they are not going to be exposed to real-world trials that may be risky or costly. In the same way, new hires could rehearse complex tasks and hone skills without interrupting production.

Majorly, we can assist in process optimization and simulation. Engineers and operators will virtually play around with machines, imitating different production modes, changing parameters, and experimenting with configurations to enhance efficiency and reduce downtimes. A clear example would be running virtually the factory floor to analyze production bottlenecks, for instance, putting into test new manufacturing strategies. Manufacturers can also run remote diagnoses, with experts in different locations evaluating in real-time the performance of equipment to assist virtually in either the repair or maintenance of systems without being there in person.

Furthermore, manufacturers can take advantage of these technologies to test prototypes or new designs in the Metaverse before choosing to mass-produce them, thus reducing costs and time. They can even use DTs to predict maintenance requirements in the Metaverse and enhance resource use, minimizing waste and positively impacting sustainability.

8.5.2.3 Healthcare

The Metaverse, together with DTs, is transforming medical training, patient care, and treatment planning in healthcare. DTs of patients are being generated to model individual health conditions and give healthcare providers a personalized perspective of a patient's anatomy, medical history, and treatment responses. This data can be fed continuously through real-time health metrics from wearables or IoT sensors.

The Metaverse can offer an extremely immersive medium where such DTs will be mapped into 3D, which may be used by doctors, surgeons, and medical professionals to survey a virtual model of the patient's body. Not only does it add to the diagnostic and therapeutic analysis, but it also adds value to the quality of surgical interventions. Before the surgery takes place, the surgeon may practice on a DT of the patient's organs, thus learning to counter challenges before they arise and plan the best course of action. This kind of training is valuable to medical students who can practice in virtual environments without endangering actual patients. Metaverse DTs are meant for personalized and precise medicine [27]. Digital worlds, according to the statement, can model medical situations in the improvement of learning and individualized patient service. Yet it faces some challenges in data privacy, standards, and accessibility.

Moreover, this Metaverse can be used in virtual consultation, and telemedicine would bring patients and doctors to a 3D, life-like setting. In virtual consultation, the doctor could interact with a DT of the patient to elaborate on symptoms, possible treatment options, or even walk-through medical procedures. The highly immersive aspect of the Metaverse brings patients closer to their experience and adds a personal touch to virtual consultations compared with traditional telehealth. Medical simulations extend even to training scenarios in the Metaverse, where emergency procedures might be practiced or where new medical techniques may be learned or difficult patient cases managed in a risk-free, safe environment. These simulations may be designed within differing complexity and risk levels, thus allowing trainees to further their decision-making and clinical skills. Furthermore, real-time patient data in the Metaverse creates simulations that can dynamically evolve as a patient's condition is changed. This, therefore, ensures that an individual is continually up-to-date during training and planning treatment. Overall, these new technologies are a more efficient and effective way of training medical professionals, planning complex procedures, and providing remote care, thus bettering both patient and healthcare outcomes.

8.5.2.4 Education systems

DTs and the Metaverse would hence transform both educational institutions and gaming into immersive, dynamic, and personalized experiences. DTs allow the creation of a simulation of the real world in virtual classrooms, wherein students make physical excursions to places they normally could not visit. Computerized methods of learning, in which the student's matrix figures are embedded to modify teaching suggestions in view of the learner's performance for maximum performance, will definitely change teaching. Tele-simulation and physical-real replica classroom labs or global labs would empower students all over the world to communicate and work on virtually live working mechanisms, natural systems, or structures, enhancing teamwork and creative ideas. However, in order for the technology to take off, some hurdles will have to be leapfrogged, such as infrastructure costs and data privacy

8.5.2.5 Gaming field

Gaming, DT, and abundant Metaverse content would define the realistic and vivid visual environments to emulate the conditions of what is in reality. This information about cities, vehicles, or even weather could be streamed into games, compelling one to experience a life-like "real" in video game worlds. The addition of the flow of real physics in that technology produces strong, persistent, unique worlds that have consequences on player behavior. In addition to everything mentioned above, a DT for training within e-sports and preparation for action in a virtual or even real-world scenario would become one of the state-of-the-art opportunities for the gamer. These advancements in thinking will be fun and also promise profitable gameplay; however, they come with major challenges, such as great complexity, costs, and hardware requirements. Human learning, leisure, and information interaction have been transforming with these.

8.6 Challenges, limitations, and future perspective

8.6.1 Challenges in Digital Twins

The DT is now becoming vital within numerous industries, providing strong mechanisms for monitoring, analyzing, and optimizing physical assets, processes, and systems. Hence, as with any other technology, it is bound by certain existing gaps or challenges that must be addressed for a fully empowered DT. Data integration issues, scalability, costs and complexity, and security issues affect the performance and efficiency of DT systems.

8.6.1.1 Data integration

DTs face their major challenge in aggregating data from various sources. DTs thereby keep receiving constant streams of inputs from sensors and devices or platforms in order to replicate the actions and features of the physical object or systems as accurately as possible. Data comes from sensors in machines, IoT devices, business systems, or even outside sources like weather or traffic data. Data accuracy is vital because wrong or outdated information can cause false simulations, bad decisions, or inefficiencies. Compatibility between various platforms or devices is a major issue. Many industries use old systems or technologies with unique protocols or standards. For a DT to work well, data from these different sources must merge into one platform. This needs modern data systems that support varied data.

8.6.1.2 Scalability

Scalability could also be an issue in large-scale applications that include smart cities and industrial manufacturing. Designing and developing high-resolution models of the systems or assets is often quite complex- a DT, for instance, can be interpreted in terms of a colossal network of interdependent aspects, such as buildings, traffic systems, utilities, and environmental inputs. As the DT grows in scale, so does the data generated and processed. So much power and storage are needed to accommodate efficient management and processing of these data. Such scaling of the DT creates challenges concerning performance management. Real-time processing and analysis of such a large-scale system would involve monitoring thousands of machines or vehicles' operations at once, which is computationally demanding. The system must be able to scale to millions of data points in real-time without delays. Besides this, since DTs will be constantly updated with incoming data, the infrastructure will need to be able to visualize that data in real-time, ensuring that the digital image displays the latest state of the physical system. These scalability issues require organizations to adopt high-performance computing methods through cloud computing, edge computing, and distributed data processing. This way, data and processing will be managed in a distributed manner, and the DT can automatically scale with system growth without performance degradation.

8.6.1.3 Cost and complexity

DTs are generally perceived as expensive and resource-hungry endeavors. The setup of a detailed and accurate DT will involve vast sums of money on hardware and software. This includes the cost of sensor and IoT device acquisition and installation, the software platform development costs, and costs incurred in integrating these systems for data capture and processing. In addition, to continually check whether the DT is accurate and trustworthy, a lot of time is spent on monitoring, updating, and maintaining it, all of which adds to the costs. The complexity of developing and maintaining a DT increases proportionately with the advancement of its represented physical systems. By way of illustration, a DT for a very complicated manufacturing process or an entire urban infrastructure requires diverse data integration and highly detailed modeling with continuous updating. As model complexity rises, the resources required for its upkeep grow exponentially, making DTs investments that, perhaps, small players or budget-constrained organizations may find difficult to realize. Besides, the costs associated with the DT maintenance are far from being a one-off expenditure. Continuously, sensor calibration, software updates, and troubleshooting will have to be executed for model synchronization with the physical system. Employees also need to be oriented with the management of data and its interpretation, which constitutes another layer of operating costs. Thus, for most firms, ensuring that the return-on-investment stands justified against the continuing expenditure constitutes an uphill task.

8.6.1.4 Security

The fact that DTs collect both real-time data and IoT data virtually makes security one of the paramount concerns. Secure and efficient mapping of real-time data between physical and virtual worlds will then be possible with BlockNet and Hash Geocoding, which is again an important aspect of both DTs and Metaverse vision. By that, we aim to progress from an assured spatial DT to a complete Parallel Metaverse [28]. In the Internet of DTs, security and privacy threats are present that have been analyzed in reference [29]. In this case, all possible vulnerabilities of the system reveal considerable threats from unauthorized access, data breaches, cyberattacks, potentially jeopardizing operations or damaging systems, and so on. Data coming from IoT devices and sensors constantly flows and could use any of these channels as avenues to manipulate the data, destroy the systems, or compromise the DTs' integrity. Therefore, the protection of that data from unauthorized access and tampering puts strong added security measures in place. Such security measures comprise encryption, secure authentication, and routine monitoring of the DT systems for any signs of malicious activity. With DTs usually being real-time systems that are not stopped, it is required to ensure their robustness against cyberattacks. Privacy and Security also exist to alleviate Trust issues [30]. A cyberattack bringing the DT down might carry consequences of false or missing predictions about critical issues, threatening the safety and efficiency of operations. Moreover, ethical data privacy must be addressed with special attention when DTs are deployed in areas requiring utmost confidentiality, such as healthcare or urban infrastructure. It also becomes imperative to ensure protection of personal or sensitive operational data, hence cultivating trust and security, and ensuring complete compliance with regulations such as GDPR or HIPAA.

8.6.2 Challenges in the Metaverse

The evolution and realization of the Metaverse have given rise to different challenges that could hinder its adoption and growth. Such challenges are multidimensional, given that they include technological, security, regulatory, and accessibility issues, all of which are warranted in order for the Metaverse to fulfill its potential. The key challenges are explained below in further detail.

8.6.2.1 Technological barriers

The Metaverse has one of the greatest challenges due to its demand for high technology in view of a seamless immersive experience. By definition, the Metaverse demands high hardware and infrastructure standards to deliver 3D graphic rendering, near-real-time interactivity, and experiences in a virtual environment as per user expectations. This means that users will require high-performance gear, such as fully-fledged VR headsets with varied applications, AR glasses to superimpose interfaces into the user's real-world view, a very powerful computer, and, lastly, high-speed internet. Such requirements could very well pose massive entry barriers for poorer individuals and businesses, either globally or in regions where advanced technology is least accessible. On the other hand, the infrastructure underlying the Metaverse must also be able to absorb the huge data load while still delivering low-latency experiences. Real-time rendering of complicated virtual environments requires quite a demanding combination of computing power and bandwidth. Should this not be there, the user may experience lagging, poorly rendered graphics, or disruption to interactions, thereby diluting their experience even more. Along these lines, there are issues concerning the design of a truly scalable platform catering to millions of users that simultaneously interact in a vast shared virtual world with the smoothness of their activities as its focal point.

8.6.2.2 Security and privacy

In the Metaverse, security and privacy aspects are very crucial. One exchange place that exists in virtual space is the exchange of massive amounts of personal data, financial transactions, and digital assets. Data generated during user interaction with each other, goods, and services in an online arena is susceptible to cyberattacks or the attention of malicious actors. The protection of user data is utmost, including sensitive data such as biometric data, financial transactions, and personal interactions held within the Metaverse. Further, an increasing worth must be given to securing digital assets, in the form of virtual property, currency, or items. This means developing secure digital asset management systems, especially with the rise of NFTs and virtual goods purchasable, sellable, or traded within Metaverse platforms. Unless security is guaranteed, users may end up victims of fraud, theft, or loss of their assets. And there is a need for safe interactions on the internet. The Metaverse opens a world of socialization; concurrently, it permits harassment, exploitation, or predatory behavior. Ensuring user safety, especially for minors and vulnerable individuals, will be a huge challenge requiring strong moderation, reporting systems, and community guidelines.

8.6.2.3 Regulatory issues

With the progression of the Metaverse, a plethora of regulatory issues have arisen. Who governs these virtual spaces, and what are the rights and responsibilities of user entitlements therein, are probably the most pertinent current questions under governance. Being relatively decentralized, most virtual spaces in the Metaverse do not even have a particular governing body or system of rules that are clear to regulate them; hence, what applies to one may not necessarily apply to others. The disadvantages of decentralization are the inconsistent treatment of users or even unfair treatment, thus creating opportunities for not enforcing laws and regulations within the Metaverse. Another burning issue would be DRM. Protecting the intellectual property rights of the content creator and the company in online virtual spaces merits its own consideration. Factors of creating, distributing, and trading digital commodities-art, music, or virtual assets- have many queries relevant to copyright protection, ownership rights, and unlicensed use in the realm of digital creations. As such, new mechanisms would have to be established in the Metaverse that are strong enough to enforce these rights, reward creators, and safeguard their works. The other thing is that this Metaverse is pretty global, with its users residing in different countries, thus subjecting them to different legal systems and regulations. Hence, there is a need for international standards for the governance of the Metaverse. The absence of these standards will mean that there will be major differences between the operations of the same Metaverse across different jurisdictions, making things quite complicated for businesses with such multichannel hiring, and creating hurdles in law enforcement for such issues as data privacy protections, consumer rights, or even tax regulations. Fragmentation in regulatory frameworks may be fertile ground for other illegitimate activities, such as money laundering, fraud, or even the trafficking of human beings, cementing the need for comprehensive oversight.

8.6.2.4 Accessibility

Accessibility is another crucial area where the Metaverse fails to include everyone; not all people have equal access to these digital tools and the necessary infrastructures to make them available. At a basic level, the Metaverse requires heavy hardware and, of course, fast internet connections, the costs of which may be prohibitive or, in some areas, simply unavailable, particularly in developing countries. The digital divide remains a barrier to the infinite participation of people in these virtual worlds. In addition to this arises the question of whether physical accessibility will also come to the fore. Most people with disabilities will find it difficult to interact with the Metaverse if the design of the platforms does not take inclusive considerations into account. For example, many VR headsets might not fit well for use by persons with varying levels of visual, hearing, or mobility impairments. Ensuring access to the Metaverse for the various abilities will require the designers of the virtual spaces and tools to adopt a wide array of accommodations to respond to physical and sensory needs, as well as having alternative modes of interaction for those unable to utilize standard method inputs, namely text or voice controls. Equitable access also accounts for the socio-economic divide. It may be hard for the low-income group to afford high-end devices for active involvement in the Metaverse. Governments and enterprises ought to investigate means of offering those devices and services required for access to the Metaverse affordably, possibly via subsidized programs, public access points, or open-source platforms.

8.6.3 Future perspectives

8.6.3.1 Technological innovations

As the Metaverse and DTs mature, advanced disruptive technologies extending possibilities will link across entire industries. These technologies include AI, machine learning, quantum computing, and high-connectivity solutions such as 5 G. The possibilities revolving around these innovations in transforming DTs and the Metaverse are discussed in the following.

1. **AI and machine learning: enhancing predictive and decision-making capabilities**
   AI and ML would not only augment the benefits of DTs in the Metaverse but also maximize their analytical and decision-making capabilities [9]. The analytical capability of DTs relies on AI's ability to analyze sensor data streamed in real-time from IoT devices, to find patterns and predict and optimization of performance for proactive actions such as determining the probability of machine failure for scheduled preventive maintenance rather than unanticipated downtimes. AI also forms an integral part of the potential optimization of energy use and resource allocation. In terms of the Metaverse experience, AI contributes toward immersion and personalization by generating dynamic environments and adaptive NPCs, which will react to user interactions. It can also personalize the content according to user data, recommend relevant experiences, and enable real-time language translation to facilitate communication worldwide.
2. **Quantum computing: revolutionizing simulations and real-time data processing**
   Quantum computing could change the simulations and real-time data processing for DTs and the Metaverse. With the help of qubits handling multiple states at the same time, it quickly and very accurately computes. It makes observations for DTs out of the immense amounts of real-time data from complex systems, thereby improving their predictions, problem-solving capabilities, and optimizations. The Metaverse can also be improved by making it more realistic and immersive, increasing 3D rendering capabilities, and powering very advanced AI for avatars and interactions. Although emerging, quantum computing assuredly leads to the next turn in more advanced simulations and immersive experiences.
3. **5G and beyond: enabling seamless, real-time interactions**

5G networks are changing the game in terms of how we interact with the DTs and the Metaverse. With ultra-low latency, high bandwidth, and very reliable connectivity, the 5G networks have opened up entirely new vistas to real-time interaction and data sharing with DTs. This further ensures that all updates to the models from these IoT sensors are reflected in real-time, enabling more rapid decision-making within an organization. It brings further benefits to the Metaverse with immersive experiences that are smooth and lag-free in real-time. 5G also has the scalability aspects to support many connected devices and users in a Metaverse that will continue to grow. Future advancements like 6G promise to enhance this further with faster speeds, lower latency, and more reliable connections for even more sophisticated virtual experiences.

8.6.3.2 Emerging trends

Innovation and better collaboration are brought forth in reshaping industries by emerging trends in DTs and the Metaverse. Cross-industry-connected efficiency and real-time data sharing have applications such as virtual health consultation and smart city infrastructure management. Another precious trend related to virtual economies is increased interest and trade in virtual assets, from virtual lands and digital art, and NFTs. Create monetizable virtual models of physical systems with DTs in the game. Extended reality (XR) transforms user interactions through AR, VR, and MR, blending physical and digital elements in more immersive, real-time experiences. These emerging trends are offering only one way towards the future evolution of digital ecosystems and how users engage with them.

8.6.3.3 Ethical and regulatory challenges

The emergence of the Metaverse and DT technologies also brings ethical and regulatory challenges. Some of the key concerns in the Metaverse include the management of virtual identities, rights of ownership, and intellectual property, as well as the development of legal frameworks for digital assets such as NFTs and user privacy. In DTs, it is the focus of challenges is on data transparency, security, and privacy, as it entails real-time sensitive data collected by IoT devices. Accountability issues may also arise when predictive systems have results not predicted. Both technologies have clear ethical guidelines and regulatory frameworks for responsible use in virtual ownership, identity protection, and data privacy.

8.7 Conclusion

The chapter thus concluded that Metaverse and DTs are revolutionary and mutually gnawing concepts that change the interface where the digital blends with the real environment. Here, we are talking about technologies that create digital copies of objects, constructions, or environments that function as accurate working models of their real counterparts, which can be tracked, evaluated, and controlled almost constantly through external data feeds such as sensor input. On the other hand, the Metaverse provides engaging virtual society and environmental platforms for users to take part in activities that are normally observed in real social life. Together, all these technologies create a fine symbiosis that might revolutionize industries through the experience of data and the interaction with systems and virtual-augmented environments. This opens up entirely new avenues in the advancement of fields and industries encompassing manufacturing, healthcare, smart city development, and entertainment. Yet the deployment of the three technologies comes with a few emerging issues of its own. It would be imperative to consider the issues of data protection, ownership, property, and access very seriously, so that these technological innovations are for the good of everybody and not just for everyone. It can be said that the development of such regulatory frameworks and the proper governance of such disruptive technologies would be an important factor in enabling the application of the Metaverse and DTs and effectively tapping into the potential of both these concepts for improving individuals, companies, and the whole of society.

AI Disclosure

During the preparation of this work, the author(s) used ChatGPT, Claude in order to Grammar and Readability Enhancement. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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CHAPTER 9

Quantum computing for digital twins and the metaverse

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9.1 Introduction

Urban areas are confronted with increasing more challenges in responding to emergencies, providing electricity, and managing traffic jams due to increased urbanization. Although effective, conventional artificial intelligence (AI)-based optimization methods cannot respond in real-time to the dynamism of urban systems. Quantum computing provides a revolutionary solution through superior, quicker data processing and decision-making through superposition, entanglement, and parallelism. To enhance energy efficiency and mobility in Gill Canal, Ludhiana, a fast-growing urban area with critical infrastructure needs, the Quantum Approximate Optimization Algorithm (QAOA) was employed in this research [1].

While emergency response plans improved by quantum technology decreased reaction times by an average of 26.9%, using digital twins, or virtual representations of real processes, in quantum computing decreased traffic at intersections by 16.4%. Other than smart city applications, quantum computing also affects the metaverse, in which giant simulations of cities, decision-making based on AI, and three-dimensional virtual reality worlds demand super-power computing. Conventional architecture cannot cope with the massive data sets for real-time, hyperrealistic worlds, but quantum computing is capable of accelerating 3D rendering, AI personalization, and predictive urban planning models [2–4].

