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Digital Twins of Physical Objects and Their Role in The Modern Industrial Revolution

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Abstract

The paper investigates the role of digital copies of physical objects (digital twins) in the development of the modern industrial revolution. The author determines that the technologies and research of digital twins (DT) have been subjected to critical and systematic analysis from a special point of view of application in the manufacturing industry and energy. Even taking into account the fact that the manufacturing and energy industries are the flagman of many digital technologies, reports and publications on the application of energy DT technologies and research turned out to be relatively few in comparison with the manufacturing and construction sectors.

Energy DT can provide higher energy efficiency and the use of renewable energy sources by expanding the scope of application to include meso- and macro-scales and cover the entire life cycle, but this issue will be studied in the future.

Keywords: digital twins, physical objects, industrial revolution, energy consumption, energy efficiency.

Introduction

Modern industrial enterprises today operate in conditions of aggravation of global environmental problems, in connection with which there is a growing need of reducing the energy consumption and greenhouse gas emissions, but at the same time, in order to remain competitive, it is necessary to ensure optimal operating costs and maintenance costs. Accordingly, it is an extremely urgent issue to conduct large-scale research for the development and implementation of new technological processes, integration of technological systems, the use of environmentally friendly fuels and digital technologies, minimizing greenhouse gas emissions, etc.

It is known that industry uses a huge amount of thermal energy in production processes, which entails a third of all global CO2 emissions. Issues related to the development of energy management systems were studied by a number of researchers who proposed solutions such as the development of energy efficiency KPIs and the long-term definition of strategic goals, the removal of barriers to energy management, etc.[1] Experts also pointed out that most modern systems of monitoring, control and management of energy consumption need serious rethinking and modernization to ensure the rapid reduction of emissions needed in the near term. The researchers also considered, among other things, the introduction of digital copies of physical objects (digital twins) technology, which demonstrates great potential as a digital tool for determining optimal physical solutions, which makes it possible to effectively use the company's assets and carry out its anti-crisis environmentally safe operation.

The process of digitalization with the help of digital twins in the energy sector is being considered for effective management and optimization of operations at facilities in order to minimize specific energy consumption, assist in energy-efficient design and development of their production processes and facilities, as well as for the development of an environmentally friendly energy roadmap for the transition to renewable energy sources, fuel. The above technology can lead to a paradigm shift that will radically change the way the facility operates, resulting in minimizing specific energy consumption and increasing the integration of renewable energy sources in all time horizons, including real–time coordination, production planning and transformation of existing technologies [2].

The purpose of the study is to consider the role of digital copies of physical objects (digital twins) in the development of the modern industrial revolution.

Materials and methods

In the process of writing the study, an array of literature was analysed within the framework of the research topic, comparative and analytical research methods were used to process the data obtained.

Results

The term "digital twin" (DT) was introduced in 2003 and was intended to describe a system that includes a physical part, a digital (or virtual) copy and a connection between two domains. The subsequent expanded version of this concept included categories such as prototype DT, instance DT and aggregate DT.

Some authors later defined DT as a high-precision simulation without a clear indication of the connection between the virtual and physical parts. As DT research progressed, more and more researchers focused on the connection between virtual and physical parts, including "live" models, updated virtual models, and bidirectional connections. In addition, the concept of self-adaptation in DT began to be studied with ideas such as adaptability and self-evolution [3].

Since 2010, significant growth has been noted in the development of DT technology, while it has interested specialists from the fields studying renewable and sustainable energy sources. In particular, with regard to these areas, it was proposed to divide the definition of DT into three separate categories according to the level of data integration (from smaller to larger): digital model, digital shadow and digital double. The connection between physical and digital counterparts was considered an important and distinctive feature. As a result, the digital model should only include an automated data flow between the physical and digital twins.

The digital shadow includes a one-way automated data flow, while the digital twin requires their two-way automated flow. Written from the point of view of management engineering, the study narrowed the definition of DT to fully automated applications. It was proposed to classify the DT representations into 5 categories: the complexity of the model, the existence of a physical twin, obtaining data from a physical twin, machine learning of operator preferences and machine learning of the system and environment. In this definition, additional discrimination of DT is carried out based on their connection with a physical twin, and the complexity or accuracy of DT is introduced, while the focus is only on approaches to machine learning modelling, and not classification of DT modelling in a broader sense [4].

