DEVELOPMENT AND APPLICATION TRENDS OF DIGITAL TWIN TECHNOLOGY WORLDWIDE AND IMPLICATIONS FOR VIETNAM[1]

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Summary:

Digital twin is a virtual representation of objects, processes, and systems existing in real-time. This technology plays a crucial role in meeting diverse requirements of the Fourth Industrial Revolution. With the ability to simulate and execute all functions easily, efficiently, and minimizing risks, digital twin technology is widely adopted globally, bringing numerous benefits not only to various industries but also to the public sector. This paper systematically reviews theoretical research on the concept, characteristics, benefits, and applications of digital twin technology, along with some experimental studies on digital twins worldwide. From this, it draws lessons to provide directions and policy implications for Vietnam.

Keywords: *Technology; Technology Applications; Digital Twin; Industry 4.0.*

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1. Introduction

The Fourth Industrial Revolution encompasses various new technologies and digital advancements that transform the way businesses produce products through the integration of the real and virtual worlds. This integration contributes to creating factories where human presence is significantly reduced, and the safety of labor is optimized. To maintain competitiveness in the coming years, manufacturers need to invest in Industrial Internet of Things (IIoT) platforms for data collection and analysis, as well as digital twins-utilizing data to monitor, manage, and enhance business operations *(Ammar et al., 2021; Souza et al., 2019; Wu et al., 2020)*. However, many organizations are still hesitant to develop comprehensive digital ecosystems for their production processes, integrating IIoT platforms with digital twins of manufacturing equipment and production lines.

Digital twins simulate the behavior of specific physical components and their interactions with others. Utilizing digital twins can enable remote

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operation, maintenance, and predictive optimization using virtual and augmented reality *(Liu et al., 2021; Matulis and Harvey, 2021; Negri et al., 2019; Sepasgozar, 2021)*. For a comprehensive use of digital twins, a large amount of data from various sources is needed to build an accurate version of real-world objects and provide valuable feedback. Particularly, after emerging from the Covid-19 pandemic, the period from 2021 to 2023 has witnessed robust investments from industries to develop the potential of technology. This investment acts as a driving force for recovery and stimulates the growth of business activities for enterprises and society as a whole. Digital twins deserve recognition for making a profound impact on how humanity applies technology and brings significant transformations to business operations and various industries/sectors.

In Vietnam, this trend is still in its early stages and is only being applied by some organizations and businesses. Organizations and businesses across all industries and levels need to develop a knowledge platform, understand the potential applications, identify essential skills when recruiting talented personnel, or enhance the skills of existing personnel to quickly seize opportunities and keep pace with the global development trends of this technology. The digital twin solution is suitable for various sectors interested in digitizing their activities and assets.

The main research objectives of this article are as follows:

- Providing an overview of the concept, characteristics, and benefits of digital twins;
- Exploring the applications of digital twins for businesses in the context of the Fourth Industrial Revolution.

2. Digital twin technology

2.1. Concept of digital twins

The term "Digital Twin" was first introduced in 2002 by Dr. Michael Grieves of the University of Michigan, with the aim of establishing the Product Lifecycle Management Center. But until 2017, the terminology and fundamental understanding of digital twins were officially published *(Grieves and Vickers, 2016)*. This period coincided with the explosion of new technologies such as artificial intelligence, cloud computing, IoT platforms, fostering the robust development and widespread recognition of this terminology and technology.