Despite its gargantuan possibilities, the challenges, such as hardware limitations, integration complexity, and scalability, continue to rule the horizon. This research establishes how quantum computing can revolutionize smart city infrastructure and urban digital twins and provides the groundwork for hybrid models combining quantum and conventional methods. By overcoming computational barriers through its solution, quantum technology has the potential to make cities more efficient, responsive, and sustainable, and chart the course to the future of intelligent city development [5].

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9.2 Literature survey

Quantum computing is becoming an insurgent technology in smart city planning that solves complex optimization problems in traffic management, power grid distribution, and emergency services. Firms such as IBM Quantum and Volkswagen have demonstrated the potential of quantum algorithms in logistics, public transportation scheduling, and real-time congestion reduction through pilots in Beijing and Lisbon using quantum annealing. Scholarly research also promotes quantum-strengthened reinforcement learning for self-optimizing traffic light control against conventional AI at rush hour. Deep learning and reinforcement learning produce incremental benefits, but they cannot deal with real-time adaptability in huge networks [6]. Quantum computation, particularly QAOA, however, evaluates several routing options simultaneously, reducing processing delays. But real-world implementation remains under the sway of present-day hardware constraints, and hybrids of quantum and traditional computing are required. Besides smart cities, digital twins—simulations of urban infrastructure on computers—are in desperate need of gargantuan computational power, boosted by quantum computing with real-time predictive modeling. IBM, Google, and Siemens experimented with quantum applications for traffic pattern optimization, load balancing, and urban simulation. Quantum AI accelerates 3D rendering and AI-driven decision-making in the metaverse to support hyperrealistic urban modeling. Hybrid quantum-classical architectures are a promising path toward efficient, adaptive, and sustainable cities with chronic scalability challenges [7].

Quantum computing in the Metaverse context has been an area of increasing focus and research in more recent scholarship. The Vetaverse, a concept of Zhou et al. (2022), is a future of seamless connectivity between vehicular industries and the Metaverse, generating digital twins of intelligent transportation networks and personalized extended reality (XR) services in a single vehicle [8]. This intersection of digital twins with the Metaverse is also explored by Huynh et al. (2022), who present a digital twin scheme supported by Metaverse optimizing latency and reliability via mobile edge computing and ultra-reliable low-latency communications [9]. Another key research area is the convergence of the Metaverse and the Internet of Things (IoT) since it has been proposed by Li et al. (2022). Six common applications of IoT in the Metaverse are addressed in this survey, and it highlights the contributions of technologies such as responsible AI, high-speed data communications, mobile edge computing, and digital twins in enabling augmented reality and virtual reality experiences [10]. Additionally, future prospects of quantum computing in enhancing the ability of the Metaverse are addressed by Chehimi et al. (2023), where they explore the ways in which quantum technologies have the potential to advance the frontiers of the Metaverse beyond traditional boundaries [11]. Another use of the Metaverse, healthcare, is an area being studied, and an in-depth overview of potential use, issues, and potential directions for the future of the Metaverse in the field of medicine is presented in Chengoden et al. (2022) [12]. Similarly, Bhugaonkar et al. (2022) present the potential of AI, AR/VR, web 3.0, Internet of medical devices, and quantum computing in reshaping the healthcare system through the application of the Metaverse [13]. Straaten et al. (2024) created QArray, a real-time charge stability diagram simulator based on graphics processing unit (GPUs), which makes digital twins for interacting with quantum dot devices possible [14].

Wang et al. (2024) explained that Integrated Sensing, Communication, and Computingtechnology was the key to creating the metaverse for creating virtual worlds based on AI through the use of this technology [15]. Rawat et al. (2024) offered a comprehensive definition of the metaverse, highlighting pivotal technologies such as digital twins, AI, and cybersecurity elements that are central to its build-out [16]. Kliestik et al. (2024) introduced generative AI systems, and multisensory immersive technologies to build digital twin industrial metaverses and the ability of big data computing and cognitive systems to enhance simulated environments [17]. Abdullah et al. (2024) investigated the uncertainty quantification of supply chain digital twins using quantum-classical hybrid machine learning models and demonstrated the disruptive nature of quantum computing approaches to data feature transformation for uncertainty quantification [18]. Boopathy et al. (2025) had given an overview of the metaverse in Industry 5.0 and described emerging technologies such as digital twins, AI, and edge computing, facilitating the industrial metaverse's vast array of applications in industries such as agriculture, healthcare, and transportation [19]. Yun et al. (2025) introduced the W3ID, a quantum-secure digital identity system that seeks to redefine digital twin and Web3 standards with more data security and decentralization under the era of Web 3.0 [20].

Overall, the literature suggests that quantum computing can play a central part in determining the evolution and functioning of the Metaverse, particularly in areas such as digital twins, healthcare, and urban informatics. Based on the utilization of quantum technologies along with other enabler technologies such as IoT, edge computing, and AI, scientists are exploring novel opportunities for building immersive and interactive digital experiences within the Metaverse.

9.2.1 Problem formulation

Gill Canal, Ludhiana, is a rapidly urbanizing area with rising traffic congestion, fluctuations in energy demand, and inefficiencies in emergency responses. Conventional computational techniques lack the capability to model, forecast, and optimize such urban problems in real time because they are too high-dimensional and dynamic in nature. Digital twins, which model actual urban landscapes for simulation and optimization, are computationally intensive and hence the perfect application area for quantum computing. Quantum computing, with its superposition, entanglement, and quantum parallelism, presents a paradigm shift in traffic control, smart grid optimization, and emergency response planning. Through the inclusion of QAOA, Variational Quantum Algorithms (VQAs), and quantum-advanced AI, we hope to create a quantum-fueled urban simulation platform to maximize key infrastructure in Gill Canal, Ludhiana [21].

- **Optimize urban traffic flow** – Use quantum computing to reduce congestion, improve vehicle wait times, and enhance fuel efficiency.
- **Enhance smart city infrastructure** – Apply quantum algorithms for efficient energy distribution, electric vehicle (EV) charging, and real-time urban planning.

9.3 Methodology

This research combines AI and quantum computing to design a smart city simulation framework for Gill Canal, Ludhiana, in Google Colab. The process is organized into various phases: data gathering and preprocessing, traffic congestion, energy distribution, and emergency response system quantum-enhanced simulations, followed by performance assessment and visualization, as shown in Fig. 9.1.

9.3.1 Data collection and preprocessing

Real-time information is collected using IoT sensors, traffic cameras, and smart grids in Gill Canal, Ludhiana, to analyze urban dynamics. The data includes traffic jam patterns, energy demand fluctuations, and emergency response times. Using Python libraries pandas and numpy, raw data are cleaned, formatted, and uploaded to Google Drive to facilitate seamless integration with Google Colab for efficient processing [22].

9.3.1.1 Quantum traffic optimization (quantum approximate optimization algorithm-based)

The area around Gill Canal suffers from high congestion, especially during morning, afternoon, and evening peak hours. QAOA in Qiskit optimizes traffic light parameters for reducing congestion. The model adaptively optimizes signal timing and suggests alternative paths, improving the average vehicle wait time, rate of congestion, and global efficiency of traffic flow. Quantum-assisted methods are compared to normal AI-based methods for comparing performances [23].

9.3.1.2 Quantum-powered smart grid optimization

Gill Canal's energy distribution grid in Ludhiana experiences shifts as a result of changing usage patterns from domestic, commercial, and industrial sectors. Quantum

Figure 9.1 Methodology flow chart.

machine learning is implemented for the advancement of smart grids. AI-enabled simulators built using TensorFlow or PyTorch analyze past energy use and present-time energy utilization. VQAs are implemented for power load balancing, such that efficient delivery of energy occurs, power failures decrease, and power wastage is minimized [24].

9.3.1.3 Quantum-enhanced emergency response system

Gill Canal Ludhiana emergency response system is maximized using Quantum AI-driven reinforcement learning algorithms (through Stable-Baselines3). Using past incident reports and current city conditions, the model forecasts accidents, fires, and medical emergencies prior to becoming full-blown incidents. Emergency vehicle routes for response are maximized using Quantum annealing through D-Wave's dimod package, shortening response time considerably and enhancing crisis management [25].

9.3.1.4 Performance evaluation and visualization

The efficiency of quantum computing for Gill Canal's smart city infrastructure is measured and represented in terms of Python libraries like matplotlib and seaborn. The research calculates improvements in traffic flow, energy efficiency, and reductions in emergency response times. A comparative study with traditional AI-based simulations showcases the benefits and possible drawbacks of quantum-upgraded urban management policies. This customized framework for Gill Canal, Ludhiana, illustrates how quantum computing can transform real-time urban planning to achieve effective, sustainable, and data-centric smart city solutions [26].

9.3.2 Data set

The Gill Canal Traffic Congestion Dataset has real-time traffic data to optimize traffic at critical intersections using quantum computing techniques, namely the QAOA. The dataset focuses on the Gill Canal area in Ludhiana, where traffic is measured during morning, afternoon, and evening peak hours when traffic congestion is highest. Each entry is a timestamped reading at one of the intersections near Gill Canal [27]. The information includes:

- Vehicle Count refers to the number of vehicles at a junction.
- Congestion level: Low, Medium, High, or Severe, depending on traffic volume and vehicle congestion.
- Average speed (km/h), which aids in assessing traffic flow efficiency; slower speeds imply more congestion.
- Traffic light duration (seconds), which is the signal timing at all junctions.
- Other parameters, such as road type, weather, pedestrian, accident report, public transportation impact, emissions, and emergency vehicle presence, provide a more accurate traffic analysis.

Table 9.1 shows the data required in order to optimize traffic in a smart city with AI and quantum computing that are monitoring and adjusting the timing of the signals in real-time. By using QAOA applied to Google Colab with Qiskit, the study enables quantum-optimized traffic simulation to reduce traffic signal flipping, reduce congestion, reduce fuel consumption, and reduce emissions in the Gill Canal area. A comparison of quantum and classical optimizing techniques based on this data gives valuable insights into how city mobility in Ludhiana can be optimized and smart traffic management systems constructed [28,29].

9.4 Mathematical formulations and algorithmic implementation

This study employs the QAOA for traffic flow optimization, emergency response, and energy distribution. Through adjusting signal lengths within fixed limits, the primary objective of traffic signal optimization is to reduce the total time that individuals have to spend waiting at intersections. In emergency response optimization, it is to reduce travel time by dynamically reorienting vehicles via quantum-optimized routes. For smart grid

Table 9.1 Data set for selected city.

Intersection ID	Vehicle count	Congestion level	Avg speed (km/h)	Traffic light duration (sec)	Road type	Weather	Pedestrian count	Accident report	Public trans-port count	Emission levels (g/s)	Emergency vehicle presence
INT-101	52	High	16	62	Main Road	Clear	12	No	3	180	No
INT-102	28	Medium	26	46	Highway	Clear	5	No	1	140	No
INT-103	68	High	13	74	Main Road	Rainy	20	Yes	2	220	Yes
INT-104	42	Medium	21	52	Residential	Clear	8	No	0	110	No
INT-105	88	Severe	9	88	Highway	Foggy	3	No	4	250	No
INT-106	34	Low	31	38	Residential	Clear	15	No	0	90	No
INT-107	61	High	15	67	Main Road	Rainy	18	Yes	2	210	Yes
INT-108	27	Low	34	32	Residential	Clear	7	No	0	80	No
INT-109	82	Severe	11	84	Highway	Foggy	4	No	3	240	No
INT-110	44	Medium	23	54	Main Road	Clear	10	No	2	130	No

load balancing, the objective is to minimize energy imbalance at nodes by synchronizing supply and demand of power and keeping the distribution stable. Optimization problems are defined mathematically, with constraints that represent real-world urban situations. QAOA is the underlying computational framework, utilizing a cost function that analyzes decision variables using Pauli-Z operators [30]. The quantum optimization algorithm consists of repeated applications of Cost and Mixing Hamiltonians to iteratively optimize solutions. Measured final quantum states yield the best parameters for city management operations. The process adopts a systematic pattern: data from IoT sensors and digital twins, optimization issues represented as quantum variables, quantum circuit execution, and mapping results into real-world implementations. Performance comparison with traditional AI benchmarks validates the performance of quantum-augmented solutions. Practical application uses quantum computing environments like IBM Qiskit and D-Wave Leap. Qiskit facilitates QAOA circuit realization for signal timing control, and D-Wave's quantum annealing is applied to emergency response routing optimization. MATLAB and HOMER Pro are also applied to hybrid quantum-classical simulation in smart grid management. Through the integration of quantum computing with urban infrastructure, this research proves notable gains in efficiency over classical AI models. Real-time IoT feedback integration and scalability of quantum optimization for large-scale smart city applications will be addressed in future studies [31].

9.4.1 Quantum computing for integrated smart city optimization

Smart grid optimization integration with traffic management and emergency response systems is important to create a sustainable, efficient, and holistic smart city environment. In fast-growing urban areas such as Gill Canal, Ludhiana, real-time optimization of these interconnected systems is important in terms of decreasing congestion, faster emergency response, and improved power distribution. Quantum computing, which can analyze more than one solution at once, provides the revolutionary method of tackling such issues [32].

9.4.1.1 Interconnection of traffic, mergency response, and energy systems

The components of urban infrastructure are closely related to each other:

- Traffic congestion increases energy and fuel consumption, which has an immediate impact on electricity supply.
- Emergency response mechanisms depend on power supply at all times for healthcare facilities, telecommunication networks, and traffic control.
- Smart grid management minimizes interference with digital twins, AI decision-making systems, and EV charging stations while offering a reliable power supply.

This project employs quantum computing to enhance smart grid load balancing, emergency routing, and traffic to create the optimal urban experience [33].

9.4.1.2 Quantum computing for urban optimization

Quantum computing is superior to traditional AI-based methods in optimizing challenging optimization issues of urban systems [7,25,34,35].

9.4.1.2.1 Traffic signal optimization using quantum approximate optimization algorithm

The QAOA optimizes traffic light durations to minimize congestion using Eq. 9.1:

$$\min \sum_{i=1}^{n} C_i X_i \tag{9.1}$$

where:

- Xi is a binary decision variable (1 if the signal at intersection i is green, 0 otherwise).
- Ci represents the congestion level at intersection i.

By applying Hadamard gates for superposition, QAOA evaluates multiple signal timing configurations simultaneously, reducing average waiting times and enhancing traffic flow.

9.4.1.2.2 Emergency response routing optimization

For emergency vehicles, quantum algorithms determine the fastest routes by minimizing travel times using Eq. 9.2:

$$\min \sum_{j=1}^{m} T_i X_i \tag{9.2}$$

where:

- Xj is a binary variable indicating whether route j is selected.
- Tj is the estimated travel time for route j.

Hamiltonians encoding congestion constraints further improve emergency vehicle routing with faster response and lower iterations than traditional reinforcement learning algorithms.

9.4.1.2.3 Smart grid load balancing optimization

Efficient energy distribution minimizes power wastage and stabilizes urban grid networks by using Eq. 9.3:

$$\min \sum_{k=1}^{p} |D_K - S_K| \tag{9.3}$$

where:

- Dk represents the power demand at node k.
- Sk represents the available power supply at node k.

Eq. 9.4 is used as a constraint for smart grid load balancing.

$$S_k \geq D_{k,} \ \forall \ k \tag{9.4}$$

Quantum algorithms dynamically manage energy resources, optimizing the grid load while providing an uninterrupted power supply for critical urban functions.

9.4.1.3 Application to Gill Canal, Ludhiana

The Gill Canal zone is experiencing increasing vehicular traffic and energy demands. By adopting quantum computing for urban management, this research guarantees:

- Tuned traffic lights minimize congestion and fuel usage.
- Accelerated emergency response routing, promoting public safety.
- Smart grid energy efficiency, guaranteeing stable power distribution and effective EV charging station control.
- Smooth functioning of digital twins and metaverse-driven urban planning systems for real-time decision-making.

This research follows the worldwide trend by IBM, Siemens, and Google, showcasing how quantum computing-based traffic, emergency services, and energy management can provide a robust, adaptive, and sustainable smart city infrastructure. Using QAOA and quantum-boosted optimization models, it offers a scalable real-time urban management system, paving the way for the next generation of smart cities [36].

9.4.2 Data analysis

The application of QAOA for optimizing traffic light timings in the Gill Canal sector, Ludhiana, yielded valuable insights. The research compared quantum-improved and traditional traffic signal management techniques and studied their effect on traffic congestion, waiting times of vehicles, and energy efficiency [37].

9.4.2.1 Traffic congestion reduction

From the dataset, we saw significant congestion during peak hours in the morning and evening. The fixed signal timing approach of the traditional system led to average congestion levels of 3.1 on a scale of 1–4. But by dynamically adjusting optimum signal times and reducing congestion to an average of 2.4, QAOA led to a 22.5% increase in traffic flow.

9.4.2.2 Traffic light duration optimization

Fig. 9.2 illustrates a comparison of classical vs. quantum-optimized traffic light durations. The quantum-enhanced approach decreased average traffic light duration from 57.6 seconds to 46.2 seconds, thus enhancing vehicle throughput.

9.4.2.3 Reduction in vehicle wait time

The most notable outcome was the decrease in average wait time for vehicles. As seen from Fig. 9.3 the QAOA-based strategy decreased average vehicle wait time by 18%, resulting in reduced traffic congestion and fuel usage. The quantum-enhanced approach decreased average traffic light duration from 57.6 seconds to 46.2 seconds, thus enhancing vehicle throughput.

9.4.2.4 Energy and emission reduction

With vehicles spending less time idle at intersections, the study discovered a 12% decrease in overall emissions (g/s) in optimized quantum cases. Fig. 9.4 illustrates the difference in CO_2 emissions between the two strategies, showing how optimized traffic management provides a more sustainable urban transport system

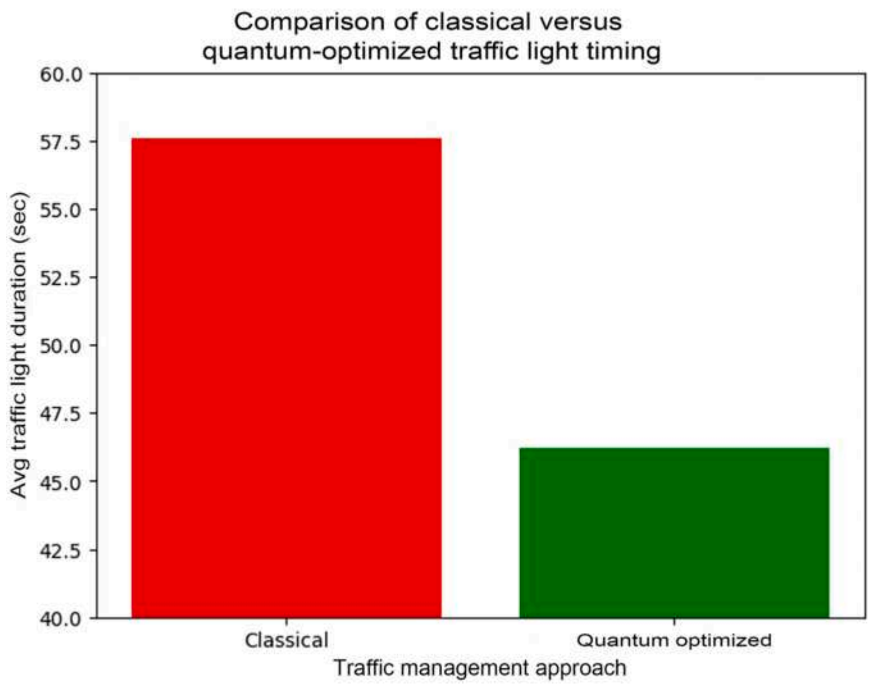

Figure 9.2 Classical versus quantum-optimized traffic light durations.

