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Digital Twin Technology: A Comprehensive Review Exploring the Potential, Evolution, Applications, and Future of Digital Twin Technology

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Abstract:- This review explores Digital Twin technology's evolution since 2003, beyond replicating physical entities to encompass data ecosystems and service relationships. Analyzing its inception, growth, and multifaceted uses, the review illuminates Digital Twins' transformative role in modern sectors. It delves into their impact on manufacturing, healthcare, smart cities, defence, agriculture, and utilities, showcasing their ability to enhance decision-making and operational efficiencies. Yet, significant obstacles hinder Digital Twin adoption, including IT infrastructure establishment, data quality assurance, privacy concerns, and ethical implications. These challenges obstruct the full realization of Digital Twins' potential benefits.

The study concludes by outlining critical avenues for future research, emphasizing standardization, data quality, privacy preservation, trust-building, and cross-domain applications. Bridging these gaps is vital for harnessing the true potential of Digital Twins in revolutionizing industries. This review aims to present a comprehensive view of Digital Twins, highlighting their benefits, challenges, and the imperative for further research to unlock their transformative impact.

Keywords:- *Architecture, Digital Twins, Ethical Considerations, Evolution, Internet of Things, Multidisciplinary Applications, Origin.*

I. INTRODUCTION

Due to the lack of Information Technology in the past, the majority of operations were primarily controlled by physical space, which had negative effects on efficiency, accuracy, and transparency. Technology such as computers, simulation software, the Internet, and wireless networks provided a parallel virtual environment to virtualize physical assets and allow for remote interaction with assets up to the 20th century. This has enabled more effective and efficient execution of plans and activities. With the advancement of new information technology, the interaction and integration of real and virtual places are now becoming more and more crucial. It is within this context that Digital Twin Technology comes to the forefront, revolutionizing various industries by fundamentally altering the way we simulate and optimize physical systems.

Digital twin technology has emerged as a powerful tool in various industries, revolutionizing the way we simulate and optimize physical systems. This technology offers the unique capability to delve deep into the inner workings of systems, comprehensively understand the interactions between different components, and predict the future behaviour of their physical counterparts. Digital twin technology offers a comprehensive solution by integrating various technologies such as the Internet of Things, simulation, data analysis, and modelling [1].

One of the most enlightening aspects of digital twin technology lies in its ability to establish a feedback loop between the physical system and its digital cyberspace model [15]. This innovative approach signifies a shift in industrial thinking, where efforts are directed toward integrating physical world occurrences into digital space. Achieving full lifecycle tracking with loop feedback represents a paramount concept, ensuring the harmonization of the digital and physical realms throughout the entire lifecycle. Such synchronization enables diverse simulations, analyses, data accumulation, and mining based on digital models, augmented by artificial intelligence applications, ensuring their adaptability to real-world physical systems. This capacity epitomizes the significance of digital twins in intelligent manufacturing; accurate modelling by digital twins is imperative for the successful implementation of so-called intelligent manufacturing systems. Moreover, digital twins facilitate rapid iterations and optimization of product designs, surpassing the speed of physical prototype testing. They also significantly enhance product quality, demonstrating their pivotal role in improving the customer experience, understanding needs, enhancing existing products and services, and driving the innovation of new business models.

For instance, GE's pioneering use of a "digital wind farm" illustrates the transformative potential of digital twin technology. By leveraging the digital environment, GE analyzes data from each turbine, feeding it into its virtual equivalent to inform the configuration of every turbine

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before construction. This approach aims to achieve a 20% gain in efficiency by harnessing the insights gleaned from the digital twin of each turbine. Such innovative applications showcase how digital twins enable rapid optimizations and informed decision- making, resulting in tangible improvements in productivity andperformance.

For two years in a row in 2016, and 2017 Gartner has ranked digital twins among the top ten strategic technological development trends[2]. Gartner also disclosed that organizations were beginning to deploy digital twins on a widespread basis in 2019[2]. The adoption of digital twin technology has been particularly widespread in manufacturing plants, where it supports digital transformation and the adoption of Industry 4.0 concepts. Due to its capacity to accurately simulate and analyze a physical entity's behaviour in actual contexts, digital twin technology has been increasingly popularin recent years[3].

The applicability of digital twins spans a diverse range of domains, with significant impact observed in smart cities, urbanplanning, freight logistics, healthcare, engineering, and the automotive industry, among others [4]. The largest weapons producer in the world, Lockheed Martin, ranked the digital twinas one of the top six technologies for the future of the aerospaceand defence sectors in November 2017 [2].

The concept of digital twins has undoubtedly captured the attention of various industries and academic circles, sparking excitement and curiosity. However, it is essential to acknowledge that this technology is still in its formative stages of development. Despite its immense potential, there is a notable scarcity of comprehensive studies focusing on the practical deployment of digital twin technology within specificapplications.

In this comprehensive critical review, the intent is twofold: Firstly, it aims to conduct a holistic exploration of digital twin technology across a diverse spectrum of domains. This endeavour includes an in-depth investigation into its integrationacross different maturity levels.

- *Secondly, this review seeks to address a series of fundamental research questions:*

- **Q1**: What are the key challenges and limitations faced by industries when adopting digital twin technology?
- **Q2**: What are the specific advantages offered by the digital twintechnology implementation?
- **Q3**: How has digital twin technology evolved in response to the demands of Industry 4.0?
- **Q4**: What are the emerging trends and technological advancements in the field of digital twins?
- **Q5:** What are the key ethical considerations and concerns that emerge with the widespread application of digital twin technologies across various domains?

Beyond the purely technical aspects, this study also delves into the myriads of benefits offered by digital twins and criticallyexamines the essential considerations for their successful implementation. By fulfilling these objectives and addressing these research questions, this comprehensive review aspires to serve as a valuable guide for researchers, practitioners, and stakeholders navigating the dynamic landscape of digital twin technology. Ultimately, the aim is to contribute significantly to a deeper understanding of digital twins and their potential to reshape industries and domains within the Fourth Industrial Revolution's context.

This review aims to comprehensively explore Digital Twin Technology's applications, challenges, and potential across diverse industries. The objectives encompass several key aspects. Firstly, the objective is to trace the technological evolution of Digital Twins within the context of Industry 4.0, shedding light on its emergence through the convergence of the Internet of Things, data analytics, and simulations. Secondly, the review will evaluate the advantages offered by Digital Twins, encompassing real-time monitoring, predictive analysis, and decision support capabilities.

Furthermore, this comprehensive examination will feature multiple case studies showcasing successful Digital Twin deployments across various domains, including healthcare, engineering, and smart cities, providing tangible insights into real-world implementations. Additionally, the intricate challenges associated with deploying Digital Twins will be explored, spanning technological intricacies, organizational hurdles, and domain-specific issues such as data integration andprivacy.

Lastly, ethical considerations and societal implications stemming from the widespread implementation of Digital Twin Technology will be examined, including concerns related to data protection and transparency. Encompassing diverse sectors like manufacturing, healthcare, smart cities, the automotive industry, engineering, and construction, this review aspires to contribute to a comprehensive knowledge repository. By delving into Digital Twins' historical evolution, advantages, limitations, and ethical dimensions, it aims to empower practitioners and researchers to harness their potential effectively and navigate the complexities inherent in their implementation.

Within the forthcoming pages, readers will find a comprehensive exploration of digital twin technology and its diverse applications across various industries. The structure of this exploration encompasses an examination of the technological evolution of digital twins, placing their emergence within the context of Industry 4.0. Following this, case studies across diverse sectors illustrate successful digital twin deployments. Subsequently, the focus shifts to the advantages derived from digital twin implementations, encompassing real-time monitoring, predictive analysis, and decision assistance. The inquiry then addresses the challenges inherent in establishing digital twins, including technological complexities, organizational hurdles, and industry-specific issues such as data integration, model precision, and privacy concerns. Finally, the exploration extends to the ethical considerations and societal impacts that accompany the widespread use of this technology. This structured journey aimsto serve as a comprehensive guide for researchers, practitioners, and stakeholders navigating the dynamic landscape of digital twin technology.

II. LITERUTRE REVIEW

A. Origin of Digtal Twin

In 2003, The concept of "Digital Twin" was initially introduced by Michael Grieves of the University of Michigan [4]. Since then, its concept has evolved as several researchers have presented different definitions of this technology. It is alsosaid that the phrase "Digital Twin" was used originally in the work of Hernández and Hernández [1]. Up until then, it has evolved to provide benefits such as virtual-real integration, iterative operation and optimization, real-time interaction, and full-factor data drive.

The concept of a digital twin, first adopted by NASA in 2010, involves creating a virtual representation of a physical system. The identical vehicle that carried out the mission in space was the one that remained on Earth [5]. This virtual replica serves as a platform for scenario planning, sensitivity analysis, and modelling of responses to changes or perturbations in the chemical or environmental spaces.

Later in 2014, Grieves introduced the three basic dimensions of digital twins which are the digital Model, the physical model and the connections of data and information. Additionally, in 2018 Tao et al. [6] expanded the current three- dimensional Digital Twin model by integrating two extra dimensions, namely data and services, thus producing a more thorough five-dimensional DT model. This was done in an effort to promote wider applications of DT across many sectors. Later several other models were introduced making it beneficial for more industries. Furthermore, Tao et al. [6] established the idea of the DT shopfloor in January 2017 and provided an in- depth analysis of its traits, composition, operational mechanism, and essential technologies. For reference, significant DT development milestones are depicted in Figure 1.

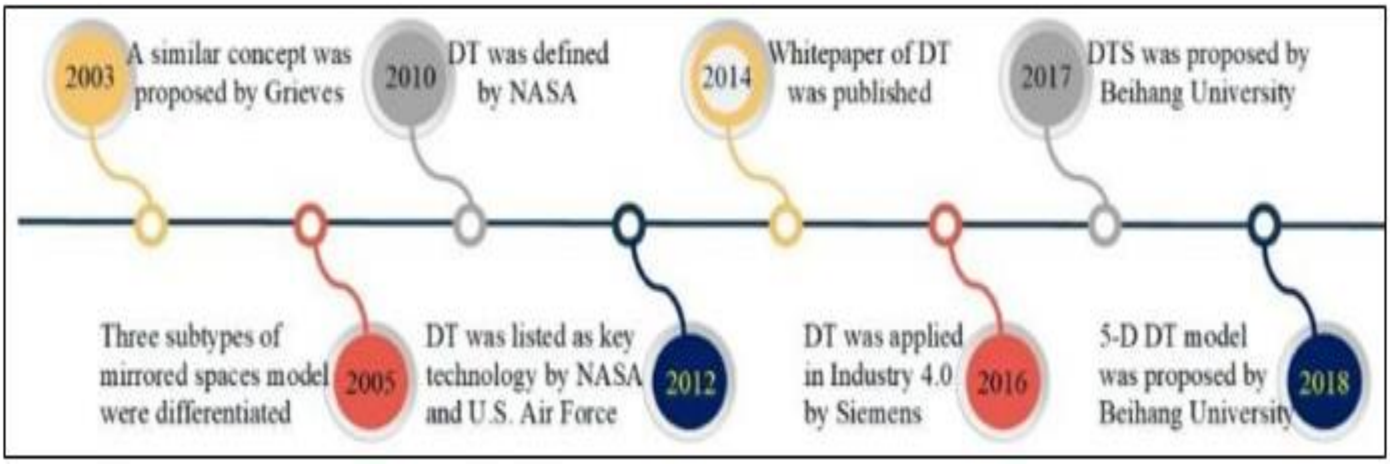

Fig 1 The Milestones of DT Development [6]

While Grieves' contribution is noteworthy, the evolving definitions of digital twins highlight the dynamic nature of this concept. These variations in definition underscore the complexity and interdisciplinary nature of digital twin technology.

