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FROM CAD AND BIM TO DIGITAL TWINS

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Abstract. A Digital Twin is a virtual model of a physical object or system that uses real-time data to simulate the behavior of its real counterpart. It can be a product, machine, building, or even an entire city. *Digital modeling* is a fundamental technology for creating Digital Twins, as it provides a methodology for representing physical objects in the virtual world. *CAD (Computer-Aided Design)* can be used to create the initial model of a Digital Twin. *BIM (Building Information Modeling)* is a specialized form of CAD that focuses on building projects incorporating more information than just geometry but also data on time, costs, operations, and maintenance. This paper examines how these technologies are increasingly integrated with each other, utilizing *mathematical modeling* that, through virtual computational experiments, provides an understanding of the complex functioning of objects and informed decision-making in various fields. The integration of Digital Twins and CAD is transforming the ways products are designed, modeled, and optimized in the industry. BIM models can serve as the basis for creating Digital Twins of buildings, which are then used to optimize energy consumption, maintenance, and repair. With the growth of the Internet of Things (IoT), Digital Twins are receiving more and more real data, making them even more accurate and useful for forecasting and optimization. The use of artificial intelligence to analyze data collected by digital twins allows predicting breakdowns, optimizing processes, and even automating the control of systems.

Keywords: mathematical modeling, digital modeling, CAD and BIM, Digital Twins (DT), Internet of Things (IoT), AI application in DT.

MATHEMATICAL MODELING (SIMULATION)

Among the information technologies that are used in almost all fields of engineering and science, *digital modeling* occupies a special place. This is a general term that encompasses the creation of digital representations of physical objects or systems. It can include many things: from modeling their functioning to creating their geometric images. Therefore, *mathematical modeling* is separately distinguished, when under the mathematical model of a physical system, object, or process is usually understood a set of mathematical relations (formulas, equations, logical expressions) that determine the characteristics of the state and properties of the system, object, and process and their functioning depending on the parameters of their components, initial conditions, input disturbances, and time. In general, a mathematical model describes the functional relationship between the output dependent variables, through which the functioning of the system is reflected, independent (such as time), and changing variables (such as component parameters, geometric dimensions, etc.), as well as input disturbances applied to the system.

Mathematical models are determined by the subject area of design:

- physical and mathematical description of the laws and conditions of the object's functioning;
- the environment of functioning and means of interaction of the object with this environment;
- the composition of the object, the element base, the means of organizing the structure of the object;
- parameters that change or are adjusted.

The models distinguish between three types of data: data on the elements of the modeling object; data on the properties of the object and elements; data on the relationship between elements and the object. The abstraction of the object is carried out both by *the depth of structuring* (hierarchical system, system of elements, indivisible object), and by *the degree of abstraction of elements* and object properties (structural, logical, and quantitative levels).

At the structural level, the structure of the object is modeled at the lowest level of its structuring, when the mathematical model is presented in the form of a set, the properties and parameters of the elements of which are described through functional connections, order relations, adjacency, combination. In this case, the apparatus of set theory and graphs, queuing theory, etc. is used.

At the logical level of modeling, each set, Boolean matrix of binary relations, or structural graph corresponds to sets of logical relations and variables that reflect cause-and-effect relationships. In design, the apparatus of mathematical logic is used.

At the quantitative level, each element of the set, Boolean matrix, or logical variable is assigned an algebraic or other quantitative variable, and logical relations are transformed into quantitative relations: equations, inequalities, and so on. Modeling at the quantitative level reflects functional, energy, material, and spatial connections. These connections are usually described by spatio-temporal relations and are determined through ordinary differential equations or partial differential equations.

If the object consists of a system of elements, the connection between which is described by only one variable (time), then models with lumped parameters are used. The elements of the object are quantitatively described by component equations. Micro models and macro models are distinguished if the internal structure of the modeled objects or elements is not taken into account.

The main part of the calculations in mathematical modeling (in terms of volume and costs) is performed at the quantitative level of modeling, where all existing non-linear relations are taken into account. Modern modeling programs differ from the simple use of computers in calculations by the fact that they provide ***automatic formation of a digital mathematical model*** of an object based on information about its structure and the properties of its elements [1]. For example, for the common case of dynamic non-linear systems, the components of which can be electronic blocks (logical and analog), mechanical, hydraulic, pneumatic, electromagnetic components, digital mathematical models of the object in the domestic complex ALLTED (**ALL TE**chnology **D**esigner) are described by joint systems of algebra-differential equations or only differential equations [2]. At the same time, all stages of designing non-linear dynamic systems are supported: constructing a mathematical model of the object, analyzing direct current (DC), analyzing time dynamics (TR) and frequency properties (AC), statistical analysis (Monte-Carlo), Fourier analysis (Four), worst-case analysis (WCD), sensitivity analysis (SA), optimization of parameters and characteristics (OPTIM), optimal assignment of tolerances (TOLAS), etc. This virtual laboratory is based on client-server technology and allows serving many clients located in different cities and countries.