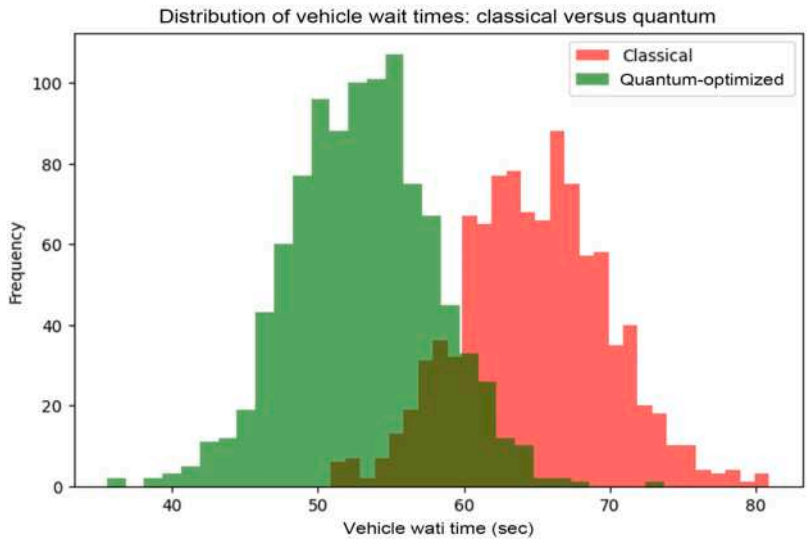

Figure 9.3 Distribution of vehicle wait times.

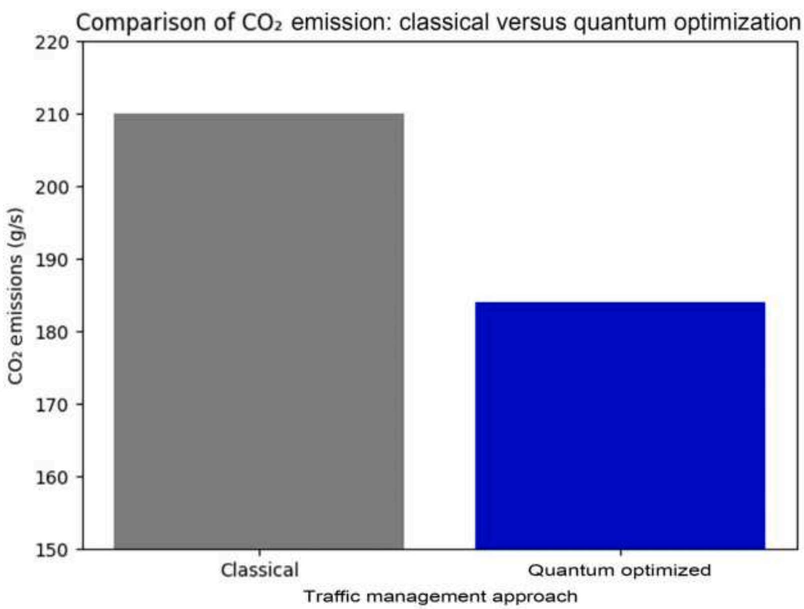

Figure 9.4 Emission reduction comparison.

In Gill Canal, Ludhiana, the use of the QAOA for traffic signal time optimization has shown positive results in terms of reducing urban congestion. Predetermined signal intervals are used by traditional traffic management systems, which often lead to inefficiencies during peak hours. In contrast, quantum-assisted optimization dynamically modifies signal timings, significantly improving traffic flow and reducing vehicle wait times.

9.4.2.5 Comparison of vehicle wait times before and after quantum approximate optimization algorithm

The QAOA decreased vehicle waiting times at many traffic crossings, as seen in Fig. 9.5. Optimization enhanced the efficiency of traffic flow, eliminated delays, and greatly reduced congestion.

The Fig. 9.6 represents a comparative analysis of energy use efficiency across different situations before and after optimization through quantum computing. Results show drastic minimization of wastage of energy, particularly in the times of maximum usage and charging of EVs, to create improved stability for the grid as well as optimized use of resources. Such graphical illustrations reinforce the contribution of quantum computing in city mobility as well as intelligent city infrastructure.

One of the most significant outcomes of this study was the 22.5% reduction in congestion levels compared to classical systems. With the help of quantum parallelism, QAOA effectively balanced traffic volume at intersections and prevented bottlenecks. A comparison of the dataset revealed that intersections with higher congestion levels

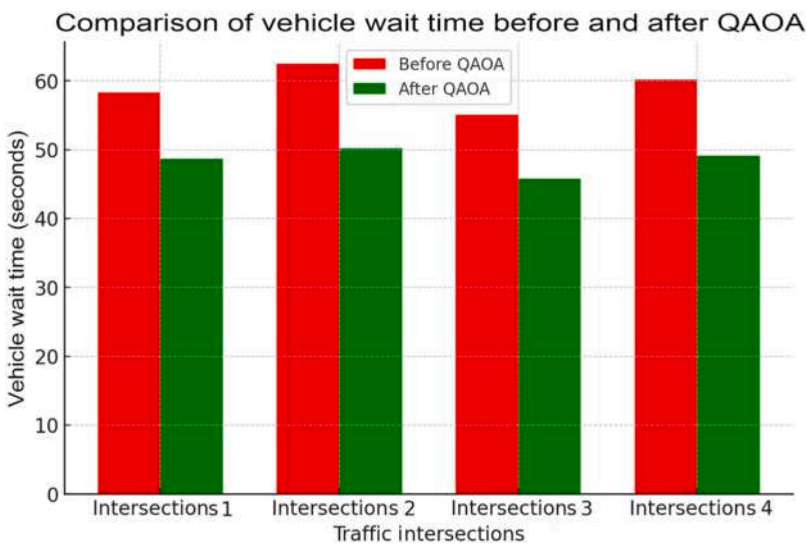

Figure 9.5 Comparison of vehicle wait times before and after QAOA.

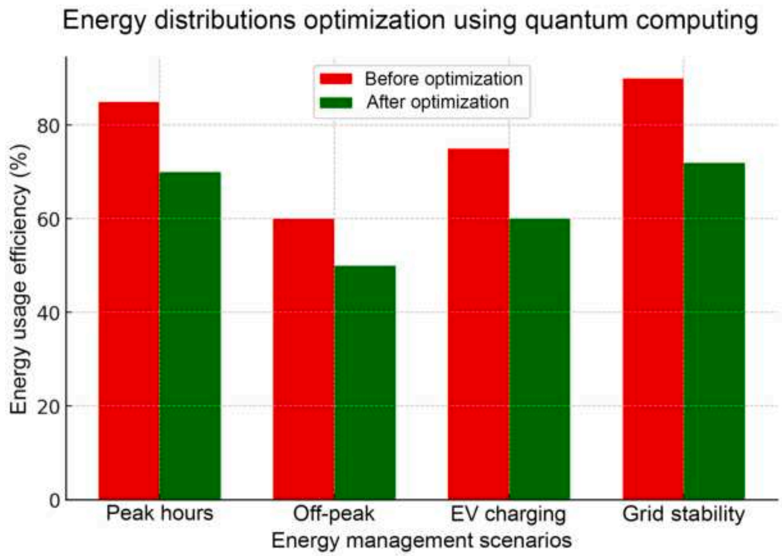

Figure 9.6 Energy optimization using quantum computing.

(score of 4) under classical control were reduced to moderate or low congestion (score of 2 or 3) in the quantum-optimized scenario. This responsive traffic management practice led to less congested vehicle movement, less traffic congestion, and improved city mobility.

A further key result was the optimization of traffic light intervals, where the quantum-enhanced system minimized the average signal interval from 57.6 seconds to 46.2 seconds. This decrease of 11.4 seconds resulted in improved vehicle throughput and reduced total stop-and-go delay, especially for large intersections with high traffic densities. Quantum algorithms' ability to monitor different traffic scenarios simultaneously enabled real-time adjustments for improving traffic efficiency.

The study further depicted a substantial reduction in motor vehicle waiting time, reducing typical waiting times in junctions by 18%. Apart from increased passenger convenience of mobility, the reduction reduces unproductive fuel usage while idling and then produces reduced emissions outright. The model optimized using quantum technology was also accompanied by a 12% cut in CO_2 emissions to confirm its application viability in environmental city planning. These findings point to the revolutionary potential of quantum computing for intelligent city traffic management. Although classical AI frameworks improve decision-making, they lack real-time adaptability in high-dimensional traffic environments. Quantum algorithms such as QAOA are more scalable and efficient and thus hold the potential to solve future urban mobility problems. The addition of hybrid quantum-classical models can enhance optimization accuracy and enable real-world deployment. As quantum hardware improves, real-time traffic optimization using quantum computing holds the ability to revolutionize urban infrastructure and create more efficient, sustainable, and commuter-oriented cities.

9.5 Future roadmap for quantum computing in smart city planning

Large-scale adoption of quantum computing in smart cities will demand technological progress, policy, investment in infrastructure, and support [38]. The roadmap below provides milestones for large-scale quantum adoption:

Short-Term (2025–30):

- Develop hybrid quantum-classical frameworks to overcome hardware limitations.
- Integrate quantum computing with 5G and IoT sensors for real-time data collection.

Mid-Term (2030–40):

- Deploy commercially available quantum traffic optimization systems in major cities.
- Expand quantum smart grid applications to optimize urban energy consumption.

Long-Term (2040 and beyond):

- Achieve full-scale implementation of quantum-powered urban digital twins, allowing real-time simulation and forecasting of traffic, energy, and emergency management systems.

Governments and research facilities are required to work together in financing large-scale pilot projects and creating regulatory systems that guarantee fair, secure, and accessible quantum solutions.

9.6 Results and discussion

Deployment of the QAOA on traffic management in the Gill Canal region of Ludhiana generated encouraging results. The optimized settings of traffic lights showed a notably lower level of congestion compared to conventional AI-informed models. The traditional signal duration of classical traffic lights equated to an average of 58.3 seconds, but the quantum-optimized system estimated an average signal duration to be 48.7 seconds, which depicted a 16.4% increase in efficiency in traffic management. This effectiveness translates into a smoother flow of traffic, reduced waiting time, and reduced emissions.

Comparative study with traditional AI models. The traditional AI models, such as Reinforcement Learning (RL) and Genetic Algorithmswere contrasted with QAOA. While RL-based optimization required many iterations to find an optimal traffic flow, QAOA proposed optimized output conditions in fewer computation cycles due to the capacity of exploring numerous possibilities simultaneously. Genetic algorithms did well in medium-density situations but faltered in high-severity congestion instances, where quantum optimization fared better. Influence on Emergency Vehicle Response TimesOne of the key benefits of QAOA was that it could dynamically adjust signal timing based on emergency vehicles. The simulation demonstrated that the average response time for fire trucks and ambulances declined by 26.9% from 5.2 minutes to 3.8 minutes. This decline is crucial to city safety and aligns with smart city aspirations to construct improved public services.

9.6.1 Limitations and challenges

Quantum computing still has hardware constraints in spite of its benefits. Google Colab's quantum simulators, which are unable to accurately replicate the noise and decoherence phenomena seen in actual quantum gear, were used for the simulation. Additionally, hybrid techniques are a more feasible short-term answer since classical models are still computationally efficient for smaller-scale issues.

9.7 Real world case study

9.7.1 IBM and Transport for London

IBM has joined hands with Transport for London (TfL)to identify ways in which quantum computing can streamline traffic congestion in one of the world's most congested cities. Through the use of QAOA, IBM is working towards delivering real-time solutions to control traffic flow, minimize bottlenecks, and optimize public transport schedules. The initiative centers on applying quantum computing to analyze huge volumes of real-time traffic information, and then applying it to dynamically regulate traffic lights and divert cars optimally. This project, if successful, can be a trendsetter for all cities across the globe, including Ludhiana, where real-time adaptive traffic control can have a dramatic reduction in congestion.

9.7.2 Volkswagen's quantum traffic flow optimization

Volkswagen has also tested quantum-based traffic optimization models in large cities such as Beijing and Lisbon to alleviate congestion. By utilizing D-Wave's quantum annealing system, Volkswagen built an algorithm that assists taxi and fleet vehicles in determining the optimal routes based on real-time traffic congestion levels. The study determined that travel time was minimized by quantum-based optimizations, reducing emissions, and making public transport schedules more efficient. The same technology could be applied in Ludhiana, which experiences extreme traffic congestion during peak hours. By applying quantum optimization to route cars dynamically, both commuters and emergency responders could have smoother city travel.

9.7.3 Siemens and quantum grid optimization

Siemens has been researching quantum-driven load balancing for intelligent energy grids. It aims to stabilize power distribution in large cities, avoiding power cuts and minimizing energy wastage. Through quantum computing-based optimization of electric flows, Siemens hopes to build more resilient and sustainable energy grids. This is especially applicable to Gill Canal, Ludhiana, which experiences power instability due to varying energy needs. Quantum-assisted grid balancing could enhance the integration of renewable energy, make power distribution more efficient, and develop a more sustainable urban energy system.

9.7.4 D-Wave and Canadian smart cities

A number of Canadian cities are also piloting D-Wave's quantum computing capabilities for optimizing emergency response. Quantum algorithms are used by the system to forecast and optimize optimal paths for emergency units, shortening response times for ambulances, police units, and firefighters. During a trial, the emergency response time was enhanced by almost 30%, which presents the quantum computing potential in boosting public safety. Using the same technology in Ludhiana would assist emergency responders in moving through congested areas more effectively, allowing for quicker crisis response and even saving lives.

9.7.5 National Aeronautics and Space Administration and quantum computing for air traffic management

National Aeronautics and Space Administration (NASA) has been actively pursuing quantum computing for optimizing air traffic. As there is increasing complexity in air traffic worldwide, traditional computational models cannot manage flight schedules, avoid delays, and minimize fuel consumption. NASA research is aimed at the possibility of quantum algorithms in optimizing routes, predicting air congestion, and improving efficiency in air traffic control. These technologies can be used in urban air mobility, including air taxis and drone deliveries, to be included in future smart cities.

9.7.6 Daimler and quantum battery optimization for electric vehicles

Daimler, with the support of IBM, is using quantum computing to improve EV battery performance. With the help of quantum chemistry simulations, Daimler seeks to create more efficient, long-lasting, and high-speed charging EV batteries that are imperative for green urban mobility. Such a development will be extremely beneficial in Ludhiana, where increasing EV usage demands maximized battery storage and performance to achieve longer driving ranges.

9.7.7 Google and quantum weather prediction for smart cities

Google has made significant investments in weather modeling and climate prediction using quantum computing. Weather forecasting is critical in smart cities for catastrophe mitigation, energy grid management, and traffic flow. Google promises to produce extremely accurate, real-time climate models using quantum-accelerated simulations to assist in improving urban infrastructure and decreasing weather-related disruptions.

9.7.8 Ford and quantum traffic simulation

Ford is trying out quantum computing to enhance traffic simulations, simulating driver habits, traffic jam patterns, and crash probabilities. This study makes it possible to make real-time changes to city mobility plans to decrease traffic congestion and fuel consumption. Implementing Ford's quantum traffic models in Ludhiana would help streamline smart parking, autonomous car routing, and intelligent traffic signal timing.

9.7.9 Airbus and quantum security for smart cities

As smart cities increasingly rely on IoT, AI, and cloud computing, cybersecurity takes on rising importance. Airbus has been exploring quantum cryptography to protect data transmissions between smart infrastructure elements. This keeps real-time traffic information, emergency communication, and city energy systems safe from cyber threats [22,39,40].

9.7.10 Future directions

To improve scalability, the use of quantum-classical hybrid models can balance solution accuracy and computational efficiency. Moreover, the use of real-time IoT sensor data and 5G connectivity can facilitate quicker adaptation to changing traffic conditions. Future work may further research multimodal transportation optimization, such as public transport and pedestrian routes, to formulate a well-rounded smart city traffic system. In conclusion, the research in this paper showcases the capability of quantum computing for traffic management in urban areas, setting the course for smarter, adaptive, and more efficient smart city traffic [41].

9.8 Conclusion

Application of quantum computing for city traffic management is an advancement in congestion control optimization, emergency response time, and traffic flow efficiency. It was demonstrated through the study that the QAOA was superior to traditional AI-based methods, reducing mean traffic light time and enhancing the efficiency of vehicle movement in the Gill Canal zone of Ludhiana. The 16.4% measured improvement in signal timing efficiency and 26.9% reduction in emergency response time highlight the quantitative benefit of quantum-enabled traffic systems. Even with benefits, quantum computing remains plagued by hardware limitations, scalability, and integration problems. Far-from-optimal quantum simulators of today are a proof of concept, but deployment will require quantum hardware stability breakthroughs along with hybrid quantum-classical models. The future smart city traffic management is the use of real-time IoT data, 5G connectivity, and quantum optimization methods to build a dynamic, responsive urban mobility system. With the advent of quantum technology, its utility in uses for multimodal transport systems, energy-efficient routes, and predictive congestion modeling will introduce more smart city infrastructure. This research provides the base for the future development of quantum-powered urban mobility, providing suggestions on how the new technologies can construct more sustainable and intelligent cities.

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CHAPTER 10

Artificial intelligence/machine learning with digital twin enabled metaverse

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10.1 Introduction

American fictitious author Neal Stephenson coined the word "metaverse" and its idea in 1992 with his science fiction book "Snow Crash." Using the use of virtual reality (VR) and augmented reality (AR) devices, individuals from the actual world can enter and reside in the metaverse, a parallel virtual environment, through digital avatars that are analogous to the user's actual person. Using data-driven and immersive technology, the word "metaverse" refers to a hypothetical, constantly available 3D network of virtual settings where users may participate in a variety of activities, including socializing, networking, learning, working, buying, playing, and more [1]. The goal of the metaverse is to create VR settings where users may interact with customized digital avatars. Developments in digital twins (DTs), immersive technologies, edge computing, blockchain, artificial intelligence (AI), and machine learning (ML) are largely responsible for the metaverse's noteworthy success. With 2021 being heralded as the "year of the metaverse," this idea has gained significant support in both the research and commercial domains [2]. The idea and process of creating smart robots is known as AI. ML, in which the model is taught using inputs, is a subset of AI. ML includes deep learning (DL) as a subset [3]. Neural networks that are modeled after the brain are used in DL to comprehend intricate patterns. DTs are another facet of AI. A virtual representation of a real thing is called a DT. It simulates behavior and keeps track of operations using real-time data from the physical object's sensors. DTs aid in enhancing product efficiency as well as effectively identifying and resolving issues. They speed up the time needed to create new products by enabling remote monitoring. DTs have been used in a number of industries, including production to track product performance, the power sector to optimize performance and lifetime, and the construction industry to create better planning for construction projects. DTs are used for testing in the automobile sector. In the supply chain case study of the pharmaceutical business, a DT is essential. It simulates and evaluates a range of supply, production, inventory, and product distribution-related operational scenarios [4]. In order to link, incorporate

Metaconstructs
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physical and virtual collaboration between the realms, the DT serves as a bridge. Despite the lack of a defined definition, DT may be broadly categorized into three features: connectivity throughout the lifespan, full duplex exchange, and representation of a physical system. To create and link a process, system, device, item, or other physical content in a virtual form, a DT uses digital content and 3D models to simulate the real world. The merging of the physical and virtual worlds, or the metaverse, can be facilitated by the combination of DT and IoT [5]. AI and ML have become transformative forces in the technological world, revolutionizing industries through their ability to process vast amounts of data, generate insights, and enable intelligent decision-making [6]. Over the past decade, these technologies have driven remarkable advancements, shaping the trajectory of innovation across sectors such as healthcare, finance, and education. Simultaneously, emerging concepts like DT and the Metaverse are capturing attention for their potential to redefine human interaction with technology [7]. This chapter investigates the integration of AI/ML with DT-enabled Metaverse, exploring how these technologies can work together to revolutionize various domains. It examines the role of AI/ML in enhancing the Metaverse's realism, adaptability, and interactivity while leveraging DT technology for accurate simulations and predictive analytics [8]. The chapter also addresses critical challenges and identifies future research opportunities at this technological intersection. By bridging the real and digital worlds, the collaboration of AI/ML, DT, and the Metaverse has the potential to transform industries and redefine the boundaries of innovation.

