ТЕОРЕТИЧНІ ТА ПРИКЛАДНІ ПРОБЛЕМИ І МЕТОДИ СИСТЕМНОГО АНАЛІЗУ

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DIGITAL TWINS: STAGES OF CONCEPT DEVELOPMENT, AREAS OF USE, PROSPECTS

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Abstract. The results of a review of the digital twin concept development, the areas of their use, and the prospects are highlighted. The history of the emergence and development of the digital twin concept, its definition, and its classification are given. The relevance of the technology under consideration is reflected. The purpose of this review is to provide the most complete, up-to-date information on the current state of the digital twin technology, its application in various fields of human activity, and further prospects for the development of the industry. An extensive bibliography on the topic is provided, which may be helpful for researchers and representatives of various industries.

Keywords: Industry 4.0, digital twin, classification, areas of application, Internet of Things, physical and mathematical models.

INTRODUCTION

The increasing complexity of production management task necessitates the adoption of new management methods and systems. Today, production management requires Industry 4.0 competencies [1], which have emerged relatively recently and are largely interconnected with IT technologies. The traditional pyramidal model for designing production management systems is being replaced by modern approaches to direct interaction between the components of the production system based on the concept of the Internet of Things (IoT). The digital twin refers to a new innovative toolkit that helps to exploit the advanced scenarios of the Internet of Things and other technologies. This toolkit is used to create digital models of the physical environment, and digital analogues will be able to perceive information from the world around them, interact and exchange data. The result is a completely new environment where the intelligence embedded in applications will allow to assess what is happening in the physical world, take into account the accumulated information and experience to support decision-making. This environment creates qualitatively new conditions for business and ensuring environmental safety at work. Thus, the digital and physical worlds are being united, with applications, services, networking components and edge devices being the Internet of Things. Each element of the Internet of Things in production will have a digital twin, i.e. its virtual model for rational production management. Based on a systematic literature review and a thematic analysis of 92 publications on digital twins over the past ten years, [2] this work describes this technology, identifies knowledge gaps and necessary areas for future research. In the characterisation of a digital twin, the state of the concept, key terminology and related processes are identified, discussed and combined to produce 13 characteristics (physical entity/twin; virtual entity/twin; physical environment; virtual environment; state; implementation; metrology; duplication; duplication rate; physical-virtual connection/twin; virtual-physical connection/twin; physical processes; and virtual processes) and the complete structure of the digital twin and its operation process. Following this characterisation, seven knowledge gaps and topics for future research are identified: perceived benefits; digital twin in the product lifecycle; use cases; technical implementations; confidence levels; data ownership; and integration of virtual entities, each of which is necessary for digital twin implementation. There are also other reviews [3]–[6] on the digital twin application in various industries.

The history of the digital twin concept. The first digital twin in history (at that time, such name and concept did not exist) can be considered a program used by NASA in the 1960S to design the Apollo 13 mission. It was created to test how the future object would behave in the physical world. Later, engineers discovered that the virtual model could be used to control equipment and predict what would happen to it. The sensor readings during the flight were compared with those predicted in the digital model in real time [7]. This idea later became the basis for the creation of modern digital twins.

The emergence of the digital twins concept is associated with the work of Michael Greaves, a professor at the University of Michigan. In 2002, as part of a presentation at the University of Michigan for industry representatives, he proposed a model consisting of three components: a real space; a virtual space; and a mechanism that ensured the exchange of information between them. At the time, this concept was called “ideal PLM” (Product Lifecycle Management) [8]. A similar concept named “Mirror Worlds” [9] was proposed earlier by computer scientist David Gelernter in 1991.

In response to the M. Greaves publication, K. Främling et al. 2003 [10] proposed to modify the PLM concept to solve the problem of organizing the exchange of information between a virtual object and a physical one using the Internet of Things. In particular, the authors argued that the standards already existing at that time were sufficient to organize the computing architecture. In 2003, the idea was not widely supported due to the imperfection of technologies for processing a large data flow in real time, with most data stored in paper form.

Later, Michael Greaves developed this idea and presented it in his course on PLM systems, which he taught at the same university. Despite the fact that the term “digital twin” appeared a little later, the basic concept of having a physical object, a virtual object and ensuring the information exchange between them was developed already then. In the following years, one of the names of this concept was the “model of mirror spaces” [11], in the period 2006–2010 the term “model of information mirror” was used [12].

