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INNOVATIVE TRENDS
IN THE DEVELOPMENT OF INFORMATION CONTROL SYSTEMS AND TECHNOLOGIES

Monograph

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The monograph delves into cutting-edge trends in developing and deploying advanced information technologies such as artificial intelligence, machine learning, cloud computing, big data, blockchain, and industrial Internet of Things within information control system architectures. It explores conceptual and methodological principles for designing various types of information control systems in organizations, manufacturing, technical facilities, higher education institutions, and the medical field. This exploration takes place amidst heightened global instability, cyber threats in the digital sphere, and significant digital transformations. Special emphasis is placed on creating and advancing applied information control systems, including their components and technologies. The monograph also examines the use of hybrid intelligent systems and specialized computer systems for managing logistics, transportation, organizational information security, energy facilities, aircraft, and smart systems.

It targets teachers, researchers, graduate students, undergraduates, and specialists involved in integrating innovative technologies into information system design and implementation across enterprises, organizations, IT sectors, education, and healthcare.

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CONTENT

INTRODUCTION

The current stage of development of the world economy is largely ensured by high rates of development of scientific and technical, production and information technology support, and the level of competitiveness of national high-tech products through the introduction and use of innovative information management systems and technologies (ICST). Therefore, the problem of introducing innovative information technologies into the process of designing information management systems (ICS) for various purposes remains extremely relevant, especially now in connection with the strengthening of global international instability, the emergence of additional risks, threats, and significant digital transformations. This leads to the need to develop and implement new tools for system analysis, modeling, forecasting, and design of information systems in the management of technical objects, socio-economic systems, and financial systems in the context of ensuring sustainable, competitive, and safe development of systems of different levels of hierarchy. The monograph discusses the following studies:

The first section «Trends and Problems of Development of the Sphere of Use of Information Control Systems and Technologies» considers the state, trends, and prospects for the development of ICST in the fields of economics, technology, education, and medicine. A classification of ICS is carried out in the context of state programs of informatization, development, and implementation of information technologies in the process of designing ICS, where promising classes of ICS are allocated based on the implementation of the principles of hybridization, integration, and specialization (hydride systems, Internet of Things systems, industrial Internet of Things systems). The informational, technological, and organizational aspects of the development and implementation of ICST programs in various sectors of the economy and technology are considered. The impact of digitalization and external risks on educational activities is determined, which is characterized by the introduction of new forms and methods of distance learning, continuing education, transnational learning, and virtual education using innovative information technologies and E-learning systems. The results of the study of the article «Theory and Practice of Cyber Threat Identification in the Information Space» allow us to analyze and assess threats in terms of risk levels for vital areas of economic activity of organizations. The section also analyzes the possibilities of using diagnostic medical tools using artificial intelligence, and electronic medical records with the functionality of data mining, nanotechnology, and genomics in healthcare institutions of the United States of America, based on which an automated system for remote control of medical parameters is proposed, which provides constant monitoring, management of the treatment and rehabilitation process based on the provision of practical recommendations.

The second section is devoted to «Conceptual and Methodological Principles of Design of Various Classes of Information Control Systems» at the level of implementation of Industry 4.0, 5.0 in applied ICS. The study systematizes and summarizes application systems based on technologies that characterize the achievements of Industry 4.0, as well as shows their limitations and approaches to their elimination in the context of the development of Industry 5.0, which uses new technological achievements. such as predictive-based services, hyper-customization in industry, cyber-physical cognitive systems, and collaborative robots to overcome the challenges of Industry 4.0. Moreover, it is determined that Industry 5.0 provides huge research opportunities, especially in the field of security and data integration, which is considered the most significant challenge in IoT. It is determined that the development of information systems in the sphere of public administration depends on a wide range of factors, among which the development of infrastructure, innovation, legislation, education, and personnel are especially important. The proposed Concept of Research on the Introduction of Innovative Technologies in Digital Educational Activities considers the theoretical, methodological, and practical foundations (components) to improve the efficiency of the processes of introducing innovative technologies, the development of a holistic set of interrelated models, methods and approaches to assessing the effectiveness of digital educational activities, their practical application for the development of digitalization processes of higher education institutions. The development of digital platforms of enterprises is another confirmation of the critical importance of aligning digitalization projects with the business goals of the enterprise, therefore, to achieve the goals, it is necessary to plan and control complex digital initiatives, coordinate all digital resources and processes, knowledge sharing with partners and stakeholders. This section also considers the conceptual foundations of the sustainable development of energy facilities in modern conditions, considering various attributes and aspects that contribute to the ability of the system to survive and function in conditions of uncertainty and change.

The third section of the monograph «Methods, Models and Processes of Modeling Research Objects in Information Control Systems» considers the possibilities of the model of the logistic problem of a traveling salesman and the problem of distributing the power of data transmission channels under conditions of uncertainty. This section proposes an approach to solving the problem of improving the distribution of power of communication channels to increase the efficiency of organizational management of technical systems in network structures based on modern methods of distribution and processing of information flows. A new method of adapting information transmission devices to the parameters of the communication channel is proposed, which provides the ability to optimize the amount of information required for duplication during its transmission by preliminary measurement of the level of interference in the communication channel from the transmitter side, which, in turn, allows to significantly increase the bandwidth of the data transmission channel without changing its physical properties. The section also describes the proposed methods and basic principles of collective intelligence in ICS, it is shown that a promising direction in the development of artificial intelligence methods is the use of multi-agent methods of intelligent optimization, modeling the collective intelligence of social animals using Swarm Intelligence methods. Considers theoretical, methodical, and practical aspects of creating and modeling information objects in graph models of data representation. A unified methodology of information modeling has been proposed and its key ideas have been demonstrated in the example of creating a graph educational and professional program «ICST» of the second (master's) level of higher education, which was introduced at the Kyiv National Economic University named after Vadym Hetman. It is determined that graph databases provide flexible management of unstructured data, improving data visualization and analysis, which is critically important for modern higher education institutions. The section also shows that an important component of research in the field of medical implantology is the proposed approaches, methods, and means of assessing the electromagnetic compatibility of materials in contact with the tissues of the human body.

The fourth section «The Use of Modern Models of Artificial Intelligence in Information Control Systems» explores the application of modern AI models, particularly Deep Learning architectures, in ICS. It highlights the potential of these models to revolutionize decision-making processes, optimize operations, and drive innovation across various industries. The key findings emphasize the capabilities of deep learning models, such as Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), and transformers, in analyzing vast repositories of structured and unstructured data, including images, videos, and text, to extract valuable insights and support informed decision-making. This section discusses the construction of an ICS based on Deep Neural Networks (DNNs) for forecasting the financial market. The proposed ICS combines CNNs to identify hidden regularities and generate predictors with Gated Recurrent Units (GRUs) to capture dependencies in the time series. The section presents a conceptual scheme for developing the ICS, demonstrating the effectiveness of the DNN-based ICS in forecasting financial market trends.

The fifth section «Development of Applied Information Control Systems, Their Components and Technologies» is devoted to the creation of information systems for managing logistics processes at special-purpose enterprises, and business intelligence systems for small enterprises. An analysis of descriptive, diagnostic, predictive, and methods of prescriptive analytics has been carried out, which makes it possible to choose the best results and determine the economic efficiency of the system. The section presents the main results of a comparative analysis of different types of machine learning (unsupervised, controlled, weak or semi-supervised, and reinforcement learning) when using big data in Applied Information Control Systems. Recommendations on the specifics of using cloud services for increasing the efficiency of deep machine learning proposed applied tasks for the primary implementation of deep machine learning in ICS. The main directions of development of blockchain business models are considered, and their characteristics and examples of implementation in multi-level structures of corporate blockchain models are provided.

The sixth section «Innovative Approaches to the Development of Technologies for Building Specialized Computer Systems» is devoted to controlling unmanned aerial vehicles, managing vehicles, and identifying bank customers using IoT technologies. These specialized computer systems are created as real systems using microcontrollers. Given examples of implementation of technical systems and tested software. A study on the use of various types of innovative technologies for semantic search of textual and graphic information on the example of the AMAZON KENDRA service is carried out, a methodology for semantic search for objects of textual and graphic information based on the use of vectors and similarity of vector elements, based on the distance between its elements, is provided. The parameters of search for textual and graphic information, indexing, and ranking are demonstrated, which contributes to the effective and relevant search for information based on similarity in the latest servers.

SECTION 1
TRENDS AND PROBLEMS OF DEVELOPMENT OF THE SPHERE OF USE OF INFORMATION CONTROL SYSTEMS AND TECHNOLOGIES

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STATE, TRENDS AND PROSPECTS FOR THE DEVELOPMENT OF INFORMATION CONTROL SYSTEMS AND TECHNOLOGIES IN VARIOUS SECTORS OF THE ECONOMY AND TECHNOLOGY

The experience of the leading countries of the world shows that success in the social and economic activities of the state in the current conditions of globalization of the world economy is primarily ensured by the extent of the scientific, production, technological, information, and communication support in the country, as well the level of competitiveness of national science-intensive products through to the introduction of the latest information management systems and technologies (ICST).