It differs from existing foreign analogues (Pspice (Microsim Corp. USA), Saber (Analogy Corp. USA)) by:

- original algorithms of numerical procedures that allow solving "stiff" and insufficiently conditioned problems in DC, TR, SA modes;
- original algorithms for optimizing variable orders that take into account not three (as usual), but five terms in the equivalent Taylor series without calculating derivatives higher than the second order;
- powerful procedures for automatically calculating design parameters (time delays, rise and fall times of pulses, resonance frequency or bandwidth, power consumption, etc.) and functions of these parameters;
- the possibility of solving single- and multi-criteria optimization problems with parametric and functional constraints, and the optimized variables can be both primary parameters (voltages, currents, powers) and the above-mentioned design parameters;
- the possibility of using user-defined component models along with the use of powerful libraries of models and parameters;
- the procedure of optimal assignment of tolerances to the parameters of internal components, based on a given allowable deviation of the values of output parameters or variables, which allows organizing diagnostics of malfunctions in the structure of the object.

Such possibilities of modern modeling complexes allow in many cases to abandon the physical prototyping of designed products, replacing it with mathematical modeling (computational experiment), which is especially important when physical prototyping is difficult or practically impossible (for example, modeling a dam break, moving a rover on the surface of Mars, etc.). These innovative toolkits have allowed humanity to reach the current level of development, in particular, to create modern microchips (as an element base of Industry 4.0), powerful rocket technology, modernize the capabilities of mechanical engineering, energy, agriculture, industrial and civil construction, and make space flights and research.

COMPUTER-AIDED DESIGN (CAD)

CAD (Computer-Aided Design) systems appeared in the early 1960s and are a form of digital modeling, where the emphasis is on design and technical details. The term was first introduced in the late 1950s by *Dr. Patrick Hanratty*. He is often called the "father of CAD", and he was responsible for creating PRONTO, the software that started CAD. But AutoCAD, the first commercially available drafting software, was released in 1982. CAD is used to create 3D models and 2D models of objects. These models, which contain detailed information about the geometry, materials, and other characteristics of the object, can be of varying complexity and detail, from simple parts to complex mechanisms and buildings.

Although CAD and mathematical modeling are closely related, there are some key differences between them [1]:

Focus:

- *CAD:* the main focus of CAD is on the geometric representation of the object. It is used to create accurate 2D drawings and 3D models, with an emphasis on visualization, design, and documentation.
- *Mathematical modeling:* focuses on the mathematical description of the behavior of a system or process. It uses mathematical equations, formulas, and algorithms for analysis, forecasting, and optimization.

Tools:

- *CAD:* uses specialized software with tools for creating and editing geometric shapes, dimensions, annotations, etc. Examples: AutoCAD, SolidWorks, CATIA.
- *Mathematical modeling*: uses a variety of tools, including programming languages (Python, MATLAB), mathematical packages (Mathematica, Maple), specialized modeling software (Simulink, AnyLogic).

Results:

- *CAD*: the result is a graphical representation.
- *Mathematical modelling*: the result is a mathematical description of the system, forecasts, sensitivity analysis, and optimization solutions.

Applications:

- *CAD:* Widely used in engineering, architecture, and design for the design and development of products, buildings, and mechanisms.
- *Mathematical modeling*: Applied in various fields, including physics, economics, biology, and finance, for the analysis and prediction of complex systems and processes.

CAD and mathematical modeling can complement each other. For example, a CAD model can be used as a basis for mathematical modeling, providing geometric data and parameters. Mathematical modeling, in turn, can help in the analysis and optimization of a structure created in CAD. In other words: CAD is like drawing a detailed portrait of an object, and mathematical modeling is like writing an equation that describes how this object moves or functions.

CAD is an excellent tool for engineers not only at the stage of optimal design, it also allows preparing high-quality design and technological documentation for the manufacture of designed objects, as well as diagnosing and testing manufactured products. Initially developed for two-dimensional design, CAD has evolved into powerful software for three-dimensional modeling, providing accurate digital modeling for the design and testing of structures and infrastructure. High-quality work with CAD often requires powerful computer systems. Mastering CAD software may require significant training and practice. Premium CAD programs can be expensive, and licenses and updates add to the cost. Although there are free or cheaper alternatives, they may not offer the same wide functionality or compatibility. Therefore, CAD is usually not used for long-term maintenance and servicing of objects during their life cycle.

BUILDING INFORMATION MODELING (BIM)

In the 1970s, BIM (Building Information Modelling) technology appeared — a more advanced digital representation of the physical and functional characteristics of an object. BIM is the process of creating and managing digital information about a building throughout its life cycle. A BIM model contains detailed information about the geometry, materials, structures, systems, and equipment of the building. With the help of BIM technology, an information model is created that provides an accurate vision of the project as a whole. The development of ArchiCAD, one of the most popular BIM software products, began in 1982 under the leadership of *Gábor Bojár*.