In the recent period, the use of the term "digital twin" in the scientific literature has increased dramatically, which indicates the following: technological and energy y DT are new areas in the field of digitalization that require more attention due to the pace and scale required to reduce greenhouse gas emissions in the face of global environmental problems [5].

Each of the definitions contains the same basic elements as the original one, but also includes changes specific to the specific application area. The popularity of the DT concept has increased, and now it covers many research disciplines and industries.

The study of multiple definitions highlights the breadth of expectations placed on the concept of DT. The general concept that can be distinguished is that DT is a digital representation and is associated with something physical; however, what exactly is represented varies depending on product design, process design, asset operation and system management, depending on the experience and goals of the party proposing the definition [19].

To date, there is a significant number of definitions of the concept of DT in the literature. The main ones are presented in Table 1.

Table 1 *Definitions of the concept of "digital twin" in the scientific literature*

Source	Definition
E.H. Glaessgen, D.S. Stargel [6]	DT — it is an integrated, multiphysical, multiscale, probabilistic simulation of a vehicle or system in its assembly state, which uses the best available physical models, sensor updates, fleet history, etc. to reflect the life of the corresponding twin.
J. Lee, E. Lapira, B. Bagheri, H an Kao[7]	A cyberphysical model is a DT of a real machine that runs on a cloud platform and simulates a state of operability with integrated knowledge from both data—driven analytical algorithms and other available physical knowledge.
M. Grieves [8]	The DT conceptual model consists of three main parts: a) physical products in real space, b) virtual products in virtual space, and c) data and information connections that link virtual and real products together.
J.D. Hochhalter, W.P. Leser, J.A. Newman, E.H. Glaessge n, V.K. Gupta, V. Yamakov, S.R. Cornell, S.A. Willard, G . Heber [9]	DT is a lifecycle management and certification paradigm, according to which modeling consists of the state of the vehicle in the state of construction, tested loads and conditions, as well as other vehicle—related stories, to ensure high-precision modeling of individual aerospace vehicles throughout their entire service life.
R. Rosen, G. von Wichert, G. Lo, K.D. Betten hausen [10]	The DT concept is the next wave of modeling and simulation, and simulation is the main functionality of systems that use continuous support throughout the entire lifecycle, for example, operation and maintenance support with direct communication with operational data.
Y. Chen[11]	DT is a computerized model of a physical device or system in which all functional features and connections with working elements are presented.
Z. Liu, N. Meyendorf, N. Mr ad [12]	DT is a living model of a physical asset or system that constantly adapts to operational changes based on collected online data and information and can predict the future of the corresponding physical counterpart.
Y. Zheng, S. Yang, H. Chen g [13]	DT is a set of virtual information that fully describes potential or actual physical production from the microatomic to the macrogeometric level.
F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, F. Sui [14]	Based on previous literature, the authors proposed characteristics of DT, including: (a) real-time reflection; (b) interaction and convergence; and (c) self-development.
W. Kritzinger, M. Karner, G. Traar, J. Henjes, W. Sihn [15]	Classification of DT into three subcategories according to their level of data integration, including digital model, digital shadow and digital copies.
A. Madni, C. Madni, S. Luce ro [16]	DT is a virtual instance of a physical system (twin), which is constantly updated with data on the performance, maintenance and status of the latter throughout the life cycle of the physical system.
P. Wang, M. Yang, Y. Peng, J. Zhu, R. Ju, Q. Yin [17]	DT can be considered as a paradigm in which selected online dimensions are used, which are dynamically assimilated into the

	modeling world, while the working modeling model adaptively directs the real world in the opposite direction.
Q. Liu, B. Liu, G. Wang, C. Zhang [18]	DT refers to a virtual object or set of virtual things defined in a digital virtual space that have representation relationships with real things in physical space.

As a generalized definition, DT is a digital (or virtual) representation that looks, behaves and connects to a physical part or system in order to improve or optimize decision–making for temporal horizon. The combination of all three attributes determines the paradigm shift of DT, separating DT from traditional representations that fix either the similarity or behavior of a physical part or system, but do not have a close connection with the physical system. Although all three attributes are necessary to achieve the best results, the validity of each attribute depends on the purpose and application of the DT. In this light, DT is a comprehensive class that includes many possible variations and provides freedom for researchers from different disciplines to advance in the field of DT.