State target programs and programs for developing economic sectors in the use, implementation, and creation of the latest ICST for individual organizations and spheres of public life of Ukraine are targeted at carrying out measures directed at effective cooperation between Ukraine and the European Union [1].

The main factors of economic growth and development of European countries are 17 key areas that were adopted at the UN Summit on Sustainable Development 2030. In particular, «Goal 9» refers to «Building resilient infrastructure, promoting inclusive and sustainable industrialization and innovation» [2] in the creation of the latest ICST, which are effectively used in organizations, manufacturing enterprises, associations, and business centers, open a fast path for the development of the national economy, as well as ensure efficient functioning of many related industries, since this market is an effective tool for integration into the world economic space due to its significant features, in particular the development of world information and communication technologies and high-tech production systems.

The IT sphere is especially important for Ukraine now in the context of the general economic crisis and military risks. Therefore, domestic and foreign IT companies open a fast path for the development of the national economy, ensuring the functioning of many related science-intensive industries, since this market, despite the limitation of investment resources, is a fairly effective tool for the development of the latest products – information management systems (ICS) for various purposes in the fields of economics, technology, medicine, and education, and also allows for rapid integration into the world economic Space.

«Information Control Systems and Technologies» as an educational and professional program (EPP) at the second (master's) level of higher education in the specialty 122 «Computer Science», field of knowledge 12 «Information Technologies» of the «Kyiv National Economic University named after Vadym Hetman» is focused on the synthesis and improvement of the efficiency of ICS design solutions and their components, development, improvement, and maintenance of systems using modern information technologies in the economy, science, technology, education, industrial and infrastructure facilities of the national economy, in particular, these are production and economic enterprises, banking institutions, social infrastructure, international IT companies, business IT sphere, financial and industrial groups, concerns, holdings. It is aimed at training ***a new generation*** of IT specialists who will have deep theoretical and practical training in the use of innovative information technologies, mathematical and computer modeling of processes and phenomena, methodologies of design, optimization, system analysis, and acceptance management decisions, analysis of knowledge and data of large arrays capable of solving non-standard tasks, making optimal decisions, generating original and effective ideas, applying modern research tools in specific conditions, taking into account modern challenges and principles of humanization of the digital sphere [3]. The scientific component of the EPP «IUST» specialty 122 «Computer Science» is focused on developing and implementing real ICS projects, students' participation in domestic and international conferences, circles of IoT technologies, artificial intelligence components, and programming systems.

1. Relevance and problems of ICS development

Research should focus on developing ICS capable of quickly responding, adapting, and preventing consumer demands to external conditions, as well as quickly reconfiguring the production of various batches of high-tech products. Integrating knowledge and technology, taking into account safety, social responsibility, and vitality, is a prerequisite for accelerating the transformation of European industry and the Ukrainian economy. The knowledge economy is based on new knowledge that has an information basis and is embodied in innovations, which, in highly developed economies, through the latest technologies and relevant products, ultimately provide the dominant weight of GDP growth. Therefore, the problem of introducing innovative information technologies into the process of designing ICS for various purposes remains relevant.

Advantages of ICS:

Improved decision-making: The ICS provides managers with timely and accurate information, allowing them to make more informed decisions. ICS can provide insights into trends, patterns, and opportunities to help managers identify problems, evaluate alternatives, and make the best decisions for their organizations.

Increased efficiency: ICS automates many routine tasks, such as data entry, processing, and reporting, reducing the time and effort required to perform these tasks manually. This allows employees to focus on more valuable tasks, improving the overall efficiency and productivity of technological processes or organizations.

Improved communication and collaboration: ICS allows employees to share information and collaborate more effectively both within and between departments, businesses, and associations. This improves communication and coordination, reduces errors and delays, and improves the overall productivity of the organization.

Advanced strategic planning: ICS provides senior executives with the necessary information to develop and execute effective strategic plans. By analyzing data and information from a variety of sources, managers can identify opportunities and threats, evaluate different scenarios, and make informed decisions about the future direction of their organizations.

Competitive advantage: ICS provides organizations with a competitive advantage, allowing them to respond faster and more efficiently to changes in the market and customer needs. Using data and information, organizations can identify new opportunities, develop innovative products and services, and improve overall customer satisfaction.

2. Classification of information control systems

The classification of ICS is carried out according to the following classification criteria, which are shown in Fig. 1:

1. Level of management.
2. Scope of use.
3. Source of information.

4. Method of access to information.
5. Organizational level.
6. Type of intelligent information systems.
7. Type of interaction of objects in specialized computer systems.

Level of management	• **Operational** • **Tactical** • **Strategic**
Scope of use	• **Financial activities** • **Marketing activities** • **Production activities** • **Personnel activities** • **Logistics activities**
Source of information	• **Internal source** • **External source** • **Combined source**
Method of access to information	• **Online** • **Offline** • **Mobile** • **Cloud**
Organizational level	• **Departmental** • **Organizational** • **Cross-organizational**
Type of intelligent information systems	• **Systems with communicative abilities** • **Expert systems** • **Self-learning systems** • **Adaptive systems** • **Hybrid Intelligent System (GIS)**
Type of interaction of objects in specialized computer systems	• **The Internet of Things (IoT)** • **The Internet of Everything (IoE)** • **The Internet of Nano Things (IoNT)** • **Internet of Mission Critical Things (IoMCT)** • **The Internet of Mobile Things (IoMT)** • **The Industrial Internet of Things (IIoT)**

Figure 1. ICS classification based
on different classification features

Source: Developed by the author

2.1. Based on the level of management, ICS can be classified into three categories depending on the level of management that uses them:

An operational ICS is a type of information system that supports day-to-day operations and decision-making at an organization's operational level. It provides real-time information about operational activities such as sales and inventory levels, order processing, and production schedules. The primary purpose of the operating ICS is to improve the efficiency, productivity, and quality of operations. Examples of operating ICS are sales and inventory management systems, production planning systems, customer service systems, etc.

A tactical ICS is a type of information system that supports decision-making at the tactical or middle level of an organization's management. Provides insights into key performance indicators such as sales, costs, and customer satisfaction. The primary purpose of tactical ICS is to help managers monitor performance, identify trends, and make tactical decisions. Tactical ICS provides aggregated data and reports that middle managers use for monitoring productivity and decision-making. Examples of tactical ICS are supply chain management systems, human resource management systems, and sales and marketing systems.

A strategic ICS is a type of information system that supports decision-making at the strategic level of an organization. It provides information about the organization's external environment, market trends, and long-term goals. The main goal of a strategic IMS is to help top managers make strategic decisions that determine the direction and future of the organization. It aids in identifying new opportunities, managing risk, and allocating resources to achieve long-term goals Organization. Examples of strategic IMS are business intelligence systems, enterprise performance management systems, and strategic planning systems.

2.2. Based on the scope of use. The ICS supports several categories of functional levels in the organization's field of activity and helps to improve decision-making, increase efficiency, and optimize work. The ICS must integrate all functional areas of activity to ensure the smooth flow of information and decision support throughout the organization. There are the following types of ICS depending on their functional scope of use:

Financial activities. To support decision-making in financial management and accounting functions, the ICS helps to monitor financial performance, analyze financial data, and make informed decisions about budgeting, resource allocation, and investments. The financial ICS provides aggregated data and reports on financial transactions, assets, liabilities, and equity. Examples of ICS in the field of financial and economic activity are general Ledger systems, accounts payable systems, and accounts receivable accounting systems.

Marketing activities. ICS in marketing activities helps track the marketing process's effectiveness, analyze marketing data, and make informed decisions about product development, pricing, promotion, and distribution. Marketing ICS provides aggregated data and reports on marketing activities such as sales, customer behavior, advertising, and market research. It allows marketing managers to track the performance of marketing campaigns, identify growth opportunities, and make informed decisions. *A* few examples of marketing IMS are sales analysis systems, customer relationship management systems, *and* market research systems.

Production activities. ICS in the field of production activities helps to monitor production productivity, analyze production data, and make informed decisions on production planning, inventory management, quality control, and resource allocation. A manufacturing ICS provides aggregated data and reports on production activities, such as production schedules, inventory levels, quality control, and resource utilization, enabling production managers to monitor the efficiency of production processes, identify areas for improvement, and make informed decisions. Examples of ICS in the field of production activities are inventory management systems, production management systems, product quality control systems, etc., and fixed assets management systems of the enterprise.

Personnel activities. The ICS in the field of HR organization is designed to manage human resource information and processes such as hiring, training, payroll, performance evaluation, and employee benefits. It enables organizations to automate HR processes, increase efficiency, and streamline administrative tasks about employee data, allowing them to make informed decisions and support strategic business goals. Examples of using HR ICS are employee data management systems, compliance management systems, and performance management systems.

Logistics activities. ICS in the field of logistics activities is designed to manage and optimize logistics processes and supply chain management in an organization. ICS assists in managing logistics operations such as purchasing, transportation, inventory, and warehouse management and enables organizations to automate logistics processes, increase efficiency, and reduce costs. It provides logistics professionals with access to accurate and up-to-date information on inventory levels, order status, and shipping information and maintains strategic business goals. Examples of logistics ICS are procurement management systems and warehouse management systems.