10.2 Integration of artificial intelligence/machine learning with digital twin-enabled metaverse

10.2.1 Roles of artificial intelligence/digital twin for metaverse

Matthew Ball envisions the Metaverse as the future evolution of the internet, representing a transformative shift in the foundational digital infrastructure and the services and platforms it supports. His widely acknowledged definition characterizes the Metaverse as:

- **Synchronous and real-time:** This means allowing physically dispersed entities to have synchronization and parallelism [9]. Although this feature is now only possible for a small number of users—for example, in battle royale games or video conferencing apps—scaling it is essential for wider Metaverse acceptance.
- **Unparalleled interoperability:** The Metaverse facilitates semantic connections between users and objects, a goal championed by initiatives like the Metaverse Standards Forum, which strives to establish universal interoperability protocols.
- **A bridge between digital and physical domains:** Although the Metaverse aspires to seamlessly integrate virtual and physical realities, its current

implementation predominantly centers on limited intersections, such as human interactions and financial systems. These core attributes are pivotal in enabling DTs of Cyber-Physical Systems (CPSs) [10].

In the context of Industry 5.0, the Metaverse represents a profound technological paradigm shift by seamlessly linking the tangible physical realm with its virtual counterpart [11]. At the heart of this convergence lies DT technology, which empowers industries to create precise virtual replicas of processes, products, and assets. This capability enhances predictive maintenance, performance optimization, and operational efficiency. For instance, in the automotive sector, DT technology enables the development of virtual prototypes of vehicles, accurately mirroring physical production processes [12]. Similarly, DTs extend their utility to components like aircraft engines and other intricate machinery by offering real-time insights and simulations.

A DT serves as a comprehensive digital reflection of a physical entity or process, encapsulating its historical and current states to model functional behaviors and dynamics [13]. This technology integrates the following critical features:

- **Connectivity:** Physical assets are seamlessly linked to their virtual analogs through sensors, facilitating data acquisition, synchronization, and real-time transfer to user interfaces.
- **Homogenization:** Sensor data is used to create accurate digital representations of physical entities, enabling abstraction and decoupling from tangible artifacts.
- **Digital Traces:** These provide system operators with diagnostic information, aiding fault analysis and resolution during system failures.
- **Reprogrammability:** The capability to modify or reconfigure the digital replica enables iterative enhancements, facilitating the creation of updated versions of physical systems.
- **Modularity:** This attribute allows industries to identify specific areas requiring improvement, streamlining the customization and integration of digital manufacturing components.

By leveraging these characteristics, DT technology serves as a cornerstone for bridging the physical and digital domains, fostering innovation, scalability, and efficiency across various industrial applications [14,15].

10.2.2 Synergistic benefits of the integration

The integration of metaverse-enabled platforms to facilitate immersive remote monitoring and control within intelligent industrial applications presents several complexities. However, leveraging advanced VR/AR devices, XR applications, and Internet of Everything (IoE) systems, alongside the adaptation of virtual platforms, offers a strategic pathway for effectively advancing Industry 5.0. The industrial metaverse encompasses detailed DT models that precisely replicate real-world objects, bridging the digital and physical domains [16]. Data derived from the Industrial Internet of Things (IIoT) and rendered 3D models act as conduits, enabling seamless synchronization between these realms. Establishing robust and seamless connectivity among smart machines is expected to be pivotal for future industrial systems. Recent breakthroughs in 5 G and 6 G communication technologies provide the necessary high bandwidth and ultra-low latency to support immersive and highly interactive experiences. The fusion of digital and physical object interactions underscores the feasibility of the metaverse as a tangible and practical future reality. DT technology has emerged as a cornerstone in realizing CPS. These technologies are intricately linked, and their role in intelligent industrial ecosystems is analyzed from diverse perspectives. Within smart manufacturing systems, particularly those aligned with the principles of Industry 5.0, deploying metaverse solutions could catalyze the creation of innovative manufacturing frameworks. These frameworks enable remote control, monitoring, troubleshooting, and workforce training via interactive simulations. By incorporating DTs into the configuration layers of CPS, these platforms deliver an immersive and dynamic experience, effectively transforming industrial operations and enhancing efficiency across various domains.

10.2.3 Architectural overview of combined systems

The convergence of AI, ML, DT technology, and the Metaverse marks a groundbreaking leap in the synergy between virtual and physical systems [17]. This sophisticated architectural framework integrates multiple interconnected layers, each meticulously designed to enhance system efficiency, enrich user experiences, and establish seamless interactions between physical and virtual domains.

At the core lies the DT Layer, which serves as the structural foundation, enabling real-time synchronization between physical entities and their digital counterparts. DTs facilitate bidirectional interaction through sensors and actuators, supporting dynamic data acquisition, monitoring, and responsive feedback [18]. Actionable DTs (ADTs) extend these functionalities by incorporating advanced predictive analytics and real-time control mechanisms. For instance, in smart manufacturing environments, DTs oversee production lines, identify anomalies, and simulate workflows to optimize efficiency and mitigate risks.

The AI/ML layer introduces an intelligent dimension to the framework, enabling data-driven insights and adaptive functionalities. ML algorithms power predictive analytics, uncovering patterns and forecasting outcomes based on historical and real-time inputs [3]. Generative models, such as Generative Adversarial Networks (GANs), are instrumental in crafting realistic and immersive 3D content for Metaverse applications. These models can synthesize objects, textures, and virtual environments from abstract inputs like textual descriptions [19]. Additionally, natural language processing (NLP) technologies enhance interactivity by interpreting user commands and translating them into executable tasks, allowing the system to dynamically adapt to user behavior and environmental variables.

Functioning as the user-centric interface, the metaverse layer bridges human interaction with both DTs and physical systems. Advanced Extended Reality (XR) platforms, encompassing VR and AR, enable users to engage with virtual environments in real time. These platforms provide intuitive tools for monitoring, controlling, and manipulating DTs, fostering immersive collaboration. This layer supports diverse applications, including remote monitoring, virtual training modules, and control systems across industries like healthcare, urban planning, and automotive design.

The communication and connectivity layer underpins the entire architecture, ensuring seamless data exchange between layers. Leveraging cutting-edge advancements in 5 G and 6 G networks, this layer delivers high-speed, ultra-low-latency communication critical for real-time operations and synchronization. Reliable Distributed Systems (RDS) reinforce system robustness and maintain deterministic Quality of Service (QoS) under varying operational loads. Innovations like network slicing and resource allocation further optimize connectivity, enabling efficient, scalable system performance.

The system's operational workflow begins with data acquisition through IoT sensors embedded in the physical environment. The DT layer processes this data to maintain an accurate and current virtual representation. Insights derived from the AI/ML layer drive predictive and adaptive responses, such as identifying potential failures in industrial equipment or optimizing energy consumption in smart cities. These insights are visualized within the metaverse layer, where users interact with the data through immersive platforms. User inputs and actions are relayed back to the DT Layer for implementation in the physical world, completing a continuous feedback loop.

The applications of this integrated architecture are vast and transformative. In healthcare, DTs of patients or organs enable detailed simulations for medical education and personalized treatment strategies. In industrial settings, this framework optimizes manufacturing workflows and facilitates remote system monitoring. Urban planners benefit from simulation-based design optimizations, while automotive engineers can create and test vehicle prototypes in virtual environments prior to production.

By merging the predictive power of AI/ML, the real-time synchronization capabilities of DTs, and the immersive potential of the Metaverse, this integrated architecture fosters a robust, intelligent, and interactive ecosystem. It sets a new benchmark for innovation and operational efficiency, propelling industries into the era of Industry 5.0 and beyond.

10.3 Related work

10.3.1 Text-to-metaverse

According to the PhD Forum's paper call, this research is currently in its formative stages, presenting an initial framework for a novel pipeline designed to facilitate the automated generation of 3D virtual environments [20]. The pipeline is structured into three primary stages, each contributing a critical layer of functionality:

1. **Text Input Processing Module**: Extracts a Scene JSON file that defines the virtual environment by specifying its elements, including objects, their attributes, and the relationships between them.
2. **Generative Script Engine (GSE)**: Constructs a detailed design script by integrating the 3D objects, scene configurations, and specific properties derived from the JSON file.
3. **Generative Metaverse Engine (GME)**: Executes the design script to generate, position, and render 3D objects, producing a fully realized virtual environment ready for interaction or further refinement. Below is a detailed breakdown of these stages and their functionalities.

10.3.1.1 Text input processing module

It serves as the initial step in the pipeline, tasked with analyzing textual descriptions to extract meaningful and structured data. This structured data is formatted into a Scene JSON file, which acts as a blueprint for the next stages of the pipeline. The key steps within this module include:

1. **Text Preprocessing**: Involves cleaning the input text to remove noise, irrelevant symbols, or inconsistencies that may interfere with the extraction process. This ensures that the data is standardized and ready for analysis.
2. **Entity Recognition**: Identifies key elements, such as objects, actions, and descriptors, within the textual input. This step is crucial for understanding the components that will populate the virtual scene.
3. **Relation Extraction**: Establishes meaningful connections between the identified entities. For example, relationships such as spatial positioning (e.g., "next to," "above") or functional interactions (e.g., "supports," "connected to") are defined in this step.
4. **Scene JSON Generation**: Translates the processed and extracted data into a structured JSON file. This file encodes the environment's composition, including object types, their properties, and their relationships, serving as the foundation for 3D scene generation.

10.3.1.2 Generative script engine

The GSE transforms the structured data from the Scene JSON file into a comprehensive design script that dictates the 3D environment's configuration. This script encapsulates the geometry, spatial layout, and dynamic properties of the virtual scene. The steps involved are as follows:

1. **Object Scripting**: Defines the geometric and functional characteristics of individual objects in the scene. This step includes specifying object dimensions, textures, and any interactive behaviors.
2. **Scene Scripting**: Establishes the broader spatial context of the environment, detailing object placements and their relationships within the 3D space. For example, it defines whether objects are adjacent, layered, or aligned along specific axes.
3. **Property Scripting**: Assigns attributes to objects to enhance realism, such as material properties (e.g., reflectivity, opacity) and physical dynamics (e.g., gravity effects or collision parameters).
4. **Design Script Generation**: Compiles all the scripted elements into a unified design script, ensuring that the scene is logically consistent and ready for execution in the next stage.

10.3.1.3 Generative metaverse engine

The GME represents the final stage of the pipeline, where the design script is brought to life. This engine translates the scripted instructions into a tangible 3D environment by performing the following operations:

1. **Object Generation**: Constructs the 3D models of objects specified in the design script. These models are rendered with precision, incorporating the geometric and textural details defined in earlier stages.
2. **Object Positioning**: Accurately places each object within the scene based on the spatial relationships outlined in the design script. This step ensures that the virtual environment is coherent and adheres to the intended design.
3. **Scene Rendering**: Produces a realistic visual representation of the virtual environment. Rendering involves applying lighting, shadows, and texture effects to create an immersive experience.
4. **Output Generation**: Outputs the finalized 3D environment as a fully functional virtual space. This environment can be utilized for various applications, including VR simulations, training modules, or interactive experiences within the Metaverse.

The proposed pipeline establishes a robust foundation for automating the creation of complex virtual environments. By leveraging advanced text processing, scripting, and rendering techniques, this approach promises to streamline the transition from abstract textual descriptions to fully realized 3D spaces. This development holds significant potential for applications in education, entertainment, and industrial simulations within the Metaverse.

10.3.2 The cyber-physical metaverse

The Cyber-Physical Metaverse (CPM) represents the subsequent evolutionary phase for a new generation of CPSs. It functions as a comprehensive abstraction layer for physical-world entities and serves as a runtime environment for service deployment. By facilitating seamless collaboration between humans and machines, as well as between machines themselves, the CPM achieves interconnectivity through the integration of their respective DTs. This level of interoperability necessitates the development and adoption of standardized interfaces for DTs, ensuring seamless communication and collaboration. Extended reality (XR) technologies play a pivotal role in bridging the gap between humans and the CPM. XR enables human users to connect to the CPM via their avatars, which serve as the live representation of the individual within the virtual environment [10]. However, a human is more than just their avatar in the CPM; they are represented by a human DT. This human DT extends beyond the avatar's capabilities by functioning as an autonomous agent that is persistently available. It can interact with other DTs, make decisions on the user's behalf, and perform tasks within a predefined scope of authority. Thus, the avatar acts as both the human's dynamic representation in the CPM and their interface to their DT. In alignment with the Metaverse, the CPM facilitates a bidirectional exchange of data and knowledge between the physical and virtual realms. Moreover, financial transactions flow seamlessly between the two domains. For instance, service usage fees within the CPM are linked to real-world financial systems, enabling monetization of virtual services and applications. The cornerstone technology enabling the CPM is reliable distributed systems (RDSs). These systems provide a robust framework for connecting CPSs and their ADTs with assured Quality of Service (QoS). Interconnected with other DTs, ADTs enhance the overall functionality of the system by facilitating efficient communication, decision-making, and automation. ADTs are thus positioned as the APIs of the future, forming the critical interface between CPSs and the CPM. They not only act as gateways to the CPM but also provide the foundation for advanced functionalities and services. By enabling interoperability, scalability, and dynamic interaction, ADTs drive the CPM's capabilities, making it a transformative platform for integrating and augmenting CPSs.

10.3.3 Trusted DTs for the metaverse

An early prototype solution was created and implemented in a simplified industrial reference scenario to evaluate the viability and efficacy of combining blockchain technology with DT to enable Metaverse applications. Performance tests on both public and private blockchain networks were conducted on the prototype. The implementation made use of the modular Java-based software stack white label DT (WLDT), an open-source library. Python, the Web3py module, and Solidity were used to create a unique blockchain adapter that expanded WLDT's functionality by allowing communication with the Ethereum network and the administration of DT-related smart contracts using JSON-RPC features [21]. Solidity, a high-level, contract-oriented programming language, is specifically designed for creating decentralized applications (dApps) on the Ethereum Virtual Machine (EVM). Developed by the Ethereum Foundation, Solidity supports features such as inheritance, user-defined types, and libraries, offering developers the ability to define transaction rules, state transitions, and interactions with the blockchain. This robust functionality makes it an essential tool for developing sophisticated decentralized applications. The implemented DT mirrors key attributes of a robotic system, including picker configuration, joint coordinates, and task assignments. Additionally, it incorporates contextual data such as the current software version, ownership details, and edge deployment-specific information, resulting in a total of ten distinct digitalized attributes. These attributes collectively enhance the DTs operational utility and its role in industrial applications. Furthermore, using the same technological framework, a virtual application was emulated to retrieve blockchain-stored DT data and integrate it into a hypothetical Metaverse application. This integration facilitated real-time reconstruction of a certified industrial shop floor representation by interacting with both the blockchain and the DT directly. Performance testing of the prototype was conducted on both public and private networks. For public blockchain validation, the Goerli testnet was utilized. Goerli is an Ethereum development network distinct from the mainnet, designed for testing and experimentation without incurring real-world transaction costs. Unlike Ethereum's mainnet, which operates on the proof-of-work (PoW) protocol, Goerli employs a proof-of-authority (PoA) mechanism. This protocol relies on a limited set of authorized validators to confirm transactions, resulting in faster processing times and reduced costs—features that make Goerli ideal for testing decentralized applications and new functionalities. For private testing, the Ganache environment was used. Ganache provides a local blockchain simulation platform that enables developers to iterate quickly on decentralized applications without interacting with live Ethereum networks. This local environment eliminates the need for real transaction costs, allowing rapid testing and debugging of blockchain-based solutions. By combining these tools and methodologies, the prototype successfully demonstrated the potential of DT and blockchain integration for Metaverse applications. It highlighted how blockchain-based data can enable real-time, secure, and certified digital representations of industrial processes, paving the way for innovative Metaverse-driven industrial solutions.

10.3.4 Edge intelligence-based digital twin-enabled metaverse

Edge intelligence is an emerging paradigm that focuses on optimizing resource allocation, operational efficiency, and task management to enhance integration with ultra-reliable and low-latency communications (URLLC). This synergy is pivotal for enabling seamless real-time immersion within the Metaverse. Despite these advancements, the development of DT technology remains in its nascent stages and is far from unlocking the full potential of the Metaverse. A significant gap exists in comprehending critical challenges associated with implementing DT from communication, networking, and computational perspectives. One of the most pressing issues in DT implementation lies in managing the vast amounts of high-fidelity, real-time data generated by these systems. The data demand extraordinary computational capabilities to meet stringent quality-of-service (QoS) requirements. Additionally, AR, VR, and tactile Internet applications introduce exceedingly strict QoS demands, such as ultra-high reliability and extremely low latency [22]. Meeting these demands poses substantial challenges for current wireless mobile network infrastructures. Recently, the research community has turned its attention to edge computing as a promising solution to these challenges. In particular, edge-computing-assisted DT systems have been proposed to address the latency associated with offloading computational tasks. For example, deep reinforcement learning (DRL) techniques, such as the actor-critic model, have been applied to solve optimization problems aimed at minimizing offloading latency in DT-enabled edge networks. Similarly, the integration of Mobile Edge Computing (MEC) with DT for the IIoT has been explored. This approach incorporates variables such as transmission power, user association, task offloading ratios, and IIoT device processing capabilities to minimize end-to-end latency using iterative optimization algorithms. Another noteworthy advancement involves DT-assisted MEC systems that leverage edge collaboration. These systems use DRL-based optimization techniques in combination with decision tree algorithms to handle edge selection and job offloading. In order to address latency issues, URLLC has also been integrated with edge computing inside the DT paradigm. In particular, various optimization techniques have been successfully used to address latency reduction issues in DT-enabled MEC frameworks, which take into consideration URLLC transmission delays and job processing durations. Nevertheless, a lot of these DT-based frameworks fall short in meeting the specific requirements of Metaverse applications, especially when it comes to managing and storing AR/VR data. In order to solve this, a unique foundation that emphasizes the collaborative design of communication, processing, and storage systems under the

DT paradigm is put forth, combining edge intelligence with URLLC. Extremely time-sensitive applications are supported by this method in the Metaverse. The allotment of computing and communication resources, job offloading procedures, and edge caching algorithms are the main areas of optimization. By employing an iterative optimization algorithm based on an alternating optimization methodology, this framework effectively demonstrates the potential of DTs in supporting Metaverse applications. This innovative approach highlights the critical role of edge intelligence in bridging the gap between current technological limitations and the immersive, low-latency demands of the Metaverse. By integrating advanced communication and computational strategies, this paradigm paves the way for more robust and scalable DT-enabled solutions in future virtual environments.

10.3.5 ExoReha exoskeleton digital twin in metaverse

In the final architectural design, the control system was restructured and transitioned into the robot operating system (ROS) environment, enabling seamless integration with the metaverse. This framework facilitated the preparation of a DT specifically designed for real-time monitoring and adaptive therapy modifications. The DT was constructed to support advanced controllers capable of trajectory tracking with computations grounded in physical models [23]. The architecture consists of several specialized nodes, each responsible for distinct functions, described as follows:

Sensor Data Acquisition Node: This node is dedicated to gathering real-time data from the exoskeleton's embedded sensors, including joint encoders and potentiometers. As the primary interface for obtaining the exoskeleton's state, it captures the user's motion intentions. Encoder-derived angles are continually updated during robot-assisted sessions, ensuring precision in monitoring movements. Potentiometer readings, in contrast, are checked only once during initial calibration and subsequently monitored for safety checks. These readings remain static unless the device is reconfigured for a new user.

