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Digital twins in the oil and gas industry

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Abstract

The paper provides a review of Russian and international scientific sources concerning digital twins in the oil and gas industry. The review considers the origin of the concept and its development from inception to present. Due to ambiguity in use of the 'digital twin' as a term, several definitions are provided and briefly analyzed. The paper covers classification of digital twins as well as various approaches to their creation and technologies employed in the process. Use cases are taken from practice of Russian and global companies. Conclusions are made on prospects of the analyzed research field, including advantages and disadvantages of implementing digital twins in industrial facilities.

Keywords: *Digital twin; Simulation; Technologies; Smart manufacturing; Multilevel components circuit.*

1. Introduction

The question of transition to more efficient high-tech manufacturing methods in the context of global competition has become more relevant recently. Thanks to intense development of information technologies, now we may collect, store, transmit and analyze large arrays of data, leading to change in perception of standard industrial control approaches. A number of countries around the globe developed and approved strategic development programs, such as Plattform Industrie 4.0 in Germany, Made In China 2025 in China, Usine de Future in France, National Technological Initiative in Russia and some others. They all are aimed at increasing workforce productivity, implementing modern knowledge-intensive technologies and increasing economic efficiency of manufacturing.

In practice, implementation of such strategies appears as increased level of industrial automation and a wider digitalization of production processes. Fundamental causes for such changes are found in the necessity for fast and precise modeling of both product and its production process with the aim of saving the resources and keeping the manufacturing profitable in the modern age, when there is a significantly larger demand for customized products. Researchers actively discuss transition to so-called Smart Manufacturing, that is, control based on network-enabled information technologies and analysis of large volumes of data [1].

The approach that allows bringing together various automation technologies and describes interactions between virtual (sensor data, mathematical and geometric models) and physical (machinery, actuators, robots) layers has become known as Digital Twin (DT) approach. Gartner (USA), a global leader in research consulting and S&P 500 company, named digital twin technologies in its 2018 list of 10 Technologies of Strategic Importance. That company is of the opinion that by 2021 a half of large industrial companies would use digital twins, at that "IoT-related digital twins are especially prospective during the next three to five years" [2].

This review paper traces the history of appearance and development of the digital twin concept, analyzes various definitions and classifications, as well as technologies employed and industrial use scenarios.

The second half of the 19the century was a period of the Second Industrial Revolution. One of its main issues was location-related limitation of manufacturing. People could perform their activities only when they were next to each other; this fact inhibited improvements of analog technologies.

In the second half of the 20th century, the Third Industrial Revolution opened access to computers and the Internet. Thanks to this breakthrough, it became possible to get remote access to objects by means of parallel existence of physical and virtual spaces. Obviously, appearance of the virtual space significantly improved production efficiency.

Currently we are undergoing the Fourth Industrial Revolution, where new generation of information technologies are being rapidly developed. It should be noted that the virtual space gets significant importance in various fields of human activity. In industry, the main vector of development is an ability for seamless merger of the physical and the virtual spaces. Digital twins are integrators that help companies develop and gain leadership in international markets.

2. History of digital twins

Despite the fact that the definition of digital twin has appeared only recently, its history goes back to late 20th century.

Let us consider them chronologically. David Gelernter was one of the first to speak about digital twins back in 1991. However, in his report they were named differently, 'mirror worlds'. He described their principle of operations in the following way: a model of a certain physical object is created, akin to creating its mirror image from the real world.

Several years later, in 2002, Michael Grieves presented a similar report in the University of Michigan. His concept also assumed creating a model of a physical object, however it included a special mechanism that connected real object with its copy and provided information exchange between them. New name for this concept was Mirrorspace Model.

However, these developments had a common problem in inefficient transmission of production data necessary for control of the product life cycle. In their own turn, a number of researchers proposed using digital twins as a technique to overcome drawbacks of paper-based workflow in product life cycle control.

In 2006, the Mirrorspace Model created by M. Grieves underwent changes. Then it was assumed that there may be multiple virtual copies of the same physical object in order to facilitate experimentation and data collection and analysis. The new name for digital twins was the Information Mirroring Model. Unfortunately, back then it stayed only at a development stage due to insufficient level of technologies.

The modern term "digital twin" was first used only in 2010 in NASA Integrated Technologies Development Plan and assumed a simulator of a vehicle or of a system as a whole that in addition to copies of the physical object used its operational history.

In 2019 a more detailed definition of digital twin appeared. It assumed presence of a detailed virtual copy of a real object that accurately reflects the object's parameters and dynamics, thus allowing for efficient control of products in the virtual space [4]. The main stages in the development of the digital twin concept may be seen (Fig.1).