B. Digital Twin Evolution

Even though Digital Twin (DT) technology has pulled a lot of attention lately, its conceptual roots go back further in time. This idea first came to be in 2003 at the University of Michigan, where Michael Grieves oversaw its integration into the field ofproduct lifecycle management (PLM)[7].

David Gelernter proposed a similar idea in 1991 known as "Mirror Worlds," where software models mimicked real-world scenarios using data from physical sources [7]. A parallel architecture framework with a "virtual counterpart" or agent for each product item was introduced by Kary Främling et al. in 2003[8]. These early conceptualizations laid the groundwork for digital twins, but it is essential to recognize that technological constraints of the time limited their practical application. The inefficiencies caused by the manual transfer of production data on paper within PLM were the focus of this innovation.

Later, in 2006, the Grieves conceptual model underwent a name change from the "Mirrored Spaces Model" to the "Information Mirroring Model"[7],[8]. This paradigm introduced the idea of several virtual spaces that correspond to a single physical area and emphasized the bidirectional linking mechanism between two spaces, making it easier to explore alternative concepts or designs (see Figure 2).

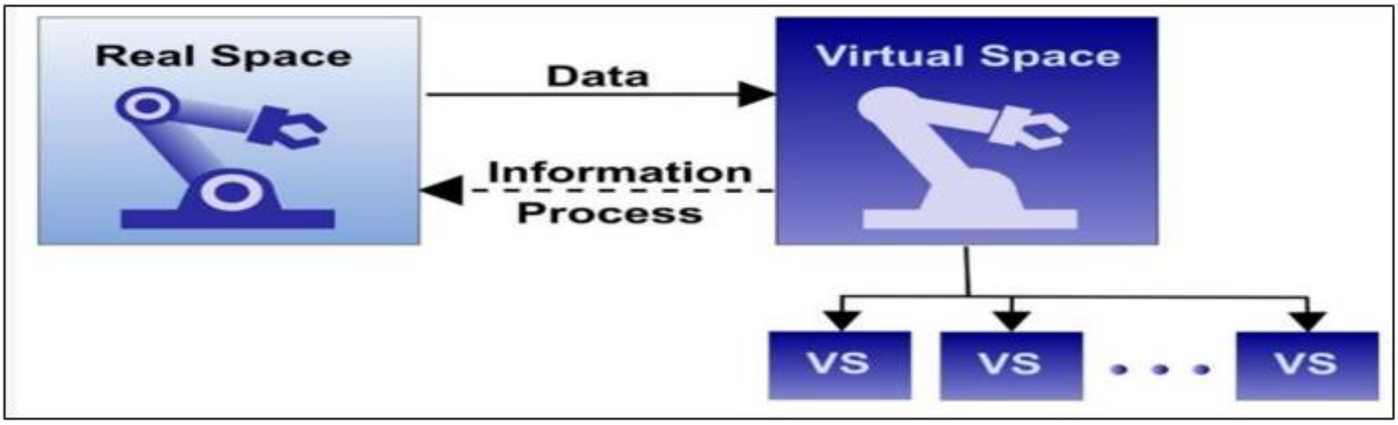

Fig 2 Michale Grieve's Proposed Mirrored Spaces Model/Information Mirroring Model.[8]

During this time, technological constraints continued to impede the practical application of DT. These constraints included things like confined processing power, device internetaccess restrictions, difficulties with data storage and management, and the early stages of machine learning algorithms.

In NASA's proposed technical roadmap from 2010 [5], the term "Digital Twin" (DT) first appeared. DT was also referred to as the "Virtual Digital Fleet Leader" in NASA's roadmap. Figure 3 illustrates the evolution of DT in a graphic way.

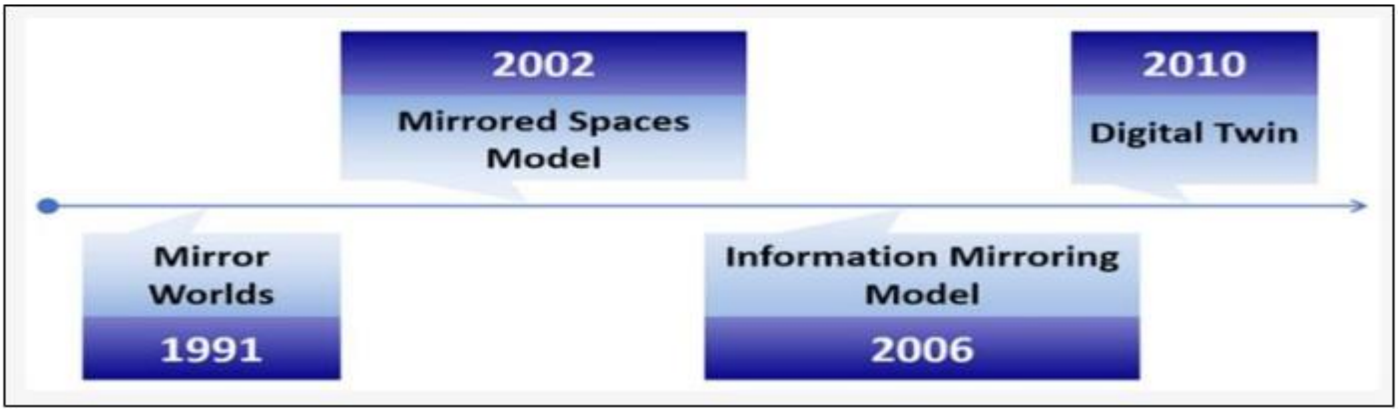

Fig 3 Evolution of Digital Twin [5]

C. Definition and Concept of Digital Twin

As several academics have offered various interpretations of this technology, its definition has undergone a number of revisions. The Digital Twin is a depiction of an active, singular "product" that can be a concrete thing like a machine, object, service, or intangible asset, or it can be a system made up of a tangible thing like a product and its associated services.

To be categorized as a Digital Twin, a model needs to fulfil certain characteristics, such as fidelity (capability to match the physical model), expansibility (capability to incorporate models), interoperability (capability to convert between different representation models and establish equivalence between them, and scalability (capability to evaluate dissimilarscales of information) [9]. The emphasis on these characteristics highlights the need for precision and adaptabilityin digital twin models, ensuring their relevance across diverse domains.

In general, "Digital Twin" is identified as a virtual representation of physical objects throughout their existence that is capable of comprehension, learning, and real-time data- based reasoning. Alternatively, the term "Digital Twin" is described as an informed simulation model that collects data from real-world sources and initiates actions within physical devices [2].

In the context of manufacturing, a "digital twin" is a virtualmodel that is continuously updated with its real-world equivalent of a system, procedure, or product [10]. A digital twin (DT) is a very accurate depiction of a process's current state and of how it naturally interacts with its surroundings in the real world. It is used to forecast product performance in addition to serving as an illustration [9].

The industrial environment shows a variety of ways that the digital twin concept has been interpreted. In order to increase production adaptability, some manufacturers focus on creating a connection between virtual and real products. While some firms use Digital Twin to trace a product's journey throughout its lifecycle and improve manufacturing quality, others use DTto improve product design.

D. Digital Twin Architecture

The fundamental concept of a digital twin is the accurate and real-time relationship between a real object and a digital object. However, it is hard to define the concept of architecture. Numerous conceptual models and reference frameworks for digital twins have been suggested. A thorough "Digital Twin 8- dimensional model" was introduced by Stark et al. [11] in a study with the goal of defining the range and classification of digital twins. Four of the model's dimensions were devoted to describing the depth of the capabilities of digital twins, while the remaining four were intended to capture the contextual and environmental features of the digital twin domain (see Figure 4). While these models provide valuable insights into the architecture of digital twins, it is important to recognize that their complexity can pose challenges in practical implementation.

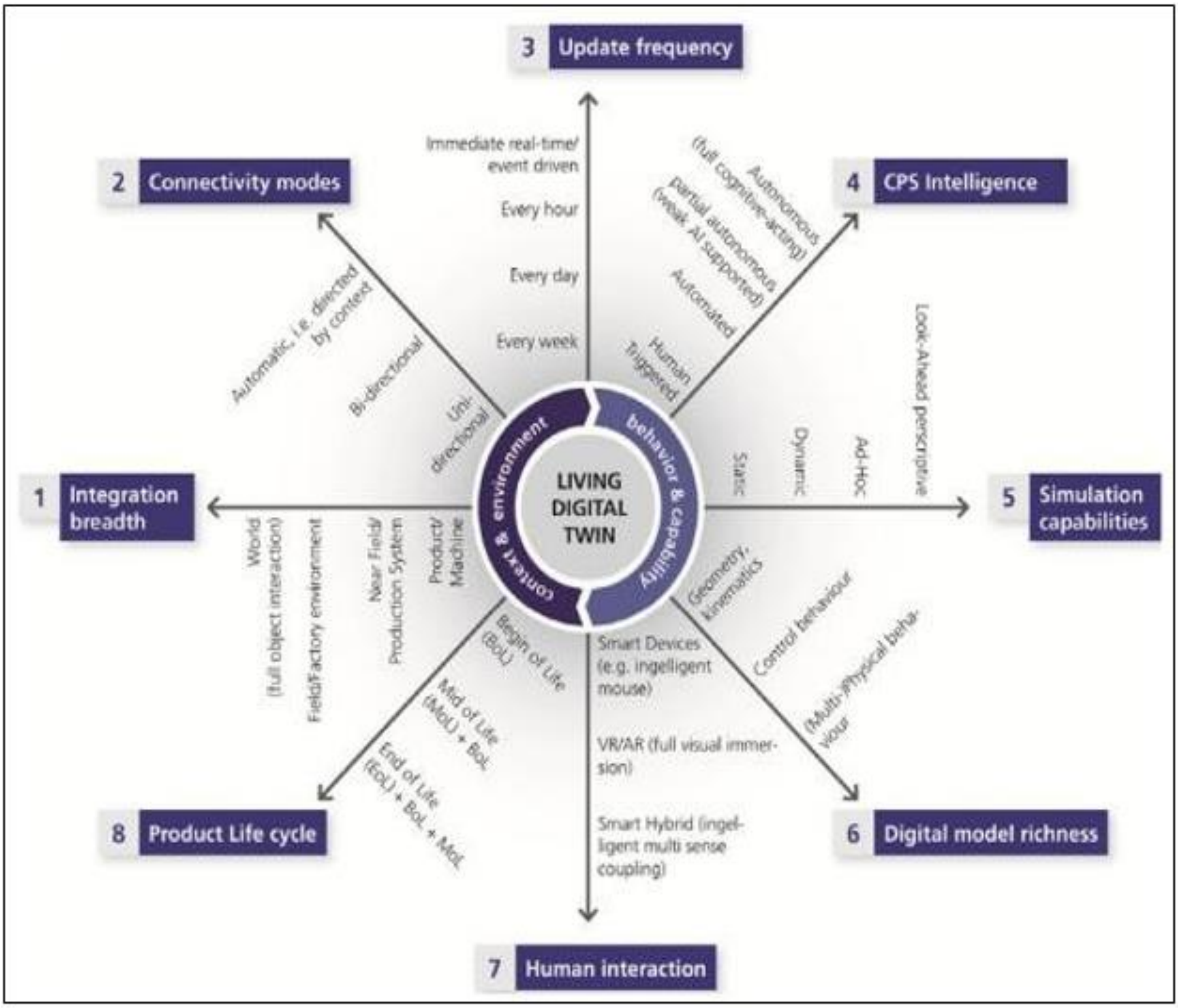

Fig 4 Digital Twin 8-Dimension Model[11]

Grieves' [12] conceptualization of the digital twin has three main parts: physical entities, virtual counterparts, and the infrastructure that connects them for the flow of data and information. This model emphasizes the essential components of digital twins but may not fully address the nuances of specific industries or use cases. The possibilities of the digital twin reference model in terms of interoperability, expandability, scalability, and fidelity were studied by Schleich et al. [6] in detail. They also explored other processes related to this reference model across the whole product lifecycle, including conversion, evaluation, composition, and decomposition [13]. These studies straighten out critical aspects of digital twin architecture but may require adaptation for industry-specific applications. In a study done by Qi et al. [14] they have mentioned a digital twin model with five key dimensions, encompassing physical entities, virtual counterparts, service components, digital twin data, and connections (see Figure 05).