2.3. Based on the source of information. ICS can be classified based on the nature of the origin of the source of the information they process and manage:

Internal source. The ICS processes and manages the organization's information, as well as helps manage its internal operations by providing accurate, relevant, and timely information to support decision-making and business operations. By automating and streamlining internal processes, organizations can save time and resources, reduce costs, and increase productivity in enterprise resource planning, customer relationship management, and inventory management.

External source. The ICS processes and manages information from external sources outside the organization. The primary purpose of an external system is to help organizations collect, analyze, and interpret information about the external environment to make informed decisions and gain a competitive advantage. Examples of ICS are market research, economic analysis, and monitoring of social networks.

Combined source. The ICS functions within the framework of internal and external information flows in a single information space of a given subject area to obtain, process, and optimize all the main aspects of the organization's management activities. Examples of ICS tasks are operational planning of resources (financial, human, material) for the production of goods (services), operational management of the implementation of plans (including supply, sales, and contract management), etc.

2.4. Based on the method of access to information, it is possible to classify into the following categories of ICS work:

The online mode of operation of the ICS provides users with real-time information through web applications. It allows users to access the system from anywhere, anytime, and from any device that has an Internet connection. The system uses a client-server architecture, where the server provides data and services, and the client accesses and interacts with the data through a web browser. Examples of online systems are business intelligence systems, dashboards, and customer relationship management systems.

Offline – **the system** provides information in the form of reports, documents, and other printed media. It generally does not require an internet connection to access the information, and users can access the information offline. Examples of offline systems that organizations can use are directories, reports, and newsletters.

Mobile ICS provides users with real-time information using mobile devices such as smartphones and tablets. The mobile system allows users to access the system from anywhere, anytime, and on any mobile device with an internet connection. The system uses a client-server architecture, where the server provides data and services, and the client accesses and interacts with the data through a mobile application. Examples of mobile ICS are mobile business intelligence systems, mobile dashboards, mobile supply chain management systems, etc.

Cloud ICS provides information and services to users through a cloud computing platform. The system uses a client-server architecture, where the server provides data and services, and the client accesses and interacts with the data through a web application. Cloud-based ICS allows users to access the system from anywhere, anytime, and any device with an internet connection. Some examples are cloud-based ERP, cloud-based SCM, and cloud-based HRM.

2.5. Based on the organizational level. ICS are classified based on their relationship to other ICs in the organization**.** Organizational information deals with the organization’s environment where organizational goals are achieved. ICS can be classified based on the attribute – organizational level since they are designed to support specific functions and operations in a particular department, the entire organization (enterprise), or between several organizations (associations):

Departmental sign. Departmental ICSs designed for the operation of an organization’s department are information systems that are designed to support the information needs of individual departments of an organization and focus on the specific needs of any particular department or function within the organization, such as production, marketing or accounting, marketing, or production. The purpose of the systems is to provide department leadership with the information they need to make better decisions, improve efficiency, and achieve their department’s goals. ICS typically perform tasks related to department activities, such as sales, customer, financial, inventory, or production data. Examples of departmental ICS are sales management information systems, marketing management information systems, and Accounting Management Information Systems.

Organizational feature. ICS (organization-wide) or information systems that combine and manage data from different departments and functions of the entire organization. This includes the so-called corporate information systems (CIS) to provide a comprehensive view of the organization’s activities and facilitate decision-making at the strategic level. CIS is designed to process large amounts of data, integrate various information systems and databases, and provide information in a format that is easy to use and understand. CIS can contain modules for multiple functions such as finance, accounting, human resources, marketing, and operations, and can integrate external data such as market trends, competitor analysis, and economic indicators. CIS is aimed at large companies and can support geographically remote nodes and networks. They usually have a hierarchical client-server structure with server specialization. During the development of such systems, the same database servers can be used to develop group information systems.

Cross-organizational trait. ICS of this level allows different organizations (production associations, corporations, etc.) to exchange information and cooperate in business processes. ICS facilitates the exchange of data and information between organizations, allowing them to work together more efficiently and effectively. ICS across organizations is particularly important in today's business environment, where many organizations operate in complex networks of suppliers, customers, partners, and other stakeholders. By sharing information and collaborating on business processes, organizations can improve their agility, responsiveness, and competitiveness. The most common servers for corporate systems are Oracle, DB2, Microsoft SQL Server, SAP, and document management systems. CIS includes, for example, the systems of such organizations as the Open Joint Stock Company «Ukrtelecom», «Ukrzaliznytsia», the National Bank of Ukraine, the Unified Automated System for Urban Passenger Transport Management in Kyiv, which combines four autonomous systems: dispatch control of urban public transport, management of route facilities, automated traffic and parking management. Surveillance cameras will be used to ensure the efficient operation of the electronic traffic controller at intersections. Examples of systems on an inter-organizational basis are supply chain management systems and the production of high-tech products at the corporate level, such as the Antonov enterprise, customer relationship management system, electronic data interchange, etc.

2.6. Based on the types of intelligent information systems. Intelligent information systems allow building programs of expedient activity to solve the tasks assigned to them based on a specific situation that is currently developing in the environment. At the same time, intelligent systems must remain operational in case of unforeseen changes in the properties of the controlled object, control goals, or the environment (be adaptive).

Types of intelligent information systems for various purposes are widely considered in the literature [4], in particular,

- **Systems with communicative abilities** (intelligent databases, natural language interfaces, hypertext systems, contextual reference systems, cognitive graphics);
- **Expert systems** (classifying, pre-recognizing, transforming, multi-agent);
- **Self-learning systems** (inductive systems, neural networks, precedent-based systems, information repositories);
- **Adaptive systems** (CASE-technologies, technology components).

The paper analyzes intelligent information systems that use modern technologies, in particular, **a hybrid approach to the construction of such systems**:

- **Hybrid Intelligent System (GIS).** GIS is usually understood as a system in which several methods are used to solve a problem, as a rule, from different classes to solve management and design problems. Various artificial intelligence (AI) methods are widely used in GIS [5]. GIS is a multitude of AI tools, where each tool – neural networks, fuzzy logic, evolutionary algorithms – plays a role.

GIS allows you to use the advantages of traditional technologies and methods of ICS design, overcoming some of their shortcomings and limitations, and can more effectively solve complex problems in the context of growing technologies such as AI, Big Data, ML, AutoML, DLd in the practice of ICS design:

A model for combining paradigms for the use of rules and use cases.

This model allows you to improve the efficiency of exception handling without complicating the rule set. Thus, each component deals with what it is best focused on: rules deal with generalizations of the subject area, and precedents deal with individual atypical cases. This technology involves looking for precedents that are analogous to the current case if it is an exception to the rule. This approach requires that the database of use cases be indexed according to the rules to which they are exceptions. The algorithm assumes the following order: first, rules are applied to solve the current problem, as a result of which some solution is formed. Then, the library of use cases is reviewed for exceptions to the relevant rule, shown in Fig. 2.

This model can be used in complex production systems of process control systems and the defense sector [6]. In production systems, the construction of a database is identified with an extended set of rules, the completeness of coverage of the tasks of the subject area, and the correctness of the system's functioning.

Popular algorithms and methods combined in such systems are:

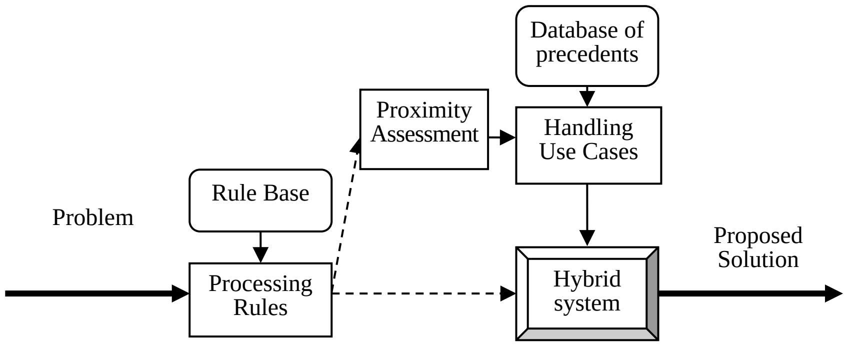

Figure 2. Architecture of hybrid use of rules and use cases

Source: Developed by the author

A hybrid combination of technologies, rules, and neural networks in IIS.

A hybrid approach to building knowledge-oriented ICS can solve an important problem of learning a system. After all, knowledge-oriented ICS is mainly built for subject areas characterized by the need to update and expand knowledge in knowledge-intensive industrial areas. With this in mind, GIS should contain a module that allows you to upload new knowledge to the system and edit old knowledge. Of increasing interest is the automated acquisition of knowledge (self-learning), or the creation of new concepts or rules based on existing data and knowledge, checking them for indisputability with existing ones and inclusion in the knowledge base. The collection and storage of expert knowledge is best done by a knowledge-oriented system, but it does not adapt to change immediately. Neural networks, on the other hand, are not very good custodians of expert experience, but they can be trained to prolong learning. Neural networks can sift through large amounts of data and find cause-and-effect relationships that will help them adapt to changes in their environment.