In 2010, the term “Digital Twin” first appeared in NASA’s technology roadmap, its authorship could be attributed to J. Vickers. This publication also used the term “Virtual Digital Fleet Leader” [13]. Since 2011, the concept of digital twins has been used by the US Air Force Research Laboratory (AFRL) to effectively resolve the design issues, maintenance and forecasting of the aircraft service life [13], [14]. A virtual copy of the aircraft accompanied the real object throughout its life cycle. In 2013, Germany proposed the concept of Industry 4.0. Its key idea is the cyber-physical system (CPS). CPS combines people, machines and things that provide a continuous exchange of information to monitor, collect data, analyse and optimise production processes. To implement such processes, it is necessary to use a digital twin [15]. The concept of a "digital twin" is a part of the fourth industrial revolution and is designed to help businesses detect physical problems faster, make more accurate predictions, develop better products [16], [17].

M. Greaves gave a detailed description of the digital twin in 2014 in the so-called White Paper, intended for corporate society. Some industrial companies, such as Siemens, almost immediately adopted the terminology and paradigm outlined in the book [18]. In his book "The Origin of Digital Twins", M. Greaves divided any digital twin into three main parts [19]: a physical product; a virtual product; and data and information that unite the virtual and physical products. In his opinion, "under ideal conditions, all the information that needs to be obtained from a product can be provided by a digital twin".

The design of digital twins is based on simulation modelling methods that provide the most realistic representation of a physical environment or object in the virtual world. A mathematical description of digital twins can be obtained via statistical modelling, machine learning or analytical modelling methods. The mathematical models of a digital twin for supporting and predicting the functioning of a physical process of a real objects are given in [20], [21]. The parametric uncertainty of the mathematical description of the physical process is taken into account. As an example, the design of a digital twin is given on the example of an analytical model of an electric heater.

In 2023, the concept of a digital twin is evolving into something more subtle and incredibly practical: an executable digital twin (xDT). Simply put, xDT is a digital twin on a chip. xDT uses data from a (relatively) small number of sensors embedded in a physical product to perform real-time simulations using reduced-order models. Based on the data from a small number of sensors, it can predict the physical state anywhere within the object (even in places where sensors cannot be placed) [22].

The main stages of development of the digital twin concept are shown in Fig. 1, from the inception of the idea in 1960 to the current state. Source: compiled by the authors based on [7]–[22].

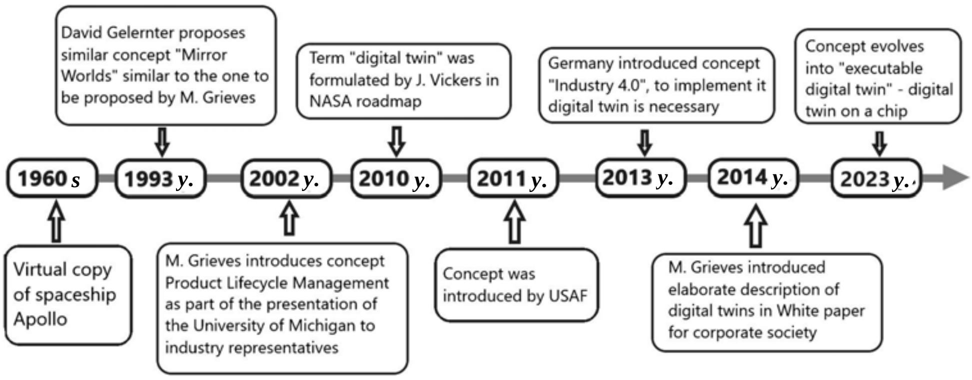

Fig. 1. Key stages in the development of the digital twin concept. Source: compiled by the authors on the basis of [7]–[22]

Definition of a digital twin. The review has shown that there is no single accepted definition of digital twin. The paper “Digital twin paradigm: A systematic literature review” counted 30 definitions given by researchers and organizations [7]. Therefore, we will present the definition proposed by the author of the concept of digital twin and one of the modern ones, which, in our opinion, is the most complete among the existing ones.

Definition by M. Greaves. A set of virtual information constructs that fully describe a potentially or actually produced physical product from microatomic to macrogeometric level [8].