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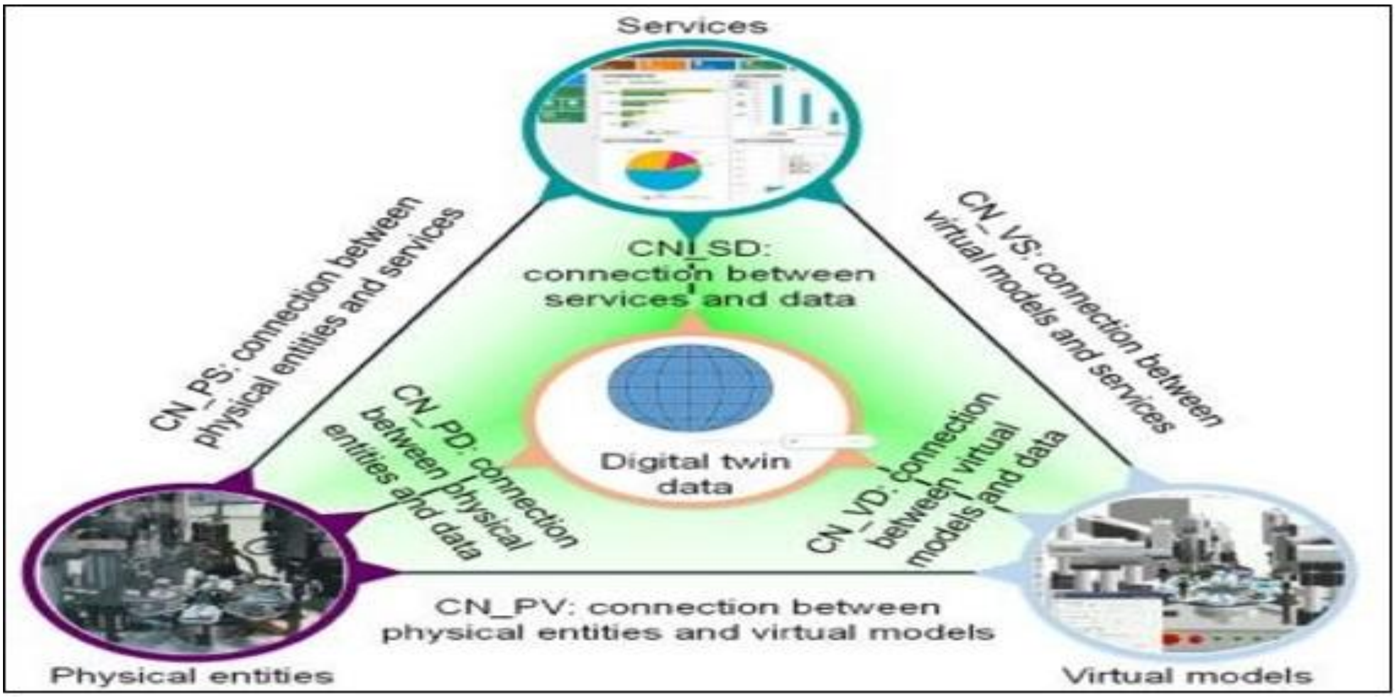

Fig 5 Five-Dimension Digital Twin Model[14]

Leveraging this five-dimensional model, they have conducted an investigation into representative applications across diverse domains. While this model provides a simplified framework, its applicability to complex industries may require further refinement. The examination of various digital twin architectures underscores the importance of flexibility and adaptability to meet specific industry needs.

The foundational Digital Twin models described above have not only served as fundamental constructs within their respective domains but have also catalyzed the development ofnumerous derivative frameworks across diverse industries. These derivative frameworks draw inspiration from, or directly incorporate elements of, the aforementioned foundational models, thereby contributing to a rich tapestry of Digital Twin applications and paradigms. However, it is essential to acknowledge that while these frameworks offer versatility, they may require customization to address industry-specific challenges effectively.

One such framework is the AgriLoRo framework which was proposed by Angin et al. [15] for smart agriculture. In this framework, farm fields are virtually recreated using the framework so that they can be monitored virtually in real-time. The framework uses a wireless sensor network and cloud servers to find weed patches, nutrient deficits, and plant illnesses (figure 6). This framework demonstrates the potential of digital twins in agriculture, yet its scalability and applicability to different agricultural settings may need further investigation.

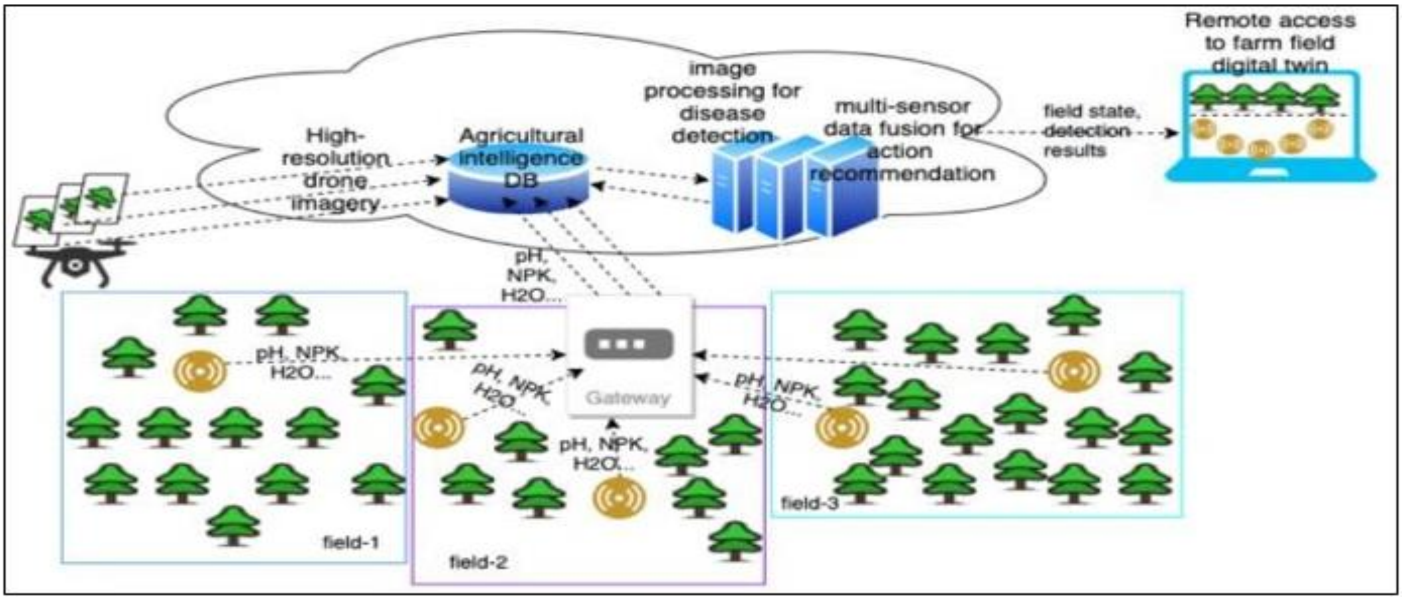

Fig 6 Farm Field Digital Twin Framework (AgriLoRa) [15]

Another such model is the implementation layer model proposed by Jeong et al. [16] which is a 5-level model including Digital Virtualization, DT Synchronization, Modeling and Simulation, Federated DT and finally Intelligent DT services. According to its description, the deployment, operationalization, and maintenance of digital twin technologies fall under the purview of the implementation layer model. Figure 7 describes digital twin implementation layers. While this model offers a structured approach to digital twin implementation, its real-world feasibility and adaptability to various industries warrant examination.

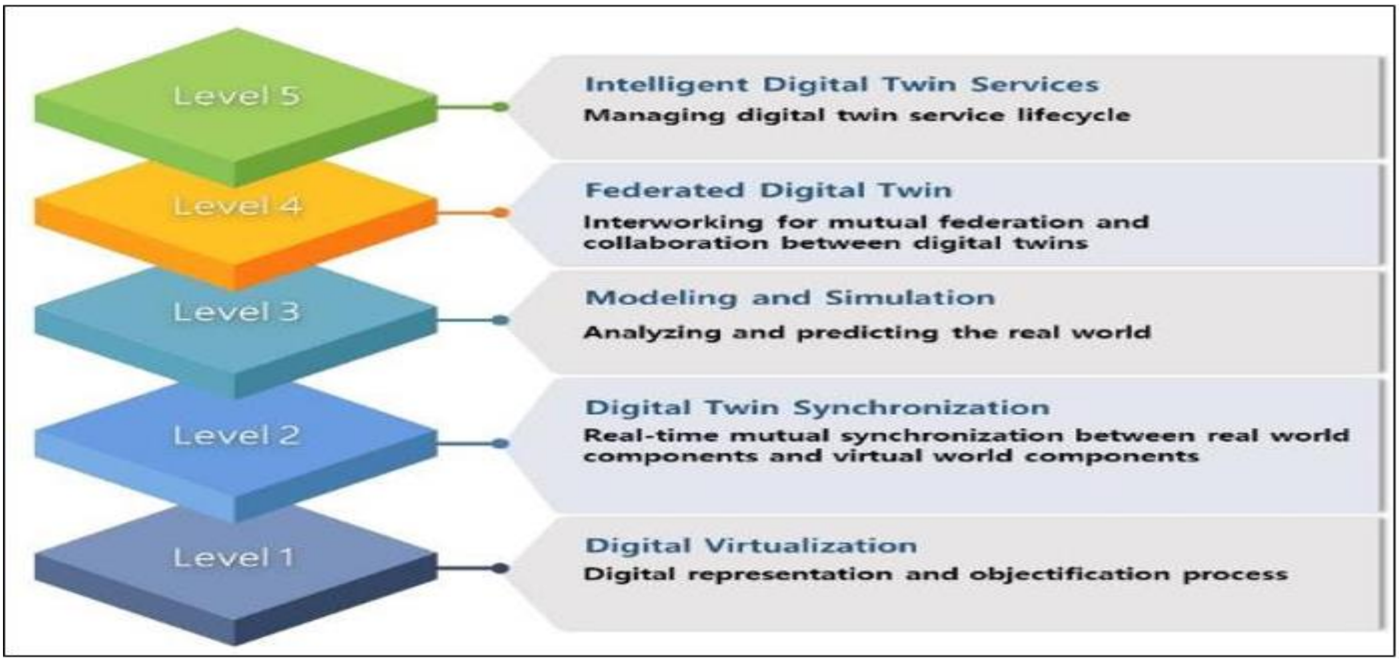

Fig 7 Digital Twin Implementation Layers [16]

Another such model was proposed by Hassani et al.[17] for the healthcare industry. In Figure 8 the proposed digital twin model is shown. This model encompasses distinct healthcare stages, from preconception care to lifetime healthcare and the afterlife stage. At the core of this model is the virtual twin of the human or patient, serving as a digital representative. It facilitates the integration of information and model digital twindata, aligning with the well-established five-dimensional digital twin model. This model presents intriguing possibilities for healthcare, yet the practical challenges of integrating digital twins into healthcare settings should be explored.