Grieves and Vickers (2016) define a digital twin as a set of virtual information structures that fully describe a physically manufactured product or a potential product from the atomic micro-level to the macro-level geometry. IBM (2023) provides a definition of a digital twin as the virtual representation of an object or system that extends its lifecycle, updated from real-time data and using simulation, machine learning, and reasoning to help making decision. A digital twin can be a computerized replica of a physical entity, such as a jet engine or wind farm, or something more significant, like a structure or even an entire city. Beyond tangible assets, digital twin technology can be used to replicate processes to gather data on how they would operate *(Maggie Mae Armstrong, 2020).*

However, this is not the identifying distinctive feature of digital twins. A digital twin is a computer program that replicates the physical components and behaviors of IoT devices at all stages of their lifecycle, using sensors to collect real-time data from elements in the real world. This data is then used to create a digital twin that can assist users (scientists, researchers, managers, etc.) in understanding and analyzing real-world objects or systems *(Kholopov et al., 2019; Židek et al., 2020*). Thus, under ideal conditions, any information from a physical object can be retrieved from its digital twin at the same moment.

In simpler terms, digital twin technology involves creating a highly complex virtual model, an exact replica of an object. This "object" could be a car, a building, a bridge, or a jet engine. Sensors connected to the physical asset gather data, which is mapped onto the virtual model. Now, anyone looking at the digital twin can see crucial information about how the physical entity is operating in the real world.

2.2. Essence and operation model of digital twins

At its core, a digital twin is a computer program that receives input data from supporting sensors that collect real-world data about an object or physical system *(K. Shaw, 2022)*. These physical devices are equipped with a sensor system to monitor operational parameters, operating conditions, location, and other vital factors. These sensors are connected to a cloud platform, where the data is collected, stored, processed, and analyzed. This data is used as an input to generate predictions or simulations about how the object or physical system operates. After the operational data is analyzed under different assumed contextual conditions, different outcomes will be simulated.

This nature allows digital twins to simulate the physical object in real-time or provide detailed information about the performance and business-critical issues of concern. In some cases, digital twins can act as a prototype before any physical version is manufactured. Significant discoveries in this virtualization environment will expedite the real-world deployment process and minimize potential risks *(Javaid et al., 2023).* Digital twins must meet three requirements: they must look exactly like the original object, including all the small details; they must operate precisely like the original object during testing; and they must have the ability to analyze information about the original object, predict potential issues, and propose solutions.

3. Benefits of digital twins

3.1. Real-time data provision

The primary advantage of digital twins is their provision of real-time data that supports learning, inference, and understanding of how objects and systems operate *(Uhlemann et al., 2017).* It enables users to analyze, model, and optimize the performance of a physical object throughout its lifecycle. Due to its numerous advantages, many businesses use digital twins to model and simulate the assets of their infrastructure.

3.2. Production process optimization through forecasting

However, the goal of digital twins is not only limited to simulating physical objects or systems but also predicting the operation methods of a product or manufacturing process. Based on this simulated and predicted information, users can make better decisions. Additionally, users can automate the adjustment of equipment, production lines, and efficient production systems *(Dalibor et al., 2020; Liu et al., 2020).* Alongside machine learning, users can also utilize digital twins to identify issues before they occur and predict outcomes for the future. Multiple forecasted outcomes can be obtained as input parameters/data change, providing users with a basis for decision-making to achieve optimal results.

Digital twins can help manufacturers increase efficiency, create innovative products, and enhance processes. Manufacturers can assess improvements to increase capacity or reduce downtime by modelling the production process. The smart factory is the seamless integration of separately individual manufacturing processes, from planning to drive equipment actuators. Very soon, devices and machines will use self-optimization features to enhance operations. Systems will adapt to networked working environments with a traffic profile. Autonomous mobile robots are essential components of the smart factory. Their self-aware intelligence links factories, enabling smooth operations (*Javaid et al., 2021; Qi et al., 2021*).

3.3. Remote monitoring

Digital twin technology also allows users to monitor remotely. In practical terms, a digital twin enables users to track and control systems remotely, access this program from anywhere *(Major et al., 2021).* This technology also enhances teamwork, helps users to automate manufacturing processes and access systems 24/7. This also supports technical specialists to focus on collaborating with each other, improving productivity and operational efficiency.