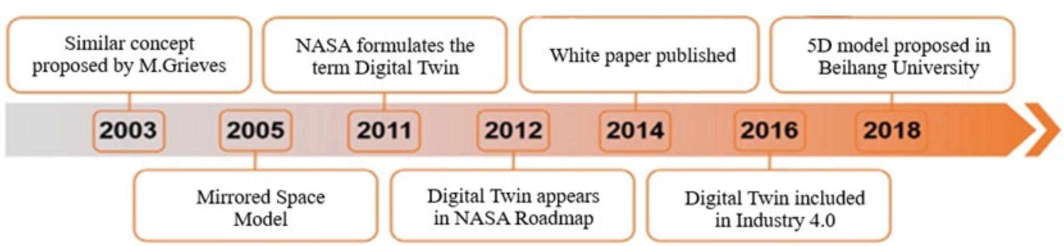

Fig. 1. Principal stages in the development of the digital twin concept.

2.1. Approaches to construction of a digital twin

A digital twin is not a pre-defined technology for construction of virtual copies, quite the opposite, it is a plethora of various technologies. This fact complicates practical implementation of the technology as there is no concrete plan for what and why shall be done. However, researchers generalize their experience and propose various techniques for implementation, some of them are described below in more detail.

Worthy of note is [5], where a more systemic approach is taken and all the stages in digital twin construction are listed as may be seen in Figure 2.

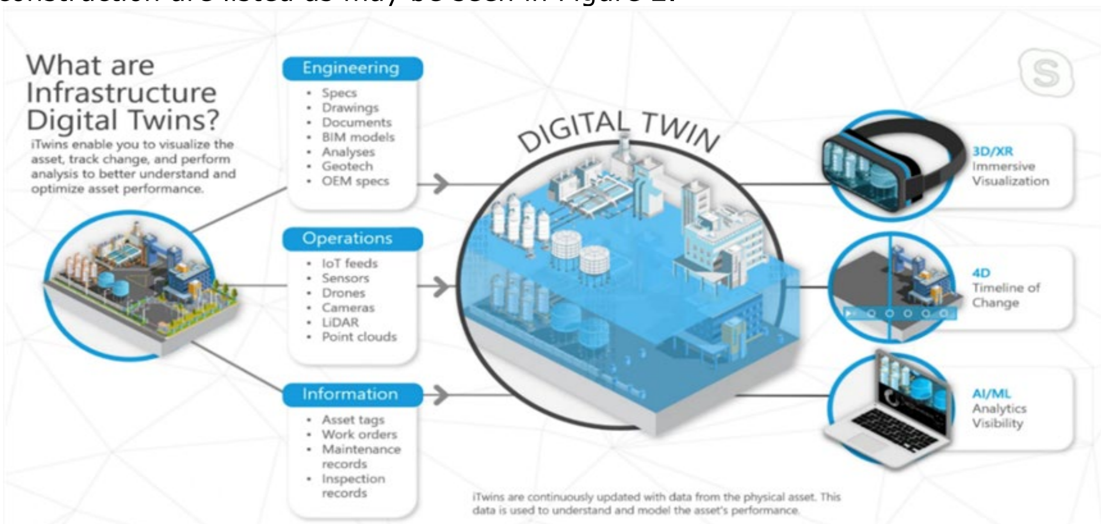

Fig. 2. Stages in digital twin construction.

Let us consider stages as per this work in more detail. At the first stage, a virtual representation of a physical product is created with the help of 3D CAD systems – ComputerAided-Design.

The authors of [5-6] state that the model shall consist of three levels: components (geometric and physical model), behavior (analysis of the product and its interactions) and rules (assessment, optimization and forecast).

The nature of the second stage is in analyzing the data obtained from various sources and their visualization to facilitate design-related decision making. Thus, twins may visualize various data, from environmental ones to those related to a production process. At that, the data shall be transformed in concrete dependencies, including hidden ones, for subsequent use in design. In case of hidden data, artificial intelligence technologies are used to obtain automated recommendations for design.

At the third stage, various situations are simulated in order to model the product's behavior in a virtual environment. All this happens thanks to simulation modeling with subsequent visualization in a virtual reality environment. An example of this stage is given in [7].

At the fourth stage, control of the physical object is performed to make it consistent with what is deemed necessary. This process is performed with the help of special sensors serving as the digital twin's backbone. The sensors may be of two varieties: one performs the tasks in perception of real-world information, one the other change the physical object in accordance with the digital twin data. This technology is called Augmented Reality.