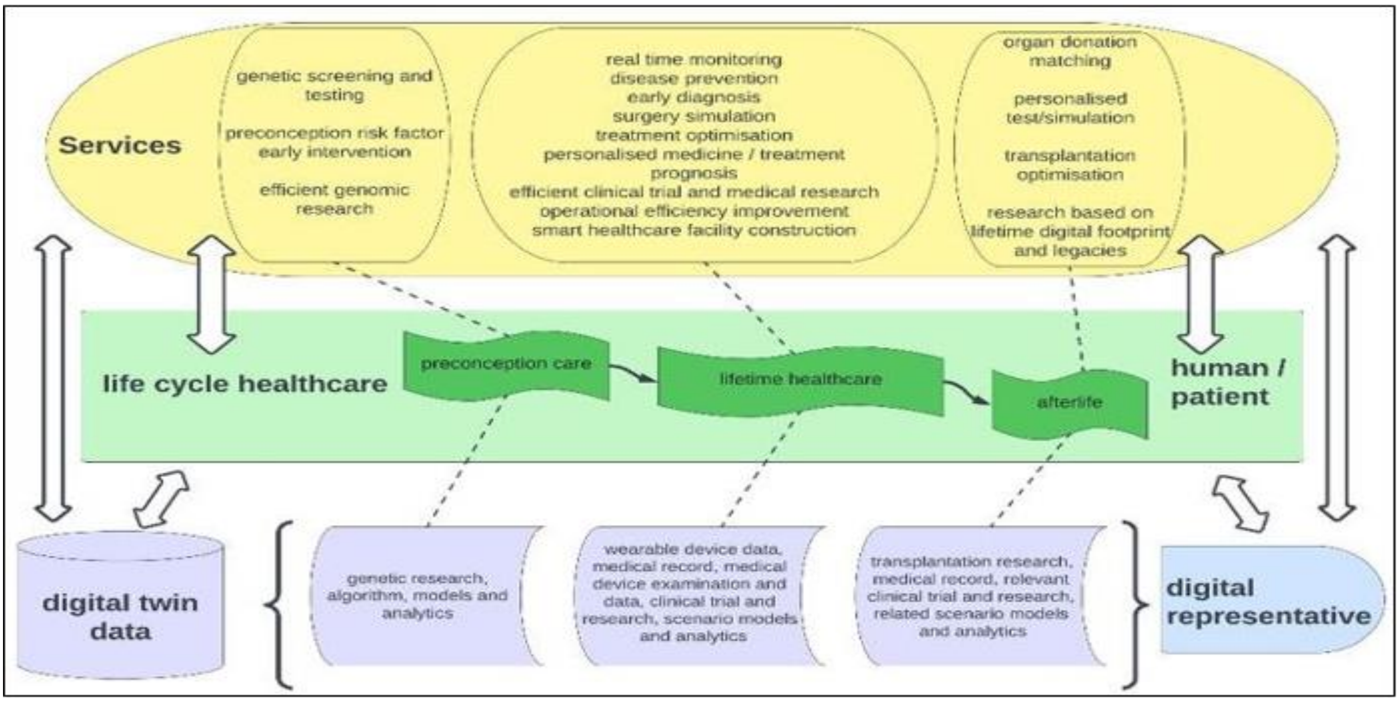

Fig 8 Digital Twin Model in Healthcare [17]

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In the domain of offensive military cyber operations (OMCO), the architecture of digital twins holds a distinctive significance. Defined as a technological system encompassing cyber abstractization, physical system representation, and their interconnected data and communication flows, the digital twin in OMCO acts as an advanced system mirroring the physical realm within a cyber environment. This architecture, as proposed, comprises two core components: the Digital Twin Layers and the Digital Twin Levels. The former includes eitherthree digital twin modules with an integration component or four standalone digital twins, facilitating communication and data exchange. Meanwhile, the latter delineates the physical, data, communication, and cyber elements within a singular digital twin or across four integrated digital twins. Ensuring modularity and configurability, this architecture stands poised for training, exercises, and real operations within offensive military cyber contexts. This structured approach addresses the complexities of OMCO, allowing for comprehensive modelling, decision-making support, and integration of ethical considerations through Responsible AI (RAI) and Explainable AI (XAI) methodologies.[18]

This architecture, depicted in Figure 2, illustrates the flow of information between targeting phases, emphasizing modularity, and configurability to adapt to varying operationalrequirements. Its role extends from the design and development phase through execution and assessment, aligning with the needs of responsible and accountable offensive military cyber operations.

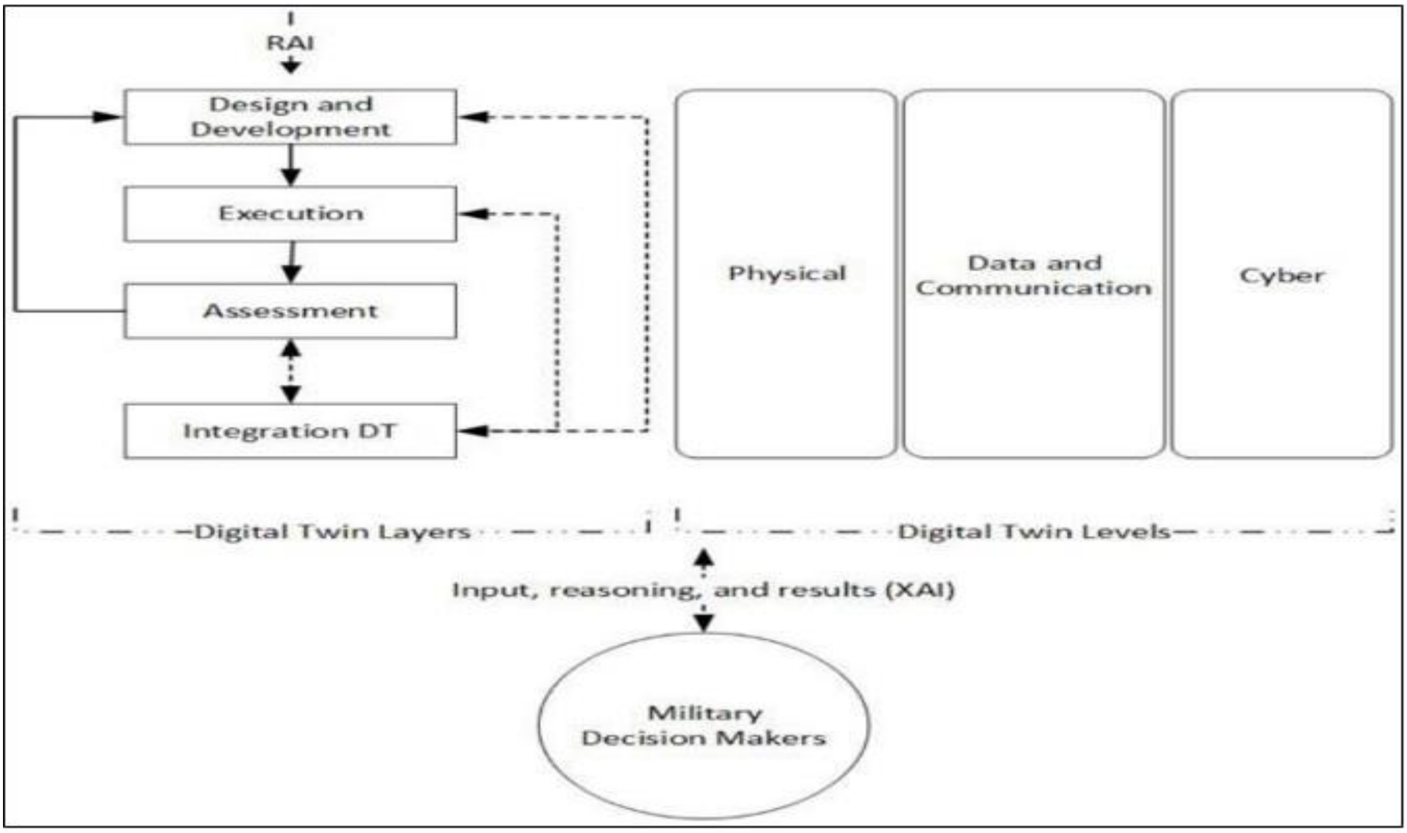

Fig 9 A Digital Twin Architecture of OMCO**[18]**

The digital twin notion is a flexible idea that may be used with a range of cutting-edge technologies and is not limited to any one particular technology. While this flexibility is an advantage, it also poses the challenge of defining clear boundaries and best practices for different industries. Therefore, future research projects should aim to provide explicit clarification and specialization within different industrial fields. Such research can help harness the potential benefits of digital twins by tailoring their architectural and modelling facets to specific industry applications.

E. Key Enabling Technologies of Digital Twin

Data acquisition, modelling, and application are the three core aspects that define digital twins[19]. The production of a Digital Twin requires the use of four different technologies, each of which contributes to the collection of real-time data, the retrieval of information for insightful analysis, and the development of a digital representation that mirrors a physical object[2]. These technologies include cloud computing, artificial intelligence (AI), the Internet of Things(IoT), and extended reality (XR). Furthermore, the nature and specifications of the particular application domain determine the choice and scope of use of particular technologies inside the Digital Twin framework. The role of these technologies in shaping digital twin capabilities is pivotal, but it is essential to recognize that their effectiveness may vary depending on the specific application domain. Figure 09 Shows how the key enabling technologies are associated with digital twin technology's implementation.

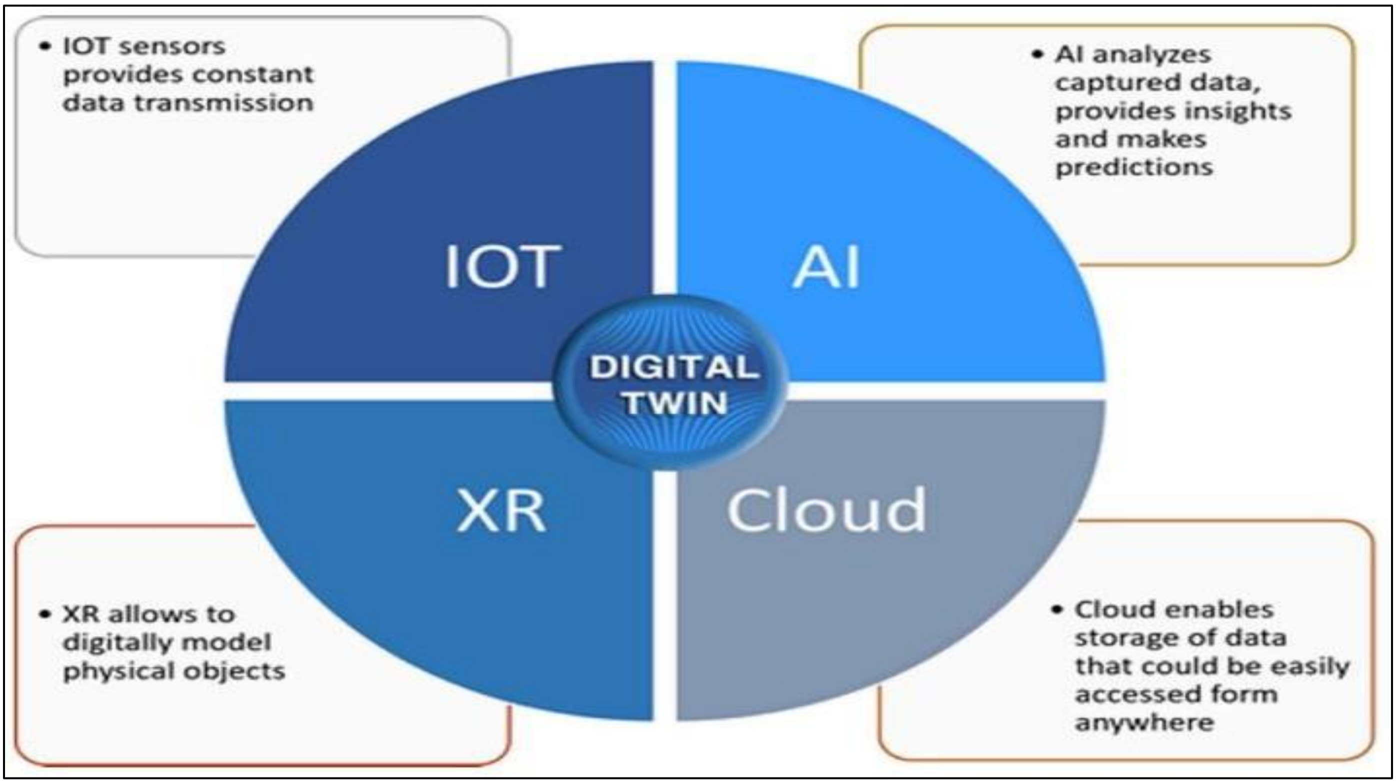

Fig 10 Key Enabling Technologies of Digital Twin [2]

F. Digital Twin in Various Domains

➢ *Digital Twin in Manufacturing*

Rapid technical breakthroughs are driving the current significant restructuring of the manufacturing sector. A rising number of people are interested in using technology like digital twins to improve production procedures in response to this changing environment. The manufacturing business is undergoing a paradigm transition, and digital twins hold the ability to completely transform many elements of it[20]. The capability of digital twins in manufacturing is substantial, but practical challenges may arise during their implementation, such as data integration and cybersecurity concerns.