Definition by Asimov et al. 2018. A virtual copy of a physical object that can monitor data consistency, perform data mining to identify existing and predict future problems, and use artificial intelligence to support business decisions [23]. However, the definition of a DT is not finalized. For example, a 2021 meta-analysis that included 24 articles showed that 83% authors agreed that the concept was in the early stages of development [24].

The relevance of the topic of digital twins. According to a study conducted in September 2022, the number of publications in Scopus on the topic of "digital twin" is growing every year [25]. The popularity of this topic can be seen from the graph of the number of publications depending on the year. Interest in the creation of digital twins has been growing significantly since 2016.

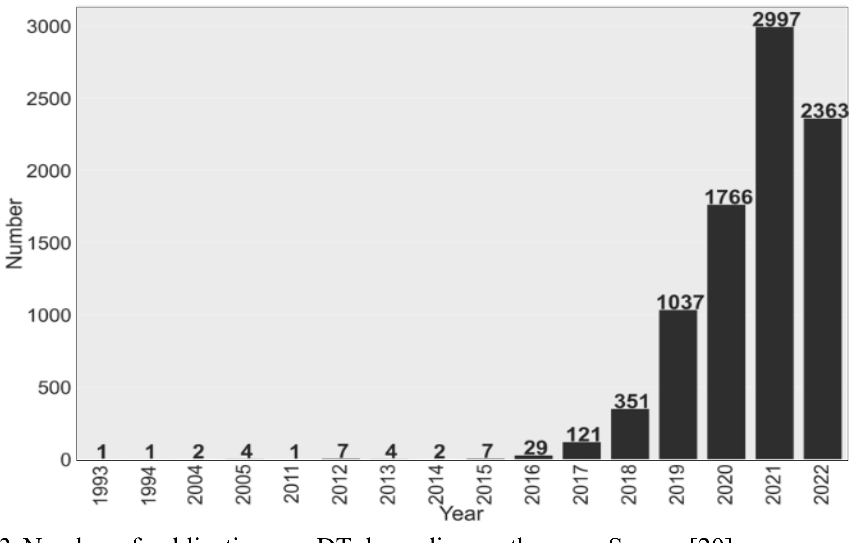

Fig. 2. Number of publications on DT depending on the year. Source [20].

More and more countries are adopting development plans based on technologies that combine physical and information space: “Industry 4.0” in Germany [15], “Advanced Manufacturing” in the United States [26], “Society 5.0” in Japan [27], “Made in China 2025” in China [28], and a similar project for the EU, “The Factory of Future” [29]. Topic relevance is confirmed by numerous highly cited publications. Authors of these publications have high H-index (Table 1).

Table 1. The most cited works on digital twins

Title	Year	Number of citations	H-index of authors
		Scopus / Google Scholar	
Jay Lee, Behrad Bagheri, Hung-An Kao "A cyber-physical systems architecture for industry 4.0-based manufacturing systems" [30]	2014	3003/5088	Jay Lee: 58/73 Behrad Bagheri: 12/19
Fei Tao, Jiangfeng Cheng, Qinglin Qi, Meng Zhang, He Zhang, Fangyuan Sui "Digital twin-driven product design, manufacturing and service with big data" [31]	2018	1433/2084	Fei Tao: 69/81 Jiangfeng Cheng: 14/16 Qinglin Qi: 23/24
Dmitry Ivanov "Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case" [32]	2020	1079/1821	Dmitry Ivanov: 62/74
Werner Kritzinger, Matthias Karner, Georg Traar, Jan Henjes, Wilfried Sihn "Digital twin in manufacturing: a categorical literature review and Classification" [33]	2018	1114/1718	Wilfried Sihn: 22/31
Fei Tao, He Zhang, Ang Liu, Andrew Yeh-Ching Nee "Digital Twin in Industry: State-of-the-Art" [34]	2019	1197/1750	Fei Tao: 69/81
Michael Grieves, John Vickers "Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems" [35]	2017	1063/2076	Michael Grieves: 7/16
Abram L. J. Walton, Cynthia L. Tomovic, Michael W. Grieves, "Product Lifecycle Management: Measuring What Is Important – Product Lifecycle Implementation Maturity Model" [36]	2013	6/13	Michael Grieves: 7/16 Tomovic Cyn-thia: 5/9
F Tao, Q Qi, L Wang, AYC Nee "Digital twins and cyber-physical systems toward smart manufacturing and industry 4.0: correlation and comparison" [37]	2019	487/712	Qinglin Qi: 23/24 Fei Tao: 69/81

Source: compiled by the authors on the basis of [30]–[37]

The study by Semeraro et al. 2021 [7] provides the following facts about the popularity of the term "digital twin" in the Scopus, Elsevier, and ScienceDirect databases: 60 journals have published papers on this topic; it was discussed in 47 conferences; 8 chapters in various books have been found.