At the fifth stage a real-time connection is established between the physical and the virtual product. This stage is performed by means of cloud storage and cloud calculations. For instance, Bluetooth, QR codes, barcodes, Wi-Fi, etc. All this is done in order to ensure availability of resulting information for both designers and users of the product.

At the final, sixth stage it is necessary to collect data on the product from such sources as: clients' feedback, viewership and downloading records. All the collected data shall be sent to the first stage of the processing chain in order to introduce changes into the twin. As one may see, the system forms a closed loop with feedback. Such an approach to data collection for introduction of the digital twin technology into production systems is given in [8].

In [9], its authors present a five-dimension digital twin model, where a problem is seen at a somewhat different angle; this model is described by a formula:

$$M_{DT} = (PE, VM, Ss, DD, CN) \quad (1)$$

where PE is physical objects; VM is virtual models; Ss is services; DD is data from the digital twin; CN is interaction protocols.

The model is shown in Figure 3 and while it is similar to the model presented in [5], it is capable of complete structural description of a digital twin and its related tools.

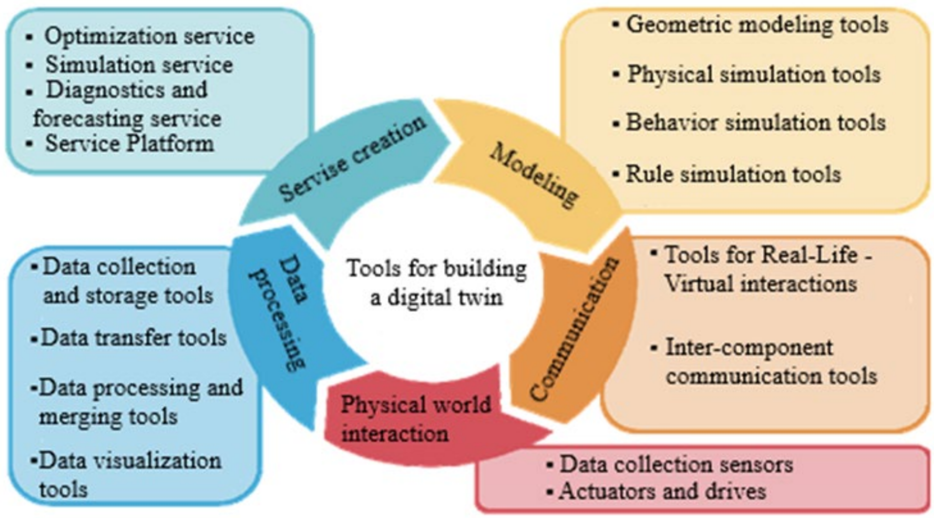

Fig. 3. Description of digital twin components.

Let us consider tools for working with a digital twin in more detail. Tools for interaction with the physical world form a foundation for object's digitalization. The digital twin turns data into information using special systems for finding and collecting data, including transmitters and sensors. The twin may use various actuators and mechanisms to change a physical object, thus the digital twin is a new control method in the Industrial Internet of Things (hereinafter – IIoT).

Modeling tools are a key in constructing a digital twin. Due to development of CAD/CAE systems, this model includes the first and the third stage of those described above. In order to achieve a close integration between the virtual and physical spaces and thus improve the simulation technology, the authors of [10] introduced an Experientable Digital Twin.

In order to improve convenience of operations with a digital twin, some processes may be transformed into web services, such as applications. Their implementation requires relevant tools for building services and applications. At that, achievement of more vivid representation of digital twin data in such services would require graphing, image processing and visualization tools, as well as a technology ensuring synchronization with virtual and augmented reality systems. In the modern context, access to a digital twin shall be equally convenient from both mobile and desktop platforms.

Data processing requires tools capable of collecting, storage and processing data. Data sources are the digital twin's hardware and software, as well as network. A key issue here is mixing of various data formats from different sources, as many software packages produce and store data in their own proprietary format.

Solution to this issue lies in the use of cloud services, as the authors have previously considered in [11]. Another prospective area related to a digital twin data control is blockchain technology. In [12], its authors consider peculiarities of data storage and access, cooperative use, data validity and overwriting.

To achieve the necessary result, different parts of a digital twin shall be capable of real-time interaction. Currently existing solutions are usually oriented towards solving very narrow tasks and often do not meet the modern requirements. Creation of such universal protocols is an important task for ensuring efficient interaction between all the components of a digital twin. Thus, the 5-dimensional model vividly shows complexity of efficient digital twin construction; this task requires a complex approach and ensured interaction between various components.