The neural network approach is especially effective in expert evaluation tasks because it combines a computer's ability to process numbers with the brain's ability to generalize and recognize.

So, like neural network algorithms and systems with fuzzy logic, expert systems are technology used in a knowledge-oriented system. These systems are also capable of learning, that is, of forming their knowledge base based on examples from the subject area.

Neural Networks + Expert Systems. The most popular example, which has its name, is **neural expert systems** or communicative expert systems. The combination of data-driven learning and human experience (expert knowledge) is often used to improve financial forecasting and medical diagnosis. The combined use of the expert system and the apparatus of artificial neural networks provides the necessary flexibility and self-learning based on knowledge; at the same time, the knowledge obtained from experts allows for significantly simplifying the structure of neural networks, reduces the number of neurons and network connections—general overview of GIS [7].

Neural Networks + Fuzzy Logic (Fuzzy Neural Networks) [8]. Classical fuzzy systems have the disadvantage that in order to formulate logical rules and membership functions, it is necessary to involve objective subject matter experts, which is quite difficult to ensure. The concept of fuzzy neural networks (or adaptive fuzzy systems) involves the implementation of logical proof based on the apparatus of fuzzy logic. Still, its necessary components are a set of appropriate linguistic rules, and the optimal form of membership functions is selected in the process of training a neural network based on experimental data. To do this, the fuzzy control module is presented in the form of a multilayer neural network, and an error inverse propagation algorithm is used. A fuzzy neural network typically consists of four layers: the input variable phasification layer, the activation condition value aggregation layer, the fuzzy rule aggregation layer, and the output layer. The architecture of fuzzy neural networks such as ANFIS and TSK is currently the most widespread; these networks are universal approximators. The advantages of adaptive fuzzy systems, such as the ability to obtain new knowledge and transparent interpretation of accumulated knowledge, have made these systems today the most promising and effective tools for «soft» computing.

Neural Networks + Genetic Algorithms. The combination of these technologies involves the selection of inputs for the neural network in the form of natural selection and training of the neural network by selecting adequate parameters at two stages: to search for general parameters of the neural network (the number of hidden layers and neurons) and at the final stage of training (to find all values of the neural network weights and activation functions). Genetic algorithms are used to improve neural networks already created and trained using any algorithm. Experts have divided how neural networks are supported by genetic algorithms into three types, namely: the use of genetic algorithms to select functions or transform the function space used by a neural network, the use of genetic algorithms to select learning rules or parameters that control the learning of a neural network, and the use of genetic algorithms to analyze a neural network.

It is worth noting that neural networks are also used to support genetic algorithms. For example, a hybrid system was developed in which a genetic algorithm played two roles: finding a set of favorable parameters that the heuristic procedure uses to create highly efficient breakpoints and finding a set of heuristic selection rules to find the minimum path. The parameters encoded in the chromosome to find breakpoints are the initial set of assignments that heuristics try to improve. The parameters encoded on the chromosome to find the minimum path determine the select-insert heuristics (e.g., «nearest neighbor», «cheapest insert», etc.) for each breakpoint. This approach has also been used to solve the problems of the traveling salesman [9].

Machine learning systems. Unlike knowledge-based systems, they do not require clear rules but rely on statistical models and algorithms that learn from the data. Such systems include those that use supervised learning, unsupervised learning, or reinforcement learning. The advantages of machine learning systems are their adaptability, that is, the ability to improve over time as new data sets arrive, as well as the ability to search for non-obvious patterns and relationships. The main application areas of such systems are stock markets and spam filtering. That is, those areas where it is important to analyze large amounts of data and find patterns for making a decision or providing conclusions [10]. Automated machine learning (AutoML) provides methods and processes to make machine learning accessible to non-machine learning experts, improve the efficiency of machine learning, and accelerate research in the field of machine learning.

Deep learning system. These systems are inspired by the complex architecture of the human brain. They use artificial neural networks that mimic brain structures to learn from huge amounts of data, especially good at tasks related to big data, such as images and natural language. Deep learning methods in the hierarchy of AI systems are believed to be part of machine learning systems and have a huge impact on the development of modern AI.

Deep learning methods include those based on the unattended learning architecture of pre-trained networks, convolutional neural networks, recurrent neural networks, and recursive neural networks [11].

Different types of neural networks are used for different use cases and data types. For example, recurrent neural networks are commonly used for natural language processing and speech recognition. In contrast, convolutional neural networks (ConvNets or CNNs) are most widely used for classification and computer vision tasks. Convolutional neural networks now provide a more scalable approach to image classification and object recognition problems, using the principles of linear algebra, in particular matrix multiplication, to identify patterns in an image.

Recursive neural networks (RvNN) are a special type of deep learning that can work with structured inputs, such as parse trees in natural language processing or molecular structures in chemistry. The network processes input recursively, combining information from child nodes to form a representation for parent nodes. RvNN is mainly used in some NLP tasks, such as analyzing the mood of the interlocutor. RvNN processes parsing trees by assigning vectors to each word or phrase based on information from its child nodes, allowing the network to capture hierarchical relationships and dependencies within a sentence [12].

A recurrent neural network (RNN) is a type of artificial neural network that uses sequential or time-series data. These deep learning algorithms are typically used to solve ordinal or temporal tasks such as speech translation, natural language processing (NLP), speech recognition, and image captions; they're included in popular apps like Siri, voice search, and Google Translate. Like direct and convolutional neural networks (CNNs), recurrent neural networks use training data for training. They are distinguished by their «memory» because they take information from previous inputs to influence current inputs and outputs. While traditional deep neural networks assume that inputs and outputs are independent of each other, the output of recurrent neural networks depends on the previous elements in the sequence. While future events can also be useful in determining the output of a particular sequence, unidirectional recurrent neural networks cannot account for these events in their predictions.

The «Dropout» method is one of the key examples of the application of deep learning systems. Deep neural networks with a large number of parameters are very powerful machine learning systems. Large networks are slow to use, making it difficult to combat overfitting by combining the predictions of many large neural networks during testing. Screening is a method of solving this problem.

The key idea is to randomly remove elements (along with their connections) from the neural network during training. This prevents the elements from co-adapting excessively. During the training, samples are screened out from an exponential number of different «thinned» networks. During testing, it is easy to approximate the effect of averaging the forecasts of all these thinned networks by simply using one unbranched network that has less weight. It has been shown that the screening method significantly improves the performance of neural networks in the tasks of guided learning in the fields of vision, speech recognition, document classification, and obtaining results on reference datasets [13].

Deep learning in ICS development. Deep learning has become widespread in a variety of fields, including ICS. Its ability to learn complex patterns based on big data provides the potential to improve functionality and efficiency. Deep Learning:

- enables businesses to build predictive models to predict future trends, behaviors, and outcomes. Deep learning models can analyze vast amounts of data, identifying patterns and making accurate predictions. Recommender systems, which are widely used in e-commerce, streaming media, and personalized marketing, use deep learning algorithms to suggest relevant products, movies, music, and content to users based on their preferences and behaviors;
- optimizes supply chain operations by forecasting demand, optimizing inventory levels, and improving logistics. It can analyze historical data, market trends, and external factors to improve decision-making and streamline operations;
- is crucial for fraud detection and strengthening cybersecurity measures. Deep learning models can analyze large amounts of data in real-time, identifying patterns, anomalies, and potential threats. They are used to detect credit card fraud, detect network intrusions, detect malware, and filter spam, among other tasks. Deep learning models continuously learn from new data, increasing their ability to detect new threats and improving threat detection [14].

Machine Learning + Situation-Based Reasoning. Improving the process of combining defined patterns with logical rules for navigation and decision-making. An example of such a system would be personalized learning systems, which combine learning models with field-specific knowledge to tailor learning content to the individual needs of users. There is also an interesting study on the application of hybrid intelligent methods to model the diffusion of light hydrocarbons in bitumen in the road sector. According to the analysis, the combination of methods such as ANFIS (Adaptive Neuro-fuzzy Inference System) and PSO (Particle Swarm Method) is best suited for analysis compared to ANFIS+GA and ANFIS+R2 [15].

Coevolutionary algorithms can be considered part of synergistic systems. In coevolutionary algorithms, two or more populations of individuals evolve together. Their adaptability is determined by how well they interact and cooperate, not just their performance. This interdependence forces populations to adapt and learn from each other, leading to new and effective solutions. The behavior of the coevolutionary algorithm depends on the interaction between individuals. In this case, individuals are not evaluated in terms of an explicit fitness function but rather in terms of direct interactions between individuals taken from populations. Traditional evolutionary algorithms assess an individual's fitness objectively, regardless of the population context in which it is placed. Coevolutionary algorithms work the same way as traditional algorithms, except that fitness assessment is not objective but subjective: an individual is evaluated through interaction with other individuals in the evolutionary system. Two types of interaction have been developed: cooperative and competitive.