Discussion

Experts note that energy DT technology can provide greater integration and optimization at industrial (and commercial) facilities, which will lead to a phased increase in energy efficiency and the use of renewable energy sources. The implementation can also be extended to the "edge of the site" to further minimize resource consumption, waste and emissions [20]. The edge of the site refers to the community in the area surrounding the site, such as other industrial facilities, commercial and public facilities, and residential buildings. In many ways, energy DT technology can help to put into action and synthesize the concepts of circular economy and circular integration, industrial symbiosis and industrial ecology, full integration of the facility and extended control throughout the facility [21].

Industrial facilities often contain several operations and processes that output signals, measurements and other data that form the main input data for energy DT. They can also receive input data from the "edge of the site" (for example, measurement of solar energy on roofs in a community) and from external factors (for example, weather data and forecasts). Strategic, multidimensional goals of energy DT (for example, minimizing the cost of the life cycle, energy and emissions) and restrictions (for example, 100% renewable energy) are set by the owner of the business, which is affected and limited by government regulation. The proposed energy DT structure provides one standard solution to achieve the decision-making process from government regulations to plant divisions.

The output of energy DT includes a wide range of effectors that allow you to optimize the operations and assets of the site. These actuating elements at the facility can be automated or non-automated and include, for example, changes in control models and settings, plans for the installation of new technologies and modernization of existing technologies, as well as information about the status of assets for preventive maintenance [22]. An additional set of signals and effectors is also transmitted from the DT energy twins to the "edge of the site" in order to influence the management, operation and installation of relevant assets in the community. Assets in a community can be sources or absorbers of energy ad have a number of ownership patterns in relation to the property, including off-site ownership, joint ownership with the site and off-site assets owned by the site. The ownership model and any subsequent contract determine how the site can interact with the site's edge asset. For example, a site may own solar panels on the roof of a residential complex and, therefore, have full control over their operation and pay rent for roof space to individual owners.

The energy DT itself includes components of a digital model, a shadow copy and a manager to perform the necessary information exchange and complex calculations. The structure also establishes a high-level relationship between the three levels of DT technology associated with the attribute. The "Digital Model" element contains basic digital descriptions of the similarity and behavior of each site resource (dynamic or non-dynamic). The "Digital Shadow" element includes and applies multiple instances of digital models to simulate and predict how the site (and others) assets will work over time. The Digital Manager element uses multiple instances of digital shadows to test, validate, and optimize operations with assets in the digital domain before outputting valuable information through various effector signals to change the action [23].

To date, research directions in the field of energy DT technology, according to the analysis of the literature, include the following:

1) Improvement of applications of DT energy twins in operation. In particular, the development of energy DT technology in the service sector is underway in many systems and industries, such as automotive, manufacturing, construction and aircraft construction. Since many researchers note that maintenance should be the main area of energy DT, this should become the direction of further development of energy DT applications in the technological thermal power industry [24].
2) Representation of energy DTS in multiple application scales and determination of their full life cycle.

Current research and applications of energy DT are aimed at micro- and mesoscales, for example, at a specific work unit, such as a furnace and a power plant. In order to obtain overall optimization and efficiency of the system, it is necessary to expand the scale of energy DT to a macro scale that can combine various energy sources, such as solar, hydro and wind energy, with different requirements in both industrial and residential sectors [25].

The development of energy DT for technological thermal power engineering is usually focused on one of three stages: individual design, processing and maintenance. In the future, energy DT technology should cover the entire life cycle. For example, based on the current technological situation, the energy DT can provide a proposal for process modernization to improve energy efficiency and an optimal maintenance schedule at the same time.

Taking into account the full life cycle also means that there is an opportunity to focus on life cycle energy and emissions reduction. Many countries have set target years for achieving net zero emissions in carbon equivalent (for example, for some European countries, the target is 2050). Researchers should use energy DT technology to help the manufacturing and energy industries achieve zero carbon emission goals by ensuring optimal process design using renewable energy sources, improving processing energy efficiency, and obtaining an optimal maintenance schedule.

3) Development of adaptive technology of energy DT.

It is well known that the productivity of processes changes over time (for example, pollution), state transitions occur (for example, cleaning) and they work in constantly changing conditions (for example, external energy markets). It is necessary to develop a new type of energy DT technology that automatically detects and adapts to these changes. The selfadaptability attribute for energy DT adds the ability for energy DT to change and recalibrate their behavior and likeness when working and external conditions change, so that it satisfies operational goals and constraints (which can also change over time) and adapt to a possible future. changes in physical assets [26].