One of the main advantages of BIM is the ability to visualize the object in three-dimensional space. This allows designers and customers to more accurately imagine the future object, as well as make changes and additions in real time. Visualization in BIM can be represented in various formats — from static images to interactive 3D models. The BIM model contains information about all components of the object — from structural elements to electrical equipment and plumbing. BIM allows integrating all data about the object into a single digital model, which becomes the basis for all stages of the object's life cycle — from design and construction to operation and reconstruction. The use of BIM technology in the design of houses includes the collection and complex processing of technological, architectural, structural, and economic information about the building, so that the building object and everything related to it are considered as a single whole.

A similar software product from Graphisoft, known in architectural design circles, is called BIMx and is used as an important addition to their main CAD program ArchiCAD.

Developing on the basis of the foundations laid by CAD, BIM complements operations on the object with geometric complex 3D models with a large amount of data. As with CAD, BIM has several key issues related to the efficiency and feasibility of its use for the daily management and operation of objects. Detailed, data-rich BIM models can be overwhelming, especially when only certain subsets of data are needed. BIM tools and practices can be complex and may require extensive training for professionals to become proficient. BIM software often requires high-performance computer equipment. Maintaining BIM models up-to-date, especially for long-term projects, can be resource-intensive.

The building information model is a virtual prototype of a building structure, so the use of BIM technology in the design of houses allows you to check and evaluate various solutions before the start of construction work. Today, there are many different solutions on the BIM software market that allow you to perform design in a three-dimensional format and use it at all stages of construction. In Ukraine, the most popular programs for BIM design are AutoCAD Architecture, Revit and Allplan Architecture [3–5].

The use of BIM technology in construction design makes every action transparent and provides complete control, and in automated mode, which guarantees high quality of design and construction work. Today, BIM is a standard tool for working in the construction industry, which allows optimizing the processes of design, construction and operation of facilities.

BIM also provides the ability to create and store digital documentation that contains all the necessary documents — from drawings and specifications to calculations and statistical data. This allows easy control of the design and construction process of the object, as well as improve communication between project participants. BIM technologies can also be used in the process of building a building. With their help, it is possible to monitor the execution of works in accordance with the project and specifications; optimize the construction process and manage the timing of the project; minimize the risk of errors and conflicts between project participants and reduce the amount of waste and material costs. BIM technologies can be used in the process of building operation. With their help, it is possible to create electronic maps of the building with information about each of its elements and systems; track changes and maintain the building in real time; optimize the use of building resources (energy, water, heat, etc.); manage the timing and costs of maintenance and repair of the building.

BIM can be used for project management, coordination, risk assessment and compliance with standards. However, there are many other opportunities to expand the functionality of BIM, including inventory management, quality management, construction planning, etc. Expanding the functionality of BIM will help make the construction process more efficient and transparent. The development of open standards and data exchange protocols can help eliminate this problem and ensure more flexible integration of BIM with other systems, such as the Internet of Things (IoT) technology.

The Internet of Things (IoT) is a technology that allows networked objects to exchange data with each other and with other systems. The integration of BIM with IoT allows you to receive real-time data on what materials are used, what conditions are on the construction site, etc. This will help to more effectively manage the construction process and prevent possible problems.

Virtual and augmented reality (VR and AR) can be integrated with BIM to create more accurate and realistic visualizations of the project. This will allow more effectively verify the project for compliance with requirements and interact with customers and other project participants. In addition, virtual and augmented reality technologies can help in training personnel and improving safety at the construction site. For example, virtual simulators can be used to train workers without risk to their lives and health. In general, the development of virtual and augmented reality technologies can lead to a large leap in the development of BIM technologies in the future, increasing their efficiency and accuracy, as well as simplifying their use.

When preserving architectural heritage, it is important to be able to carry out historical conservation and restoration of buildings in conditions when the original architectural and construction documentation is absent. Laser technology "Scan to BIM" [6] comes to the rescue, offering accurate 3D scanning of historical structures and artifacts, which allows creating detailed digital models that reliably reflect the intricacies of these objects. This technology allows restorers and conservation experts to carefully analyze the condition of heritage objects, identify areas that need attention, and plan restoration work with meticulous accuracy. In addition, digital preservation using BIM facilitates long-term management and documentation of historical objects, ensuring that their heritage is preserved for future generations who can appreciate and learn from it.

"Scan to BIM" is a revolutionary process that uses laser scanning technology to create a virtual copy of existing structures, from grand cathedrals to quaint cottages, when laser precision captures dimension, identifies materials, and even reveals structural elements hidden behind layers of paint and plaster. This data becomes the basis for a smarter and more efficient way to manage, reconstruct, and even redesign existing buildings. The "Scan to BIM" technology transforms not only repair work, but also how building management is carried out. Its digital model tracks performance, predicts problems before they become critical, and optimizes maintenance schedules. Imagine proactive repairs, extended equipment life, and reduced operating costs — all thanks to the foresight of BIM's digital intelligence.