Cooperative coevolutionary algorithms are often used in situations where a problem can be naturally decomposed into subcomponents. Individuals present such subcomponents and are evaluated in a series of interactions with other individuals to form complete solutions. The fitness of a subpopulation is an assessment of how well it «cooperates» with other species to produce reasonable solutions. Cooperative-coevolutionary algorithms have been successful in various fields, such as production planning, optimization of functions, design of artificial neural networks, and painting of premises. An example of the application of a cooperative coevolutionary algorithm can be its use in multi-agent systems (MAC) to improve the interaction between agents.

Competitive coevolution occurs either within a single population engaged in «competitive games» or between multiple populations. Competitive co-evolution has several types of interactions. To gain shared resources and space, they compete with each other. Competitive co-evolution of a single population has been successfully applied to the iterative prisoner's dilemma, chase, and evasion, as well as to the search for reliable game strategies [16]. An example of the application of these systems is robot control training, where several robots can jointly develop their movement and coordination strategies to perform complex tasks. Also, computer players (computer-controlled players) with artificial intelligence in competitive games can change their strategies to become more unpredictable and efficient.

2.7. Based on the types of interaction of objects in specialized computer systems.

The Internet of Things (IoT) is a technology where physical objects are interconnected with each other through the Internet and can identify themselves. It is a huge network with a combination of different sensor devices such as RFID, GPS, etc., which are used to identify, manage, and control devices [things connected to an IoT platform where we can collect and share any information through machine-to-machine (M2M) communication. The Internet of Things (IoT) consists of an Arduino/Raspberry Pi IoT board, an RF module, a sensor module, an access point (Wi-Fi/4G/3G), an IoT server, and a cloud point. Communication with each other is carried out through an IP address without human intervention [17, 18].

The Internet of Everything (IoE) is an extension of IoT made up of people, things, and processes, with data spanning business and industrial processes. The exchange and collection of information takes place from machine to machine (M2M) or person-to-person (P2P) or person-to-machine (P2M), where in the case of IoT, it is only for things. In IoE, it stands for the Internet for Everything/Everyone [19].

Internet of Nano Things (IoNT) – refers to nanocomponents in an integrated circuit, where miniature sensors are connected to each other via a nanonetwork to receive data from objects. Nanodevices with nanocomponents are integrated into a single device to perform multiple tasks. It will work according to how we connect devices over the internet. The main differences between the Internet of Things (IoT) and the Internet of Nano Things (IoNT) are that nanocomponents will not be achievable in IoT [20].

Internet of Mission Critical Things (IoMCT) – The Internet of Mission Critical Things (IoMCT) is driven by the convergence of detection, communication, computing, and control. The main goal of IoMCT is to improve the use of network surveillance. IoMCT technology is approaching critical events such as military operations, border patrols, search and rescue, and monitoring and surveillance of critical objects [21].

The Internet of Mobile Things (IoMT) is a technology for mobile devices that uniquely identifies owners, their locations, and security of use. It gains scalability in mission-critical missions of subjects and surveillance objects [22].

The Industrial Internet of Things (IIoT) is a network of intelligent and connected industrial components that are deployed to achieve high performance with reduced operating costs through real-time monitoring, efficient management, and control of industrial processes, assets, and operations [23]. IIoT devices connect wirelessly to internal networks as well as to the global Internet. These devices represent a new stage of automation – collecting unprecedented amounts of data from all aspects of the process and sharing it with a central server. This data allows you to analyze and take action that has not been seen before, resulting in increased efficiency and productivity. Implementing IIoT technologies is a key element of Industry 4.0 initiatives, manifested in the strategies of «smart» industrial facilities.

3. Identification of basic trends in innovative technologies in ICS

In connection with the high rates of development of information technologies, the classification of ICS, the introduction of the principles of hybridization, and the integration of methods and technologies into ICS, it is necessary to determine the basic trends of innovative technologies that are used in the methodology for designing various types of ICS and with the help of which organizations, the production sector of the economy, as well as in the technical and educational spheres and modern medicine can effectively stay and compete in business thanks to the real-time efficiency of using them provided by such a current information technology industry.

3.1. Trend 1. The Impact of AI Innovation on ICS

Development and implementation of machine learning algorithms. AI continues to rank at the top of emerging technologies.

Artificial intelligence (AI) is defined as the science and engineering aimed at creating intelligent machines, information systems, their components, and computer algorithms and programs [24–26]. Breakthroughs in AI have been driven by the development of two key areas: machine learning (ML) and deep learning (DL).

Machine learning is a fundamental technology in AI that allows systems to learn and improve based on experience without explicit programming for each task. This is achieved through algorithms that analyze large amounts of data by identifying patterns and using them to make informed decisions or predict future events.

One of the key advantages of machine learning is its ability to improve itself: the more data a system analyzes, the more accurate its predictions and decisions become. However, ML algorithms need access to large amounts of structured, well-organized data to work effectively. Unstructured or poorly organized data can significantly reduce the efficiency of algorithms, leading to an increase in the importance of deep learning being able to work effectively with such data.

With the availability of large amounts of data, machine learning has become an integral part of decision-making and efficiency processes in many industries, including finance, manufacturing, healthcare, and many others.

Deep learning, a subfield of machine learning, uses multi-layered artificial neural networks to mimic the human brain, allowing the system to learn with incredible accuracy. DL effectively solves tasks that are difficult for traditional ML algorithms, such as speech recognition, image recognition, and automatic translation. Yann LeCun, Yoshua Bengio, and Geoffrey Hinton, in their 2015 article in the journal Nature, describe how deep learning has become a key element of modern AI, allowing systems to learn efficiently from large amounts of data and solve complex problems that were unattainable by other machine learning methods [27].

Automated Machine Learning (AutoML) in ICS. The main breakthrough in machine learning will be related to automated machine learning. Despite its value, machine learning is resource-intensive and takes time to develop training models. AutoML helps developers and researchers derive highly efficient predictive models. This allows them to identify the best hyperparameters, neural architectures, preprocessing, and even entire data processing pipelines for the existing dataset and metric [28].

This is especially useful in ICS, where you need to adapt to new data and requirements quickly. For example, using AutoML to analyze sensor data in production allows you to optimize production lines, predict equipment failures, and improve product quality. For instance, Siemens uses AutoML to analyze large amounts of data from its turbines, significantly reducing downtime and increasing equipment efficiency. Other examples are using AutoML algorithms in medicine to analyze medical images, predict the course of diseases, and personalize treatment. For example, Google Health uses AutoML to improve diagnosing diabetic retinopathy by automating the process of analyzing retinal images. In banking and asset management, AutoML helps analyze financial markets, predict lending risks, and optimize investment portfolios. JPMorgan Chase uses AutoML technologies to develop algorithms that aid in risk management and identifying new investment opportunities.

Improving the efficiency of programming and improving the quality of ICS applications. AI can make a significant contribution to enhancing software development. Software companies that want to keep up with the times actively use AI technologies: ML – on methods of building algorithms, DL – focuses on data classification; Natural language processing (NLP) – specializes in speech recognition technologies in the development of ICS applications, which allows for effective communication with the user, automation of routine tasks and ensuring a high level of security.

Apps face numerous security challenges, from malware attacks and data breaches to privacy and user authentication issues. These security challenges not only threaten user data but also affect trust in app developers. Integrating AI into the application development lifecycle can significantly improve security measures. Starting with the design and planning phases of ICS design, AI can help predict potential security flaws. AI algorithms can identify vulnerabilities developers may miss during the coding and testing phases. The implemented neural networks can provide suggestions and recommendations in the coding process, which leads to an increase in the efficiency of ICS implementation, as well as the process of testing, prototyping, scaling, and versioning systems. Software quality assurance plays an important role in the software development life cycle when testing and scaling applications and significantly reduces unforeseen problems when implementing applications in ICS [29].

Improving ICS security. Organizations collect and accumulate large amounts of data that need to be protected. AI identifies patterns [24] that allow security systems to learn and improve continuously. AI contributes to improving cybersecurity by searching for undetected threats, detecting anomalies by analyzing the basic behavior of users and servers, and improving the security of systems through network policy and network topography.

Therefore, to ensure the security and confidentiality of the data collected for AI purposes, a robust architecture for the functioning of the ICS should be created: first, AI is changing data management because it relies on data for training and data to improve system performance; secondly, much of the data may be confidential and, if fraudulent, may lead to identity theft; third, the problem with AI is ambiguity, which can occur due to the use of complex algorithms that lead to layering of variables and a delay in identifying data on server platforms. AI allows you to effectively predict potential problems, which contributes to the stable functioning of the system and provides recommendations for solving them.

3.2. Trend 2. Cloud Computing – Improving ICS Efficiency

ICS is used to store and analyze a large amount of data needed to perform various tasks of organizations and companies, as well as to help managers develop and implement a business plan.

Cloud technologies have emerged as a response to business needs to reduce IT deployment and scaling times and have opened up a range of functionalities for businesses: expanding business markets both geographically and in terms of more fully reaching new customer segments, especially such as small/medium-sized businesses, as well as entering new fast-growing vertical markets.