3.4. Risk identification and mitigation

Digital twin technology helps users identify risks quickly. With the ability to create a replica of the product manufacturing process, digital twins assist businesses in evaluating products before they are released to the market. Digital twins allow users to inspect every step of the process, help rapidly detect errors or unexpected situations. As a result, risk assessment is significantly improved. Additionally, the speed of developing new products and the credibility of the manufacturing process is enhanced. Data collected for the digital twin can indicate when equipment maintenance is needed and when faults might occur. Timely reporting of these needs to supervisors can save time and money for the business, reducing downtime for equipment repairs. Accurate maintenance planning is promoted, boosting production efficiency, and reducing maintenance costs.

3.5. Cost savings

Finally, digital twin technology helps save costs. Digital twins minimize risks to actual production activities. They allow users to practice and simulate processes in a virtual environment, which is often easier, quicker, and more cost-effective. You can eliminate any process-related risks and ensure the product meets expectations. The benefits of digital twins extend beyond the design and manufacturing processes because they also help extend the lifespan of the product/equipment. Instead of wasting time and money continuously replacing physical prototypes, users can make changes and test immediately on digital replica, avoid potential difficulties in the future *(Agostino et al., 2020; Guo et al., 2020).*

4. Applications of digital twins

The following section covers some practical applications of digital twin technology in various fields and industries.

4.1. Space

Previously, digital twins were used in aerospace engineering. An example is the Apollo 13 Program. Then in 2002, the digital twin concept was introduced by John Vickers from NASA. The idea of a digital twin was born at NASA in the 1960s as a "living model" of the Apollo mission *(Allen, 2021)*. In response to the Apollo 13 oxygen tank explosion and subsequent main engine failure, NASA used multiple simulators to evaluate the failure and expanded the vehicle's physical model to include digital component parts. This first-of-its-kind digital twin enables continuous data input to model to analyze the events, leading up to the accident, for forensic analysis and exploration of next steps. Fast forward half a century passed away and NASA, along with others in the aerospace community, continue to develop and use highly accurate digital models of physical systems and components as well like the harsh environments in which they operate. NASA aims to travel further and stay longer in space through the Artemis program, taking humans from the moon to Mars by establishing a sustainable presence on the Moon in preparation for missions to Mars.

Today, the importance of digital twins in the aerospace industry is acknowledged by experts. With a digital twin, engineers can use predictive analytics to foresee any future problems related to the airframe, to engines or to other components to ensure the safety of those people on the plane.

4.2. Promoting CAD technology in design

Digital twins bring many benefits to industry. One of the significant benefits of digital twin technology is the advancement of CAD (computer-aided design) technology in design. CAD software has long been used to design physical products and various factory layouts and operating systems. In general, CAD design software will allow the creation of surfaces; The 3D contour defines the shape, and then engineers start building the real-life system. Digital twin technology allows the simulation and implementation of all the above functions without the need to build a physical system. This is made possible by the ability to almost exactly linking and matching the physical and digital entities reproduced by the digital twin. This alternative provides more robust, more realistic models, and comprehensive measures of unpredictable risks. Also, with digital twin technology, architects can exploit all potential, simulate contexts, and test many different arrangement and management options before deciding to invest. From there, the risks of the entire project are minimized, and project implementation time will also be faster while saving significant costs *(Lee et al., 2021; Pérez et al., 2020; Uhlenkamp et al., 2019*).

4.3. Production activities

This is the most suitable area when applying digital twins in business operations. Because digital twins reflect the entire life cycle of a product, they can be applied in all stages of production, from design and production to finished product completion. Factories apply this technology to simulate their production processes. They help manufacturers quickly resolve any unexpected situations. Thereby, the products brought to the market will be of better quality.

Not just limited to products, replicas of an entire factory can also be created. All machines, processes, etc. are inputs to the software. This helps users design and plan factory layouts. In addition, digital twins allow simulation of employee interactions with the entire production line, making improvements or changes easy, seamlessly and limiting possible risks. happen. This helps operations managers test multiple solutions to different bottlenecks and implement process improvements easily and effectively.