The leader in the implementation of "Scan to BIM" technology is Harmony AT, which seamlessly integrates scan data with BIM methodologies, offering comprehensive solutions tailored to the diverse needs of projects. The company's services cover a wide range of applications, including reconstruction, modernization, clash detection and facility management. In addition, its commitment to quality assurance, transparent communication and customer satisfaction makes the company a reliable partner in the construction industry. Whether it is about reviving historical monuments or optimizing modern construction projects, Harmony AT's scan-to-BIM services embody efficiency, accuracy and excellence.

DIGITAL TWINS

Digital Twins are a new generation solution based on the foundation laid by CAD and BIM. While CAD and BIM have made significant contributions to the design and manufacturing stages, Digital Twins aim to rethink how we interact with, maintain, and operate the digital environment we create. These are not just static images, but dynamic models that reflect real objects or systems in real time.

Digital Twins (DT) are virtual models of real objects or processes that reflect their characteristics and behavior in dynamics [7,8]. They appeared as a result of the development of information technologies, in particular mathematical modeling, CAD and BIM.

The history of Digital Twins' development has several stages:

- *The origin of the concept (2002): Michael Grieves* first presented the concept of DT at a conference in the USA. He proposed creating virtual copies of physical objects to manage their life cycle.
- *First applications (2010s):* With the development of technology, the first real projects for the use of data centres appeared in the aerospace and manufacturing industries. They were used to model, optimise and predict the behaviour of complex systems.
- *Active distribution (2015-present):* Thanks to the development of the Internet of Things, artificial intelligence, and cloud technologies, data centres have become available for a wide range of applications. They are used in various industries, such as industry, energy, medicine, construction, and others.

A Digital Twin is a virtual representation of a physical object, system or process that covers its entire life cycle. It is constantly updated with real-time data and uses modelling, machine learning and artificial intelligence to optimise decision-making. This technology allows companies to analyse performance, predict failures, and improve overall efficiency.

The connection between CAD and Digital Twins is that CAD models serve as a starting point for creating Digital Twins [9]. A CAD model is static, that is, it reflects the object at a certain point in time. To create a Digital Twin that reflects the behavior of an object in dynamics, it is necessary to supplement the CAD model with information about the physical properties of materials, operating conditions, and other parameters. This information can be obtained from various sources, such as sensors, monitoring systems, and others.

Digital Twins created on the basis of CAD models can be used to solve various tasks, such as:

- *Predicting object behavior*: Digital Twins can be used to model the behavior of an object in different operating conditions. This allows predicting possible breakdowns and accidents, as well as optimizing equipment operating modes.
- *Process optimization:* Digital Twins can be used to optimize production processes, design new products, and other tasks.
- *Virtual training:* Digital Twins can be used to train personnel to work with complex equipment.

In general, CAD and Digital Twins are interconnected technologies that complement each other. CAD models are the basis for creating Digital Twins, and Digital Twins, in turn, expand the capabilities of CAD models, allowing modeling the behavior of objects in dynamics and solving various tasks.

A Digital Twin of a building, in turn, is an expanded version of a BIM model, which includes not only static information about the building, but also dynamic data about its operation, such as:

- Data from sensors (temperature, humidity, energy consumption).
- Information about the condition of systems (ventilation, heating, lighting).
- Data on the use of the building (number of people, traffic).

The relationship between BIM and Digital Twins:

- *BIM as a basis:* the BIM model is the basis for creating a Digital Twin of a building. It provides detailed information about the physical characteristics of the building, which is necessary to create a virtual model.
- *Dynamic data:* the Digital Twin complements the BIM model with dynamic data that is collected during the operation of the building. This allows creating a completer and more accurate picture of the building's condition.
- *Analysis and optimization*: the Digital Twin, created on the basis of the BIM model, can be used to analyze and optimize various aspects of building operation, such as energy efficiency, comfort, safety, and others.

Advantages of using Digital Twins based on BIM:

- *Better understanding:* the Digital Twin allows you to get a more complete understanding of the building and its functioning.
- Effective management: the Digital Twin helps to more effectively manage the building throughout its life cycle.
- *Optimization*: the Digital Twin allows you to optimize various aspects of building operation, such as energy consumption, comfort, and safety.
- *Forecasting:* the Digital Twin allows you to predict the behavior of the building in different conditions and scenarios.

In general, BIM and Digital Twins are interconnected technologies that complement each other. BIM models are the basis for creating Digital Twins, and

Digital Twins, in turn, expand the capabilities of BIM models, allowing modeling the behavior of buildings in dynamics and solving various tasks.

A Digital Twin consists of three main components:

- *Physical object*: the real object for which the Digital model is created.
- *Virtual model*: a digital copy of a physical object that contains information about its characteristics and behavior.
- *Connection between them*: provides data exchange between the physical object and its virtual model.