3. Digital twins today

Currently, a digital twin represents two components: physical and virtual ones. The physical part exists at real-life factories, let us call it hardware. The virtual part–let us call it software–serves to study and control production processes at the same factories.

Digital twins provide its users with a number of advantages. They give an opportunity to simulate and analyze behavior of individual devices in the context of the production system as a whole. Thus, digital twins significantly improve transparency, manageability and flexibility of production processes.

Let us consider stages in introduction of digital twins at a production facility. First, it is necessary to create a digital model for an individual machine or production process, and only if application of digital twin technology is successful at that stage, one may gradually expand the scope of the technology to cover larger facilities, through production lines to enterprise as a whole. It is vital to start small and gradually expand to larger and larger objects still after polishing the technology at smaller objectives [13].

The concept of digital twins is actively applied in electric car manufacturing. Here, Tesla Motors is a vivid example, where each car has its own digital twin that provides the company with all the information about its real-life counterpart. Such an approach allows developers, designers engineers and other specialists to constantly trace the quality of the product and improve their cars resolving issues as they arise.

In the energy sector, digital twins allow operators to manage and control well drilling in real-time. They are capable of tracing changes in well parameters and providing timely reaction in the form of grounded decisions.

In health care, digitalization provides for more accurate diagnostics, improvements in development of new medicines and teaching medical professionals using realistic virtual models. All these factors facilitate improved efficiency and quality of health care.

A great example of digital twin application is a 3D model of Singapore, a detailed digital twin of the East Asian city-state. Singaporean authorities are using this interactive digital model to solve a wide range of urban tasks. As a result, virtual models may now be applied at both large and small companies in various industries.

In recent decades, possibilities opened by digital twins were significantly widened due to a number of factors. First, there is a constant improvement in simulation and modeling software. Such tools become more advanced and provide more functionality. They provide an ability to create complex imitation models that may go beyond real-life conditions. At that, such tools are capable of processing and analyzing large volumes of data.

Besides, increasing number and variety of competing simulation software developers stimulates further development and improvement. Large selection of software solutions stimulates competition and innovations in the field.

Second, new sources of data emerged in the market, significantly improving and expanding capabilities of digital twins. This includes such real-time monitoring technologies as LIDAR and FLIR, as well as Internet-of-Things sensors embedded into both equipment and production chains [14].

These new sources of data obtained directly from the physical world allows digital twins to continuously monitor and analyze the parameters which are impossible to measure directly.

Thus, digital models become more realistic and accurate, reflecting actual state of the corresponding physical objects.

Emergence of such new technological solutions significantly enriches information content of digital twins making them more valuable tools for simulation, forecasting and decision making.

3.1. Oil deposit digital twin

Some oil and gas companies offer access to a digital twin as a bonus to their product. It allows buyers to improve the production volume by up to 6% and cut the downtime by 4%. This practice may be found in Russia and globally [15].

3.2. Digital twin in drilling

The main area for this technology in drilling under complex geological conditions where there are high temperature and pressure. Digital copies help monitoring the process and controlling the cement layer, as well as finding optimal parameters, e.g., determining tubing running speed that prevents formation damage. Digital copies allow for continuous real-time monitoring of updated well indicators and comparing them with prediction statistics, thus reducing risks related to possible failures and allows for earlier discovery of issues (Fig.4) [16].