The main impacts of cloud technologies on ICS are as follows:

Use of available IT infrastructure. Cloud computing provides customers with the flexibility to customize the power of their computer systems, allowing them to scale up or down resources to meet their needs. This adaptability contributes to the growing demand for cloud solutions, allowing businesses to optimize IT resource costs. Cloud computing offers significant economic benefits for companies, including reduced costs for managing and maintaining IT infrastructure. The study presented at the 2018 International Conference on Information Technology highlights that cloud-based solutions allow companies to reorient their IT needs, offering both quantitative and qualitative advantages compared to purchasing and operating their own IT systems [30]. This allows for a more in-depth analysis of the cost and benefits of using cloud computing for enterprises.

Cloud computing can significantly reduce the cost of managing and maintaining IT infrastructure, particularly through the possibility of using hybrid cloud solutions. This allows companies to reduce the cost of purchasing and maintaining complex equipment.

The growing demand for cloud platforms and services is driving the development of networking links between the information systems of different companies, contributing to the creation of more integrated and efficient digital ecosystems.

Global technology leaders such as Google Cloud, Microsoft Azure, and Amazon Web Services demonstrate the active use of global public clouds. There is a growing demand for hybrid cloud services, requiring data centers to ensure continuity and «connectivity» to act as digital hubs.

Tech giants like Amazon and Microsoft are investing heavily in hybrid cloud computing.

The cloud computing market offers a wide range of services for various business sectors, including B2C, B2B, and B2G, demonstrating the flexibility and adaptability of cloud technologies to a variety of business needs.

Increasing the scalability of business projects. The service provider quickly updates cloud storage systems and applications that use cloud computing to ensure scalability and save a significant amount of time. For a business company, it is critical to be able to quickly scale up or down operational operations and meet storage requirements to guarantee smooth business operations. Therefore, there is no need to purchase and install ICS hardware and software to perform the update process.

The article «Adaptive scaling of Kubernetes pods» considers scalability as the ability of a resource or application to expand to meet growing needs. In the context of cloud computing, automatic scaling algorithms are becoming increasingly important. This paper proposes adaptive autoscaling «Libra», which automatically determines the optimal set of resources for a single container or group and then manages the horizontal scaling process. If the load or environment changes, Libra adapts the resources for the container and adjusts the horizontal scaling process accordingly [31].

There is also a dynamic scaling model based on queue theory to scale virtual container resources and meet customer service level agreements (SLAs) while keeping scaling costs low. The goal is to improve the utilization of virtual computing resources and meet SLA constraints regarding CPU utilization, system response time, system failure rate, number of tasks in the system, and system throughput [32].

Instead of building their IT infrastructure, they need to communicate with dozens of equipment suppliers, integrators, and companies that support the IT infrastructure; the client needs to communicate only with the cloud service provider. The general trend towards shortening the supply chain is also evident despite the need to integrate cloud services from different providers. In its turn, a cloud platform that provides self-service tools can bring in a large pool of customers with minimal service maintenance costs. Cloud technologies have created the basis for the development of other technologies, such as mobility, social networks, and big data, which in turn have led to the creation of companies with new business models such as Uber, Netflix, Airbnb, and others – that are changing the rules of the game in their sectors of the economy.

Modern realities have accelerated the digital transformation of businesses and countries around the world and strengthened the priority of cloud technologies, which help optimize infrastructure costs and quickly increase capacity for large-scale projects.

3.3. Trend 3. Big Data in ICS

Digital transformation involves significant technological developments such as AI, machine learning, the Internet of Things, and big data (IoT). The proliferation of IoT-connected devices is projected to increase dramatically, with an estimated 25.44 billion devices expected by 2030, up from 10.07 billion in 2021. This surge in connected devices is a notable source of a growing big data reservoir. Machine Learning Tools and AI are ready to play a key role in analyzing the flow of big data coming from colossal data centers. They will manage the operation of these systems, identify hidden connections in the data, and efficiently store and extrapolate information. IDC predicts that global data will grow by about 61 % annually. By 2025, this figure will reach 175 zettabytes. [33]. Today, Big Data helps solve various problems in many areas, including finance, industry, energy, retail, medicine, tourism, ecology, entertainment, etc. Thanks to the processing and analysis of a large amount of data, representatives of government, business, science, ICS developers, and IT companies improve the quality of goods and services and develop business. In Ukraine, big data is used by mobile operators. For example, Big Data technologies make it possible to determine which roads Ukrainians travel more often.

Expanding Big Data Research Methodology

Big Data Analysis Methods:

Classification is used to predict consumer behavior in specific market segments. This method allows companies to tailor their marketing strategies and products to the needs of their target audience.

Cluster Analysis is used to group objects according to similar characteristics. This aids in the identification of natural divisions in the data, simplifying further analysis.

Crowdsourcing is used to collect data from a wide network of sources. This approach allows for the involvement of a large number of people in the collection of information, providing diversity and volume of data.

Data Mining – allows you to discover previously unknown but valuable information from large data sets. This facilitates informed decision-making in various fields of activity.

Machine Learning – includes the creation of models capable of self-learning and efficient information processing. The use of neural networks opens up new opportunities for data analysis.

Signal Processing – is used to recognize and analyze signals against background noise, which is critical in many technical and scientific applications.

Data Integration – allows you to combine heterogeneous data into a single format, simplifying their analysis and processing. This is especially true when working with audio, video, and text files.

Unsupervised Learning – is used to identify complex relationships in data without predefined labels or categories.

Data Visualization – transforms analysis results into clear and attractive visual representations, such as graphs and animations, contributing to a better understanding of information.

The application of analytics is the key to maximizing the value of big data. Accordingly, big data analytics is seen as the analysis of large and diverse data sets, including structured, semi-structured, and unstructured information from various sources, ranging in size from terabytes to zettabytes. Big data analytics reflects the challenges associated with data that is too large, too unstructured, and too fast to be managed by traditional methods. Due to technological developments and the increasing amount of information that enters and leaves companies daily, faster and more efficient means of evaluating such data have become necessary. Thanks to standard methodologies and data management and analysis infrastructures, datasets of this type can no longer be easily analyzed. Therefore, new tools and methodologies specializing in large-scale data analytics are needed, as well as the necessary systems for storing and managing such data.

Application of decision support technologies based on Big Data. The development of big data has a significant impact on everything from the information itself and its acquisition and processing to the final judgments obtained. Therefore, the Big Data, Analytics and Solutions (B-DAD) framework was proposed, including tools and methodologies for big data analytics in decision-making. The framework reflects various large-scale storage, management, and governance tools, analytical tools, and techniques, as well as tools for mapping and evaluating many adoption processes Solutions. A Big Data environment requires magnetic, flexible, deep (MAD) analytical capabilities that differ from the traditional enterprise data warehouse (EDW) context. First, typical EDW methods prevent the inclusion of new data sources until they have been cleaned and integrated. Due to the ubiquitous presence of data nowadays, the big data ecosystem must be magnetic and thus encompass all data sources, regardless of their quality. Big data storage should also allow analysts to create and modify data quickly, given the growing volume of databases and the complexity of data analysis. This requires a flexible database that can synchronize physical and logical content with rapidly changing data. After all, since modern data analysis uses a complex statistical methodology and analysts need to analyze large amounts of data by digging, a big data warehouse must also be thorough and have a smart, algorithmic working mechanism.

A wide range of innovative technologies and trends in working with Big Data: Initially, the set of approaches and technologies included tools for massively parallel processing of indefinitely structured data, such as NoSQL DBMS, MapReduce algorithms, and Hadoop project tools. Later, big data technologies began to include other solutions that provide similar capabilities for processing ultra-large data sets, as well as some hardware.

MapReduce is a model of distributed computing in computer clusters that was introduced by Google. According to this model, the application is divided into a significant number of identical elementary tasks that are performed on the nodes of the cluster and then naturally reduced to the final result.

NoSQL Not Only SQL, not just SQL, is a general term for various non-relational databases and repositories and does not mean any specific technology or product. Conventional relational databases are well suited for fairly fast and uniform queries, and on complex and flexibly constructed queries typical for big data, the load exceeds reasonable limits, and the use of DBMS becomes inefficient.

Hadoop is a freely distributed set of tools, libraries, and frameworks for developing and executing distributed applications that run on clusters of hundreds or thousands of nodes. It is considered one of the fundamental technologies used in most data collection.

R is a programming language for statistical data processing and working with graphics. It is widely used for data analysis and has become a standard for statistical applications.

Teradata, EMC, and others offer hardware and software systems designed to process big data. These complexes are supplied as ready-to-install telecommunication cabinets containing a cluster of servers and control software for massively parallel processing. This sometimes includes hardware solutions for analytical processing in RAM, in particular, SAP's Hana hardware and software complexes and Oracle's Exalytics complex, even though such processing is not initially massively parallel, and the amount of RAM of one node is limited to several terabytes. In addition to the NoSQL, MapReduce, Hadoop, and R technologies considered by most analysts, McKinsey also includes Business Intelligence technologies and relational database management systems with SQL Big Data support in the context of being suitable for processing big data.