4.4. Promote e-commerce

In addition, digital twin technology allows businesses to build store systems, develop product showroom chains, or organize exhibitions or new product launch events right on the Internet. digital space *(Jeong et al., 2022)*. From there, the business's products and services reach target customer groups not only in Vietnam but also around the world in the most intuitive and vivid way. Businesses can enhance brand recognition, diversify their ability to reach customers, expand their scale of operations and improve their competitiveness in the market.

With the development of digital twins, many e-commerce platforms have been able to achieve customized shopping experiences for certain customer groups, recommendations are provided based on their search history. Besides, this technology is also used to improve conversion rates by resolving buyer doubts when products belong to certain categories such as clothing, furniture, etc. Digital twin technology asks users to upload images of themselves, then goes through the technical steps of giving customers multiple suggestions by showing them images of themselves using the product *(Hinduja et al. event, 2020).*

Integrating a digital twin into inventory and supplying chain management in e-commerce can deliver many important benefits, from improving forecasting to optimizing the overall supply system performance. Based on real-time data and parameters such as demand forecasts, order status, and shipping information, this technology can perform inventory forecasting and help optimize goods import and export planning, thereby minimizing unnecessary inventory and ensuring supply readiness *(Yevgenievich Barykin, 2021).* It also helps integrate data on traffic conditions, weather, and similar factors to provide optimal scenarios for transporting goods, aiming to save time and costs *(Greif et al., 2020).*

4.5. Enhance customer experience

Digital twins are not only useful for manufacturers but also help customers enjoy fantastic experiences *(Zhang et al., 2019).* Digital twins provide direct services to customers. In the pre-shopping stage, digital twins can suggest and recommend personalized products to customers based on their search history and habits, helping them save time to research and access the products they need to buy more quickly *(Muschkiet et al., 2022).*

Next, when customers make purchases, it acts as a virtual mirror of physical interaction, helping customers see the effectiveness of using the product without actually using the product *(Dahmen and Rossmann, 2021).* This not only gives buyers a better overview of the product, but also helps them minimize the possibility of purchasing inappropriate products. A typical example of this application is the use of this technology to simulate fashion based on customer perceptions.

4.6. Smart city model

Digital twin technology will reshape city governance structures and rules, providing ongoing momentum for the growth and transformation of cities. Many important cities in the world have launched plans to build digital replica cities. The rapid development of digital twin technology also makes the construction of digital twin cities possible *(Deng et al., 2021).* Digital twins can gather detailed information from various sensor networks and smart systems. Thanks to that, the policy making and city planning process take place effectively. Actual smart city projects have been deployed in many countries, such as Virtual Singapore 3D *(Cheong Koon Hean, 2016).* Smart city planning and implementation with digital twin data and IoT helps enhance economic development, effectively manage resources, and increase the overall quality of citizen life.

4.7. Health care

As simulation is playing an increasingly important role in medicine, providing each patient with customized diagnosis and treatment is considered part of the future of precision medicine. Such customization will become possible through the emergence of digital twin technology *(Sun et al., 2023).* The digital twin provides a virtual hospital for users. Their purpose is to create a safe environment. At the same time, the digital twin can also control changes to system performance. In addition, this technology helps improve the quality of medical services for patients. In fact, doctors often rely on digital twins to simulate heart data before surgery. Healthcare providers and pharmaceutical companies can also use digital twin pairs to model a patient's genomic code, physiological characteristics, and lifestyle for supply companies to provide personalized care, such as specific medications for each patient.

4.8. Maintenance

The digital twin can analyze performance data collected over time and under different conditions. For example, a racing engine can have condition levels defined to determine when maintenance is needed, such as when a component is running low on power or is about to explode. Chevron applies digital twins in oil fields and refineries machinery to save maintenance costs *(Newsroom, 2023).*

In recent years, digital twins have been deployed in various industrial sectors, but among them maintenance is one of the most researched applications, because the tasks of performing maintenance can have a huge impact on companies' business operations *(Errandonea et al., 2020)*.