There are several advantages to digital twins in the manufacturing industry. These include the remote control, simulation, and real-time monitoring of physical assets using their digital equivalents. Furthermore, by giving producers a better grasp of customer wants, digital twin technology holds the prospect of raising customer happiness. This knowledge then paves the way for the creation of new service offerings, operational upgrades, and product improvements [2]. However, while digital twins offer improved insights and operational advantages, they may require significant initial investments and changes in workflow.

Manufacturing businesses might switch from reactive to predictive strategies with the help of digital twins. With the use of this technology, manufacturers are able to optimize machine efficiency, extend the useful lives of their products, and investigate redesign options. While predictive capabilities are valuable, they rely heavily on data accuracy and may not be foolproof. Digital twins also make it possible for usage-based design, pre-sales analytics, and the integration of information into manual operations, improving visibility into client needs and preferences.

The use of Digital Twins in manufacturing is being driven primarily by the emergence of smart cities and the necessity of connectivity. This is steady with the tenets of Industry 4.0, also identified as the fourth industrial revolution, in which the connectedness of gadgets is crucial to making the idea of Digital Twins a reality for production processes [21]. Industry 4.0 principles offer opportunities, but the integration of digital twins into traditional manufacturing processes can be challenging.

Examples from the real world demonstrate how digital twins have revolutionized the manufacturing industry. While Siemens utilizes them to model and improve wind turbine production, General Electric uses them to monitor and optimize the performance of gas turbines[22]. These examples show how the use of digital twins in industrial operations has the potential to increase productivity, decrease downtime, and generate cost savings. Real-world cases illustrate the benefits, but it is essential to consider the adaptability of digital twins to different manufacturing settings.

Digital twins offer predictive capabilities and optimization potential, yet the challenges of data integration, accuracy, and cybersecurity hinder their full potential. While enabling a shift from reactive to predictive strategies, they heavily rely on data accuracy and quality. The initial investments and workflow changes required may limit widespread adoption. Research should focus on refining predictive models and addressing data quality issues for comprehensive implementation.

➢ *Digital Twin in the Automotive and Aviation Industry*

In the automotive industry, Digital Twins are transforming customer engagement by enabling personalized vehicle customization through interactive online dashboards. This technology also empowers companies to monitor consumer behaviour and enhance existing vehicle models. Furthermore, ongoing research is exploring the implementation and potential of Digital Twins in intelligent vehicles. While digital twins offer personalized experiences, there may be concerns about data privacy and security.

In the automotive industry, BMW uses digital twin technology to simulate the production process and optimize the assembly line. This has led to a 5% increase in productivity and a 50% reduction in the time it takes to develop a new model[22]. BMW's success demonstrates its potential, but it is important to note that results may vary depending on the specific implementation.

For engine and car part simulation and data analytics, the automotive sector has adopted digital twins, with Tesla serving as an example [21]. The implementation of digital twins in the automotive sector is promising, but it requires careful consideration of data quality and analytics capabilities. By analyzing real-time vehicle data to predict parts functioning in the present and future, artificial intelligence (AI) plays a crucial part in improving testing accuracy. Even industry behemoths inthe aerospace industry, like Boeing, have used digital twins to advance the quality and safety of aircraft systems and parts, yielding a staggering 40% improvement in part and system quality[2]. Boeing's success highlights the potential benefits of digital twins in aviation, but it is critical to address safety and regulatory concerns.

Optimized assembly lines and enhanced testing accuracy are primary benefits; however, ensuring high-quality data and navigating privacy concerns are significant challenges. The potential for personalized experiences is immense yet results vary based on specific implementations. Future research shouldemphasize data privacy protocols and enhancing data accuracyfor widespread implementation.

➢ *Digital Twin in Healthcare and Life Sciences*

Digital Twin technology is making significant inroads into the healthcare sector, offering unparalleled potential for transformative change. The synergy between technological advancements and healthcare is unlocking new possibilities, driven by cost-effective and accessible IoT devices that enhance connectivity [23],[24].

One promising application is the creation of a Digital Twin of the human body, providing real-time health analysis. Real- time health analysis can be lifesaving, but it requires robust data sources and accuracy. Another practical use involves simulating the effects of drugs, aiding in drug development. While digital twins offer advantages in drug discovery, their accuracy and reliability should be continuously improved. Additionally, Digital Twins play a crucial role in surgical planning and execution, ensuring precision in complex procedures [21].

Beyond patient-centric applications, Digital Twins empowers researchers, hospitals, doctors, and healthcare providers to simulate tailored environments, both in real-time and for future developments. Simulation capabilities can improve healthcare, but they should be validated rigorously to ensure their effectiveness. Collaborating with AI algorithms, Digital Twins enable intelligent predictions and decisions, influencing patient care positively.

While Digital Twins in healthcare are still in their infancy, their potential is vast. They offer solutions ranging from the management of beds to large-scale hospital operations. Crucially, real-time capabilities are paramount in healthcare, where timely actions can be lifesaving. These digital counterparts also support the repair of medical equipment and predictive maintenance, making life-saving decisions based on historical and real-time data possible [21].

The confluence of IoT, Artificial Intelligence, and Industry 4.0 is driving the growth of DT applications in healthcare. As healthcare providers adapt to digital transformation, Digital Twins stand at the forefront of enhancing efficiency, reducing costs, and, most importantly, improving patient care [2].

Furthermore, the life sciences industry, underpinned by Digital Twins, is advancing drug discovery and development.The COVID-19 pandemic has hastened the digital transformation in healthcare, increasing the adoption oftechnologies like Digital Twins [25]. The pandemic has highlighted the importance of digital solutions, but their scalability and long-term sustainability should be considered. An illustrative case comes from Dassault, a pioneering software company, which has crafted an experimental Digital Twin of the human heart, aptly named the "Living Heart." This innovative software transforms a 2-dimensional scan of the human heart into a precise, full-dimensional model, accounting for intricate aspects like blood flow, electricity, and mechanics. The model of the living heart is now being deployed globally, revolutionizing the design and testing of novel medical devices and drug treatments [25]. Figure 10 illustrates some Digital Twin settings in healthcare services.

Digital Twins are poised to revolutionize patient care and healthcare operations. Their application spans from simulatingbodily functions to improving drug development, with the potential to enhance efficiency, reduce costs, and ultimately save lives. As technology continues to advance, the role of Digital Twins in healthcare is set to expand, offering innovativesolutions for a brighter healthcare future.

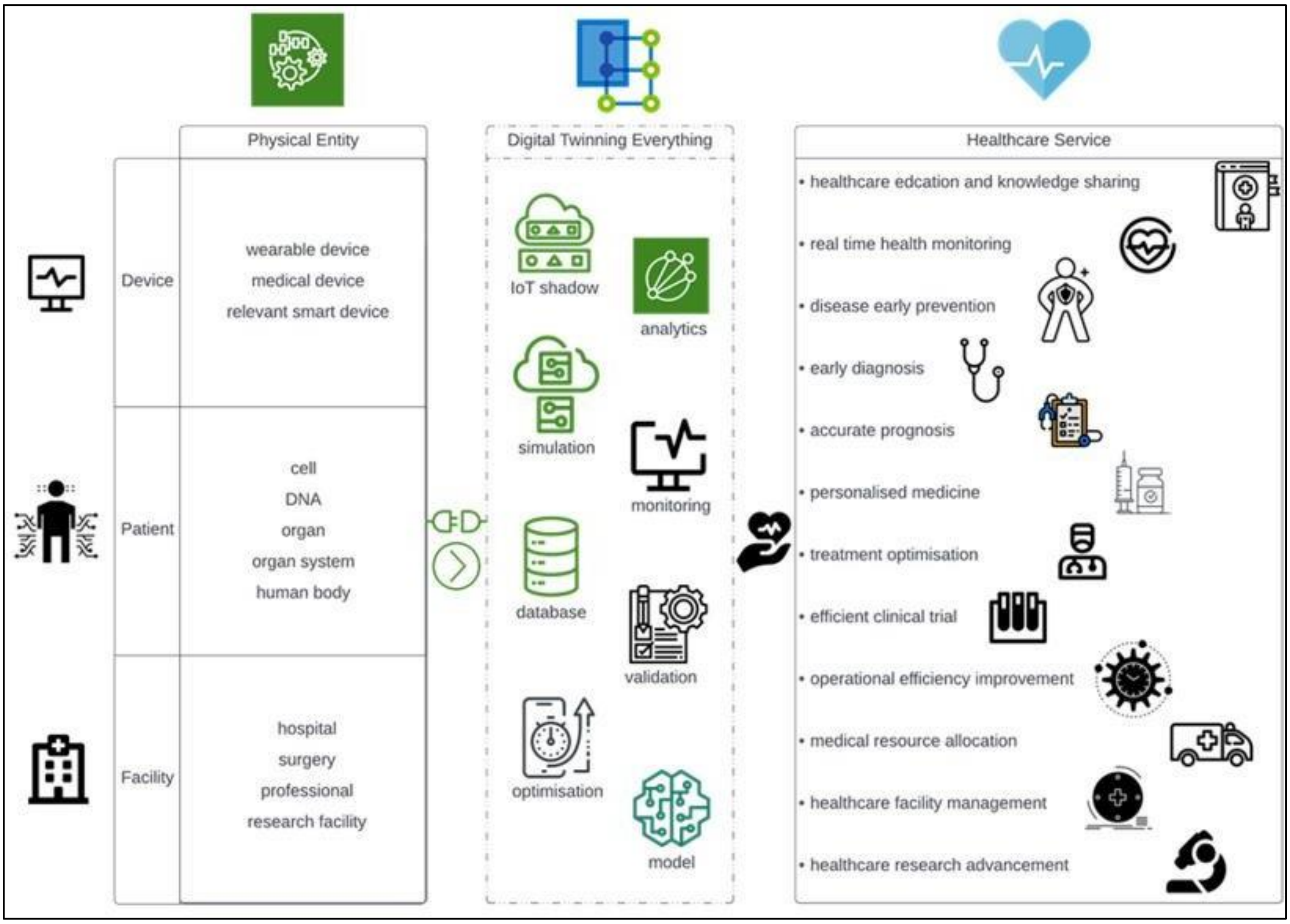

Fig 11 Digital Twin in Healthcare Services **[25]**

Real-time health analysis and drug development offer groundbreaking possibilities, but challenges persist in data accuracy, ethical considerations, and treatment planning reliability. The potential for patient-centric applications is vast, but continuous improvements in accuracy and reliability are crucial. Ethical considerations and rigorous validation of simulation capabilities are necessary for real-world applications.

➢ *Digital Twins in Agriculture*

Digital Twins technology emerges as a transformative force in agriculture. These digital replicas enable a virtual representation of farms, enhancing efficiency, productivity, and cost-effectiveness. For instance, through simulated modelling, Digital Twins offer predictive insights into weather patterns and climate change effects, aiding farmers in proactive decision- making [26].