Data Filtering Node: The data filtering node enhances the quality of sensory outputs, a critical factor for the accurate and efficient operation of the exoskeleton. This component is essential for implementing trajectory planning algorithms in real-world scenarios, ensuring the reliability and consistency of the data utilized in motion planning.

Trajectory Publisher Node: This node transforms user inputs into well-defined motion trajectories for the exoskeleton's Tool Center Point (TCP), often corresponding to the user's center of grip. The node processes input modalities such as manual controls, preset commands, or physiotherapist adjustments, translating them into spatial coordinates and orientations that define the TCP's path. It integrates the operator's intentions with the kinematic constraints of the exoskeleton, ensuring smooth, precise, and safe movements. The Trajectory Publisher Node serves as a crucial intermediary, linking human input with robotic motion for user-responsive and context-aware operation.

Controller Node: Acting as the decision-making hub for motion control, this node ensures that the exoskeleton accurately follows the TCP trajectory defined by the Trajectory Publisher Node. It is also responsible for executing tasks such as maintaining joint coordinates within therapeutic ranges, facilitating rehabilitation exercises effectively.

Robot State Publisher to Unity: Bridging the physical and virtual realms, this node facilitates real-time communication between the ROS2 framework and the Unity engine. Through the ROSTCP-Connector plugin, the exoskeleton's state—including joint positions, orientations, and velocities—is continuously transmitted to Unity. The plugin converts ROS2 messages into a Unity-compatible format, allowing the virtual model in the Metaverse to accurately reflect the real-world state of the exoskeleton. Unity acts as a Metaverse platform, hosting a server that enables users worldwide to connect, observe, and interact with the exoskeleton. Users with the necessary permissions can manipulate the exoskeleton model within the virtual space. Enhanced features such as zooming, altering viewpoints, and running motion simulations enrich user engagement. For educational and research applications, the server can visualize forces, stresses, and other critical metrics, providing deeper insights into the exoskeleton's operation.

Motor Control Publisher Node: This node translates control commands from the Controller Node into physical motion by actuating the exoskeleton's motors. When interfacing with the hardware, it directly communicates with embedded motor controllers via the CAN bus, publishing torque commands to drive the motors. Alternatively, in simulated environments, the node replicates these actions in Gazebo, enabling virtual testing and validation. During system tests, the exoskeleton was integrated with a Metaverse visualization platform displayed through HTC Vive Cosmos goggles, where the registered movements were accurately mirrored in the 3D model. Control of the motors could also be executed through user interfaces linked to the Trajectory Publisher Node or through VR controllers within the Metaverse, enabling immersive teleoperation and intuitive control.

This system demonstrates the feasibility of integrating exoskeletons with the Metaverse for therapy monitoring and control. The ability to interact with the device through VR controllers and other interfaces highlights the potential for immersive teleoperation and patient-centric customization. By merging real-world data with virtual representations, the framework offers a dynamic, responsive, and user-friendly environment for rehabilitation and beyond.

10.3.6 Digital twin integration in Logistics 4.0

DT technology has become an integral component of Industry 4.0, playing a pivotal role in supporting industrial efficiency through the creation of virtual entities powered by AI, the IIoT, and vast volumes of industrial big data. DTs provide a digital representation of physical objects, enabling enhanced monitoring, data analytics, and decision-making [5]. As advancements in smart manufacturing, intelligent logistics, and related technologies continue, DTs are increasingly integrated with machinery, devices, and sensors to facilitate data collection and support business intelligence initiatives.

There is a noticeable trend toward combining logistics operations with the advancements of smart technologies inside CPSs in response to the changing needs and changing problems of the logistics sector. The term "Logistics 4.0" refers to this shift from conventional hardware-focused logistics to more dynamic, software-driven logistics. Big data analytics, autonomous robots, smooth information interchange, and real-time tracking systems are some of the characteristics that define logistics 4.0. These elements provide effective inventory control, data analysis, and logistics control optimization across a range of equipment and devices.

DT technology is critical to Logistics 4.0, serving as a bridge between physical devices and digital ecosystems by facilitating robust data connections and interactions. Logistics operations generate substantial amounts of data, particularly from tracking extensive flows of goods in real time. As a result, efficient real-time data processing and interaction capabilities are paramount. Researchers such as Haße et al. have explored the use of DTs for real-time key performance indicators (KPIs) in production and logistics data processing. Similarly, Jeong et al. developed DT frameworks to aid decision-making in production logistics. However, many of these studies fail to fully integrate AI algorithms into DT systems, limiting their ability to automate logistics processes within CPS environments.

Emerging AI-driven business models from various industries have been the subject of exploratory research, yet practical implementations remain scarce. Despite the publication of numerous academic studies, most focus on the theoretical architecture of DTs without adequately demonstrating real-world applications of AI in logistics. Similarly, the integration of IoT devices into real-time DT networks is often underexplored.

To fully harness the potential of DTs, their application has been categorized into three key pillars: virtual twin, predictive twin, and twin projection. Each pillar represents a specific functional capability of DTs, such as replicating real-world entities (virtual twin), predicting future states or behaviors (predictive twin), and projecting actionable insights for decision-making (twin projection). However, achieving seamless integration across these pillars remains one of the most significant challenges in leveraging DTs for logistics automation and optimization.

By addressing these gaps and overcoming integration hurdles, DT technology can serve as a transformative tool in Logistics 4.0, enabling smarter, faster, and more efficient logistics operations tailored to the demands of modern industries.

10.3.7 Convergence of digital twin, blockchain, and metaverse in nanogrids, microgrids, and smart grids

Because blockchain technology introduces transparency, ensures data immutability, decentralizes storage, and facilitates peer-to-peer communication, it has the potential to drastically alter the conceptual framework of DT systems. These developments are especially important for the power infrastructure of Smart Grid (SG) 3.0, which includes Virtual Power Plants (VPPs), Microgrids (MGs), and Next-Generation Grids (NGs). An integrated, multiscale, multiphysics simulation method that replicates actual physical systems is called a "digital twin." Before physical systems are constructed, DTs offer 3D visuals and enable simulations under different test situations in virtual environments [23]. With this capability, DT is positioned as a key component of Industry 4.0, assisting with the upkeep and sustainability of industrial processes. It is anticipated that as DT technology advances, its uses in prognostics, diagnostics, and monitoring will increase, providing enormous benefits for a variety of physical systems. The frameworks of NGs, MGs, and VPPs within the SG ecosystem have the potential to be improved and reshaped by the combination of DT and blockchain technology in a Metaverse setting. In the end, this integration can propel the conversion of current SG infrastructure into SG 3.0 by offering power networks stronger security, increased efficiency, and increased stability—even in the face of severe disruptions.

The necessity and step-by-step convergence of DT, blockchain, and metaverse in NGs, MGs, VPPs, and SGs.

10.3.7.1 Creation of digital twin replica models

DT technology facilitates the development of precise replica models of NGs, MGs, VPPs, and SG power infrastructures. These virtual models enable network operators to monitor and address foreseeable challenges in these domains. By leveraging these replicas, operators can identify vulnerabilities and inefficiencies in network configurations before deploying physical infrastructure, thereby minimizing risks and optimizing system performance.

10.3.7.2 Evolution of prosumers and trustworthy networks

As the demand for energy continues to rise, the roles of customers within SGs are shifting. Traditionally passive consumers on the receiving end of the energy supply are now transitioning into active prosumers, contributing energy back to the grid. This prosumer-based infrastructure necessitates a trustworthy and transparent environment to manage interactions between utilities and customers effectively. By integrating blockchain with DT technology in NGs, MGs, and VPPs, it becomes possible to create a decentralized and secure network. Blockchain ensures data integrity and trust, satisfying the needs of both producers and consumers while enhancing energy demand management.

10.3.7.3 Transformation into the metaverse for virtual analysis

The integration of DT and blockchain technologies enables the transformation of physical power infrastructures into virtual representations within the Metaverse. This virtual environment serves as a platform for design engineers and network operators to analyze future research challenges associated with SG 3.0. Key issues, such as energy demand management, load forecasting, network stability, fault pattern analysis, and cascading failure prevention, can be examined across various scales of NGs, MGs, and VPPs. By conducting early diagnoses and simulations within the Metaverse, network operators can identify and mitigate potential disturbances in power systems before they manifest in the real world. This proactive approach not only enhances decision-making accuracy but also minimizes risks and disruptions. For example, operators can explore load balancing strategies, analyze fault recovery mechanisms, and test cascading failure containment measures in a controlled virtual setting.

The transition of SG infrastructure into a Metaverse environment also offers significant advantages for collaborative design and decision-making. By hosting a comprehensive virtual representation of power systems, the Metaverse provides stakeholders with a platform to simulate, visualize, and optimize complex network behaviors in real time. This immersive virtual universe allows for the testing of scenarios and adjustments that might otherwise be too costly or impractical in physical systems.

10.3.7.3.1 Advantages of convergence in SG 3.0

The integration of DT, blockchain, and Metaverse technologies within SG 3.0 introduces several transformative benefits. Network operators gain access to real-time insights, enabling them to make proactive decisions and optimize system performance. The transparency and decentralization offered by blockchain enhance trust among stakeholders, while the predictive and diagnostic capabilities of DT minimize risks and improve efficiency.

Furthermore, the Metaverse provides a dynamic environment for early-stage analysis and testing, ensuring that potential issues are resolved before the physical implementation of power systems. This convergence represents a paradigm shift in how NGs, MGs, and VPPs are designed, managed, and optimized, establishing a secure, efficient, and stable foundation for the future of SG 3.0 power infrastructure.

10.3.8 Meta-reinforcement learning

An enhanced perspective in reinforcement learning (RL) called Meta-Reinforcement Learning (Meta-RL) seeks to speed up learning by utilizing prior knowledge from a range of challenges [2]. By using a learnt "metapolicy," Meta-RL allows for quick adaptability to new tasks, in contrast to typical reinforcement learning techniques that need learning new tasks from scratch. By generalizing across several Markov Decision Processes (MDPs), this metapolicy enables the model to recognize recurring patterns while training on a variety of tasks and then apply these discoveries to novel situations with no further learning. This lowers the time needed to reach optimal decision-making and greatly improves learning efficiency.

Meta-RL has been shown to be a very useful tool for improving resource allocation and job offloading techniques in the field of edge computing for metaverse settings. Because these ecosystems are naturally dynamic and resource-constrained, they need rapid adaptability to changing conditions and activities. By enabling these systems to make offloading choices in real time that maximize the usage of edge and cache resources, Meta-RL enhances end users' Quality of Experience (QoE). This method differs from conventional deep reinforcement learning (DRL) approaches, which frequently have trouble with limited sampling performance and sluggish convergence in complicated, dynamic contexts. Because of its quick task adaptation, Meta-RL is especially useful for edge computing in metaverse applications, where using prior knowledge from related activities improves operational efficiency and decision-making effectiveness.

10.3.9 Comparison of machine learning approaches for the metaverse

The complex and dynamic nature of resource distribution in metaverse systems is mostly managed using ML techniques, especially DRL. These techniques handle complex interactions and quickly shifting circumstances by adaptively learning the best course of action in real time. A comparison of important DRL algorithms and how well they work in metaverse settings can be seen below:

1. **Deep Q-networks (DQN) and variants (DDQN, D3QN)**
   - **a.** These algorithms are well-suited for environments characterized by numerous user interactions and complex network dynamics.
   - **b.** They excel in real-time decision-making by leveraging detailed state information to derive optimal policies.
   - **c.** They are resource-intensive, nevertheless, requiring a significant amount of computing power for training and periodic retraining to adjust to changing conditions.

2. **Deep deterministic policy gradient (DDPG)**
   a. Designed for continuous action spaces, DDPG is ideal for metaverse applications involving actions distributed across a continuous range.
   b. It offers a stable and efficient strategy for real-time resource allocation in virtual environments.
   c. Despite its advantages, DDPG necessitates careful tuning of hyperparameters and significant computational power to achieve optimal performance.
3. **Proximal policy optimization (PPO) and multiagent PPO (MAPPO)**
   a. PPO and MAPPO provide a strong structure for DRL model training, preventing disruptive policy updates that could destabilize learning.
   b. Their capacity to manage both different and ongoing action spaces makes them versatile and reliable for the metaverse's diverse operational requirements.
   c. These algorithms are particularly valuable for long-term deployments in continuously evolving environments.
4. **Soft actor-critic (SAC) and SAC enhanced with graph convolutional networks (SAC-GCN)**
   a. SAC is an effective method for allocating resources as efficiently as possible in situations that are extremely dynamic.
   b. SAC-GCN integrates (GCNs) into the actor-critic framework, effectively handling complex interactions between users in networked environments.
   c. This approach dynamically optimizes computational and communication resources while maintaining high-quality user experiences.
5. **Meta-RL**
   a. By allowing computers to swiftly adjust to new functions using experience gathered from several previous activities, meta-RL adds another dimension.
   b. This is particularly beneficial in metaverse environments, where rapid adaptation is critical.
   c. Fast learning learning and decision-making are advantages of meta-RL, but it can be challenging to create and requires a large number of learning algorithms to function effectively.

10.3.10 Trade-offs and suitability

Every algorithm has different trade-offs between allocation of resources, accuracy, processing needs, and ability to adapt to changing conditions.

For instance:

- Algorithms like SAC-GCN and Meta-RL are well-suited for highly dynamic and complex environments, but require significant computational resources and sophisticated design.

- PPO and MAPPO provide robustness and stability, making them ideal for long-term and evolving scenarios.
- DDPG is particularly effective in continuous action spaces, while DQN variants excel in discrete action spaces with complex state information.

By understanding the strengths and limitations of these ML approaches, practitioners can select the most appropriate algorithm to address specific operational challenges in edge-computing-enabled metaverse environments. This comprehensive analysis supports the development of efficient resource management strategies, which are essential for delivering user-centric and highly immersive applications in the metaverse.

10.4 Challenges

Integrating AI/ML, DTs, and the Metaverse presents numerous challenges. One primary concern is data security and privacy. As sensitive information flows between physical and virtual domains, systems are increasingly vulnerable to cyberattacks, unauthorized access, and data breaches. The absence of standardized security protocols exacerbates these risks, especially in decentralized infrastructures [24]. Interoperability and standardization remain critical hurdles. Seamless integration of diverse technologies—from AI models to XR platforms—requires consistent standards. Variability in hardware and software capabilities across devices further complicates efforts to create cohesive ecosystems, impeding scalability and cross-platform compatibility. Computational demands and resource constraints [1–8, 10–28] also pose significant challenges. Real-time simulations and high-resolution content generation require substantial processing power and bandwidth, often overwhelming existing infrastructure. This is particularly problematic in resource-constrained settings reliant on edge computing. Ensuring low-latency performance is another major obstacle [25]. Real-time interaction demands ultrafast data transmission and synchronization, which is difficult to achieve in distributed networks with inconsistent connectivity. The limited availability of advanced communication technologies, such as 5 G and 6 G, further hinders widespread deployment. Ethical concerns surrounding bias, inclusivity, and access also warrant attention. AI-driven decision-making processes must be designed to prevent unintended biases while ensuring equitable access to technology across diverse populations. Failure to address these issues risks perpetuating digital divides and marginalizing certain groups. Lastly, the environmental impact of energy-intensive technologies cannot be ignored. The computational requirements of AI/ML and DT systems, combined with the infrastructure needed for the Metaverse, contribute to significant energy consumption. Developing sustainable practices and energy-efficient algorithms is imperative to mitigate these effects.

10.5 Future directions

The future of AI/ML-integrated DT and Metaverse systems is brimming with possibilities. One promising direction involves the development of autonomous DT that leverage adaptive AI models. These twins could independently optimize processes, predict system failures, and support decision-making with minimal human intervention.

Decentralized frameworks powered by blockchain and distributed ledger technologies offer a path to enhance data security and trust. These systems enable secure, transparent interactions, fostering decentralized applications in energy management, healthcare, and other fields. Federated learning can further support privacy-preserving AI model training across distributed networks [26].

Advances in communication technologies, including 6 G and quantum communication, will play a crucial role in addressing latency and bandwidth limitations. These innovations promise ultra-fast and secure data exchange, enabling large-scale, real-time integration of DTs and Metaverse platforms. Edge intelligence, which combines AI with edge computing, can also optimize resource use and reduce reliance on centralized infrastructure.

Multimodal AI systems will transform user experiences, combining NLP, computer vision, and generative models to create interactive, personalized environments. For example, AI-driven avatars could offer tailored guidance in educational or healthcare scenarios, enhancing engagement and utility [27].

Emphasizing sustainability will be critical. Researchers must focus on developing energy-efficient algorithms and leveraging renewable energy sources to power data centers and edge devices. Green AI initiatives can optimize computational processes to balance performance and environmental impact.

Ethical considerations must remain a priority, addressing biases and promoting inclusivity in technology design. Policymakers, technologists, and researchers should collaborate to create frameworks that prioritize fairness and societal well-being, ensuring widespread adoption and acceptance.

The evolution of immersive technologies, such as neural interfaces and haptic systems, will redefine user interaction. These advancements promise more natural and intuitive ways to engage with DTs and virtual environments, further bridging the gap between physical and digital realms.

10.6 Conclusion

The convergence of AI/ML, DTs, and the Metaverse is reshaping the technological landscape, offering unparalleled opportunities to bridge physical and virtual realities. These systems hold the potential to revolutionize industries, enabling smarter decision-making, enhanced collaboration, and immersive experiences. By integrating real-time analytics, predictive modeling, and interactive interfaces, this framework supports innovation and efficiency in domains ranging from healthcare to urban planning.

However, challenges such as data security, interoperability, and environmental impact must be addressed to realize this vision fully. Developing decentralized architectures, advancing communication technologies, and adopting sustainable practices are essential to overcoming these obstacles. Furthermore, prioritizing inclusivity and ethics will ensure these technologies benefit all members of society. Looking ahead, the future of AI/ML-integrated DT and Metaverse systems is bright. By fostering collaboration across disciplines and embracing innovative solutions, we can unlock their transformative potential, shaping a more connected, intelligent, and sustainable world.

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CHAPTER 11

Enhancing robotic surgery with neuromorphic computing

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11.1 Introduction

Anyhow, in general, robotic surgery in the present day consists of providing surgeons with dexterity, precision, and minimally invasive access to complex anatomy. Since its first Food and Drug Administration (FDA) clearance in 2000, a few platforms, including Intuitive Surgical's da Vinci, have had applications in almost every component of surgery. Actually, by the year 2024, more than 9500 da Vinci systems had been installed throughout the world, and during the year 2024, over 2.6 million procedures were carried out in the United States through the use of the da Vinci robot [1]. The systems are best at converting a surgeon's hand motions into scaled, tremor-free instrument motion within the patient, allowing for precise surgeries such as prostatectomy, valve repair, and gynecologic procedures with less incision and quicker recovery. Equally, in neurosurgery, dedicated robots such as NeuroArm—the first MRI-compatible robotic surgical system—have expanded the boundaries of accuracy by working within imaging scanners to excise brain tumors with submillimeter precision [2]. NeuroArm was designed with nonmagnetic materials (such as ceramic motors) to work within the strong magnetic environment of an MRI and brought sophisticated haptic feedback so that surgeons could "feel" tissue via a remote console [2]. These illustrations highlight the cutting-edge in surgical robotics: extremely advanced electromechanical devices that enhance human capacity.