For example, in a sector such as energy or manufacturing, maintenance operations can cause an entire production line to shut down, or in the case of wind turbine inspections, operators may face safety concerns when measuring simple indicators. Therefore, adopting smarter maintenance strategies can bring huge benefits.

5. International experience and lessons

5.1. Experience of using digital twins for land management in South Korea

To keep up with this evolving trend, South Korea has sought to apply digital twins to land management systems. A pilot project has been implemented in the city of Jeonju, with plans to conduct trials in other locations. The table below presents the applications of digital twins in land management in Jeonju.

Raw data related to land is collected and updated from primary and secondary data sources, including the National Spatial Data Infrastructure, the National Geographic Information Institute, the Land and Geospatial Information Corporation of South Korea (LX), and digitalized data collection and management units of the city. All this raw data is digitized through processing and displayed in a virtual space. In this virtual space, new land-related data is discovered through analysis and simulation. The new data is managed to support decision-making and optimal solutions applied in the real space.

However, during the testing process, several issues arose in applying this technology to Jeonju. *Firstly*, data is not systematically managed. *Secondly*, some relevant parties tend to provide information without sharing data widely, only offering limited information as required by law. *Thirdly,* it is challenging to link data automatically. *Fourthly,* data update cycles are slow, leading to untimely and challenging maintenance of consistent standards. *Fifthly*, concerns regarding the security of personal information. *Sixthly*, challenges in ensuring a budget for infrastructure and software. Categories such as software, hardware, and physical/cloud connectivity require significant costs. Additionally, building and maintaining an appropriate ICT infrastructure for the Internet of Things (IoT) and data analysis, as well as continuous maintenance due to software updates, are also considered challenges.

Table 1. Application of digital twin in land management in Jeonju

Application	Purpose	Source/Data Type
Food waste collection system	To analyze the causes of food waste increase and address related issues	Food waste data, food waste collection company, administrative area, cadastral map,…
Location analysis for planting 10 million trees	To reduce greenhouse gas emissions and solve environmental problems such as fine dust, heat island phenomenon, and heat waves	Cadastral map, river boundary, urban planning projects, district planning units, land cover maps, fine dust, …
Analysis and response to areas vulnerable to heat waves	To minimize the danger of heat waves for the elderly	Temperature, population, infrastructure for cooling centers,…
Solar power production efficiency of buildings	To provide and promote new renewable energy sources for energy independence	Energy consumption of buildings, terrain maps, street addresses,…
Anti-illegal parking solution	To control parking and stopping, ensuring security for parking lots	Illegal parking and stopping data, surveillance camera data, traffic accident data, bus stop locations, fire stations,…
Building	To reduce the likelihood of	Street addresses, terrain maps,

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Solar power production efficiency of buildings	To provide and promote new renewable energy sources for energy independence	Energy consumption of buildings, terrain maps, street addresses,…
Anti-illegal parking solution	To control parking and stopping, ensuring security for parking lots	Illegal parking and stopping data, surveillance camera data, traffic accident data, bus stop locations, fire stations,…
management and safety support	incidents and identify hazardous areas in advance	building registration records,…
Infrastructure and pollution levels in industrial clusters	To measure air pollution levels at all times through an automatic measurement system and manage the discharge of pollutants within 24 hours	Emission sources, factories, closed factory areas, fine dust, street addresses, TMS data,…
Repair and management of housing for vulnerable groups	To avoid overlapping interests in repairing and managing old houses and warehouses (Old house and warehouse repair support project by each management department)	Old housing for low-income groups, benefits of old housing, energy efficiency improvement project, reconstruction project for housing for people with disabilities

Source: Park et al. (2023)

5.2. Experience of applying digital twin technology in railway maintenance management in Taiwan

In Taiwan, the population primarily uses railway/subway transportation as the main means of commuting. However, alongside supporting the improvement of urban residents' quality of life, the rapid development of railway transportation infrastructure has, on the other hand, exacerbated congestion issues, making the management of complex construction tasks, operations, and coordination more challenging. In reality, constructing, operating, and maintaining railways is a large-scale project involving the participation of many stakeholders. Ineffective asset management can lead to serious accidents, especially in the operation and maintenance phases.