Many DT-related technologies have been patented. As part of the review, we searched for patents with the term "digital twin" using the query TAC="digital twin". At the time of writing, Google Patents returned 6181 results for this query dated 2003-01-01. The largest patent holders are large corporations: Siemens AG (13.4% of all patents); General Electric (9.8%); Beijing University of Aeronautics and Astronautics (3.4%). A study that conducted a cluster analysis of DT patents from the Webpat and Derwent databases found 140 records by 2018 [38].

The classification of DT. The most complete list of classifications is given in the paper [39]: by application, by level of integration, by hierarchy, by level of maturity/complexity, including the classification introduced by M. Greaves [40].

Reading literature, one may also encounter terms “digital model” and “digital shadow”. They should be distinguished from a digital twin. In particular, the difference between these terms was explained by Kritzinger et al [33]:

- A digital model is a virtual representation of an entity in which there is no automatic data exchange between a physical and a virtual object. All information is transferred manually.
- A digital shadow is a virtual representation of an entity where data is transferred from a physical object to a virtual one, but not vice versa. Thus, a digital shadow is a kind of logbook where all important changes are recorded.
- A digital twin is a virtual representation in which data flows in both directions, from a digital entity to a physical one and vice versa.

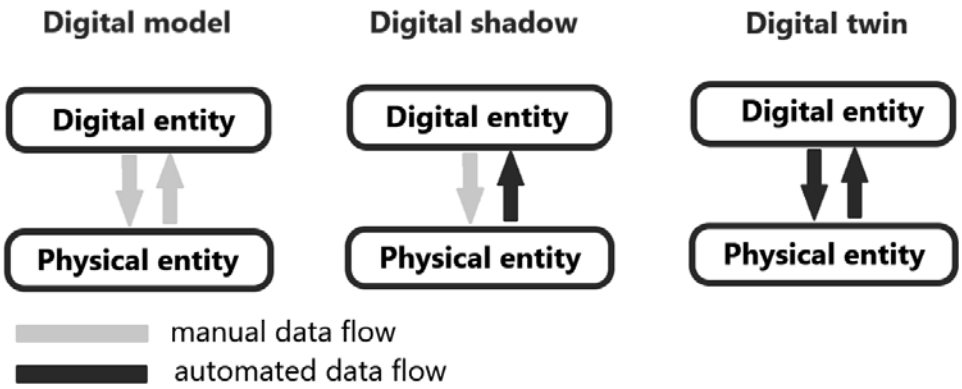

Fig. 3. Data flow in a digital model, shadow and twin. Compiled on the basis of the publication [33]

AREAS OF APPLICATION OF DIGITAL TWINS

1. **Aerospace industry.** As noted in the IEEE publication [40], leading aerospace industry agencies such as NASA, EASA, the US Air Force, and the Royal Canadian Air Force (RCAF) consider DT as a key element in production. This technology enables the implementation of the Operation & Maintenance paradigm, which prioritises the prevention of accidents and breakdowns, and fixing them before they occur.

Digital twins are indispensable in the design of critical components such as engines, which are expensive and technologically complex to test. Computer simulations allow to test different flight modes, altitudes, climatic conditions, emergency situations, and system failures before physical testing. Simulations make possible to study engine behaviour under extreme conditions without physical experiments [40].

In-service DT reduces the need to rely on probabilistic models to determine when a part may need maintenance. Various machine learning algorithms are used in the aerospace industry: Support Vector Machines, autoencoders, convolutional neural networks. A full list of algorithm applications is available in the IEEE publication [40]. More details can be found in a textbook dedicated to the problem of using DT in aircraft [41].