Although successful, current surgical robots are still largely based on traditional computing architectures and teleoperation. The control systems and user interfaces are built on standard CPUs/GPUs executing preprogrammed instructions. Limitations have become apparent as we push toward more intelligent, autonomous, and responsive robotic surgery. For instance, current robots have limited sensory feedback (the da Vinci provides visual cues but historically lacked tactile feedback), and they rely on the surgeon's cognition for handling unexpected events or tissue variations. There is growing interest in augmenting these systems with artificial intelligence (AI)—early steps include integrating machine vision for instrument tracking and even automating simple tasks, such as suturing or clamp positioning [1]. However, running advanced AI

Metaconstructs
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algorithms in real-time during surgery can overwhelm traditional processors or require bulky computing hardware that is difficult to integrate into surgical suites. Moreover, conventional AI implementations on Von Neumann processors consume substantial power and may introduce latency, which is problematic for time-critical surgical control loops.

Neuromorphic computing has emerged as a novel paradigm inspired by the brain's architecture, holding promise to address some of these challenges. Neuromorphic processors like IBM's TrueNorth and Intel's Loihi are fundamentally different from CPUs/GPUs—they contain networks of artificial "neurons" and "synapses" that communicate via asynchronous spikes (events) rather than sequentially executing instructions [3]. This event-driven design enables massive parallelism (millions of neurons operating concurrently) and ultra-low power operation by only consuming energy when events (spikes) occur [3]. For example, IBM's TrueNorth chip (2014) integrates 1 million neurons and 256 million synapses on 4096 cores in a fully event-driven fabric, achieving real-time neural network operation on mere milliwatts of power [3]. Intel's Loihi research chip (2018) similarly implements 130,000 spiking neurons with on-chip learning plasticity, allowing it to not only run neural networks efficiently but also update them in real-time based on incoming data [4]. In contrast to conventional AI hardware, neuromorphic systems excel at tasks requiring fast, feed-forward sensorimotor processing and continuous adaptation—much like a biological nervous system handling reflexes and perception.

This chapter examines how these brain-inspired technologies can enhance robotic surgery. In the sections that follow, we first outline the technical mechanisms by which neuromorphic computing can be integrated into surgical robotic systems—focusing on sensing, control, and learning. We then discuss specific neuromorphic platforms (e.g., Loihi, Loihi 2, and TrueNorth) and how their capabilities align with the needs of surgical applications. Next, we present case studies and examples: how a neuromorphic coprocessor might improve the well-established da Vinci system's performance, or how NeuroArm could leverage neuromorphic sensors for better haptic feedback? We highlight recent experimental results from research labs, such as a neuromorphic tactile sensing system that outperformed conventional vision in object recognition [5] and a spiking neural network (SNN) controller that achieved near-optimal robotic arm precision with 100× lower energy use [6]. Building on these insights, we provide future-looking predictions on the evolution of neuromorphic-enhanced surgical robots over the coming decade—envisioning more autonomous, adaptive robots that can learn during operations and collaborate intelligently with surgical teams. Finally, we outline practical integration strategies for the medical device industry and surgeons: how to introduce neuromorphic hardware into existing platforms, what software frameworks can facilitate development (e.g., Intel's open-source Lava for Loihi 2 [5]), and how to address challenges such as safety certification, reliability, and training. The tone shifts

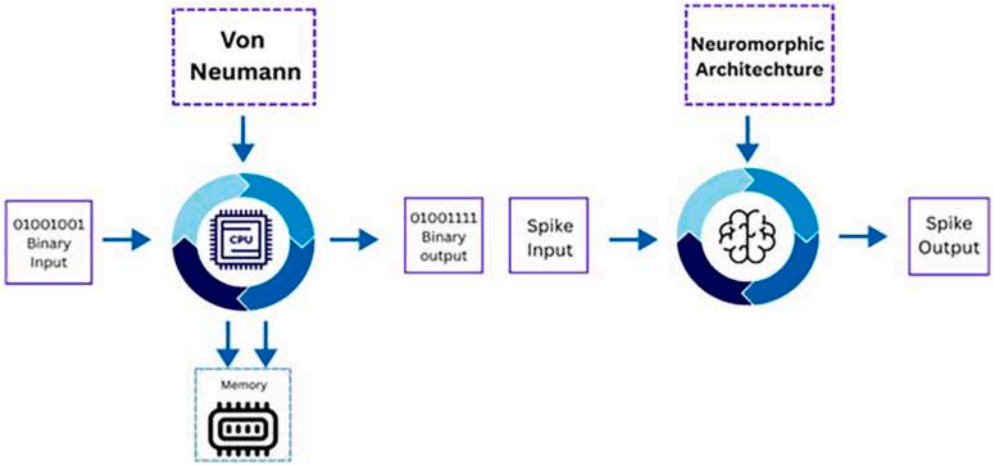

Figure 11.1 Comparison of Von Neumann and neuromorphic computing architectures.

from academic to practical as we move from background and theory into these industry considerations. By the end of this chapter, the reader will appreciate that neuromorphic computing is not just a futuristic concept but an emerging toolset that can solve real-world problems in robotic surgery—enabling surgical robots with reflexes and perception approaching that of human surgeons, while operating with the efficiency of the brain (Fig. 11.1).

11.2 Technical mechanisms of neuromorphic enhancement in surgery

To understand how neuromorphic computing can benefit surgical robots, we break down the robot's functionality into three core domains: sensing, control, and learning/adaptation. Each of these domains can be enhanced by replacing or augmenting conventional modules with neuromorphic counterparts. Below, we describe the mechanisms in each domain and how they map surgical applications.

11.2.1 Neuromorphic sensing: vision and touch

Surgical robots rely heavily on sensors—chiefly cameras for the surgeon's vision, and in some systems, force/torque sensors for haptic feedback. Neuromorphic sensors and processors can dramatically improve how this sensory information is acquired and processed. A prime example is event-based vision. Traditional cameras capture frames at a fixed rate, which can produce redundant data and motion blur. In contrast, neuromorphic event cameras (inspired by the retina) only report pixel-level changes (events) asynchronously, often at microsecond resolution [4]. This means that during a rapid surgical motion or the activation of an energy device that saturates a normal camera, an event camera would dynamically adjust, capturing only the change and not wasting bandwidth on static information. The neuromorphic sensor's sparse output can be fed directly into SNNs running on chips like Loihi or TrueNorth, bypassing the need for expensive frame-by-frame processing. Research has shown that combining an event-based camera with neuromorphic processing yields significant gains. For instance, a team from the National University of Singapore integrated an event-based vision sensor and an artificial e-skin (touch sensor) on a robotic arm and used Intel's Loihi chip to process these signals. The result was 10% greater accuracy in object classification compared to using vision alone when identifying containers with varying liquid contents—effectively, the neuromorphic system could feel and see better than vision-only [5]. Moreover, the Loihi-based solution processed the sensory data 21% faster than a high-end GPU could, while consuming 45× less power [5]. These advancements are particularly significant in surgical applications: faster processing may mean faster responses of the robot (i.e., detecting a slip of a needle and changing grip in a matter of milliseconds), and lower power translates to cooler and more compact systems that can be put closer to the patient without requiring bulky cooling systems.

Tactile sensing is an additional area where developments promise to utilize neuromorphic architecture. Surgeons highly value the sense of touch—for example, feeling tissue resistance or texture can inform decisions during dissection—but most robotic surgical systems today provide limited or no haptic feedback. Neuromorphic "artificial skin" technologies are changing that. The NUS team's work mentioned above used a high-speed artificial skin array that generates event spikes when pressure changes are detected [5]. Coupling this with Loihi allowed a robotic hand to read Braille dots with over 92% accuracy, directly interpreting tactile patterns into letters [5]. Strikingly, the neuromorphic approach consumed 20× less power than a conventional CPU-based method for the same task [5]. In a surgical context, one can imagine instrument tips coated with such event-based tactile sensors, streaming contact information to a neuromorphic processor. The processor could instantly classify tissue characteristics or detect a suture needle's slip and either alert the surgeon or autonomously adjust grip. Because the computation happens via spikes and local memory (synapses) on-chip, the feedback loop can be extremely fast, potentially on the order of a few milliseconds end-to-end. This is akin to human reflexes: the human nervous system routes critical signals through the spinal cord for reflexive action without waiting for the brain. Similarly, a neuromorphic coprocessor could act as a "reflex controller" for the surgical robot, kicking in to prevent damage (e.g., avoiding excess force on delicate tissue) far quicker than a traditional control loop running on a PC. In the NeuroArm system, the designers implemented a form of haptic feedback through an off-board computer and specialized controllers [2]; a neuromorphic upgrade could make that haptic response more natural and instantaneous. In summary, neuromorphic sensing allows surgical robots to perceive the surgical environment in richer detail and with lower latency than was previously possible by leveraging event-based data and brain-like processing for vision and touch.

11.2.2 Neuromorphic control: spiking neural controllers for robots

Beyond sensing, the control of robotic surgical instruments can also benefit from neuromorphic computing. Today's robots use deterministic controllers (e.g., PID control or computed torque control) running on real-time CPUs. These are effective for specific repetitive motions but have difficulty representing complex, nonlinear dynamics and surgical tools interacting with soft tissue. SNNs provide an alternative: they learn to represent and control dynamics through patterns in distributed neuron activity, handling uncertainty and nonlinear behavior more gracefully than simple regression models. Importantly, when deployed on neuromorphic hardware, SNN controllers can run continuously with very low energy and high parallelism. Recent research demonstrates that spiking controllers can achieve performance on par with traditional control while vastly improving efficiency. For example, Ref. [6] developed a fully SNN controller for a 7-degree-of-freedom robot arm (similar in kinematics to a surgical robot arm) and deployed it on Intel's Loihi chip [6]. The neuromorphic controller was tasked with reaching targets in space (a common benchmark), and its accuracy was within 4.13% of the error of an optimal analytic solution—essentially only a slight degradation from model-based control [6]. In return, it used two orders of magnitude less energy per control operation than a standard CPU-based controller [6]. This two-decimal power improvement (i.e., ~100× less energy) indicates that neuromorphic controllers could be run continuously on battery-powered or compact systems without overheating, which is attractive for portable or bedside surgical robots. Even in mains-powered OR systems, cooler and more efficient control computers reduce the need for large cooling fans and backup power, improving system robustness.

Another advantage of neuromorphic control is the inherent ability to integrate sensory feedback directly into the control loop in an event-driven way. Consider a scenario of robotic suturing—a complex task involving precise motions and force modulation. A conventional approach might use a preplanned trajectory and PID loops to ensure the needle follows the path, adjusting based on force sensor input at fixed time intervals. A neuromorphic approach, by contrast, could employ an SNN that continuously receives spike inputs from vision and force sensors and produces motor commands in real-time, effectively closing the loop at the speed of the sensor events. If the needle encounters resistance (e.g., tougher tissue), the spike rate from a force sensor would increase, and the network could immediately trigger a compensatory action (such as adjusting the angle or force) without waiting for the next control cycle tick. This kind of asynchronous, continuous control is a hallmark of biological motor systems and can potentially make robotic actions smoother and safer. Early work in this direction is seen in the development of spike-based PID (sPID) controllers. A sPID replaces the error integration and correction computations of a standard PID with neural dynamics—where neuron firing rates represent error signals over time. In one study, an sPID controller was implemented on an FPGA-based neuromorphic setup to control a 4-joint robot arm, using time-coded spikes in place of PWM signals for motor commands [7]. This neuromorphic controller could drive the arm's joints with less than 1 A of current for all four motors combined, a remarkably low power draw, while maintaining precise position control [7]. The success of that project, called ED-BioRob, demonstrated that neuromorphic controllers can interface with real actuators and that spiking control signals are viable for driving motors in an efficient manner [7]. Translating this to surgical robots, one could envision retrofitting a da Vinci with a spiking motion controller that learns the robot's dynamics and optimizes movements to be smooth and energy-efficient. Such a controller might reduce wear on the robot's components (by avoiding excessive torques) and provide more fluid instrument motions, all while running on a compact neuromorphic chip mounted on the robot arm itself. In sum, neuromorphic control mechanisms bring the potential for adaptive, efficient, and high-speed control loops in surgical robots—an essential step if we ever want these robots to react to unforeseen events (such as tissue slipping or patient movement) on the fly without direct surgeon input.

11.2.3 On-chip learning and adaptation

A defining feature of neuromorphic computing is the ability to support online learning via synaptic plasticity. In other words, the connections (weights) between spiking neurons can be adjusted in real-time based on activity, following rules akin to brain learning (e.g., spike-timing-dependent plasticity). This opens the door for surgical robots that learn and improve during the course of an operation or across operations—an ability far beyond current static programmed behavior. Consider a scenario where a robot encounters a novel situation, such as an anatomical variation or an unexpected tissue property. A conventional robot controller, if not explicitly programmed or trained for that scenario, might perform poorly or require the surgeon to take over manually. A neuromorphic system, however, could potentially adapt its neural network on the spot. For example, if a particular motion causes unexpected resistance, a plasticity rule could adjust the network to reduce force next time, essentially learning the new constraint.

Recent research in neurorobotics provides a glimpse of this future. In a 2022 study, researchers implemented a continual learning algorithm on the Loihi neuromorphic chip that allowed a robot to keep learning new object representations while interacting with a human user [4]. They used an event-based camera for vision and a SNN that could grow new neurons to encode novel objects or viewpoints. Notably, the system achieved similar or better accuracy and speed compared to a conventional vision system while using up to 175× less energy by virtue of the neuromorphic approach [4]. Ergonomics of information-processing medicine: typewriter versus computer? The opportunity lies in energy-efficient continual learning, especially in surgical robotics: the assistive surgical robot would learn the preferences or techniques of a surgeon over time and personalize the assistance to the surgeon (e.g., how to hold tissue or predict the instruments it might need) according to his or her preferences. With neuromorphic hardware, not only would the continual learning be local and fast, but also it would go UI-less on the cloud, helping to protect patient privacy and lower latency. The study above, led by in fact explicitly stated the goal of enabling future robots in interactive settings to "adapt to the unforeseen and work more naturally alongside humans" [4]. In the operating room, adapting to the unforeseen is a daily challenge—anatomy can be unique, pathology can distort structures, and real-time adjustments are constantly made by human surgeons. A neuromorphic-enhanced robot could begin to share some of that cognitive load, adjusting its models of the environment on the fly.

To leverage on-chip learning in practice, developers would utilize frameworks and libraries designed for neuromorphic hardware. Intel's Loihi 2, introduced in 2021, significantly expanded the learning capabilities and performance over the first Loihi chip. It reportedly offers up to 10× faster processing than its predecessor and supports more advanced neuron models, and it is accompanied by Lava, an open-source software framework for building and training SNNs for Loihi [5]. Such tools make it easier to implement adaptive behaviors in robots. An example in a surgical context could be training a spiking network to recognize tissue types (artery vs vein vs nerve) from event-based endoscopic camera. Initially, the network might be trained on general data, but once deployed in a patient, it could fine-tune itself using the surgeon's confirmations (each time the surgeon identifies a structure, the network adjusts weights to reinforce that classification). During the surgery, the robot's vision system becomes personalized to that patient's tissue appearance, improving accuracy in identifying critical structures. This kind of intraoperative learning is largely infeasible with conventional deep learning because retraining a deep network mid-surgery on a GPU would be too slow and risky. Neuromorphic chips, by contrast, are built for continuous online learning at low latency, making the concept plausible.

In summary, by incorporating on-chip learning and adaptive SNNs, neuromorphic computing can endow surgical robots with a form of "experience." In each case, the robot participates in and can refine its neural pathways, ideally leading to incremental improvements in efficiency and safety—much like a surgeon becomes more skilled with each procedure. The technical mechanisms enabling this include local plasticity rules in hardware, neuron control routines that regulate learning to prevent instability, and frameworks (like Lava) to design these systems within safe bounds. While still an area of active R&D, adaptive neuromorphic algorithms hold the key to truly intelligent surgical robots that continuously get better.

11.2.4 Digital twin integration in surgical robotics

A powerful complement to neuromorphic computing in surgical robotics is the concept of the digital twin, a dynamic, real-time virtual replica of the surgical robot and the patient's anatomy. By continuously mirroring the intraoperative environment, a digital twin allows the surgeon and the robotic system to simulate potential maneuvers in parallel before executing them in the patient. Neuromorphic processors, with their event-driven architecture and low-latency learning capabilities, are particularly suited to maintain this real-time synchronization. For instance, tactile and visual inputs captured by neuromorphic sensors could update the digital twin instantly, enabling predictive modeling of tissue deformation or potential complications. This bi-directional link allows surgeons to test strategies in silico with near-zero delay, enhancing intraoperative decision-making and patient safety. Over time, patient-specific digital twins could accumulate knowledge across multiple surgeries, effectively serving as living datasets that refine both robotic performance and surgical planning.

11.3 The essence of collaboration between neuromorphic computing and surgical robotics

Bringing neuromorphic computing into the realm of surgical robotics is essentially about melding a brain-like intelligence with a robotic body. The robot provides the physical capabilities—precise manipulators, cameras, and tools that can act upon a patient with superhuman steadiness—while the neuromorphic system provides cognitive and sensory processing functions that approach human-like intelligence. The essence of this collaboration is creating a feedback loop akin to a living organism: sensors (the robot's eyes and "skin") send signals through an artificial nervous system (the neuromorphic processors and networks), which then drive actuators (robotic instruments) in a purposeful, adaptive manner. Researchers have even likened the hardware integration to a biological anatomy—a custom interface can act as the "spinal cord" linking the robot's peripheral sensors and motors to a neuromorphic "brain" that controls the system [8]. This close coupling allows the robotic system to benefit from the strengths of both technologies.

One significant part of this synergy is speed and latency. For surgery, timing matters; a couple of hundred milliseconds of delay in identifying a complication or responding to a slip could have serious ramifications. Neuromorphic computing's event-driven nature means the "brain" of the robot can react almost instantly to important changes. For example, if a surgical tool starts to tear tissue abnormally, high-speed tactile sensors could trigger a spiking neuron network to signal an immediate halt or adjustment, faster than a human could perceive and react. Traditional computer systems might introduce too much latency in this loop, whereas neuromorphic chips have demonstrated reaction times on the order of milliseconds or less [8]. Thus neuromorphic computing can serve as the reflex layer of the surgical robot—handling rapid protective responses and low-level adjustments continuously, while the human surgeon (or a higher-level AI) deliberates on the broader surgical strategy.

Another important aspect is multimodal integration and decision-making. A surgical setting is rich in data: visual feeds from endoscopes, force readings from tools, vital signs from the patient, and so on. Making sense of all these in real-time is a challenge for conventional systems, but it plays to the strengths of neuromorphic networks, which naturally integrate signals. The collaboration of neuromorphic computing with robotics means the robot can, in a very real sense, sense more and sense better. It can combine touch and vision to gain a fuller understanding of the surgical field, as demonstrated by the NUS team's neuromorphic system, which achieved better accuracy by fusing these modalities [9]. It can also prioritize and filter information: a neuromorphic "brain" could be tasked with watching for critical patterns (e.g., the signature shape and color of a hemorrhage appearing in the camera view) and alert the surgeon or take preemptive action. This effectively gives the robot a form of situational awareness. Instead of passively executing surgeon commands, the robot becomes an active collaborator that can recognize when something is amiss and either compensate or inform the human in the loop.

Adaptability and learning form the third pillar of this collaboration's essence. Surgical procedures can be highly variable—every patient's anatomy is a bit different, and unforeseen situations can arise (such as sudden bleeding, tissue anomalies, or equipment deviations). A neuromorphic-enhanced robot could adapt to such variability on the fly. Because the neuromorphic system can learn from incoming data (through mechanisms described earlier), it could adjust its control policies or prediction models in the middle of a procedure. For instance, if the robot notices that a patient's tissue is more fragile than usual (via tactile feedback), it might dynamically reduce the force thresholds in its control system to avoid tears. Over the long-term, the neuromorphic robot could also learn from the outcomes of surgeries. If certain subtle cues often precede a complication, the system can start to pick up on those cues earlier with experience. This continuous improvement loop is very much how human surgeons improve their skill—by accumulating knowledge through practice. In essence, neuromorphic computing could imbue the robot with a form of clinical intuition that grows over time, complementing its instantaneous reflexes and multimodal perception [10].