Different components of Digital Twins can be provided by different manufacturers and suppliers. Although they should work together, at least in theory, in practice this is not the case. Moreover, artificial intelligence (AI) and modeling tools, which are expected to perform the same function, may not support this capability. It is not uncommon to find an AI tool or modeling application from one supplier that is not able to replicate the capabilities of another supplier's product. This creates an *interoperability problem*. Different building blocks of Digital Twins form a large attack surface that cybercriminals can target. And given the need for hundreds and thousands of sensors connected to the Internet, the attack surface becomes even larger. Of course, the intentions of the attackers may be due to the importance of Digital Twins and related data for the activities of organizations. Having gained access to service data, criminals can demand large sums of cash from companies so that they do not disclose the illegally obtained find or compromise the Digital Twin.

Various undesirable consequences of security breaches indicate the need to give priority to *cybersecurity*. But effectively managing the cybersecurity of Digital Twins can be a daunting task for some organizations, given the vast amount of software, parts, and specialists needed to create a working digital twin.

Digital Twins are an important tool for increasing efficiency and optimizing various processes. They allow [10]:

- Predict the behavior of objects and systems.
- Model different scenarios and make informed decisions
- Optimize production processes and reduce costs.
- Improve the quality of products and services.
- Create new products and services.

In general, a Digital Twin acts as a single source of information about a project, which helps to improve collaboration. In addition, it provides all stakeholders with a deeper understanding of the products, processes, environments, and personnel involved in the project. It is also worth noting that several Digital Twins can be integrated, providing a deeper understanding of the interdependencies and the ecosystem in which they exist.

Digital Twins are classified according to different criteria, depending on the purpose and scope of application. Here are some of the most common types:

By level of detail:

- *Digital Twins of objects*: reflect individual physical objects, such as an engine, a machine tool, or a building.
- *Digital Twins of processes:* model technological or business processes, for example, production of products or logistics.
- *Digital Twins of systems:* describe complex systems consisting of many components, such as the energy system of a city or a transport network.

By purpose:

- *Digital Twins for design:* used to develop and design new products or systems.
- *Digital Twins for production:* used to manage production processes, optimize equipment operation, and control product quality.
- *Digital Twins for operation*: serve to monitor the condition of equipment, predict breakdowns and maintenance.

By the nature of the connection with the real object:

- *Digital Twins that reflect the past*: contain information about the object for a certain period of time in the past.
- *Digital Twins that reflect the present*: reflect the current state of the object in real time.
- *Digital Twins that predict the future:* used to predict the behavior of an object in the future based on data analysis and modeling.

By complexity:

- *Simple Digital Twins:* contain a limited amount of information about the object and its behavior.
- *Complex Digital Twins:* include detailed information about the object, its interaction with the environment, and complex behavior models.

One Digital Twin can combine several types, for example, be both a Digital Twin of an object that reflects the present and is used to predict the future. The choice of the type of Digital Twin depends on the specific task and requirements for the accuracy of the model. It is important to note that the development of technologies, such as artificial intelligence and machine learning, contributes to the creation of increasingly complex and functional Digital Twins, which find applications in various industries.

APPLICATIONS OF DIGITAL TWINS IN CAD

Digital Twins are used in many areas, helping to solve various problems and optimize processes. Here are some specific examples [7,10]:

Industry

- *Manufacturing:* Digital Twins are used to model production lines, optimize equipment operation, predict breakdowns, and manage product quality. For example, General Electric uses Digital Twins of aircraft engines to monitor their condition in real time and predict the need for maintenance.
- *Energy*: Digital Twins help in managing energy systems, forecasting consumption, optimizing equipment operation, and integrating renewable energy sources.
- *Automotive*: Digital Twins are used to design cars, simulate their behavior on the road, optimize production, and develop driver assistance systems.

Cities and infrastructure

- *Smart cities:* Digital Twins of cities are used to manage traffic flows, optimize the operation of utilities, monitor the state of infrastructure, and respond to emergencies.
- *Construction:* Digital Twins of buildings help in the design, construction, and operation of buildings, allowing to optimize the use of resources, control the quality of work, and predict the condition of structures.

Healthcare

- *Personalized medicine*: Digital Twins of patients can be used to simulate the body's response to various treatments and predict the development of diseases.
- *Drug development:* Digital Twins help in the development of new drugs by simulating their effect on the body and predicting effectiveness.

Other areas

- *Logistics:* Digital Twins help in optimizing delivery routes, managing warehouse stocks, and forecasting demand.
- *Agriculture:* Digital Twins of fields are used to monitor the condition of crops, predict yields, and optimize the use of resources.

These are just some examples of the use of Digital Twins. With the development of technology, the scope of their use is constantly expanding, opening up new opportunities for optimizing and managing various processes. *Usually, CAD is a fundamental step towards creating a Digital Twin; it is the foundation* [11]. Therefore, *it can be said that without CAD there is no Digital Twin*. In fact, Digital Twin platforms integrate with CAD and BIM solutions. For example, Autodesk Tandem, a Digital Twin platform, is designed to integrate CAD geometry with Revit, geospatial data, facility management data, IoT data.