Expanding the scope of implementation of big data technologies:

A study of the forecast of the Earth's climate change. The quest for understanding requires an unprecedented influx of data from an extensive network of scientific observatories located both on Earth and in its atmosphere. This includes not only data from these observatories, but also enormous contributions from ocean research, earth sciences, meteorological research centers, and, interestingly, from the enigmatic realms of nuclear research spanning events from the Big Bang to the current age of the universe;

Search for innovative medical solutions. The role of big data in healthcare is poised for significant growth, with the potential to accelerate medical discovery by consolidating vast volumes of global medical records. The impact of big data goes beyond medical breakthroughs. It improves the staffing of healthcare facilities, automates the processing of electronic medical records, and allows you to receive real-time notifications about the condition of patients. The basis of the medical infrastructure can be the ICS of data exchange between research institutions and medical institutions, both public and private, to optimize the process of treatment, rehabilitation, and life support of patients. The transformative impact of big data in healthcare is evident, from groundbreaking research to pandemic management, cardiovascular disease treatment, and organ and tissue transplantation, marking a significant step towards improving global healthcare**;**

***The development of urban IT ecosystems based on big data* is created as cluster** associations of stakeholders around common interests and economies of scale, particularly co-financing of educational and infrastructure initiatives of higher education institutions. Technological and computing resources in such an ecosystem are closely related; monitoring and managing physical processes are carried out using IoT technologies. Traditional Engineering Models harmoniously coexist with computer ones. Example: at KNEU named after Vadym Hetman, one of the main directions of the University's strategic objective until 2025 is the formation of effective digital educational, scientific, and economic activities of the University's IT ecosystem. In order to adequately respond to changes in the market of educational services, it is also necessary to develop an integrated information system for managing the quality of educational activities of KNEU named after Vadym Hetman, the main purpose of which is to study the process of educational and scientific activities, monitoring and targeting end users to identify their requirements, assessing the degree of compliance of the quality of educational services with market needs. Overall, the Big Data ecosystem consists of various components that work together to enable efficient storage, processing, and analysis of big data. This includes not only technologies such as Hadoop, Spark, and NoSQL databases but also other tools and solutions such as ETL tools (Extract, Transform, Load), data management systems, analytical platforms, IT infrastructure and cloud computing services, ICS design technologies and methodologies;

The intersection of the application of unmanned driving technologies and big data. The use of Big Data technologies plays a key role in improving automated vehicle management and training. This process involves collecting, processing, and analyzing vast amounts of data from a variety of sources, such as sensors, cameras, and other systems installed on the vehicle. Using this data allows for more accurate and efficient driving systems that can predict potential road hazards and optimize driving routes.

One example of the application of Big Data in automated driving is the development of in-depth training models for autonomous driving, based on data obtained from simulations and real-world operating conditions. A study conducted by Symphorien Karl Yoki Donzia and others found that the use of deep learning models such as YOLO based on convolutional neural networks (CNNs) can significantly improve the ability of autonomous vehicles to recognize and respond to dangerous situations on the road in advance, through the analysis of big data collected from various sources [34].

The use of big data is not limited only to improving the direct management of vehicles but also contributes to the effective training of autonomous systems. For example, methods based on Model predictive control (MPC) and big data analysis make it possible to optimize the lateral control of autonomous vehicles, improving their ability to follow a given route with high accuracy [35].

Integrating Big Data and unmanned driving technologies opens new opportunities to improve autonomous vehicles' safety, efficiency, and reliability. In particular, using big data allows for developing systems capable of adapting to changing traffic conditions, anticipating potential hazards, and optimizing routes in real-time. This approach not only increases traffic safety but also helps reduce transportation costs and environmental impact.

Expanding the services of business companies with the help of big data. New trends in the social sphere involve the integration of all critical aspects of business operations: advertising, supply chain management, customer support, social media management, social services management, etc. Data integration is vital for a variety of purposes, including analysis, reporting, and business intelligence. Sources can range from social media pages and ERP applications to customer logs, financial reports, emails, presentations, and employee-generated reports. This integration strategy encompasses a wealth of data, ranging from customer bank transaction records, interaction patterns with internet query landing pages, geographic data, and video feeds from multiple supermarket branches to provided suggestions and customer survey feedback. Regardless of the complexity of the data, the latest analytics tools are ready to process it in real time, providing previously unattainable insights. The Transformative Impact of Big Data goes far beyond simple data analysis. It shapes the way we work, make decisions, and innovate. Netflix's system was one of the early proponents of big data analytics, but in the future, the list of organizations willing to harness the full potential of data-driven decision-making is growing.

Big data is also penetrating local retail, where another segment of DaaS providers is used – Data as a Service, which is a cloud-based software tool designed to work with data, such as to manage data in a data warehouse or analyze data using business intelligence. It is provided by SaaS software-as-a-service. DaaS is based on the concept that its data product can be made available to the user on demand, regardless of the geographical or organizational dependency between the supplier and the consumer. Big Data is widely used in retail by centers like Vodafone (Ukraine), ATB-Market, Silpo chains, etc.

3.4. Trends 4. Development of the Internet of Things (IoT) in specialized computer systems

The Internet of Things (abbreviated as IoT) is a new stage in the development of the Internet, which significantly expands the possibilities of collecting, analyzing, and distributing data that users can turn into information and knowledge. To define IoT more precisely, it is a global infrastructure for the information society that enables the provision of more complex services by connecting (physical and virtual) things with each other based on existing and functionally evolving interoperable information and communication technologies [36, 37].

The application of numerous IT solutions to improve traditional operational technologies (OT) has created a whole class of solutions commonly referred to as the Industrial Internet of Things (IIoT). Gartner's Industrial Internet of Things Standard Reference Architecture consists of three parts (Figure 3) [38].

Edge includes traditional OT hardware such as sensors and actuators, as well as an IIoT gateway that performs a multitude of tasks, such as data filtering, aggregation and storage, analytics, device management, access control, and communication with networks and applications.

A cloud platform is typically a platform-as-a-service (PaaS) that integrates data storage and analytics, event processing, process orchestration, network communication, and other functions.

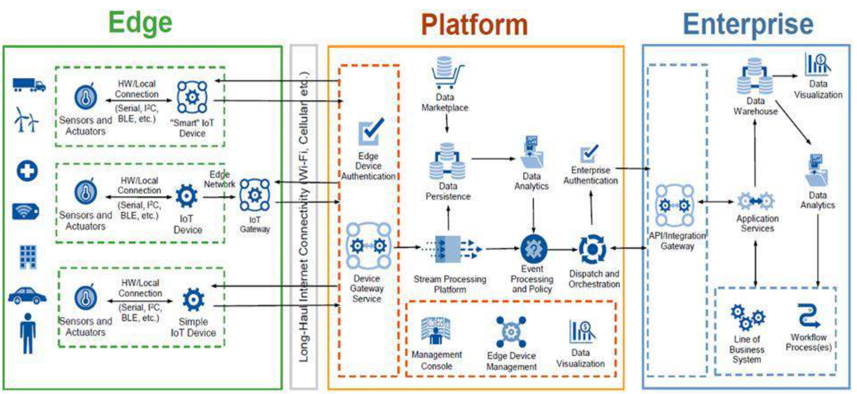

Figure 3. Gartner IIoT Standard Reference Architecture

Source: [38]

The enterprise supports server-side software and applications such as databases, data warehouses, web services, etc.

This optimized architecture bypasses traditional hierarchical levels and allows data to be exchanged directly from physical devices to cloud services or to consolidate communication through an IIoT gateway to the cloud. In IoT deployments, data is not limited to traditional hierarchies, and in fact, data no longer lives entirely within the enterprise.

IIoT is a key component of Industry 4.0, the fourth industrial revolution characterized by a combination of digital, physical, and biological technologies. It is a revolution in traditional industries, facilitating the shift from manual and time-consuming processes to automated, data-driven operations. With IIoT, equipment performance can be monitored, failures can be predicted, logistics can be optimized, product quality improvements, and more. It's about creating the smartest, efficient, and profitable industrial operation, or in other words, OT. IIoT is a subset of IoT that specifically deals with industrial applications. It focuses on improving industrial processes and operations through data-driven insights. IIoT includes more complex systems, stringent security requirements, and mission-critical operational controls. It's about improving efficiency, productivity, and safety in industries such as manufacturing, energy, and transportation. While both IoT and IIoT are powered by similar technologies such as sensors, connectivity, and data analytics, the key difference lies in their application and impact. The Internet of Things improves our daily lives by making our homes, cities, and devices smarter. IIoT, on the other hand, is transforming industries by revolutionizing how businesses operate and compete.

The development of IoT and IIoT technology architecture is based on the use of the following basic principles [39]:

- the ubiquitous typical Y.2060 communications infrastructure;
- global identification of each object of a given subject area;
- the target's ability to send and receive data using a personal area network or the Internet;

The development of IoT architecture can be supplemented with the use of

- principles of adaptability to each development of a specialized computer system, scalability, hybridization, and security of systems.