The DTs are used by Rolls-Royce in the design and operation of its aircrafts. Once released, the virtual model accompanies the aircraft during each flight, comparing predicted performance with real-world performance, and building What If scenarios [42].

2. **Automotive industry.** Digital twins are used to speed up the design of new car models. First, a virtual model is developed and tested, then a physical prototype is built and improved in parallel with the digital prototype. A virtual twin makes it possible to review different design options and run computer simulations of various situations (for example, how a car would behave on a slippery road or in icy conditions). Siemens, for instance, offers software solutions for creating digital prototypes of cars with the function of developing a 3D model and conducting simulations [43].

Maserati has replaced the costly and time-consuming wind tunnel streamlining procedure with a digital twin. Also, the engine sound (which is a symbol of the brand) is tuned in a computer simulation, whereas previously a physical prototype was built and the acoustics were tested on mannequins with microphones. In general, the use of this technology reduces the new car development time by 30% [44]. Renault uses the DT to conduct virtual crash tests, study body aerodynamics, engine efficiency, even check how well air conditioner cools the interior [45].

Digital twins are used not only for design. Cars with a high degree of computerisation form the so-called Internet of Vehicles [46], which provides the city with many advantages: increased safety, traffic optimisation, information about available parking spaces, and the possibility of remote maintenance [47]. A striking example of the use of DT during operation is Tesla, which creates a DT for each car sold. During the trip, sensor readings are continuously taken and sent to servers, artificial intelligence detects problems and forms an individual approach to their solution (such as changing the settings to make the doors close more quietly) [48].

3. **Oil and gas industry.** The digital twin plays an important role in modern drilling operations throughout the entire life cycle of a borehole, starting with the exploration stage. The DT of borehole is a complex system: the drilling model is made up of four unique elements, each of which is a digital twin itself: wellbore, drill string, drilling mud, and formation. Computer simulation allows to find the best types of tools and rig settings. Real-time monitoring of all processes and forecasting via machine learning methods helps to identify equipment problems that can lead to unplanned downtime or correct process deviations before they lead to a deterioration in the quality of the workflow [49]. Ericsson uses systems to monitor the condition of workers through smartwatches and bracelets to prevent mistakes due to fatigue [50]. The most comprehensive bibliography of the use of digital twins in the oil industry is provided by Cameron et al. 2018 [51].

4. **Chemical and pharmaceutical industry.** In the chemical and pharmaceutical industries, each batch of products is created with a DT that combines all the necessary information about the batch. Based on these data, it is possible to run simulations and predict the optimal technological parameters for the next production stages to ensure the planned product quality.

Information about changes in product properties depending on the parameters can be stored in databases, which allows to “design” new substances on the computer. This functionality makes DT a key element of the quality management process [49]. For example, such software was developed by Atos and Siemens [52].

5. **Digital Twins of Cities.** There are terms like “Smart City” and “Digital City” that do not mean that a city has a digital twin. A smart city is one that follows a strategy of saving resources through innovative solutions. A digital city is a city that has implemented IoT technologies [53].

The smart city concept emerged in response to the Kyoto Protocol, which obliged countries to reduce greenhouse gas emissions [53]. Intensive urbanisation (in particular, according to UN forecasts, 68% of the world’s population will live in cities in 2050 [54]) has led to cities being the main source of pollution. Digital transformation has been proposed as a way to reduce emissions. With the development of 3D modelling technologies, it became possible to visualise infrastructure, but the models were static and used only for infrastructure planning, they could not display real-time processes, nor could they be remotely controlled – they were not digital twins [55]. It was only with the appearance of IoT technologies, cloud computing, the implementation of artificial intelligence and big data that it became possible to set up data exchange between the physical and digital essence of the city. This moment can be considered the emergence of digital twins of cities [53].

The world’s first digital twin city was created for Singapore in 2014 at a cost of US $73 million. In 2022, the system was replaced with an advanced version that includes data from sensors, drones, government agencies, etc. [56]. The city of Zurich has its own DT with a detailed 3D map of roads, underground and above-ground facilities [57]. According to the World Economic Forum 2022, by 2030, the technology of DT will have saved $289 billion on city planning and construction; in 2020, investments in DT of Chinese cities exceeded $380 billion [58].

The most comprehensive bibliography on digital twin cities is provided in the review, which lists the main applications: planning and forecasting, visualisation, engagement, monitoring, data management [59].