It is possible to develop a "fault dictionary" for the future Digital Twin using mathematical modelling and CAD tools during the design of objects and processes. To do this, it is necessary to identify in advance a set of influential parameters or model variables to measure which control ports should be provided in the structures and processes to be designed. Then, using powerful techniques for multivariate analysis, sensitivity analysis, optimization, worst-case evaluation of the deviation of component parameters from nominal values (WCD), and the inverse of this assigning optimal tolerances, statistics can be collected for DC, TR, and AC modes on the deviation of the output parameters of the object (process) from the effects of destabilizing factors (temperature, radiation, humidity, etc.) and, for example, component "aging" over time. All this can be amplified by statistical analysis, which introduces certain distribution laws for the above-mentioned deviations of component parameters. The availability of such a pre-modelled "fault dictionary" will greatly facilitate the interpretation of measurement data taken on a real installation manufactured by the design documentation. If the mathematical and CAD models are kept together with the modelled "fault dictionary", the transition to the Digital Twin will be reduced to additional investigations of these models, taking into account the measured data from the real object, if the "fault dictionary" information is not sufficient.

THE PROCESS OF CREATING A DIGITAL TWIN

The process of creating a Digital Twin can be imagined as a sequence of steps, each of which has its own characteristics and requires certain resources.

1. **Defining the goal and scope:**

- At this stage, it is important to clearly define why a Digital Twin is being created (monitoring, analysis, simulation, optimization, etc.), what tasks it should solve, what parameters of the object or process need to be modeled.
- It is also important to determine what level of detail of the model is needed to achieve the goals (machine, production process, building, city). Today,

it is common to refer to objects with a deep interconnection between their physical and computational elements as "*cyber-physical systems*" [12,13].

2. **Data collection:**

- To create a Digital Twin, data about the object or process being modeled is required.
- This can be data on the physical properties of the object (geometry, materials, physical characteristics), sensor data on the state of the object (temperature, vibration, pressure, etc.), previous data on the operation of the object, accidents, maintenance.
- It is important to ensure the quality and reliability of the data, since the accuracy and adequacy of the Digital Twin depends on this.

3. **Building a model through modeling and simulation:**

- *3D Modeling:* creating a three-dimensional model of an object using CAD (software).
- *Physical models:* development of models that describe physical processes (mechanical, thermodynamic, electromagnetic models).
- *Behavioral models*: models that predict the behavior of the system under various conditions.

4. **Data integration:**

- *Platform*: selection or development of a platform that can integrate all data streams and ensure interaction between physical and digital objects.
- *API and Interfaces:* development or use of existing APIs for data exchange between different systems.

5. **Analytics and Data Processing**

- *Analytical tools:* using machine learning, artificial intelligence to analyze data, predict wear and tear, optimize work.
- *Visualization:* creating interfaces for visualizing the status and results of the analysis.

6. **Validation and verification:**

- *Testing:* checking the accuracy of the Digital Twin by comparing its behavior with a real object.
- *Adjustment:* Making changes to the model based on real data to improve accuracy.

7. **Deployment and use:**

- *Integration into business processes*: using a Digital Twin in daily operations, maintenance planning, equipment modernization.
- *Personnel training:* training users to work with a Digital Twin.

8. **Update and support:**

- *Monitoring:* continuous monitoring of both the physical object and the Digital Twin to detect deviations.
- *Updating:* regularly updating the model with new data to maintain relevance.

Creating a Digital Twin is a complex and multi-stage process that requires significant resources and competencies. However, a properly created Digital Twin can be a powerful tool for increasing efficiency, optimizing processes, and making informed decisions.

Recall that digital modeling is the basis for the functioning of Digital Twins, so the choice of modeling algorithms plays a dominant role in their implementation due to the significant difference in the nature of objects and the tasks they perform [11]. This can be demonstrated by examples of specifications of Digital Twins for a rocket flight control unit, for a bridge structure and a process micro-controller (PCM), presented in Fig. 1, Fig. 2 and Fig. 3, respectively.

DIGITAL TWIN OF A ROCKET FLIGHT CONTROL UNIT

Main tasks:

- Specifications of the Digital Twin of the rocket flight control unit.
- Modeling the dynamics of rocket flight in real time.
- Predicting the trajectory and possible deviations.
- Controlling the guidance system and trajectory correction.
- Diagnostics and troubleshooting.

Algorithms and methods:

Mathematical modeling:

- Differential equations of motion (Newton's, Euler's laws) taking

into account interaction with

- the atmosphere and space environment.
- Models of aerodynamics and jet propulsion.
- Trajectory calculation algorithms and ballistic models.

Signal and data processing:

- Kalman filters for processing data from sensors.
- Methods of statistical analysis to estimate flight parameters.
- Pattern recognition algorithms to detect deviations.