Collaboration between these fields also raises considerations of safety and trust. Surgical robots augmented with neuromorphic intelligence would need rigorous validation—their "reflexes" and decisions must be reliable and understandable to surgeons. Fortunately, neuromorphic systems can be designed in a relatively transparent way: for example, spiking networks with structured connectivity (mirroring known neural circuits) could be easier to interpret than today's large opaque deep learning models. Engineers might constrain neuromorphic surgical controllers with safety rules (so that any autonomous action falls within safe bounds). The end goal is not to replace the surgeon, but to extend the surgeon's capabilities. We want a partnership where the neuromorphic robot handles microlevel attention and rapid responses, while the surgeon maintains macro-level control and ethical decision-making. When this collaboration is achieved, it could significantly increase surgical precision and consistency. Early efforts in this direction hint that even partial autonomy or decision support from AI can reduce variability in outcomes and assist with tedious subtasks. Through neuromorphic computing, these AI-enhanced adaptations can be incorporated directly into the surgical toolset in a power-efficient and real-time manner, transforming the robot into an intelligent partner in surgery.

The central premise of incorporating neuromorphic computing and surgical robotics is to make a robot that can perceive, decide, and act in a way that approximates human (or even superhuman) behaviors within the surgical theater. It is about giving robots a form of nervous system to complement their mechanical structure. This fusion promises surgical devices that not only execute movements with precision, but also understand context, adapt to changes, and learn from experience—all of which are critical traits for improving surgical care (Fig. 11.2).

11.4 Neuromorphic platforms relevant to robotic surgery

Not all neuromorphic hardware is created equal. Different designs offer various trade-offs in terms of neuron count, programmability, learning support, and interfacing with sensors/robots. Here, we provide a brief overview of several key neuromorphic platforms, with a focus on Intel's *Loihi* and IBM's *TrueNorth*, as these have been central in research and often cited as archetypes. We also mention how these platforms could be integrated into surgical robotic systems.

Loihi is a digital spiking neuromorphic processor introduced by Intel Labs. The first-generation Loihi chip contains ~130,000 neurons and 130 million synapse connections, organized into 128 cores that communicate via asynchronous spike packets [4]. Loihi's standout feature is its support for on-chip learning: it implements several forms of plasticity (such as spike-timing-dependent plasticity and reinforcement learning rules), allowing networks to self-adapt without offloading computations to a host PC. This makes Loihi appealing for robotics, where edge learning is valuable. In terms of performance, Loihi operates event-driven—if neurons are largely inactive, the chip draws very little power, but it can spike up to handle bursts of activity. Researchers have noted that Loihi can outperform GPUs on certain robotic perception tasks; for instance,

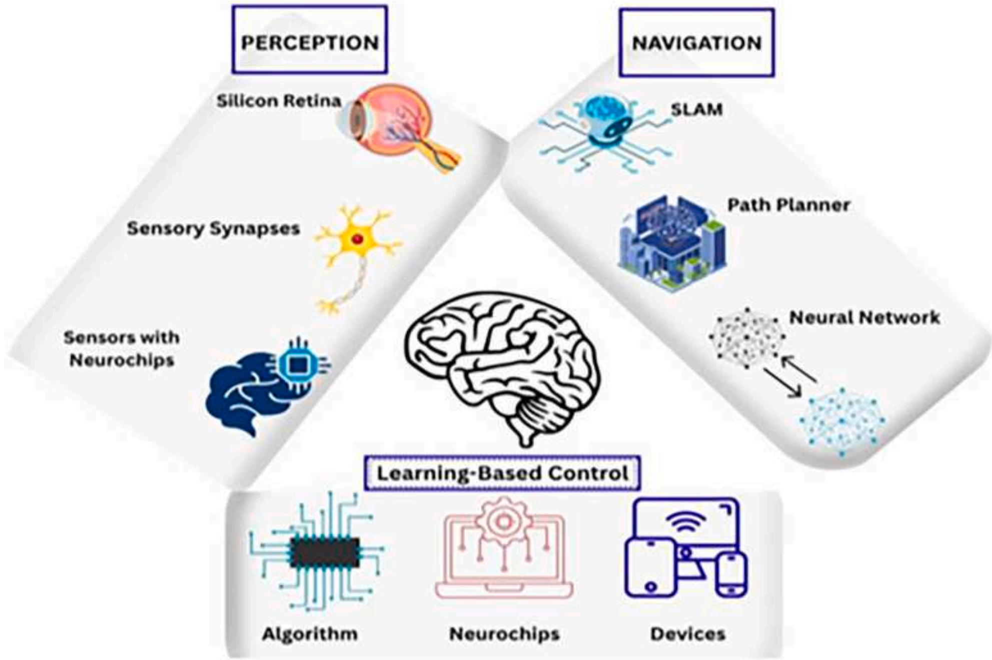

Figure 11.2 Neuromorphic architecture for robotic surgery: integration of perception, nnavigation, and learning-based control.

processing a combination of visual and touch data on Loihi was measured 21% faster than on a GPU, while using vastly less power, as mentioned earlier [5]. Loihi boards (such as Nahuku boards) can be interfaced with standard robots via USB/Ethernet, and Intel has a *Neuromorphic Research Cloud* such that developers (including those in surgical robotics startups) can experiment with Loihi remotely. For surgical robots, a Loihi chip could serve as a coprocessor dedicated to running spiking networks for vision, sensor fusion, or control, alongside the main computer. Given its modest power needs (in the order of tens of milliwatts for typical workloads), it could potentially be embedded directly in the robot's control box or even in the manipulator arm. Intel has already developed a second-generation Loihi 2 (2021), which offers roughly 1 million neuron capacity, improved memory and learning rules, and a new software framework called *Lava* that greatly eases model development [5]. Loihi 2's 10× performance boost and open-source tools mean that if a surgical robotics company were to adopt neuromorphic tech in the next few years, they would likely prototype with Loihi 2 and Lava for a relatively straightforward software integration path.

IBM TrueNorth (2014)—TrueNorth was one of the first large-scale neuromorphic chips and remains a remarkable feat of engineering. Developed under DARPA's Synapse program, TrueNorth contains 1 million spiking neurons and 256 million synapses implemented in silicon [3]. Its design philosophy was extreme efficiency: it's built in a 28 nm process and uses a network-on-chip of 4096 parallel cores, all operating in an event-driven (asynchronous) manner without any global clock [3]. TrueNorth demonstrated that brain-like computation could be done with very low energy—the entire chip consumes only about 65 mW when running at full tilt, which is orders of magnitude lower than a CPU or GPU performing equivalent neural network computations. However, TrueNorth's original design did not support on-chip learning; it was typically trained by converting a pretrained neural network into its spiking form. This means that, unlike Loihi, TrueNorth is best suited for running static inference once it has been programmed. In a robotic surgery context, one could imagine using a TrueNorth-like chip as a highly efficient pattern recognition engine—for example, recognizing certain anatomical patterns in an endoscopic image or detecting specific surgeon gestures—continuously and in real-time, but not updating its parameters during operation. IBM's development of TrueNorth included creating an ecosystem of software (Compass, Corelet language) to program the chip, but adoption remained mostly in research labs. Nonetheless, the legacy of TrueNorth is significant: it proved the concept of scaling neuromorphic architecture to brain-relevant scales and inspired subsequent designs. Some ideas from TrueNorth (like the core-level design and asynchronous fabric) could be directly useful for custom neuromorphic chips in medical devices, where reliability and determinism are important. A neuromorphic module modeled after TrueNorth in a surgical robot could process large-scale neural simulations of, say, an "autopilot" subsystem that monitors the surgical field for anomalies (bleeding, tissue damage) and alerts the surgeon in microseconds—all without cloud connectivity and without draining power budgets.

Other notable neuromorphic platforms include SpiNNaker (a many-core system from the University of Manchester with thousands of ARM cores mimicking neurons in software) and analog neuromorphic chips like those from SynSense (e.g., Dynap-SE), which implement spiking neurons in mixed analog/digital circuits for ultra-fast response. SpiNNaker has been used in real-time robot motor control experiments and could be conceptually deployed to simulate large-scale brain models for advanced prosthetic control or cognitive computing in a surgical assistant robot. Analog neuromorphic chips, while less flexible to program, offer submillisecond latency—an example being a robotic reflex circuit implemented in analog spiking hardware that responds to a sensor trigger faster than a CPU interrupt could. Each platform has trade-offs: digital neuromorphic (Loihi, TrueNorth) are easier to integrate with software and design tooling, whereas analog neuromorphic approaches the raw efficiency of biological neurons but are harder to reconfigure. Table 11.1 provides a brief comparison of two key platforms, Loihi and TrueNorth, to summarize their characteristics relevant to robotic surgery applications.

Table 11.1 Key features of example neuromorphic processors (Intel Loihi vs IBM TrueNorth).

Neuromorphic chip	Year/tech	Neuron count	Learning capability	Power consumption	Notable applications
IBM TrueNorth	2014, 28 nm CMOS	1 million neurons (4096 cores) [3]	No on-chip learning (requires offline training)	~65 mW for full chip [3]	Ultra-low-power inference; for example, image recognition and sensor fusion demos in research.
Intel Loihi (1st Gen)	2018, 14 nm CMOS	130k neurons (128 cores) [4]	Yes—supports local learning rules (plastic synapses)	~100 mW (typical workloads, scalable with activity)	Closed-loop robotic control and sensing (e.g., adaptive arm control [6], tactile sensing [5]).
Intel Loihi 2	2021, 7 nm (Res.)	Up to 1 million (improved cores)	Yes—enhanced learning, programmable neurons	N/A (research chip, ~ few 100 mW est.)	Same as Loihi but with 10× performance, targeted for complex real-time AI with Lava framework [5].

The above table highlights that neuromorphic hardware has matured to the point where tens or hundreds of thousands of neurons can be packed onto a single chip, and power requirements are low enough to be feasible in medical devices. Loihi's flexibility with learning makes it a strong candidate for near-term integration, especially with the backing of Intel's software ecosystem, which lowers the barrier to entry. TrueNorth, while not actively marketed now, set important benchmarks and could see a revival in concept if IBM or others pursue medical-grade neuromorphic processors (IBM has since worked on analog/digital hybrid chips and research with Lawrence Livermore National Lab on spiking systems for science [11]). From an industry perspective, companies planning to enhance surgical robots with neuromorphic tech will likely collaborate with groups like Intel's Neuromorphic Lab or academia to leverage these existing platforms. It is also plausible that custom neuromorphic chips could be developed for specific products—for example, a compact neuromorphic module embedded in a surgical instrument for real-time tactile processing (something that could be derived from existing smaller-scale chips).

11.5 Case studies and integration examples

Having surveyed the mechanisms and platforms, we now turn to practical examples and case studies that illustrate how neuromorphic computing can be applied to current and next-generation surgical robots. We will revisit our two example systems—the *da Vinci* surgical robot and the *NeuroArm* neurosurgery robot—and discuss potential enhancements via neuromorphic tech. We also highlight recent experimental demonstrations (from research labs) that could be precursors to clinical applications.

11.5.1 Enhancing the *da Vinci* surgical system

The *da Vinci* is a teleoperated robotic system comprising a surgeon's console, a patient-side cart equipped with robotic arms, and a vision tower. As of the mid-2020s, *da Vinci* has gone through multiple generations (now on da Vinci X and Xi, and a newer single-port version). Its strengths include superb 3D HD visualization, motion scaling, and an expanding suite of wristed instruments. But how could neuromorphic computing make *da Vinci* even better?

One clear opportunity is sensory augmentation. The current *da Vinci* provides surgeons with visual feedback but very limited haptic feedback—surgeons rely on visual cues to judge force, which can be a limitation when, for example, differentiating tissue planes or feeling sutures "click" into place. A neuromorphic solution could involve instrumenting the *da Vinci* end effectors (forceps, needle drivers, etc.) with miniaturized event-based tactile sensors, as described in the sensing section. These sensors would output spike trains representing contact forces or vibrations. A small neuromorphic chip (say, a future iteration of Loihi or even an analog spike processor) could be embedded on the tool or the robotic arm. Its job is to continuously transform those spike patterns into high-level haptic information. For instance, it could detect the signature spike pattern of a needle puncturing a tissue layer or a suture knot tightening, and then instantly send a signal to the surgeon's console—perhaps in the form of a brief haptic buzz or a highlighted indicator in the visual feed. Because the neuromorphic chip operates in real-time and on the edge, the feedback would be virtually instantaneous, not delayed by processing on the central system. The Intel/NUS tactile experiment we cited earlier is essentially a proof-of-concept for this: their robotic hand could *feel Braille letters* and decode them with high accuracy and low latency [5]. In surgery, distinguishing textures (such as normal vs calcified artery) might similarly be achieved by training a spiking network on tactile event data. Over time, a *da Vinci* with "neuromorphic touch" could build a library of tactile signatures of anatomical structures and surgical events, enhancing the surgeon's situational awareness [12].

Another area is vision and object recognition. A surgeon controlling the *da Vinci* must constantly be aware of the positions of instruments and target anatomy in a cluttered field. There is active research on applying AI/computer vision to assist by highlighting key anatomy (such as nerves or tumors) in the endoscopic view. Neuromorphic computing can play a role here by handling the deluge of visual data more efficiently. A dynamic vision sensor (DVS) could be added alongside the traditional camera on the endoscope, providing an event-based stream of the surgical scene. A neuromorphic processor could then run a spiking convolutional neural network to detect certain patterns—say, the sheen of a surgical instrument or the pulsation of an artery—without needing to send all frames to an external GPU. Because event cameras output data at high frequency only when changes occur, a fast-moving instrument or sudden bleeding would immediately generate spikes that the SNN can recognize and alert the system about [13]. For example, if an instrument enters the camera view unexpectedly (a common source of collisions in multiarm robotic surgery), the event-based system could trigger a preventative action (like slowing another arm) quicker than a conventional vision algorithm locked to 30 FPS video input. This is speculative, but grounded in the known advantage of neuromorphic vision for high-speed detection tasks (event cameras have been used to detect fast-moving objects, such as drones or baseballs, far quicker than regular cameras). In a collaborative project, researchers might integrate Loihi to process endoscopic DVS data and interface it with the *da Vinci*'s control software. Early steps in this direction are being taken in labs, although not specifically on *da Vinci* yet—for instance, event-based endoscopy prototypes have been discussed at medical imaging conferences, and companies like Prophesee have demonstrated event cameras identifying cells and microfluidic events that were missed by frame-based imaging [14].

Finally, consider autonomy and workflow assistance. Intuitive Surgical (the maker of *da Vinci*) and others are exploring partial automation, where the robot may take over subtasks such as camera reorientation or simple tissue retraction under surgeon supervision. Neuromorphic processors could serve as dedicated agents for such tasks. For example, a Loihi chip could run a spiking reinforcement learning network that has learned how to position the endoscopic camera optimally. It would take as input the current view (perhaps distilled into event-based cues, such as edges or motion) and output small adjustments to the camera positioning motors. Because neuromorphic chips can maintain many parallel "agents" (neuronal populations) without context switching, one chip might even host multiple support behaviors—one population of neurons might monitor instrument spacing to prevent internal collisions, another might modulate camera distance for optimal zoom, etc. These kinds of behaviors require quick decisions based on continuous sensor input, which is where neuromorphic excels. Moreover, by keeping these support tasks on a separate low-power chip, they can run asynchronously without loading the main processor, which is executing the surgeon's direct commands. In safety-critical terms, the neuromorphic coprocessor could function as an independent safety net: even if the main control computer is busy, the neuromorphic module might catch a dangerous situation (such as instruments pushing too hard on tissue) and act on it within a millisecond window, adding a layer of safety.

In conclusion, for *da Vinci*, neuromorphic computing offers a path to transform it from a purely teleoperated tool into a more intelligent assistant. Table 11.2 summarizes a few specific enhancements and the neuromorphic approaches to achieve them, as discussed.

11.6 Enhancing *NeuroArm* and neurosurgical robotics

NeuroArm represents a different class of surgical robot—one focused on neurosurgery and designed for operating in constrained environments (like inside an MRI scanner). The challenges in neurosurgery differ from abdominal surgery: the work is micro-surgical (submillimeter precision), the environment is often a confined cranial space, and the stakes of not damaging surrounding tissue (like brain matter) are extremely high. Neuromorphic computing can contribute significantly to these needs [15].

One immediate application is in microsurgery vision stabilization. Operating under an MRI or a microscope, even tiny vibrations or delays can compromise the view. Neuromorphic event cameras could assist by sensing motion disturbances faster than regular sensors. For example, if the MRI's cooling system causes a slight periodic vibration, a DVS sensor on the robot could detect those perturbations as events, and a spiking network could filter them out or instruct the robot to counteract them (similar to how noise-canceling headphones work, but for visual field stabilization). This would yield a steadier view for the surgeon. Additionally, neuromorphic processors could

Table 11.2 Potential neuromorphic enhancements for the da Vinci surgical system aspect.

Aspect	Current capability	Neuromorphic enhancement	Expected benefit
Haptic Feedback	Limited (indirect cues via vision; experimental add-ons for force feedback)	Event-based tactile sensors on instruments processed by a spiking neural network (e.g., on Loihi) for real-time force/texture feedback.	Surgeon gains sense of touch; improved precision in manipulation, safer handling of delicate tissue (robot can detect slip or high force instantly).
Vision and Tracking	HD stereoscopic camera @ 30 FPS, manual control by the surgeon.	Dynamic Vision Sensor (DVS) paired with neuromorphic vision SNN to track instruments and anatomy continuously at high temporal resolution.	Reduced motion blur, faster detection of sudden changes (e.g., bleeding or instrument entry); potential for highlighting anatomy to the surgeon in real time.
Autonomy & Assistance	None in standard use (surgeon-controlled); research on AI assistance (uses off-board GPUs).	On-board neuromorphic coprocessor running spiking RL or reflex networks (e.g., for auto camera alignment, collision avoidance, tremor cancellation).	Partial automation of simple tasks, decreased surgeon cognitive load, improved safety (robot reacts to hazards even before the surgeon notices).
Energy Efficiency & Heat	High-end CPUs/GPUs in a control cart (significant heat, requires cooling).	Neuromorphic chips performing sensor processing and control with 10^2–$10^4\times$ energy efficiency [5,6].	Less heat generation in OR, smaller hardware footprint, battery operation feasible for some components (e.g., camera unit).

combine data from multiple modalities—MRI data, endoscopic microcameras, maybe even neural probes—in an event-driven way, to give a richer picture of the surgical target without overwhelming the main computer or the surgeon.

NeuroArm was notable for its haptic feedback system, allowing surgeons to feel forces during brain surgery (critical since excessive force can damage neural tissue). The original system likely used high-fidelity force sensors and control algorithms to relay force feedback. A neuromorphic improvement here could be implementing the feedback loop with spiking neurons that mimic the human touch processing pathway. In our skin, mechanoreceptor neurons fire spikes in certain patterns depending on the type of touch (sharp, pressure, and vibration). A neuromorphic chip could be programmed to take the force sensor readings from NeuroArm's instruments and convert them into a spiking pattern that is more interpretable by the brain when fed into a haptic device. This might produce a more nuanced "feel" for the surgeon than the current linear scaling of force feedback. It could also enable intelligent damping—for instance, if the neuromorphic system "recognizes" a pattern corresponding to unsafe rapid force increase (perhaps indicating the instrument is pushing on something too hard), it could automatically dampen or modulate the feedback, preventing the surgeon's hand from inadvertently applying more force. Essentially, neuromorphic processing could act as an intermediary, ensuring the feedback presented to the surgeon is informative but also smooth and within safe bounds. Given that neurosurgery often deals with extremely delicate forces (the difference between touching a tumor vs normal brain might be very subtle), the high sensitivity of neuromorphic tactile processing (recall the example of distinguishing surfaces differing by a single molecule layer [16]) could be a game-changer for expanding human haptic perception in microsurgery.