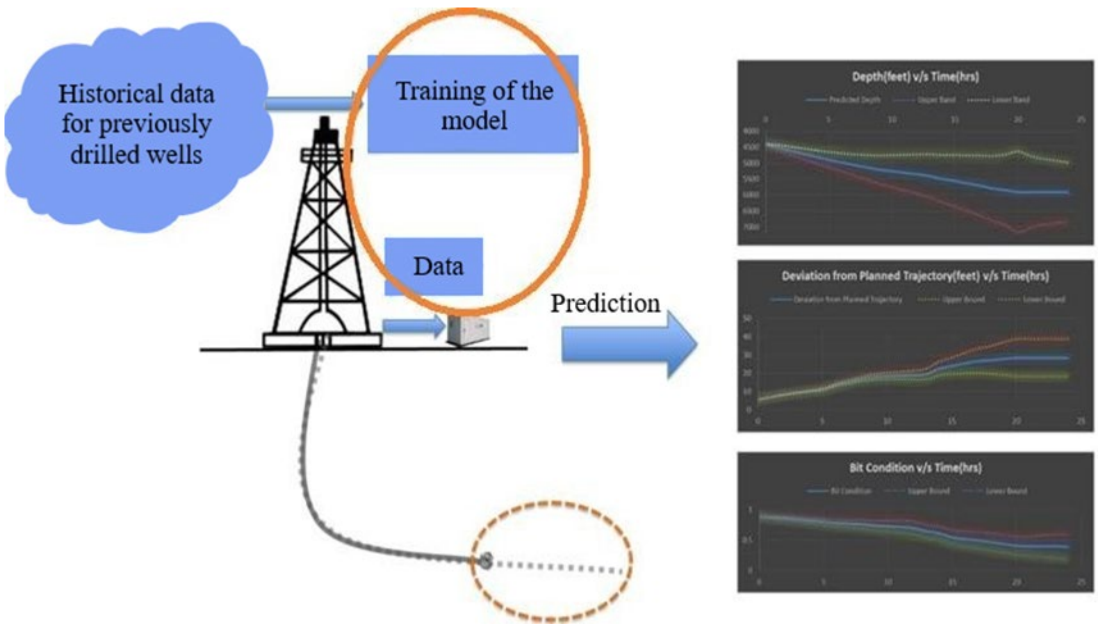

Fig. 4. A digital twin of a well.

Digitalization of drilling is a new technological area that allows for more efficient and accessible well planning, preparation and drilling.

3.3. Pipeline digital twin

Application of cloud technologies to detailed engineering of underwater pipelines and facilities allows for significant shortening of calculation times and protecting projects against human factor errors. During the project development, a set of calculations was performed related to determination of wall thickness, analysis of foundation stability, as well as estimation of parameters related to pipeline span, expansion and bumps (Fig.5).

The process of creating digital copies of OGI facilities is complex and requires cooperation between experienced specialists in the fields of AI, methodology and process technologies. Implementation of this project is possible only with powerful computers, plentiful data storage and good data transfer speeds. This is a drawback of this technology [17].

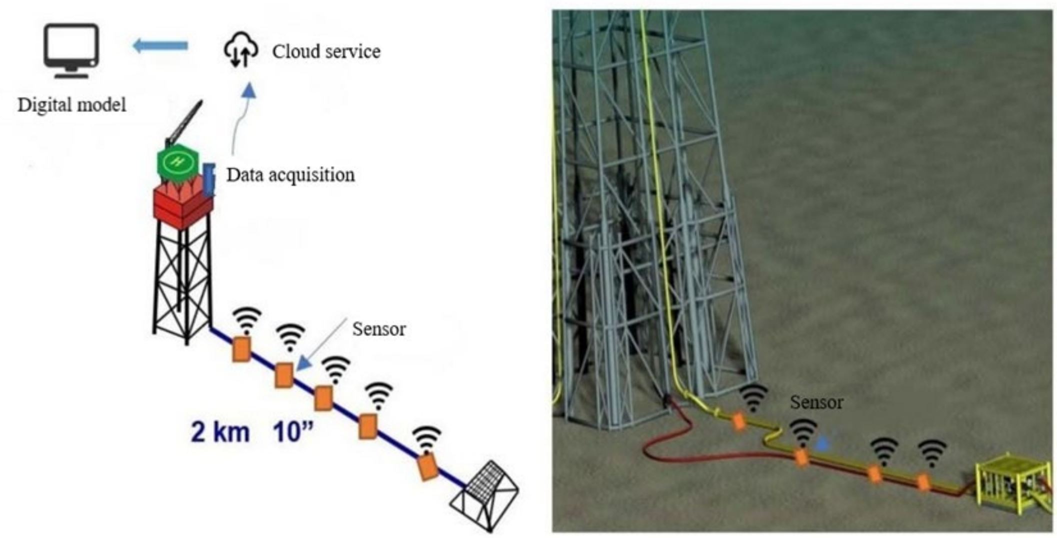

Fig. 5. Location of sensors digital twin data transfer for a subsea pipeline.

3.4. Economic assessment of digitalization of hard-to-recover reserves extraction on the basis of existing models

In order to understand how efficient, the application of digital technologies in OGI is in case of hard-to-recover reserves extraction, an assessment is performed based on comparison implementation and ownership costs of such technology with profit resulting from such an implementation. The principal costs are related to equipment and production processes, management and organization, finances, as well as operational costs.