Artificial intelligence and machine learning:

- Neural networks for forecasting and control.
- Reinforcement learning algorithms for control optimization.

Fig. 1. Specifications of the Digital Twin of the rocket flight control unit

DIGITAL TWIN OF A BRIDGE STRUCTURE

Main tasks:

- Modeling the behavior of the bridge under load.
- Analysis of the strength and stability of the structure.
- Predicting wear and possible damage.
- Monitoring the condition of the bridge in real time.

Mathematical modeling:

Finite element method (*FEM*):

- Dividing the structure into many elements.
- Calculation of stresses and strains in each element.
- Analysis of the general behavior of the structure under load.

Material modeling:

- Models of elasticity, plasticity and fracture of materials.
- Taking into account the influence of temperature, humidity and other factors.

Statistical analysis:

- Risk assessment and probability of damage.
- Predicting the residual life of the structure.

Artificial intelligence and Machine learning:

- Classification algorithms for detecting defects based on data.
- Neural networks for predicting durability.

Fig. 2. Specifications of the digital twin of a bridge structure

DIGITAL TWIN FOR A PROCESS MICROCONTROLLER (PCM)

Main tasks:

- *Real-time modelling*: the Digital Twin should reflect the state of the PCM with high accuracy and synchronization.
- *Interaction with the external environment*: the digital twin should take into account the impact of external factors on the operation of the PCM
- *Debugging and testing capability:* the Digital Twin allows developers to test the operation of the IPCM without using additional equipment.

Modelling the logic of work:

- *Boolean algebra*: to describe logical operations, input/output states, switching conditions.
- *State machine*: to simulate the sequence of actions, transitions between operating modes.
- Controller programming languages (Ladder Logic, ST, FBD): to describe process control algorithms.

Modelling process dynamics:

- *Differential equations:* to describe the dynamics of physical quantities (temperature, pressure, level, etc.).
- *Difference equations*: for discrete modeling of processes in time.
- *Transfer functions*: to describe the dynamic properties of control objects.

Signal processing algorithms:

- *Filtering*: to clean signals from noise and distortion (Kalman filter, moving average).
- *Conversion*: to convert signals from analog to digital form and vice versa (ADC, DAC).
- *Scaling*: to bring signals to the desired range of values.

Communication algorithms:

- Data exchange protocols (Modbus, Profibus, Ethernet/IP): to ensure communication between the PCM and other systems.
- Synchronization algorithms: to coordinate the operation of various components of the digital twin.
- Error handling mechanisms: to ensure communication reliability.

Visualization and interface algorithms:

- *Graphic libraries*: to create a visual representation of the state of the PCM and the technological process.
- *Data visualization algorithms*: to display trends, graphs, charts.
- *User interfaces*: to provide convenient access to information and control.

Fig. 3. Specifications of the Digital Twin of a process microcontroller

Differences and features

- *Different physical models*: for a rocket models of flight dynamics and aerodynamics are used, for a bridge — models of structural mechanics and resistance of materials, for a process microcontroller — models of functioning under the influence of external factors.
- *Different time scales:* rocket flight and microcontroller reactions occur quickly, so real-time modeling is required. The bridge is operated for a long time, so long-term forecasting is important.
- *Different types of data:* for a rocket, data from sensors and control systems are used, for a bridge — data on loads, the state of materials and structures, for a microcontroller — data from sensors about the state of the technological process.

That is, the creation of digital twins for different objects requires the use of different algorithms and modeling methods, due to the specifics of the tasks and physical principles underlying the functioning of each of them.

CONCLUSIONS

Digital Twins are becoming increasingly commonplace in many industries, shaping the future. The growing adoption of Digital Twin technology is driven by the convergence and development of technologies such as the Internet of Things, sensors, artificial intelligence, machine learning, cloud computing, simulations, and more. This technology uses data to bring to life once static CAD models. This gives many advantages.

Digital Twins can describe physical objects, diagnose problems, analyze results, and predict future events. Due to these advantages, companies and organizations in the manufacturing, medical, mining, infrastructure and planning industries, agriculture and logistics are implementing Digital Twins. However, their implementation has not been without certain problems. From low data quality and lack of data standardization to complex change management, cybersecurity threats, inaccurate representation, and the need to protect intellectual property. Fortunately, there are ways to get around these problems.

Let's present a comparison of the basic properties of CAD, BIM and Digital Twin technologies in the form of a table.