Consider the case of soil management—a critical aspect of crop growth. Digital Twins assist in analyzing soil composition and guiding decisions on optimal crop cultivation methods. By simulating outcomes throughout growing seasons, they predict yield expectations, fertilizer requirements, and necessary resources such as sunlight and water [27].

Moreover, the integration of Digital Twin concepts illustrates the interconnectedness between physical and virtual aspects of agriculture. These digital replicas intertwine physical elements like crops, machinery, and livestock with their virtual counterparts, forming a symbiotic relationship essential for informed decision-making and system optimization [28].

However, despite its potential, the practical application of Digital Twins in agriculture remains in its infancy. For example, ongoing research focuses on implementing high-precision, low-cost IoT-based frameworks. These frameworks create digital twins of farmlands, enabling real-time monitoring and intelligent data processing for informed decision-making regarding crop health, irrigation, and fertilization strategies [15].

Such frameworks utilize Wireless Sensor Networks (WSNs) for data gathering and communication. These WSNs, like LoRa-based networks, operate with low power consumption, fitting agricultural contexts seamlessly. Additionally, they leverage machine learning algorithms to detect diseases and nutrient deficiencies in crops, amalgamating collected data to provide comprehensive insights into farm fields [15].

Predictive insights into crop management and weather patterns are promising, but practical implementation hurdles exist. Adaptation of low-cost IoT frameworks and ensuring simulation accuracy are pivotal challenges. Research should focus on refining predictive models and enhancing simulation accuracy for seamless implementation.

- *Digital Twins in Clinical Research and Personalized Medicine*

Digital twin technology holds immense promise for revolutionizing clinical research methodologies. It empowers researchers to predict the outcomes of experimental treatments, glean deeper insights, and derive actionable information, all without subjecting patients to undue risks [2]. Moreover, it facilitates the study of patient data, allowing healthcare professionals to simulate treatment scenarios and identify the most promising research avenues among real patients. For instance, a Swedish University has pioneered the creation of a Digital Twin model for mice afflicted with rheumatoid arthritis. This innovative approach not only aids in understanding drug efficacy but also offers an alternative to traditional clinical trials on human subjects, thereby advancing drug development ethically [25].

The accessibility of DT solutions is transforming the healthcare industry, promising a future where personalized medicine becomes a global reality [29]. Real-world examples further illustrate its potential. For example, researchers at Oklahoma State University improved the administration of lung cancer medication by simulating the movements of aerosol medicine particles using a Digital Twin of the respiratory system [21]. Siemens created a Digital Twin of the human heart by utilizing millions of medical records and pictures, which improved our understanding of cardiac problems and the prognosis of diseases [2]. Parallel to this, a French startup created a Digital Twin model of aneurysms and surrounding blood vessels, which allows surgeons to choose the best surgical instruments for each patient based on insights from the Digital Twin [2].

Digital Twin Technology is poised to reshape clinical research and healthcare practices by offering innovative solutions. Its ability to predict treatment outcomes, improve patient care, and streamline research processes signifies a transformative potential that promises a brighter future for healthcare.

While digital twins hold promise for predicting treatment outcomes, robust data sources and ethical considerations are paramount. The potential for predictive treatment and insights is significant, yet ethical usage and validation of models require further development. Research should emphasize ethical data usage and continuous improvement in simulation accuracy.

- *Digital Twins in Smart Cities*

In the realm of smart cities, Digital Twins are emerging as a pivotal technology, yet academic research in this domain remains relatively limited. The limited research in smart city applications calls for more comprehensive studies to address specific challenges and opportunities. Existing studies encompass a broad spectrum, ranging from city-wide Digital Twins for comprehensive smart city management to specialized applications such as traffic management [30] and livestock monitoring [31], as well as renewable energy initiatives [19].

The varying scope of research within the smart cities' domain highlights the diverse applications of digital twins, but also calls for more comprehensive studies to address the specific challenges and opportunities within each area. The integration of Digital Twins with local infrastructure, leveraging 3D modelling, is a promising avenue, as demonstrated by [32], highlighting their role in smart city development and maintenance.

Digital Twins hold immense potential for enhancing efficiency and resolving challenges in urban settings, much like their impact on the manufacturing sector. The potential for digital twins in smart cities is substantial, but it's essential to address issues related to data privacy and infrastructure integration. With advancements in Digital Twins for manufacturing [2], [21], [32] the prospects for smart cities are on an upward trajectory.

In the context of smart cities, Digital Twins are revolutionizing various aspects, from traffic management to urban planning. Singapore's Virtual Singapore initiative exemplifies the breadth of possibilities, including cell tower and solar cell planning, traffic pattern analysis, and simulating pedestrian traffic. This technology aids in informed investmentdecisions and activity planning [33].

Furthermore, countries like Turkey are embracing Digital Twins for comprehensive urban planning and management, leading to the detection of illegal structures [2]. The integration of Digital Twins with building information modelling (BIM) is streamlining the entire construction lifecycle, ensuring thatbuildings exist as Digital Twins throughout their existence [2]. Nomoko is ambitiously creating a virtual environment for a global Digital Twin, incorporating diverse data sources such as BIM and traffic information to provide real-time insights [26]. Huawei's "Trafficgo" project in Shenzhen is a testament to the transformative power of Digital Twins, enabling real-time traffic management through AI [21]. Cityzenith's SmartWorldPro, a Digital Twin software solution, has been selected for the development of Andhra Pradesh's smart city capital, Amaravati [33]. This versatile platform empowers users with natural language data searches, AI-driven ROI analyses, and dynamic visualizations for diverse applications [34].

In this emerging field of smart cities, Digital Twins are becoming instrumental in urban planning, offering the capability to simulate scenarios, streamline traffic management,and enhance environmental and urban planning [4]. As investment in smart cities intensifies, Digital Twin technology is poised to play a pivotal role in addressing urban complexities and fostering sustainable urban development.

Privacy concerns, data infrastructure integration, and scalability are critical hurdles despite the transformative potential of enhancing urban planning. The technology offers a wide range of applications, but challenges in infrastructure integration limit widespread adoption. Future research should prioritize privacy protocols and scalable infrastructure for successful implementation.

- *Digital Twins in Defense and Military*

Digital twin technology has become increasingly crucial in military and defence domains due to the pressing demand for swift, scalable, and intelligent systems. Specifically, its relevance within the defence industry is amplified by the expanding reliance on space-based capabilities and the amplified risks accompanying their proliferation and commercialization[35]

Within the realm of defence space infrastructure, digital twins play a pivotal role in diagnosing faults, monitoring the health of space systems, and bolstering cybersecurity measures. By orchestrating synchronized and interoperable capabilities, digital twins effectively mitigate various physical and cyber threats facing defence space infrastructure.

These applications of digital twins materialize in diverse defence scenarios. For instance, hardware-in-loop simulations substantially truncate testing timelines and hasten developmental progress. Additionally, integrating cloud- powered solutions like Azure Orbital in satellite ground stations has revolutionized accessibility, operational efficiency, andsecure data storage, presenting an economical alternative [14].

Concurrently, digital twins present the potential for real-time predictive maintenance guidance, ensuring secure data access even in remote military locations. By leveraging SATCOM, 5G, and cloud computing, military decision-making is empowered through facilitated connectivity, data sharing, and comprehensive data analysis.[36]

Expanding beyond space-based applications, the development of digital twins now encompasses military land vehicles. The primary objective revolves around offering independent insights into engine conditions, with a particular focus on predicting and addressing crucial issues such as compression loss, which is critical for eliminating operational defects [37]

The rationale for investing in digital twins for naval assets lies in their ability to enhance operational efficiency, ensure safety, and substantially reduce life cycle costs. These high- resolution digital replicas allow comprehensive monitoring of ship components, enabling early anomaly detection and predictive maintenance measures[38].

Digital twins in the military and defence sectors exhibit adaptability, scalability, and real-time insights, positioning themselves as indispensable assets for future missions. Their applications span diverse space markets, and low-cost engineering systems, and align with NATO's space policy, signifying their pivotal role in ensuring preparedness for defence scenarios [25].

Real-time insights and predictive maintenance offer substantial benefits, but cybersecurity and comprehensive predictive maintenance remain key challenges. The potential for enhanced operations is substantial, yet cybersecurity concerns and data infrastructure integration are critical. Research should emphasize robust cybersecurity protocols andinfrastructure integration for comprehensive deployment.

G. Challenges of Digital Twin Technology

The Digital Twin technology has witnessed remarkable growth across various industries, driven by the ongoing COVID-19 pandemic, advancements in Industry 4.0, and the emergence of the Internet of Things (IoT). However, there are several challenges faced by Digital Twin technology.

Studies by Fuller et al. [21] and Attaran et al. [2] indicate that expectations, standardized modelling, domain modelling, privacy and security, trust, and data quality are some of the major issues facing digital twin technology.

- *IT Infrastructure:*

One of the foundational challenges in the realm of Digital Twins is the need for a robust IT infrastructure. Similar to analytics and IoT, Digital Twins require a well-connected and carefully planned IT framework to function effectively. Without a seamless infrastructure, Digital Twins may struggle to achieve their intended goals. Notably, the success stories of Siemens and GE highlight the importance of an integrated IT setup for the deployment of Digital Twin technology [39]. Therequirement for robust IT infrastructure can be a barrier to entry, especially for smaller organizations.

- *Data Quality:*

The quality and consistency of data are paramount for the effective operation of Digital Twins. High-quality, noise-free data streams are essential to prevent underperformance due to poor or inconsistent data inputs. Ensuring a continuous and uninterrupted data flow is crucial to enable Digital Twins to make informed decisions. Real-world examples, such as those in healthcare and energy, demonstrate the critical role of quality data in optimizing processes and making accurate predictions [25]. Ensuring data quality can be challenging, and organizations must invest in data management and quality control. Privacy and security concerns must be addressed rigorously, especially in industries dealing with sensitive data.

- *Privacy and Security:*

In industrial settings, ensuring privacy and security in Digital Twins presents a significant challenge. The vast amount of data used by Digital Twins, coupled with the risk it poses to sensitive system information, necessitates stringent security measures. This challenge is compounded by the need to adhere to evolving security and privacy regulations. Cloud-based Digital Twin platforms from industry giants like Google Cloud and Microsoft Azure emphasize the importance of trust and datasecurity [2].

➢ *Trust:*

Trust issues related to Digital Twins span both organizational and user perspectives. Building trust requires clear communication about the benefits of Digital Twins to end- users and organizations. Model validation plays a pivotal role in ensuring that Digital Twins perform as expected, bolstering user trust. Greater insight into privacy and security practices, as well as adherence to regulatory guidelines, can help overcome these trust challenges. Building trust is essential but requires effective communication and validation mechanisms.

➢ *Expectations:*

While industry leaders like Siemens and GE have accelerated the adoption of Digital Twins, managing expectations remains a challenge. It is vital to establish solid foundations for IoT infrastructure and enhance understanding of the data required for analytics. Addressing the misconception that Digital Twins should be adopted solely due to industry trends is crucial. Discussing both the positives and negatives of Digital Twin adoption can guide organizations in making informed decisions [9]. Managing expectations and ensuring alignment with organizational goals can be complex.

➢ *Standardized Modeling:*

From the initial design to simulation, there is no standard method for modelling in digital twin development. A standardized approach is essential for ensuring domain and user understanding, as well as facilitating information flow throughout development and implementation.

Standardization fosters compatibility with domains such as IoT and data analytics, ensuring the successful integration of Digital Twins [9]. Standardization efforts are necessary but can be challengingto implement across diverse industries.

➢ *Domain Modeling:*

Ensuring that domain-related information seamlessly integrates into the modelling and functional stages of Digital Twin development is another challenge. Compatibility with fields like IoT and data analytics depends on this integration, which eventually increases the usefulness of digital twins. For the development and application of digital twins in the future, it is imperative to emphasize these factors [10]. Integrating domain-specific information can be complex, especially in industries with unique requirements.