6. **Digital twins of urban water supply systems.** The problem of drinking water is becoming more urgent in the world, as such, there is a need for its rational use. The International Water Association (IWA) has published a paper on digital twins of urban water supply systems as a way to reduce water consumption [60].

An example of a successfully implemented project is the digital twin of water supply system of Valencia (Spain) and its suburbs, developed by Global Omnium. It feeds approximately 1.6 million inhabitants, and the water supply system provides water to 325,000 nodes. The programme contains a detailed model to monitor the system and predict emergencies [61]. The digital twin can predict possible problems 24 hours in advance. Simulations and records of previous accidents are used to train personnel [62].

No less successful is the H2PORTO project, a digital twin of the water supply system in Porto (Portugal). It provides real-time monitoring of the system, uses weather and tidal data to model water levels and warn of flood risk. H2PORTO can run virtual simulations of emergency situations: pipe bursts, valve closures, pumping station shutdowns [63].

7. **Energy.** Power grids are among the most complex engineering systems in the world. With the appearance of solar panels and wind turbines, power supply

networks are becoming more complex, requiring effective management. For example, Siemens has set up a research centre to develop a digital twin of Australia's power grid. In 2023, €3.4 million was invested in the project. It is planned to be developed via the Siemens programme PSS software [64].

The lack of a single standard for digital twins remains a problem in the energy sector. Management is complicated if several power grids are connected but have different digital twins. In a publication issued by the IEEE, a single standard for digital twins was proposed. The authors note that the architecture is flexible, which will spare rebuilding the system in the future and enable connecting existing digital twins [65]. The most comprehensive bibliography on digital twin power grid structures is provided in the article [66].

8. **Construction.** Several reviews have already been conducted on this topic [67, 68]. Found publications are classified by the stages of the life cycle of the object where the digital twin is used: design, construction, and operation. In the construction process, complete digital twins are used as part of the implementation of Building information modelling (BIM), a strategy to improve the efficiency of the construction process [69]. Papers have been published that propose the design of the digital twin for the operation of the building. The topics raised include building maintenance, fault detection, scheduling and personnel management, etc. [70, 71].

9. **Retail trade.** In the book "Advances in computers Vol. 130", there is a separate chapter devoted to DT in retail trade as a tool for effective planning. In its simplest form, a DT can be a virtual copy of a physical supply chain with information on weather, fuel prices, etc. This allows to simulate how, for example, a transport delay due to bad weather can affect the flow of products in the supply chain [72].

According to Forbes, retailers and companies such as Lowes, Kroger, and Tyson Foods are already exploring or implementing digital twins of their supply chains. French supermarket chain Intermarché has already created digital twins of most of its stores. [73].

10. **Preservation of cultural heritage.** Museums use digital twins to monitor the preservation of exhibits. Some institutions create digital twins of entire buildings of cultural value. Such technologies are developed by Weiss AG. For example, the Forbidden City Museum (Beijing, China) conducts periodic 3D scans of ancient buildings to monitor whether restoration is needed [74]. Digital twins are also used to organise virtual tours. More details about the application can be found in the review dedicated to the use of digital twins in museums [75].

THE PROSPECTS OF DIGITAL TWINS. THE LARGEST PROJECTS OF DIGITAL TWINS.

A digital twin of the port of Rotterdam. Currently, IBM is creating a digital twin of the port of Rotterdam [76], the largest port in the world. The project complexity is comparable to projects that develop digital twin of large city. For example, in the annual report of 2022, it was stated that revenue was 825,700,000 euros [77]. It is planned to organise the port territory into a single digital space through IBM Cloud and IBM Internet of Things systems. The digital twin of the port will provide the following opportunities [76]:

- collection of meteorological and hydrological data to determine the most favourable time for getting to the port;
- autonomous ship control and data exchange between vessels;
- fuel economy, optimisation of approach and mooring speed;

A digital twin of the planet Earth [78]. The European Union plans to become a climate-neutral region by 2050. The key point of this plan is digital transformation, and for this purpose, in particular, a digital twin of the planet Earth is being developed, in which 1 trillion euros have been invested. It will perform the following tasks:

- combining data from satellites, scientific stations, sensors, etc. into a single high-resolution information platform;
- analysis of human impact on nature, such as carbon emissions, water pollution, littering;
- more accurate forecasting of weather and climate in the long-term perspective;
- building what-if scenarios to rationally implement environmental projects.