Implementation of digital twin into the hard-to recover reserves extraction chain may give some economic effect as early as design stage, with subsequent action leading to this effect covering all the production stages. Contribution from each type of data source to the economic effect is specific for their purpose:

- during reservoir development and release of product to the market a significant time costs reduction may be attained due to organizational measures;
- technical know-hows manifest in decrease of the time period required to extract the hard-to-recover reserves, where digital twin of the deposit controlled by technical specialists is of great help;
- automated control of digital deposit combines various technological innovations that allow for minimizing error probability and fail occurrence, thus significantly reducing risks;
- one of positive labor-related effects is in the general improvement of the workflow, where efficiency increases due to streamlined distribution of tasks between specialists and hardware. This further frees more time for supplementary tasks and creative solutions, resulting in higher-quality and more productive work;
- environmental effects appear as a possibility to prevent man-made hazards and reduce maintenance and repair costs;
- networking effects appear as a result of information exchange through a network allows for significant simplification of operation, thus reducing production costs.

Cost-benefit analysis of oil production digitalization in case of hard-to-recover reserves is based upon evaluation of its technological efficiency and calculated as an ROI study of an investment project. This is a traditional approach that uses standard methods for efficiency evaluation applied to companies implementing digital technologies and facilitates risk assessment [18].

The main advantage of such an approach is application of classical theoretic principles that form a foundation of investment project efficiency.

Implementation of a complex digital system that brings together proven solutions at the deposit level is a basic principle in development of hard-to-recover reserves. Complex application and assessment of digital technologies/algorithms application to oil deposit control requires Russian companies to implement investment projects. An investment project is an economic or social project financed through investments. It includes project documentation developed in accordance with current standards that define economic feasibility, scope and time frame of investment in a certain facility. Within the investment project, optimal investment parameters and expected economic effect are calculated at several different stages:

1. necessary costs are calculated;
2. a forecasts is made for project development;
3. potential gains from the project are calculated with a year-by-year breakdown;
4. cost of money and payback period are determined.

4. Implementing digital twins in MARS multi-level computer modeling environment

4.1. Multi-level computer model structure

A multi-level component chain of complex controlled systems (MCCCCS) may be represented graphically as three interrelated levels. It includes a component chain of chemical and process-related system with connections to a real-life chemical processing system, an imitation model for the simulation experiment including functional model of MCCCCS controller and finally visualization and interactive control panel interconnected with the previous two levels [19].

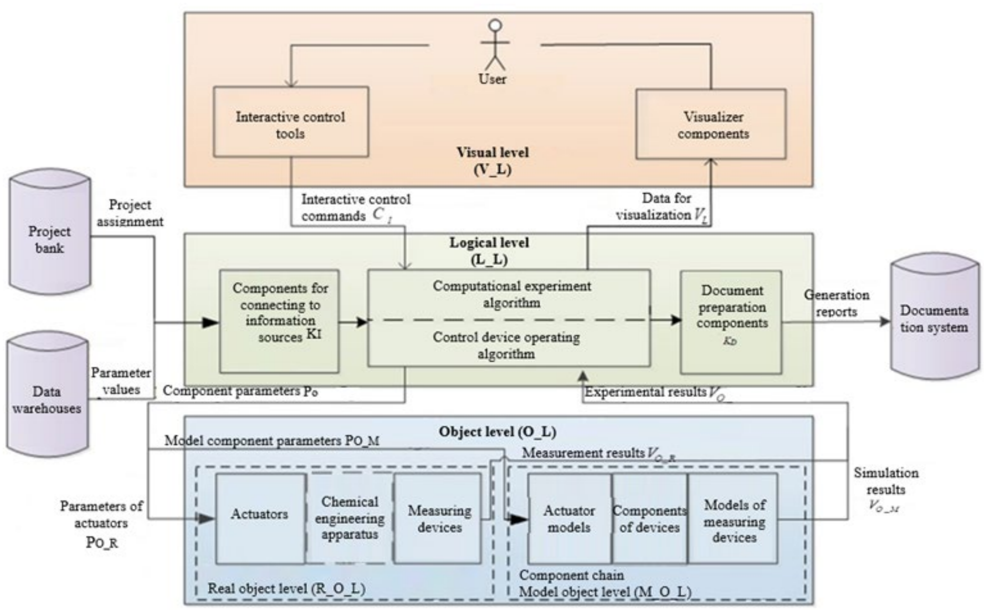

Fig. 6. General structure of a multi-level component chain.