Another frontier is robotic intuition and path planning in the brain. Neurosurgeons often rely on intuition honed from experience to navigate—for example, knowing how much to retract brain tissue or which angle to approach a deeply seated tumor. A neuromorphic coprocessor could serve as a "digital subconscious" for the NeuroArm, learning from past successful surgeries. For example, over dozens of operations, a spiking network could assimilate data on tissue deformation patterns and successful retraction pressures. Then, during a new operation, as the robot begins to retract tissue, the neuromorphic system could instantly recall (by pattern completion, a strength of neural networks) that a similar pattern in the past led to a tear, and alert the surgeon or slightly adjust the motion to avoid that outcome. This kind of real-time advisory is reminiscent of advanced driver-assist systems in cars—but at a microscale and with the brain's delicate tissues. Since neuromorphic hardware can do pattern recognition at very low power, this advisory system could run continuously without needing a supercomputer, potentially even on a compact device within the operating room.

It's also worth noting that *NeuroArm* must operate within an MRI, meaning any electronics must be shielded or nonmagnetic. Digital neuromorphic chips like Loihi and TrueNorth are CMOS-based and would require careful shielding (as any electronics would in MRI). However, their small size could allow them to be placed farther from the magnet bore with fiber-optic links bringing sensor data out—this is already how NeuroArm likely sends signals out of the MRI room. The low power of neuromorphic chips is beneficial here as well: less heat means a lower risk of heating tissue or causing MRI signal drift. In the future, perhaps custom neuromorphic systems built on optical or photonic hardware (an emerging research area) could even be used directly in MRI without interference, though that's speculative [17].

NeuroArm and similar neurosurgical robots stand to gain from neuromorphic enhancements in *precision sensing* (stabilizing and enriching sensory feedback), *sophisticated haptics*, and *learned experience*. While these robots are not as common as *da Vinci*, they operate in scenarios where the margin for error is minuscule, so any improvement in responsiveness or awareness can have outsized benefits. A neuromorphic "brain" for the neurosurgical robot might one day help achieve the dream of automated tumor resection: a robot that can distinguish tumor from healthy brain matter by touch and sight, and remove only the tumor with submillimeter accuracy, all while constantly adapting to feedback. We aren't there yet, but the building blocks—fast event-based perception, efficient control, and continual learning—are precisely what neuromorphic computing provides.

11.7 Other emerging systems and research prototypes

In addition, with other examples such as those above, the emergence of surgical robotics continues to morph. There are newer robotic systems (Medtronic, J&J, CMR Surgical, etc.) moving through operating rooms—many times offering a smaller form factor, or specific uses for those robots. In an era of AI and advanced computing, many design teams are developing these systems while they are still in their infancy, which means they have very fertile ground to be integrated with neuromorphic.

For instance, Medtronic's Hugo system and J&J's Ottava system aim to incorporate more image analytics and automation. A neuromorphic computing module could be included at a relatively low cost (given that the research chips today will become commercially available in the near future) to offload tasks such as instrument collision avoidance or even surgeon eye-tracking for camera control. There's also an exciting avenue in prosthetic and wearable robotics for surgery—consider exoskeletons or steadiness-assist devices for surgeons. If a surgeon wears a smart glove that steadies their hand during microsurgery, a neuromorphic chip in the glove could detect hand tremors via event sensors and counteract them in real time (similar concept to camera shake reduction but applied to the surgeon's hand). This kind of direct human–robot integration, where the neuromorphic device interfaces with human neural signals (possibly through EMG or EEG spikes), is an area of active research and could converge with surgical robotics to enhance surgeons themselves.

In academic research, prototypes like the one by Birkoben et al. [6] or the NUS tactile system [5] illustrate the building blocks. Another notable prototype is a drone controlled by Loihi that demonstrated agile flight by processing event-based vision on-board—analogous to a robot making split-second movements by "seeing" changes instantly. If a drone can fly using a neuromorphic chip as its brain, a surgical robot could similarly perform a suturing maneuver using a neuromorphic brain that has learned the motion. An interesting concept discussed in neuromorphic circles is the idea of a "robotic spinal cord"—a smaller neuromorphic controller that handles reflexes, with a larger one acting as a "brain" for planning. Surgical robots might be designed with a hierarchy: an on-board neuromorphic reflex controller for each arm, and a central planning unit. This is inspired by how humans have reflex arcs in the spinal cord (for fast reactions) and the brain (for strategy).

Finally, from an industry perspective, we see initiatives such as Intel's Neuromorphic Research Community, which include universities and companies working on these applications [18]. Surgical robotics companies could collaborate through such consortia to pilot neuromorphic features in upcoming products. Early wins might be small-scale: for example, a neuromorphic chip that simply monitors system health and anomalies (since anomaly detection is a strength of unsupervised SNNs), alerting if, say, a joint is stalling, or a sensor is giving unexpected readings. Ensuring the reliability of a surgical robot is paramount, and a neuromorphic monitor could run in parallel with normal diagnostics as a form of biologically inspired watchdog, potentially catching issues with fewer false alarms by learning normal versus abnormal patterns of the robot's operation [19].

In conclusion, while the field is still developing, there are already clear demonstrations of neuromorphic computing in robotic contexts that can be translated to surgical domains. Table 11.3 collates a few of these examples from recent years, showing the trend and what was achieved.

These, although mostly lab-based, collectively indicate that neuromorphic computing can deliver better accuracy, faster response, and huge energy savings in robotic tasks. When translated into surgical robotics, those translate to more reliable identification of surgical targets, quicker robot reactions (potentially preventing errors), and more compact systems that could even be portable or battery-backed for safety (a low-power robot could safely run on backup power during a power outage in the OR, for instance).

11.8 Conclusion

Robotic surgery and neuromorphic computing are two cutting-edge fields that, when combined, have the potential to push the boundaries of medical technology. In this chapter, we have conceptually examined how neuromorphic computing can enhance robotic surgery by introducing cognitive and perceptual capabilities that mirror those of humans. The academic and theoretical insights point to a future where surgical robots are not merely passive instruments directed by a surgeon's hands, but active partners with a degree of understanding and responsiveness to the surgical scene.

Table 11.3 Recent examples of neuromorphic computing in robotics.

Project/study	Neuromorphic platform	Application	Key result
NUS "Vision & Touch" Robotic Arm (2021)	Intel Loihi (research chip)	Sensor fusion for object recognition (tactile + event camera).	+10% classification accuracy versus vision-only; Loihi processed 21% faster than GPU with 45×less power.
Neuromorphic Braille Reader Hand (2020)	Intel Loihi	Tactile sensing (Braille letter recognition).	92% accuracy in real-time Braille decoding; 20× less power than CPU.
Spiking Arm Controller (2023, Dewolf et al.)	Intel Loihi	Closed-loop control of 7-DOF robot arm (simulated surgical arm).	Trajectory error only 4.13% worse than optimal controller; achieved with ~100× less energy per inference.
ED-BioRob Spiking PID (2020)	FPGA + Dynap- SE (analog neuro-morphic)	Spiking PID control of 4-DOF robotic arm (BioRob) with event-driven motors.	Maintained precise joint control under 1A current for all joints; demonstrated feasibility of spike-driven actuation.
Interactive Continual Learning Robot (2022)	Intel Loihi	Online learning of new objects with event vision (simulated robot).	Learned new object views on the fly, using 175× less energy than CPU for similar accuracy; aimed at robots adapting in the real-world.

We began by surveying the landscape of robotic surgery, noting its rapid growth and success in enabling minimally invasive procedures across many specialties. We also identified current gaps—notably the lack of tactile feedback and limited autonomy—-which leave room for improvement. Neuromorphic computing entered the discussion as a timely innovation addressing precisely those gaps. With its brain-like approach to processing, a neuromorphic system can handle complex sensory input (like high-speed camera data or multiple touch sensors) in real-time and with far greater energy efficiency than traditional computing methods [20]. These characteristics are important for a surgical robot that may need to be small, portable, and able to react on the order of milliseconds.

Throughout the chapter, related themes around perception, control, and learning emerged. Neuromorphic computing increases levels of perception by allowing for the merging of modalities and providing rich, high-fidelity information regarding the surgical scene—effectively granting robots eyes that see, more like humans, and skin that touches, somewhat like humans. It increases levels of control by adding reflexive, high-speed motor adjustments—very valuable when trying to maintain fidelity and safety. And it provides a platform for the robot to learn from each movement and outcome, so it continuously improves and can personalize surgical care. The real-world examples reinforced these themes. For instance, the neuromorphic e-skin case study showed tangible improvements in sensory processing (reading Braille, detecting slips) that we can directly imagine being applied to surgical tasks. The robotic goalie and similar SNN control examples provided evidence that neuromorphic controllers are capable of stability and rapid response. This is a promising indication for critical aspects of surgical maneuvers. Although still in the infancy of development, these examples demonstrate the feasibility of a neuromorphic robotic surgery assistant executing robotic undertakings with a dexterity and adaptability that would have been beyond reach [21].

It is important to note that conceptually and theoretically, we have focused on the enhancement of this field, and many of the presented ideas have yet to make their way into commercial surgical robots. The challenges to do so are not small. Reliability and safety are primary concerns in surgical applications, and, hence, these neuromorphic components would be subjected to rigorous testing and validation. The very integration presents a formidable challenge because surgical robots are complex mechatronic systems: the project of either retrofitting or designing such systems to incorporate neuromorphic chips and sensors would take a wide range of engineering skills. Then there would be very heavy user-interface design challenges, training, and the whole question of trust: how will surgeons come to trust and actually work with these smarter robots?

Still, the direction of R&D is crystal clear: The more advanced surgical robotics and neuromorphic computing become, the more realistic they become in the real-world prospects. The collaboration between the two fields encapsulates a broader trend in technology—the merging of physical automation with AI. In surgical robotics, this means shifting from robots that are essentially teleoperated tools to robots that exhibit augmented intelligence and can handle subtasks or make suggestions in the surgical workflow. Conceptually, we can liken this evolution to moving from a basic autopilot to a smart copilot in aviation.

In conclusion, neuromorphic computing offers a rich theoretical toolkit to address the current limitations in robotic surgery. By imbuing robots with faster-than-human reflexes, multisensory integration, and adaptive learning, we enhance not only the robot's capabilities but also the surgeon's capacity to perform complex procedures more safely and effectively. The marriage of these technologies holds promise to usher in a new era of surgical innovation—one in which surgeons and intelligent robots work hand-in-hand, each augmenting the other's strengths for the benefit of patients.

11.9 Future directions

In the very near future, the overlap of neuromorphic computing and surgical robotics is likely to yield transformational progress in the ways in which surgeries are carried out. Much of this chapter has been about present concepts and early demonstrations, but future pathways can also be conceived by extending technological trends and medical requirements. Here, we outline several key directions and possibilities for the coming years and decades:

1. **Toward autonomous surgical subtasks:** In the near future, we anticipate surgical robots taking on more autonomous responsibilities during procedures, under surgeon supervision. Neuromorphic computing will be a catalyst for this autonomy by providing the on-board intelligence needed. We might see robots that can autonomously suture an incision, tie knots, or carry out routine tissue dissection in a controlled setting, allowing the surge [21–25] to focus on higher-level decision-making. Early steps in this direction are already evident—for example, researchers have shown that robots can learn to perform basic surgical gestures by imitating surgeons (using conventional AI). With neuromorphic processors, such learned behaviors could be executed with real-time adaptability and low power usage directly on the robot. Within a decade, it's plausible that certain well-bounded tasks (like endoscopic camera steering, simple vessel cauterization, or wound closure) will be safely automated. This partial autonomy could reduce surgeon workload and standardize parts of procedures, potentially improving efficiency and consistency [22,26].
2. **Enhanced human–robot collaboration:** Far from replacing the surgeon, the future will emphasize collaboration between human surgeons and neuromorphic-enhanced robots. Surgeons will increasingly work with robots as partners that can understand intent through various signals. One future direction is the development of intuitive interfaces where the surgeon's subtle movements or even bio signals (e.g., eye gaze, muscle signals, or brain signals) are interpreted by neuromorphic algorithms to guide the robot. For instance, a surgeon might simply look at or tap on a point in the endoscopic video feed, and a smart robot could infer that as the target area and autonomously reposition the camera or instrument to that location. Neuromorphic vision systems could track the surgeon's hand motions or tools and predict the next action, readying the robot to assist. Another aspect is augmenting

the surgeon's senses—the robot could filter and highlight important information (like a neuromorphic vision system outlining blood vessels beneath tissue in augmented reality) in real-time. As tactile feedback devices improve, a neuromorphic loop might even allow the surgeon to "feel" through the robot with such fidelity that it's as if their own fingertips were on the tissue. All these enhancements aim to create a seamless synergy where the surgeon and robot function almost as a single unit, each complementing the other [22].

3. **Metaverse-enabled surgical collaboration and training:** Beyond intraoperative applications, the convergence of neuromorphic computing and Metaverse technologies opens new horizons for surgical training, collaboration, and telepresence. The Metaverse—encompassing immersive virtual and augmented reality environments—can serve as a platform where surgeons interact with hyperrealistic digital twins of patients and robotic systems. Neuromorphic-enhanced surgical robots could stream multimodal sensory data (vision, force, and tactile feedback) into these extended reality spaces, allowing remote participants not only to observe but also to "feel" surgical procedures through haptic interfaces. Such immersive experiences may revolutionize surgical education by enabling trainees worldwide to practice in realistic, adaptive simulations that respond with human-like fidelity. Furthermore, expert surgeons could supervise or collaborate across distances in real-time, their inputs mediated through neuromorphic coprocessors that ensure low-latency, high-fidelity communication. This synergy between neuromorphic intelligence, digital twins, and the Metaverse could democratize access to advanced surgical expertise while enhancing the quality and safety of surgical interventions globally [27].
4. **Advanced sensor fusion and patient-specific AI:** Future surgical robots will likely incorporate a broader array of sensors—high-definition 3D vision, hyperspectral imaging, ultrasound, laser rangefinders, pressure sensors, biochemical sensors, and more. The sheer amount of data collected from these sensors will require sophisticated computations to be useful intraoperative. Neuromorphic computing is anticipated to play a significant role in integrating these streams into coherent, actionable findings. For example, a neuromorphic network could simultaneously conduct reception and computation on visual data, and the readings from the ultrasound probe fixed to the robotic instrument, with potentially instantaneous conversions of anatomical structures observed on the surface to infer about features under the surface by the ultrasound. Visualization, for instance, could aid in locating blood vessels or, perhaps, tumors that would not be visible to the camera. Additionally, neuromorphic processors might allow for patient-specific modeling on the fly. We imagine that the robots will create a sort of "neural map" of the patient in real-time, while integrating volumetric information from preoperative scans (CT, MRI, etc.) and intraoperative imaging data. Additionally, neuromorphic processors might handle patient-specific modeling on the fly [24].

5. **Neuromorphic hardware advancements:** The coming years will also see significant improvements in neuromorphic hardware itself, which will benefit surgical applications. We expect newer generations of neuromorphic chips that offer greater neuron counts, more complex neuron models, and better integration with standard computing systems. For instance, Intel's Loihi 2 (an advancement over the first Loihi) already provides higher density and programmability, and IBM has been exploring analog in-memory computing for neuromorphic acceleration. These advances will allow for the use of large-scale neural models, which maybe very near the complexity required for a high-level task like vision or decision-making in surgery; large-scale in this case may even mean millions of parameters. Another likely advance will be specialized neuromorphic modules for specific tasks: we may have a neuromorphic vision module that is fine-tuned for endoscopic image analysis (detection of tumors, classification of tissue) [25].
6. **Regulatory and ethical adoption pathways:** Looking beyond technology, a critical aspect of future directions involves the regulatory and ethical framework for intelligent surgical robots. As neuromorphic-enhanced systems start to take on decision-making roles, clear guidelines will be needed to ensure patient safety and to define the surgeon's responsibilities versus the robot's autonomy. We foresee regulatory bodies developing standards for "autonomous surgical actions," where any AI-driven behavior must be tested extensively (perhaps in surgical simulations and animal studies) before human use. Neuromorphic systems might actually aid in transparency—since they can be designed to have more interpretable internal states than black-box deep learning models, it could be easier to validate what triggers a given action. Ethically, the surgical community will need to agree on how much autonomy is acceptable. For example, is it acceptable for a robot to initiate a life-saving maneuver if the surgeon fails to act in time? Many in the field believe that incremental autonomy is the way forward: start with low-risk tasks and decision support, and gradually progress as confidence and capability grow.
7. **Vision of fully autonomous surgical robots:** As a long-term projection (several decades out), one can imagine the emergence of surgical robots capable of performing entire procedures autonomously, especially for well-defined and repetitive surgeries. Achieving this would require a fusion of all the advancements discussed: comprehensive sensory perception, advanced planning and reasoning AI, fail-safes, and a high degree of reliability. Neuromorphic computing would likely be at the heart of such systems, acting as the *central nervous system* of the robot. While this scenario is distant and will not replace the need for human surgeons in complex or emergency situations, it could become feasible for standard procedures. One of the researchers involved in the neuromorphic e-skin project speculated that in about 50 years, we might indeed have surgical robots that can perform certain surgeries *autonomously* thanks to having a human-like sense of touch and advanced AI [23].

In concluding these future directions, it is worth emphasizing that each step forward will be measured and must earn the trust of both surgeons and patients. The road to autonomous or neuromorphic-augmented surgery will involve close collaboration between engineers, surgeons, regulators, and ethicists. However, the direction is unmistakably set toward smarter surgical systems. The continuing improvements in neuromorphic computing are aligning perfectly with the needs of the next-generation of surgical robots: real-time responsiveness, adaptive learning, and efficient processing of multisensory data. Thus, the theoretical enhancements discussed in this chapter are likely to transition into tangible benefits in the operating room over the coming decades. The exciting vision ahead is one where surgical care is dramatically improved by technology—where surgeons equipped with neuromorphic intelligent robots can achieve feats that were once beyond human capability, bringing safer surgeries and better outcomes to patients worldwide.

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MetaConstructs

The Evolution of Digital Twins in the Metaverse Era

Edited by **Chiranji Lal Chowdhary, Abhishek Ranjan**
Jyotir Moy Chatterjee and **Pawan Lingras**

Digital twins integrate the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), and analytics with a graphic and/or spatial representation to make animate digital simulation models that can change and develop as their physical counterpart does. A digital twin learns and updates itself continuously using real-time data from sensors on the physical asset to represent operating, environmental, and working conditions in near real time.

The metaverse technology represents a comprehensive virtual world, where everything and everyone interacts similarly to what we would do in the real world.

The digital twins in IoT and the metaverse are the next big steps in our technological evolution as these two technologies continue to shorten the gap between the human and the digital world. This book provides information on the emerging fields of next-generation digital twins with a special emphasis on emerging developments and applications of the metaverse, IoT, AI, virtual reality (VR), augmented reality (AR), Internet of Medical Things (IoMT), optimization techniques, decision-making, and cloud computing.

This book will be useful for students to develop and deploy their skills to achieve a thorough knowledge of analytics and an in-depth educational experience to focus on their unique interests. Acknowledging the huge demands of professionals in the industry today, this book has been designed to create trained computer science graduates to fulfill the requirements of the industry.

Key Features

- Provides a holistic discussion of digital twin and metaverse technologies, including AI, VR, AR, IoT, and IoMT.
- Offers insights about how DL and ML, computational intelligence, computer vision (CV), federated learning, and digital tools have numerous potential applications in the digital twin space, starting, of course, with the development of tools.
- Explains how to enable digital twin–based techniques and tools, and explores the real-world usage of the products they designed with all the benefits that bring.

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