In addition, adaptability can be extended by reconfiguring equipment. Similar and possibly inspired by programmable gate arrays (FPGAs) that can be modified at runtime to represent any type of logic circuit, an automated enterprise management system controlled by a digital twin will be able to quickly reconfigure processes such as manufacturing while providing change management. In addition, the FPGAs themselves can be included in the computer equipment on which the plant operates, which will allow for the rapid deployment of new control algorithms corresponding to the purpose, which will be tested for the first time on energy DTS. All this will require the creation, hopefully, of an open architectural model, specification languages and optimized reconfiguration and planning algorithms.

4) Improving the security of the energy DT platform. The manufacturing and energy industries are the most important infrastructure in the global supply chains of raw materials and advanced products. If energy DTS are directly involved in monitoring and activating the site, this provides a greater attack surface for cybercriminals and hostile nation states with the intention of gaining leverage on their target.

The researchers note the relevance of what data can be tracked and how much of it should be sent to the cloud, which can lead to greater vulnerability of the system. For example, edge computing and federated learning can be used as a means to conduct initial training locally near an industrial enterprise before sending a partially trained model that will set the raw data to a centralized location for further aggregation.

In addition, research is needed to develop active and multi-level protection for energy DT platforms. Active security means that the energy DT itself searches for and eliminates threats using self-defense mechanisms. Multi-level security allows you to penetrate the first security level in order to trigger a reaction and stop an attack at subsequent levels [27].

5) Data ownership structures of energy DT and sovereignty. EDT will need access to a large amount of data from various sources in order to make the best possible decisions. However, in a competitive market, data on industrial energy is often treated as strictly confidential due to commercial importance. As a result, it is necessary to develop a framework that allows data exchange, respecting the value of the data for the owner, as well as the broader value of the data for the country. For example, data sovereignty is an area of research that aims to identify and understand how data can be subject to laws and governance structures in a country.

6) Specification of the requirements for the energy DT software. In consultation with stakeholders, further work is needed to identify and analyze the requirements for the energy DT software in order to better establish what exactly it should perform. This is followed by the development of specification languages to describe the various components, interactions and goals that the system will have to implement, as well as the uncertainties in which it will operate. Tools and methodologies should be developed to enable the development and verification of energy DT and possibly automatically generate verified code artifacts. The standardized specification language for Energy DT will also ensure automatic compatibility of new and existing auxiliary software.

7) Development of DT energy twins based on artificial intelligence (AI). The use of machine learning and other artificial intelligence algorithms for energy DT should be

more mature, by developing a clear understanding of what these methods can provide for the manufacturing industry and energy. On the one hand, traditional AI optimization methods, such as simulated annealing and evolutionary optimization, can significantly reduce hard-to-reach search areas and are widely used for process optimization and synthesis. On the other hand, data-driven methods such as recurrent neural networks and dynamic mode decomposition with control can use computations to generate black box models or hybrid models of systems that are too difficult to model in the first principles.

In addition, time series forecasting algorithms, such as the autoregressive integrated moving average, can be used to model external factors and other uncontrolled events. Reinforcement learning methods, including deep reinforcement learning, can be used to model complex decision-making at the strategic level. However, in any data-based case, research is needed to automatically incorporate various AI engineering processes into the system, such as function development and training-validation-testing, as well as the use of explicable AI models to ensure quality [28].

8) Requirements for energy DT calculations, including energy efficiency analysis. Since the main goal of energy DT technology for the manufacturing industry is to reduce costs, energy and emissions, a careful balance must be maintained to maintain sufficiently low computational requirements, including power, energy and emissions expended during the operation of energy DTS. For example, modern deep learning algorithms are considered very energy-intensive, which is also compounded by the sharply growing volumes of network data transfer of the site and peripheral IoT data on which they will rely. If the computational requirements increase significantly, there may be a compromise between the marginal benefit obtained and the power consumed.

Conclusion

Technologies and research of digital twins (DT) have been subjected to critical and systematic analysis from a special point of view of application in the manufacturing industry and energy. Even taking into account the fact that the manufacturing and energy industries are the flagship of many digital technologies, reports and publications on the application of energy DT technologies and research turned out to be relatively few in comparison with the manufacturing and construction sectors.

From the point of view of what the processing and energy industries are interested in, the energy DT technologies that they are currently using and primarily stimulate implementation, applications are most noticeable in the energy-related areas of energy in general, energy efficiency or decarbonization.

Energy DT can provide higher energy efficiency and the use of renewable energy sources by expanding the scope of application to include meso- and macro-scales and cover the entire life cycle, but this issue will be studied in the future.

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