To enhance the construction, operation, and maintenance of railways, Taipei has developed a digital twin to help stakeholders visualize, share data, and track progress and status during the provision and use of services *(Kaewunruen et al., 2021).* The digital twin operates as a robust information platform (by integrating Building Information Modelling - BIM - and professional project assessment software - Navisworks). The digital twin can not only contain a set of information but also allows access to information throughout the entire project life cycle. By using the digital twin, all project stakeholders can collaborate, create, and collect the latest progress in real-time. The database in the digital twin can help achieve sustainability goals by enabling efficient asset management and monitoring, while also being able to identify and control carbon emissions, estimate costs, and managing time throughout the life cycle.

5.3. Lessons learned

Vietnam can draw valuable lessons from the experiences of applying digital twins in the mentioned countries.

Firstly, during the process of data collection and updating, it is essential to establish a systematic data management system. Collaboration between relevant departments and/or individuals in charge or between related organizations should be a top priority. Operating a digital twin technology system requires active cooperation among stakeholders for data sharing and interaction. Additionally, issues such as security, privacy, quality, sharing, interaction capabilities, digitalization, update cycles, and standards need to be given top priority to ensure system integrity in management.

Secondly, to achieve the intended goals in the digitalization process, ensuring an adequate budget and managing resources are crucial factors. Establishing a digital twin in any field requires significant financial costs. In addition, professional human resources need to be trained and managed, and it is also necessary to prevent the monopoly of a few companies with technical qualifications in this field.

Thirdly, trust building in the importance and effectiveness of the system with personnel responsible for building and maintaining the digital twin is crucial. Job rotation, especially in the public sector, poses a significant sustainability challenge when personnel in charge of related tasks transition to new roles, and their successors do not use models based on digital twins.

Fourthly, when making decisions, social issues that digital technology may cause need to be carefully examined. For instance, those people, familiar with digital technology easily benefit from such decisions, while those less familiar may struggle to recognize the advantages, potentially leading to social disparities.

Fifthly, the application of digital twin technology needs to be promoted and supported by legal systems and frameworks. For example, the roles of each organization in this process should be clarified through relevant regulations or laws to minimize confusion and conflicts of interest.

6. Conclusion and policy implications

This study has summarized and analyzed the prominent benefits and advanced applications that digital twins can bring across various fields. The integration of the real and virtual worlds through digital twins has opened up a new perspective with diverse applications, from inventory management to personalized shopping experiences, creating significant changes in the way how each individual approach and in the business operations of enterprises as well as the operations of public sector organizations.

In the current era of the Fourth Industrial Revolution, digital twins have emerged as a pioneering trend, playing an extremely important role in the technological development of the world in general and Vietnam in particular. To fully exploit the potential of digital twins, close collaboration between the government and organizations, businesses is necessary to create an environment conducive to the development and application of this technology. Establishing legal frameworks and regulations for protecting information, privacy, and data security related to digital twins is essential. In addition, training a workforce with knowledge, skills, and attitudes in this field is crucial for successful implementation. Furthermore, the government can prioritize investment in researching and developing new applications of digital twins. Supporting research projects and startups can stimulate and promote innovation in harnessing this technology. With the awareness that digital twins are a crucial technological trend, along with timely support and coordination measures from the government, it is hoped that Vietnam will make breakthrough developments, contributing to accelerating the industrialization and modernization of the country./.

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