The challenges in Digital Twin technology encompass a wide range of domains, from IT infrastructure and data quality to trust, expectations, and standardization. Real-world examples, such as Google Cloud's supply chain Digital Twin solution, illustrate the practical application of these challenges. Overcoming these obstacles is vital for unlocking the full potential of Digital Twins and realizing their transformative impact across industries. Tackling these challenges is essential for successful Digital Twin implementations, and organizationsshould carefully consider these factors in their adoption strategies.

Table 1 Shared Challenges [9]

Digital Twin	
Data Analytics	***Industrial IoT/ IoT***
Data	Data
IT Infrastructure	IT Infrastructure
Security	Security
Privacy	Privacy
Expectations	Expectations
Trust	Trust
-	Connectivity

H. Ethical Considerations of Digital Twin Technology

Digital Twin technology has gained prominence across various domains, offering numerous benefits. However, its adoption also brings forth significant ethical considerations that merit exploration. Some such ethical considerations which were mentioned in the research are discussed below. While Digital Twins offer significant advantages, they also raise important ethical concerns that must be addressed.

➢ *Privacy and Data Protection:*

The utilization of Digital Twins necessitates the collection and processing of extensive personal and sensitive data, sparking ethical concerns related to privacy and data protection [40]. Ensuring that personal information is handled ethically and in accordance with data protection legislation is of utmost importance. Responsible data use and robust privacy safeguardsare essential.

➢ *Transparency and Accountability:*

Ethical considerations demand transparency and accountability in the deployment of Digital Twin technology [40]. Stakeholders must have a clear understanding of how Digital Twins are employed and how decisions are influenced by their insights. Robust accountability mechanisms should be in place to address any ethical breaches or misuse of data, fostering responsible and transparent usage.

➢ *Safety and Security:*

The ethical imperative of safety and security looms large in the realm of Digital Twins [41]. As Digital Twins become integral to diverse domains, ensuring their safety and security is paramount to prevent harm to individuals, organizations, and the environment. Comprehensive measures should be taken to mitigate risks and protect against unauthorized access.

➢ *Equity and Access:*

Digital Twins have the potential to accentuate existing inequalities, especially if access is restricted or technology remains financially out of reach for certain groups [40]. Ensuring equitable access to Digital Twin technology is an ethical mandate. Initiatives should be undertaken to bridge the digital divide and guarantee that the advantages of Digital Twins are accessible to all segments of society.

➢ *Potential Loss of Privacy, Identity Theft, and Misuse of Data:*

According to Kerckove et al. [42], the development and use of personal digital twins raise concerns about the potential loss of privacy and control over personal data. Individuals may be required to share substantial amounts of personal information to create accurate digital twins, increasing the risk of identity theft or unauthorized use of sensitive data. These ethical concerns underscore the need for robust data protection and responsible handling of personal information to prevent misuse and protect individuals' privacy.

A broad consideration of ethical and social implications is indispensable in the realm of Digital Twins [41]. This technology has far-reaching societal impacts, affecting domains such as healthcare, agriculture, and more. Ethical discussions should encompass the societal consequences of Digital Twins and emphasize the responsibility of developers and users to employ them ethically and responsibly.

While Digital Twin technology offers a multitude of advantages across diverse domains, ethical considerations must not be overlooked. Privacy, transparency, safety, equity, and broader societal implications are critical in guiding the responsible development and utilization of Digital Twins. Upholding ethical standards is paramount to harnessing the full potential of this transformative technology while safeguarding individuals and society as a whole.

III. METHODOLOGY

An organized and thorough strategy was used in this literature review to locate, select, and evaluate pertinent material. The key objective was to guarantee the inclusion of relevant and high-quality studies while upholding the selectionprocess's transparency.

A. Search Criteria

Electronic databases, scholarly search engines, and academic repositories were used to find relevant literature. To find studies pertaining to digital twins, the following search parameters were used:

➢ *Keywords*:

"Digital Twins," "Digital Twin technology," "Digital Twin applications," and other relevant topics were usedin the search.

➢ *Date Range*:

The search was limited to papers published within the past five years, going back from the current year (2023).

B. Databases Used

An extensive review of the literature on digital twins was ensured by accessing several scholarly databases. Key databases and platforms included: PubMed to access studies related to Digital Twins in healthcare and life sciences. IEEE Xplore to explore studies on the technical aspects and applications of Digital Twins, ScienceDirect To access a broad range of research articles covering various domains and applications of Digital Twins, Google Scholar was used to identify a diverse range of academic sources, including conference papers, reports, and grey literature.

C. Inclusion and Exclusion Criteria

The following inclusion and exclusion criteria were used toensure that studies were chosen that were pertinent to the topicof this literature review:

➢ *Inclusion Criteria:*

- Studies that discussed the concept, applications, advantages, challenges, or ethical considerations of Digital Twins.
- Academic publications, conference papers, and peer-reviewed research articles.
- Research from a variety of fields, such as manufacturing, healthcare, the automobile and aviation industries, smart cities, and more.

➢ *Exclusion Criteria:*

- Studies not available in English, as this review focusedon English-language literature.
- Non-academic sources, such as news articles, blogs, and promotional materials.
- Studies with insufficient information or relevance tothe topic.
- Duplicate publications were removed to maintain the integrity of the review.

D. Selection Process

There were many probable sources found during the initialsearch. There was a two-step selection procedure used:

E. Title and abstract evaluation:

The relevance of each study to the research issue was evaluated by looking at the title and abstract of each study. At this stage, studies that did not meet the inclusion criteria were excluded.

F. Full-Text Evaluation:

To determine if the remaining studies were appropriate for the literature review, their complete texts were carefully examined. Studies that did not fit the research goals or lacked in-depth information about digital twins were removed.

G. Data Analysis

To gather crucial conclusions, perceptive fragments, and pertinent data, a number of papers were chosen and then analyzed and synthesized. The analysis concentrated on findingcommon themes, advantages, constraints, and gaps in the bodyof previous research.

This systematic and rigorous methodology was employed to gather, evaluate, and analyze a comprehensive body of literature on Digital Twins, ensuring the reliability and validityof the information presented in this review.

IV. DISCUSSION

The literature review provides valuable insights into the origin, evolution, definition, architecture, key enabling technologies, applications, advantages, challenges, and ethical considerations surrounding Digital Twin technology across various domains. In this section, the common themes, patterns, and trends in the literature will be identified and any discrepancies or contradictions among the reviewed sources and highlight the contributions of each study to the field.

A. Common Themes, Patterns, and Trends

➢ *Origin and Evolution of Digital Twin*

In the exploration of the concept and evolution of Digital Twins, it becomes evident that this technology has a dynamic and evolving history. Michael Grieves' initial articulation of the idea of digital twins at the University of Michigan in 2003 is where it all began [4]. To illustrate how dynamic and transdisciplinary Digital Twins are, many definitions and interpretations have developed throughout time.

The Origin and Evolution of Digital Twin reveals a commontrend in tracing the origin of digital twin technology back to theearly 2000s, with Michael Grieves often credited as the key figure in its development[43],[7]. Various sources point out the evolution of the concept, from its initial introduction to the incorporation of additional dimensions, such as data and services, to enhance its applicability across industries [6]. The requirement to increase Digital Twins' adaptability and applicability across many industries served as the motivation for these expansions.

The reviewed sources offer diverse definitions and interpretations of digital twin technology. However, some common themes emerge, such as the importance of fidelity, interoperability, scalability, and the ability to represent physical objects throughout their lifecycles [9]. It is evident that digital twins serve as virtual counterparts capable of real-time data- based reasoning, enabling applications ranging from predictive analysis to improved product design [2], [10].

➢ *Digital Twin Architecture*

It also highlights that multiple models and frameworks have been proposed to describe the architecture of digital twins [11]. While Grieves' model emphasizes physical entities, virtual counterparts, and data flow [34], other models, such as the 8- dimensional model and the 5-dimensional model [6],[14], focus on different aspects. Flexibility and adaptability to specific industry needs are recurring themes in these architectural discussions.

The literature review also emphasized various other architectural frameworks and models put out by other academics. The emergence of industry-specific frameworks as a result of the use of Digital Twins in various sectors of the economy reflects the need for customization to meet particulardifficulties.

➢ *Key Enabling Technologies*

Key enabling technologies for digital twins include cloud computing, artificial intelligence, extended reality, and the Internet of Things [19]. These technologies are crucial for data acquisition, modelling, and application. However, the choice and scope of these technologies can vary depending on the specific application domain of digital twins.

➢ *Digital Twins in Various Domains*

One recurring theme is the transformative potential of Digital Twins in multiple sectors. The reviewed literature consistently highlights the capacity of Digital Twins to revolutionize industries such as manufacturing, automotive, aviation, healthcare, clinical research, personalized medicine, defence, military, agriculture and smart cities [6]. These digital counterparts offer real-time monitoring, simulation, and optimization, providing opportunities to enhance efficiency, productivity, and decision-making.

- *Manufacturing Industry*

In the manufacturing domain, the literature underscores the shift from reactive to predictive strategies facilitated by DigitalTwins. These virtual models of physical assets enable manufacturers to optimize machine efficiency, extend product lifecycles, and explore redesign options [9]. Additionally, they support usage-based design and integration of data into manual operations, improving visibility into customer preferences and needs [34].

Digital Twins significantly enhance manufacturing efficiency by reducing execution time and enabling precise scheduling of predictive maintenance [2, 31]. For instance, they facilitate real-time behaviour simulation and optimization, aiding resource allocation and decision-making support [2]. This capability has resulted in an average reduction of 20% in execution time compared to manual processes in manufacturing coupled with NC machines [2].

Furthermore, they provide accurate predictive maintenance scheduling, which raises production line efficiency and lowers maintenance costs[44]. The interconnection of the manufacturing physical space and virtual space allows for real-time behaviour simulation and optimization of task execution sequences, ultimately controlling resource allocation and providing decision-making support [2].

In manufacturing, Digital Twins offer the advantage of real- time monitoring and remote administration. This capability not only enhances operational efficiency but also allows for quick and effective decision-making in response to real-time data andanalytics [44]. Real-time monitoring and remote administrationare valuable, but challenges related to data integration and cybersecurity must be addressed.

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Digital Twin technology offers the ability to create virtual models of physical entities, simulate real-world behaviour, and optimize asset performance [21]. This advantage extends to manufacturing companies, allowing them to manage their products digitally from design to manufacturing.

- *Automotive & Aviation Industries*

The automotive and aviation sectors leverage Digital Twinsto enhance customer engagement, personalize vehicle customization, and optimize production processes. Real-world examples, such as BMW's success in increasing productivity and Tesla's use of Digital Twins for part simulation and data analytics, underscore the practical benefits in these industries [2].

- *Healthcare & Life Sciences*

Healthcare and life sciences are another domain where Digital Twins are making significant inroads. Their applications include real-time health analysis, drug development simulation, surgical planning, and intelligent predictions [17]. Digital Twins empower healthcare professionals and researchers to improve medical resource management, precision medicine, and overall patient care [25].

Digital Twins play a pivotal role in healthcare by contributing to improvements in medical resource management, education, diagnosis, information sharing, monitoring, precision medicine, facility operation management, and research advancement [17].They empower healthcare professionals with valuable information and models, revolutionizing the delivery of healthcare services.

- *Clinical Research and Personalized Medicine*

Digital Twins hold immense promise for revolutionizing clinical research and personalized medicine. They enable predictive modelling, data analysis, and actionable insights without subjecting patients to undue risks, contributing to ethical clinical research [21].

- *Smart Cities*

Smart cities represent a promising arena where Digital Twins are increasingly adopted. They are utilized for comprehensive urban management, traffic optimization, renewable energy initiatives, and more [32]. Prominent examples, such as Singapore's Virtual Singapore initiative and Turkey's urban planning efforts, illustrate the wide-ranging applications and advantages in the context of smart cities [2]. Examples from Siemens and General Electric showcase how Digital Twins can increase productivity, reduce downtime, andgenerate cost savings [22].