Today, some companies have developed software products for creating digital twins. Digital twin software is an advanced type of modelling software that generates a digital simulation of a physical object. Here are examples of software for creating digital twins:

1. Siemens Digital Twin allows to create digital twins for equipment and industrial processes. It provides real-time monitoring and control of equipment, as well as the ability to predict possible failures and diagnose problems.
2. ANSYS Twin Builder – allows to create digital twins for various industrial systems, including automotive, electronics, and power generation. It allows to conduct virtual testing and analyse various system scenarios, which helps to reduce costs and improve productivity.
3. Microsoft Azure Digital Twins is a cloud-based solution that allows to create digital twins for different types of buildings and urban environments. It allows to visualise the structure of a building and its various systems, as well as predict and manage energy consumption.
4. Predix Digital Twin is a solution from General Electric that allows to create digital twins for equipment and infrastructure in the energy and transport industries. The software product provides equipment condition monitoring and forecasting of possible failures, which helps to reduce maintenance and repair costs.
5. The computer game Factorio is a game about building and managing factories to produce various goods. One of the key aspects is that players have to collect resources, process them and build new factories and machines to improve production and get more products.

As for the digital twin aspect, Factorio players create a virtual model of the production process. The game allows to create complex mechanisms from a variety of elements, such as conveyors, workers, sorting machines, resource mines, etc. Each element performs a specific function in the production process, and players must properly configure their work to maximise production.

In Factorio, one can create and save templates of his own production processes. This allows players to create digital twins of their factories and mechanisms that can be saved and transferred between different game worlds. In this way, players can use digital twins to quickly restore the production process in the case of a failure or destruction.

6. “AJAX Systems” is a Ukrainian company specialising in the development and production of wireless security alarm systems and intercoms. AJAX Systems main products are wireless security alarm systems that use advanced technologies and are highly reliable and efficient. AJAX systems are easy to install and configure, as well as the ability to control their operation using a mobile application. In addition to wireless security alarm systems, the company also produces wireless intercom systems that allow to control access to the building and communicate with visitors using a mobile application.

CONCLUSIONS

The article provides a detailed overview of the history of the emergence and development of the digital twin concept, provides definitions, explains the difference between this term and related concepts, and substantiates its relevance and application in various fields of activity.

The topic relevance is substantiated by calculating number of publications in Scopus, Elsevier, analysing the number of patents in Google Patents, and analysing the industrial plans of developed countries such as Germany, the USA, Japan, and China. In particular, it can be concluded that industrial giants such as Siemens and General Electric have a large number of patents for this technology. A detailed review of digital twin applications in various industries was carried out: aerospace, automotive, oil, chemical, energy, urban planning, water supply, construction, retail, and cultural heritage preservation. Links to specifically focused reviews are provided in case of need to learn more about the use of digital twins in a particular industry.

The global digital twin industry was estimated to be worth USD 6.5 billion in 2021 and is predicted to reach USD 125.7 billion by 2030. The rise of IoT and cloud technologies, as well as the motivation to reduce costs and shorten product development time, are key factors contributing to this growth.

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ЦИФРОВІ ДВІЙНИКИ: ЕТАПИ РОЗВИТКУ КОНЦЕПЦІЇ, ГАЛУЗІ ВИКОРИСТАННЯ, ПЕРСПЕКТИВНІСТЬ / Н.Д. Панкратова, К.Д. Грішин, В.Є. Барілко

Анотація. Висвітлено результати огляду розвитку концепції цифрових двійників, галузі їх використання, перспективність. Наведено історію виникнення та розвитку концепції цифрового двійника, означення, класифікацію. Відображено актуальність технології, що розглядається. Метою роботи є надання найбільш повної сучасної інформації про поточний стан технології «цифровий двійник», її застосування в різних сферах діяльності людини та подальші перспективи розвитку індустрії. Наведено широку бібліографію з теми, яка може бути корисна дослідникам і представникам різних галузей.

Ключові слова: Індустрія 4.0, цифровий двійник, класифікація, галузі використання, Інтернет речей, фізичні та математичні моделі.