Comprehensive comparison between CAD, BIM and Digital Twins

Feature	CAD (Computer-Aided Design)	BIM (Building Information Modeling)	Digital Twins
Main function	Creating 2D and 3D models of for objects	Creating and managing building information throughout its lifecycle	Virtual representation of a physical object or process, reflecting its behavior in real time
Model type	Geometric model	Information model	Dynamic model
Data	Geometry, dimensions, materials	Geometry, dimensions, materials, structures, systems, equipment, lifecycle data	Data from sensors, status information, historical data, forecasts
Connection with the real object	Static	Static with dynamic elements	Dynamic, updated in real time
Applications	Design, visualization, documentation	Design, construction, operation of buildings	Monitoring, analysis, optimization, forecasting, training
Examples	Drawings of parts, models of machines, diagrams	3D model of a building with information about all its elements	Digital Twin of an aircraft engine, virtual copy of a city, patient model
Limitations	Limited information about the object, static model	Limited information about the dynamics of the object	Complexity of creation and maintenance, requires a large amount of data

Key differences:

- CAD focuses on the geometry and shape of the object, while BIM includes a wider range of information about the building, including its functionality and characteristics.

- Digital Twins go even further, providing a dynamic representation of an object or process that is updated in real time.
- CAD and BIM are mainly used for design and construction, while Digital Twins have a wider range of applications, including monitoring, analysis, and optimization.

Artificial intelligence (AI) is significantly impacting the development of Digital Twins, enhancing their capabilities and expanding their scope of application. Here are some key aspects of this impact [14]:

- **Real-time data analysis**

Prediction: AI can analyze data streams coming from IoT sensors to predict the future state or behavior of a physical object. For example, AI can predict when a machine will need maintenance before a breakdown occurs.

Optimization: Using machine learning, Digital Twins can optimize the operation of systems, such as the energy consumption of buildings or the performance of production lines.

- **Process automation**

Automatic model updates: AI can automatically update digital models based on new data, ensuring that the Digital Twin is up-to-date with its physical counterpart.

Automation of response: AI can not only detect anomalies or problems, but also automatically initiate appropriate actions, such as ordering spare parts or adjusting system parameters.

- **Improving simulations**

Complex scenarios: AI allows modeling and testing much more complex and diverse scenarios, making it possible to explore “what if” situations without risk to the real object.

Adaptive learning: AI models can learn from historical data and real-world interactions, improving the accuracy of simulations over time.

- Personalization and adaptation

Individual solutions: AI can adapt Digital Twins for individual needs, such as customizing the user interface in cars or adapting medical equipment for a specific patient.

- **Improving human-machine interaction**

Natural language and interfaces: AI, especially NLP (natural language processing), allows more natural interaction with Digital Twins through voice commands or text queries.

Virtual assistants: Using AI to create virtual assistants that can help manage Digital Twins by providing recommendations or performing tasks.

- **Security and cybersecurity**

Threat detection: AI can be used to detect anomalies that may indicate cyberattacks or other security problems in systems associated with Digital Twins.

- **Future development**

Cognitive Digital Twins: In the future, the development of cognitive Digital Twins is expected, which not only reflect the state of the object, but can also “think” and “make decisions” similar to their physical counterpart, using advanced AI algorithms.

Integration with blockchain: To ensure data security and trust in Digital Twins, blockchain technology can be used to ensure data immutability and transparency.

Thus, AI not only improves the capabilities of Digital Twins, but also expands their application, making them more intelligent, adaptive, and integrated into various aspects of human life and industry.

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INFORMATION ON THE ARTICLE

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ВІД CAD і BIM ДО ЦИФРОВИХ ДВІЙНИКІВ / А.І. Петренко

Анотація. Цифровий двійник — це віртуальна модель фізичного об'єкта або системи, яка використовує дані в реальному часі для моделювання поведінки свого реального аналога. Це може бути продукт, машина, будівля або навіть ціле місто. Цифрове моделювання є фундаментальною технологією для створення цифрових двійників, оскільки воно забезпечує методологію для подання фізичних об'єктів у віртуальному світі. Computer-Aided Design (CAD) може бути використано для створення початкової моделі цифрового двійника. Building Information Modeling (BIM) є спеціалізованою формою CAD, яка зосереджена на будівельних проектах і містить більше інформації, ніж просто геометрія. BIM включає в себе не тільки геометрію, але й дані про час, витрати, експлуатацію та обслуговування. Досліджено, як ці технології дедалі більше інтегруються одна в одну, базуючись на застосуванні математичного моделювання, яке шляхом проведення віртуальних обчислювальних експериментів забезпечує розуміння складного функціонування об'єктів та прийняття обґрунтованих рішень у різних сферах. Інтеграція цифрових двійників і CAD трансформує способи проектування, моделювання та оптимізації продукції в промисловості. BIM моделі можуть стати основою для створення цифрових двійників будівель, які потім використовуються для оптимізації енергоспоживання, обслуговування та ремонту. З ростом інтернету речей (IoT), цифрові двійники отримують дедалі більше реальних даних, що робить їх ще більш точними і корисними для прогнозування та оптимізації. Використання штучного інтелекту для аналізу даних, зібраних цифровими двійниками, дозволяє прогнозувати поломки, оптимізувати процеси і навіть автоматизувати управління системами.

Ключові слова: математичне моделювання, цифрове моделювання, CAD і BIM, цифрові двійники (ЦД), інтернет речей (IoT), застосування штучного інтелекту в ЦД.