- *Defence and Military*

In the defence and military domain, the integration of digital twin technology unveils a transformative potential across several sectors, prominently impacting aviation and space exploration, as explored in several papers, including “[38]”.

The evidence presented across the papers in the literature review chapter showcases how digital twins have revolutionized traditional procedures, enhancing flexibility and cost-efficiency. This technological advancement has significantly streamlined processes like testing, design, and development, thereby expediting timelines and raising the bar for quality standards in the defence and military sectors.

Boeing's emphasis on the substantial quality enhancements achieved through digital twins in aircraft manufacturing, as highlighted by A. F. Mendi et al[37]., signifies a pivotal shift toward embracing "model-based engineering." This transition promises enhanced life cycle simulations and comprehensive support services, leading to faster production, optimized operational methods, and proactive maintenance strategies for aircraft and other vehicles within the defence sphere.

Moreover, the papers shed light on the profound impact of digital twin technology on cyber defence. Anticipating cyber threats, detecting irregularities, and implementing timely countermeasures, especially in critical systems like military satellites, exemplify the proactive defence strategies enabled bydigital twins.

The application spectrum of digital twins extends beyond aviation, encompassing unmanned aerial vehicles and autonomous systems, prioritizing cost-effective maintenance and remote services. As articulated in the literature, this evolution foresees an increased success rate in military applications, space missions, and exploratory endeavours. The prospect of remote vehicle repairs stands as a key driver augmenting overall operational success rates across these critical missions.

The military sector benefits from Digital Twins through improved end-to-end visibility, better forecasting, reduced manufacturing lead times, enhanced hardware maintenance, and assistance in emergency decision-making [5]. Digital Twins enable simulations, optimizations, and predictions that can be tested in a digital environment, providing invaluable insights for defence applications.

In essence, the seamless integration of digital twins into defence and military operations, particularly in aviation, portends a future marked by amplified efficiency, enriched asset management, and heightened success rates across multifaceted critical missions. The evidential support from various papers solidifies the notion that digital twins are poised to be a cornerstone technology in shaping the future of defence and military domains.

- *Other Domains*

In agriculture, Digital Twins bring personalized curation of complex systems, real-time monitoring, system failure analysis, optimization, and energy consumption analysis [26]. While theadoption in agriculture may be in its early stages, these advantages hold significant potential for sustainable and efficient farming practices.

Utilities benefit from Digital Twins by providing real-time status on machine performance, predicting issues sooner, and improving reliability and performance [21]. The technology offers insights into how utilities are distributed and used, ultimately increasing connectivity and the utilization of data.

B. Discrepancies and Contradictions

Throughout the literature, divergent perspectives on the origin and evolution of the term "Digital Twin" have surfaced. While the widely acknowledged introduction of the concept is attributed to Michael Grieves, Hernández and Hernández's early usage [1] introduces an alternative viewpoint, signifying multiple contributors in shaping and defining this technology.

For instance, Tao, Qiang, et al. [6] advocate for a more stringent definition, emphasizing Digital Twins as precise virtual representations solely of physical assets with real-time data integration. On the contrary, Fuller, et al. [21] broaden the scope, encompassing not just physical objects but also processes, systems, and environments within the Digital Twin concept.

Grieves and Hernández represent pivotal figures in this discourse, each contributing within their unique contexts to the evolution of Digital Twins. Highlighting these contributions could elucidate the diverse perspectives that have influenced the trajectory and definition of Digital Twin technology.

Moreover, Teller, et al. [45] underscore challenges related to ensuring data accuracy and preventing biases in Digital Twin systems. Li, Jun, et al. [46] delve into the impact of network latency on Digital Twin performance, suggesting varying opinions on the acceptable thresholds for effective data transfer between physical assets and their digital counterparts.

Additionally, Bao, et al. [47] [10] discuss the intricate balance between model fidelity and computational efficiency in DigitalTwin design, reflecting differing stances on the optimal complexity levels for these models.

By incorporating these conflicting viewpoints and technical debates, this review acknowledges the multifaceted nature of Digital Twin technology. It aims to present a comprehensive understanding while recognizing the evolving landscape shaped by diverse scholarly contributions and technical intricacies.

C. Contributions of Each Study

Michael Grieves' contribution to the field, particularly the introduction of the three basic dimensions of digital twins, has played a significant role in shaping the concept's development [4]. His work laid the foundation for subsequent research and models.

Tao et al.'s extension of the three-dimensional model to a five-dimensional model, including data and services, has broadened the applicability of digital twins across various sectors [6]. This expansion enhances the understanding of digital twin technology.

Stark et al.'s 8-dimensional model contributes to defining the depth and contextual features of digital twins, offering a comprehensive framework for understanding their capabilities and domains of application [11].

The literature review discusses several industry-specific models, such as the AgriLoRo framework for smart agriculture and the implementation layer model [15], [16]. These models provide insights into how digital twins can be tailored to meet the unique challenges and requirements of specific industries.

Hassani et al.'s Healthcare Digital Twin Model presents intriguing possibilities for improving healthcare services and outcomes. However, it also highlights the need to address practical challenges in integrating digital twins into healthcare settings [17].

Each study that was reviewed made a contribution to the knowledge and advancement of digital twins. They have put forth theoretical frameworks, conceptual models, and practical implementations that add to the development of the digital twin field. Especially in healthcare and drug discovery, the COVID- 19 pandemic has significantly advanced their implementation [25] and manufacturing.

The adoption of Digital Twins across various domains introduces ethical considerations, including privacy and data protection, transparency and accountability, safety and security, equity and access, and the potential loss of privacy and misuse of data [42]. These concerns highlight the need for responsible data handling, transparency, safety measures, equitable access, and protection against unauthorized data use.

Although there are still issues with data quality, privacy, and security, there are significant potential advantages in terms of predictive maintenance, personalized medicine, and urban planning and manufacturing. Each study's contributions have improved our understanding of digital twins and opened new avenues for investigation and application in a variety of fields.

In conclusion, the literature review on digital twin technology reveals a dynamic and evolving field with diverse definitions, architectural models, and applications. It is essential to recognize the contributions of various researchers who have enriched the concept. While common themes and trends provide a solid foundation for understanding digital twins, the field continues to adapt and expand to meet the specific needs of various industries. Future research should focus on further specialization and clear boundaries within different industrial fields to maximize the benefits of digital twin technology.

V. LIMITATIONS OF THE STUDY

While conducting this review on Digital Twin technology, several limitations within the study framework became apparent, influencing the depth and scope of the analysis.

The primary limitation lies in the scope of available literature. Despite efforts to encompass a wide array of sources, the vast and evolving nature of Digital Twin technology might have led to the exclusion of some recent developments or niche applications not extensively covered in existing literature.

There might exist an unintentional bias in the selection of reviewed sources. This could be attributed to the prominence of certain studies or researchers within the available literature, potentially overlooking contributions from lesser-known sources or emerging studies.

While ethical considerations were addressed, the depth of analysis might have varied across different ethical aspects. For instance, further exploration into specific real-world cases or empirical data demonstrating ethical dilemmas and their resolutions could enhance the discussion.

While the review incorporated real-world examples across various domains, limitations exist in the depth of analysis for certain applications. More extensive case studies or in-depth analyses of practical implementations could provide richer insights into the challenges and successes of Digital Twin adoption in specific industries.

The rapid evolution of Digital Twin technology poses a challenge in presenting a fully up-to-date assessment. New developments might have emerged post-literature review, influenced the landscape of Digital Twins, and warranted further investigation.

VI. CONCLUSION

The diverse world of Digital Twin technology has been investigated in this thorough literature study, revealing its rapidevolution, countless advantages, major challenges, and ethical implications. In order to wrap up this investigation, the major findings are summarized, wise conclusions are taken, and the significant implications of this study for the field are examined.The gaps in the literature are often used to propose worthwhileoptions for future research.

A. Key Findings and Conclusions

The exploration of the world of digital twins exposes a field of technology that has advanced remarkably. Digital twins, first proposed by Michael Grieves in 2003, have expanded beyond their original description to cover a range of dimensions, from virtual representations of actual objects to extensive data, service, and link ecosystems. As a result of their versatility, digital twins are now transdisciplinary and multifaceted, with uses in a variety of industries.

The numerous benefits that cut across these various disciplines are a recurring theme. By increasing manufacturing productivity, providing real-time monitoring, permitting asset performance optimization, and revolutionizing healthcare, agriculture, defence, and utilities, digital twins have shown theirvalue. It is beyond a doubt that they can improve decision- making, reduce procedures, and create operational efficiencies.

However, there are major practical hurdles in addition to these advantages. For the Digital Twin to be successfully adopted, significant obstacles must be addressed, including a strong IT infrastructure, data quality assurance, strict privacy and security measures, the delicate process of creating trust, managing expectations, and attaining standardization.

The ethical implications of digital twins are significant. Due to the substantial gathering and processing of sensitive and personal data required by this technology, serious questions regarding privacy, transparency, safety, equity, and the possible loss of privacy and the misuse of personal data have been raised. Responsible development and moral usage are essentialto navigate these intricate ethical elements.

B. Implications for the Field

The review of digital twin technology research reveals profound implications that shape the field's trajectory. Diverse definitions emphasize the technology's adaptability, urging context-driven definitions considering industry nuances. This flexibility allows digital twins to transcend sectors, fostering potential interdisciplinary applications.

Exploration across manufacturing, healthcare, smart cities, and automotive sectors underscores the opportunity for hybrid digital twins, encouraging innovation. Despite various architectures' strengths, adaptability to industry needs remains a challenge, urging standardized frameworks for broader adoption and interoperability.

Persistent challenges in data quality, integration, and security hinder digital twin potential, demanding focused solutions for robust data management and ethical governance. Ethical concerns, especially data privacy and transparency, stress the need for ethical AI and transparent communication for societaltrust.

Emerging technologies like blockchain and edge computing hint at future advancements. Their integration promises enhanced security and better decision-making, necessitating further exploration. In sum, this research guides adaptable definitions, interdisciplinary applications, standardized architectures, improved data management, ethical practices, and the integration of emerging technologies. These implications shape the future of digital twins across diverse industries.

C. Directions for Future Research

A direction for future study is set based on the identified gaps in the literature as this review comes to a conclusion. Exciting opportunities for additional research exist in these directions:

- *Standardization and Framework creation:*
To improve compatibility and promote information flow across various industries, future research can concentrate on the creation of standardized modelling methodologies and frameworks.

- *Data Quality Assurance:*
Look into cutting-edge methods for data management and quality assurance to handle problems with data quality in digital twins. It is important to investigate methods for noise reduction and uninterrupted data flow.

- *Privacy-Preserving Techniques:*
Investigate privacy- preserving strategies in Digital Twins, particularly in delicate sectors like healthcare and defence.

- *User Trust and Expectation Management:*
Look at methods for enhancing user confidence and successfully controllingexpectations.

- *Cross-Domain Applications:*
To find new opportunities for transformative impact and investigate cross-domain applications and multidisciplinary approaches to digital twins.

Synthesizing these findings illuminates the critical interplay between challenges and the broader adoption of Digital Twins. Prioritizing the establishment of a robust infrastructure, data integrity, and ethical practices will be pivotal in shaping the future landscape of Digital Twin technology.

By examining these paths for future exploration, we pave the way for Digital Twins to realize their vast potential. Their continued evolution holds promise in transforming industries, advancing decision-making, and ultimately benefiting society as a whole.

In conclusion, Digital Twins is poised for further expansion and advancement. Their enormous potential as well as thedifficulties they face have been made clear by this literature study. Digital Twins will continue to transform companies, enhance decision-making, and eventually help society as a whole by tackling these issues and exploring novel research areas.

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