This chain is intended for automation of research, project and teaching experiments consists of the following interrelated levels [20]:

– ***object level*** (*O_L*), including the MCCCCS component chain O_M, consisting of chemical processing system simulation model C_{ChTS} with simulation models MeasuredCond C_{IZ} and UsedCond C_{IS} connected to it, as well as a real-life chemical processing system O_R, used to test the results obtained with the component chain. Representation of a chemical processing system component chain is made at the *model object level* (*M_O_L*). Its analysis uses a universal compute core of the MARS simulation environment [21] with embedded methods for analysis of objects with nonuniform vector links [22]. Real-life chemical processing system together with data collection and measurement equipment form the *real object level* (*R_O_M*) ;

– ***logic level*** (*L_L*), where an algorithmic component chain C_A reflects a research and functional design scenario of the MCCCCS integrated with the device's control. Its operation is based on using the chemical processing system analysis results V_{O_M} together with the measured values coming from the real-life system V_{O_R} transmitted from the object level. Algorithmic component chain of the scenario includes parametrization commands of the component chain, mathematical analytic tools, simulation and measurement analysis tools, visualization means and managerial decision-making tools aimed at changing the parameters of the chemical processing system component chain and introducing control inputs related to the real-life system. Each command in the MCCCCS research and functional design scenario shall be represented as an algorithmic component chain C_A, pertaining to the logical level, and graphically as a set of graphic components, with input connections corresponding to the command's arguments and output connection corresponding to its results.
– ***visual level*** (*V_L*) reflection of information about current results of performed scenario steps, including control device functional scenario. This level includes *visualization and interactive control panel,* represented with a visual component chain C_V. It includes *visualizing components,* intended for display of data needed to be visualized V_L, as well as interactive control means, which are called *regulating components* and allow formation of corresponding control commands C_I. Visualizing and regulating components taken together form a set K_V.

The structure of multilevel component chains of complex technological controlled systems as shown in Figure 6 is a further development of the component chain method. It allows forming multilevel MCCCCS component chains in a graphical form. Its application allows automating the process of MCCCCS research and functional design with corresponding algorithms in gas industry facilities. Besides, multilevel chains developed in this format allows implementing various virtual and real-virtual laboratories, computerized training systems aimed at training and retraining of chemical processing industry managerial personnel.

4.2. Architecture of a chemical processing system smart control system based upon MARS modeling environment

In order to efficiently complete tasks in research and functional design of MCCCCCS based on simulation experiment, a computer model of MCCCCS may be used that includes the model of the chemical processing system integrated with a real-life object. Its structural diagram is shown in Figure 7 and includes [23]:
– *real-life chemical processing system*, where the simulation results shall be subsequently tested. Direct interactions with the chemical processing system are performed by means of *actuators* that transform information signals received from the control unit model $\widetilde{u_O}$ into proportional reaction $\widetilde{U_O}$ aimed at the chemical processing system components. *Measurement instruments* monitor observable characteristics of the chemical processing system $\widetilde{y_O}$. The real-life chemical processing system is influenced by its environment; such influence $\tilde{F}$ is often stochastic;
– *computer model* of the chemical processing system, consisting of actuator models K_{IS}, model of the chemical processing system itself K_O and measurement instrument models K_{IZ}. It is formed with respect to primary parameters and variables related to its elements. Being structurally similar to the real-life chemical processing system, the computer model allows efficiently getting analytic results in both static and dynamic mode, with a possibility for varying the values of certain parameters of components, models and sources of influence K_F;
– *controlling device*, that collects and analyzes modeling results and measurement data, as well as transmits actuating signals produced by an operator with the help of controlling means and calculations of actuating signals for a real-life chemical processing system and its computer model alike. Interactions with a library of prototypes and analogs is organized at the data transmission level through the module tasked with documenting and obtaining necessary prototypes and their values;

– *analog retrieval system*, that performs search in the library of prototypes-analogs from previous projects, which appear as computer models with a detailed description formed by the documenting module automatically;

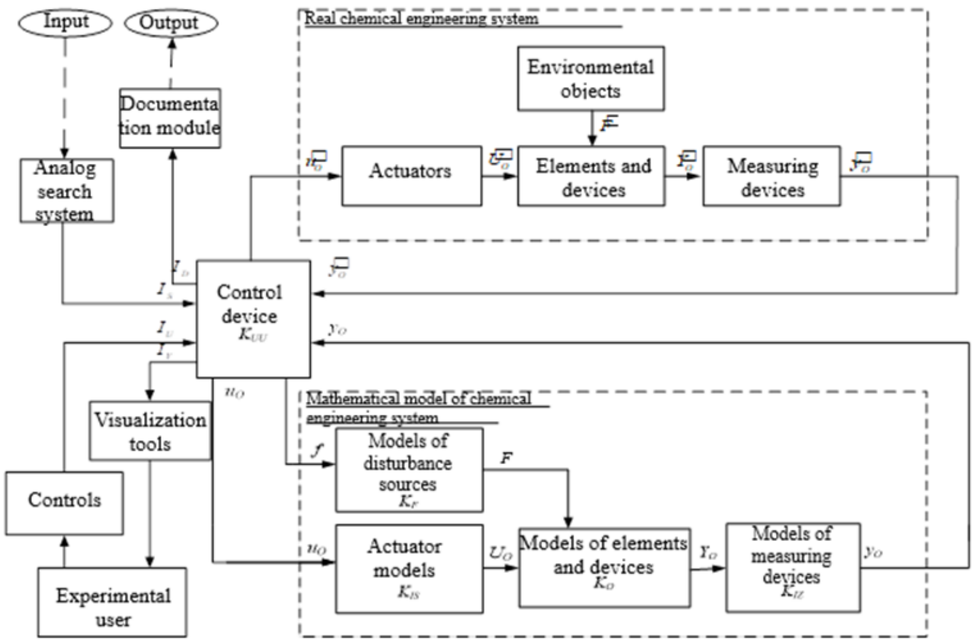

Fig.7. Structure of a computer model of a complex technical controlled system.

– *documenting module*, intended for automated preparation of current and reporting information on tasks having been attained in research, design and MCCCCS functioning for subsequent transfer to the library of prototypes-analogs for storage and subsequent retrieval by the analog retrieval system;
– *library of prototypes-analogs,* which is a server-side application to which a Chemical Processing System Modeling Environment connects in order to put the completed project to archival and to search and retrieve previously completed projects;
– *visualization means*, which are software modules for on-screen display of data reflecting changes in characteristics of the real-life chemical processing system, results of analysis of its computer model, attained tasks in research, design and functioning of MCCCCS;
– *control means* – visual components intended for influencing the chemical processing system and its computer model through direct interaction with the monitor screen.

The total of the visualization means and control means form the *visualization and control panels*, with which Research Operators (hereinafter: *operator*) interacts during the experiment. Their objectives include observation of the processes taking place in both computer-modeled and real-life chemical processing system, determination, definitions, setting and maintaining required modes of the system's operation. Efficient performance of these objectives depends on implementation of necessary research models during the experiment. The models shall contain target functions intended for improvement of adequateness of the models used and for attaining tasks in research, design and control, as well as necessary product-related knowledge models of the corresponding expert system [23].

The proposed structural computer model of the MCCCCS may be used to implement a smart control system for a technological facility and smart SCADA systems with their subsequent implementation into production chain [24].

5. Prospects of digital twins

Despite obstacles that hinder implementation of digital twins, such as high costs and insufficient qualification of personnel, digital twins are predicted to see a fast increase in adoption. It is expected that by 2026 the digital twin market will be 48 billion dollars and will see subsequent growth at a rate of 60% annually. By 2030, the digital twin concept is expected to result in cost reduction in construction and planning by 300 billion dollars, as more and more companies will adopt this technology [11].

6. Conclusion

Digital twins of objects in the oil and gas industry have been gaining increasing attention in recent years as a powerful tool for optimization, predictive maintenance, and overall performance improvement. These digital replicas of physical assets provide real-time insights into the operational status and behavior of equipment, allowing for more informed decision-making and proactive maintenance.

One of the key advantages of digital twins in the oil and gas industry is their ability to simulate different scenarios and predict potential issues before they occur. By collecting and analyzing data from sensors embedded in equipment, digital twins can create a virtual representation of the physical object and monitor its performance in real time. This allows operators to identify potential problems early on, reducing the risk of costly downtime and improving operational efficiency.

Another benefit of digital twins is their ability to optimize processes and increase productivity. By analyzing data from different sources, such as historical performance data, weather conditions, and operational parameters, digital twins can suggest ways to improve operations, reduce waste, and enhance overall performance. For example, digital twins can help optimize drilling operations by simulating different drilling conditions and recommending the most efficient approach.

Furthermore, digital twins can be used to facilitate remote monitoring and control of assets, reducing the need for human intervention in hazardous environments. By connecting digital twins to the Internet of Things (IoT) devices, operators can remotely monitor equipment from anywhere in the world and take corrective actions when necessary. This not only improves safety but also reduces operational costs by minimizing the need for on-site personnel.

In conclusion, digital twins of objects in the oil and gas industry have the potential to revolutionize the way operations are managed and assets are maintained. By providing real-time insights, predicting potential issues, optimizing processes, and enabling remote monitoring, digital twins can help operators increase efficiency, reduce costs, and improve overall performance. As the technology continues to evolve, we can expect to see even greater advancements in the use of digital twins in the oil and gas industry.

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