The latter principle is becoming increasingly widely used in specialized computer systems in various subject areas. In particular, Cisco Systems has developed a Cisco IoT model at the level of the security environment (Fig. 4).

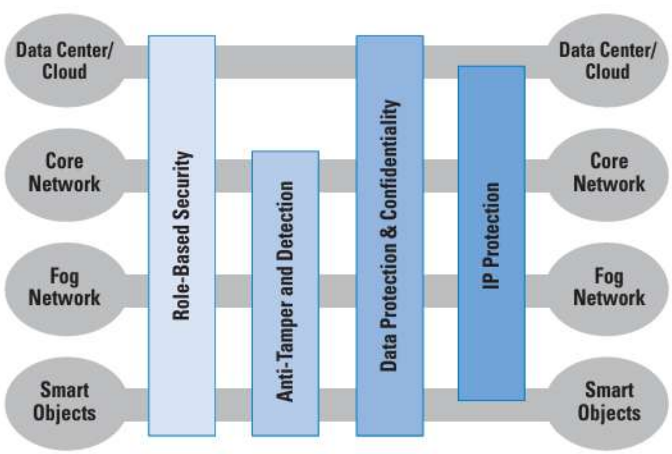

Figure 4. Cisco Security Model

Source: [40]

With this four-tiered architecture, Cisco's security model defines four common security capabilities spanning multiple layers:

- Role-based security;
- Protection from interference and detection of interference;
- Data protection and privacy;
- Secure Internet protocols.

Also, a user's sensitive personal information cannot be compromised, so data security is a key issue to overcome. There is a possibility that IoT networks are also at risk of attacks, so hardware security is an equally important component of IoT architecture development.

A typical architecture for IIoT describes the arrangement of digital systems so that they together provide network and data connectivity between sensors, IoT devices, data storage, and other layers. Thus, the IIoT architecture should have the following components [41], Fig. 5.

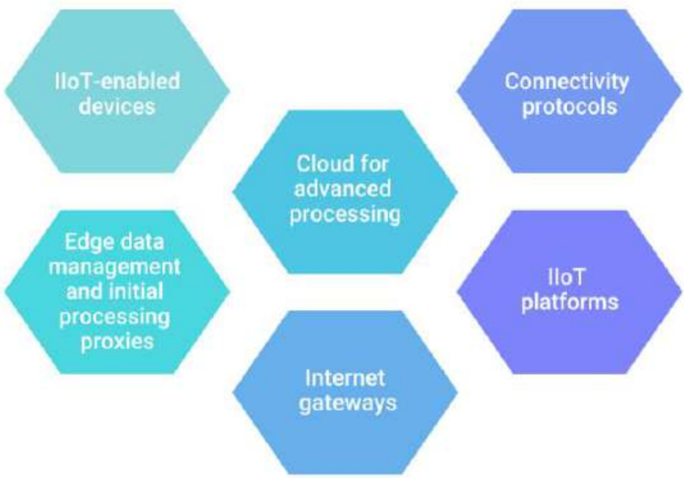

Figure 5. Typical IIoT architecture

Source: [41]

Advanced IIoT platforms. Industrial Internet of Things (IIoT) systems play a critical role in coordinating, monitoring, and managing operations throughout the value chain. They provide device data management, analytics, data visualization, and integration of AI features, working from edge devices and sensors to cloud computing and back again. This allows for fully connected, transparent, automated, and intelligent factory settings, improving manufacturing processes and efficiency [42].

The Industrial Internet Reference Architecture (IIRA) serves as a standard for the development of complex IIoT systems, promoting a systematic approach to development that includes feedback and iterations. It recommends adapting IIoT projects to the specific needs of business sectors, such as energy, healthcare, transportation, and government services [43].

Today, the Industrial Internet of Things (IIoT) is a strategic asset for large corporations and a key offering from leading cloud service providers, including Microsoft and Amazon Web Services (AWS). IIoT expands opportunities for industry in the areas of advanced data analytics and cloud computing, improving equipment maintenance, industrial operations efficiency, supply chain management, and personnel safety. The use of IIoT enables enterprises to achieve higher operational efficiency, increase productivity, and better manage industrial assets and processes through product customization, intelligent monitoring of production processes, and predictive and predictive maintenance of industrial equipment [44].

When modeling industrial facility processes, studies related to implementing the concept of a digital twin of an industrial facility, which is a complete virtual copy of a physical object for the entire life cycle of project management, from ideas to decommissioning and curtailment of production, are acquired. The necessary infrastructural conditions for implementing a given concept, including IIoT and the material base for processing large data volumes, are determined.

Given the security and privacy challenges accompanying IIoT implementation, it is important to implement advanced data protection and network security technologies. Developing and implementing robust authentication, data protection, and access control mechanisms are critical to securing IIoT devices and protecting against cyber threats [45].

Predictive data on the use of IIoT technologies. Accenture conducted an extensive study, «Winning with the Industrial Internet of Things» [46]. As part of this study, a survey of 1,400 senior executives in many countries around the world (736 of them CEOs) was conducted. The report, released as a result of the study, claims that the contribution of the Industrial Internet of Things to global manufacturing by 2030 could be about $ 14.2 trillion. However, this one potential growth is at risk because neither companies nor governments are doing enough to create the necessary conditions for the widespread adoption of new digital technologies.

IoT and IIoT challenges in ICS.

The Internet of Things has a significant impact on ICS. However, face-to-face interaction and professional activities can decrease significantly as IoT usage increases. Smart environments, smart objects, and devices bring significant lifestyle changes as people become more adaptable to technology and intelligence. As more devices connect to the internet, the quality of services may decline accordingly, highlighting the need to improve the relevant IT infrastructure. In addition, the security and confidentiality of data and big data are critically important to consider in IoT technology, which can seriously jeopardize the stable operation of the ICS. The interoperability of different types of devices that connect to each other through a single IoT platform is another issue that needs to be considered when designing an ICS, which can be solved by using the standard protocols and platforms of different IoT devices in the ICS.

4. Prospects for the development of ICST

4.1. Information Aspect of the Development of ICST Programs

The National Informatization Program, which is regulated by the Law of Ukraine «On the National Informatization Program» [47], forms a set of tasks, programs, projects, works on informatization aimed at the development of the information society through the concentration and rational use of financial, material, technical and other resources, production and scientific-technical potential of the state, coordination of the activities of state bodies, local self-government bodies, as well as enterprises, institutions, organizations regardless of ownership. The National Informatization Program is formed and implemented in accordance with the Concept of the National Informatization Program [48]. It is aimed at the formation of the national infrastructure of informatization, informatization of priority areas of the economy, informatization of socio-economic development processes, solving problems of information society development, increasing the efficiency and effectiveness of public administration, national security and defense, democratization Society.

A comprehensive and balanced solution to the problems of socio-economic development is possible only on a modern information-analytical, system-technical base, with the help of situational centers for providing information support for the functioning of the public sector of the economy, conducting a balanced budgetary, credit and tax policy, the emergence of knowledge-intensive industries in strategically important areas [3]. ICST will provide scientific approaches to solving social problems of society. This direction of informatization is based on the creation of databases and knowledge, as well as means of their processing, focused on effective informatization of state statistics bodies and accurate forecasting of the processes of socio-economic development, in particular, information and reference systems of the labor market, goods and services, quality control of consumer goods and others with their subsequent use for the formation of information systems for the management of given economic objects and processes.

Prospects for further research will be to study the problems of developing a system of cooperation between education, science, business, and the state on the basis of the active application of a systematic approach to the development, implementation, and commercialization of innovative information technologies on the concepts of Industry 4.0 technologies. Informatization of education will be aimed at the formation and development of the intellectual potential of the nation, improving the forms and content of the educational process, the introduction of computer methods of teaching and testing, which will make it possible to solve the problems of education at the highest level, taking into account world requirements. Among them are the individualization of education, the organization of systematic control of knowledge, the ability to take into account the psychophysiological characteristics of each child, etc. The results of the informatization of education should be:

- development of human information culture (computer education);
- development of the content, methods, and means of teaching to the level of world standards;
- shortening the term and improving the quality of education and training at all levels of training;
- integration of educational, scientific and industrial activities;
- improvement of education management;
- staffing of all areas of informatization of Ukraine through specialization and intensification of training of relevant specialists.

Also, today in Ukraine, the processes of digital transformation in management and administration are important, especially in the context of the introduction of e-government and digitalization of public services, which are key elements of modern information policy. These processes aim to improve the efficiency, accessibility, and transparency of management and administration through the use of information technology. They cover a wide range of activities and initiatives, from the development of electronic reporting and permitting platforms to the registration of property rights. Digitalization of public services is about digitizing service delivery processes, making them faster, more efficient, and more user-friendly. This includes the development of electronic platforms for reporting, obtaining permits, registration of property rights, electronic appeals of citizens, electronic auctions, etc.

4.2. Technological Aspect of the Development of ICST Programs

The technological aspect of the development of ICST programs covers a wide range of innovations aimed at improving the efficiency, reliability, and accessibility of information processes in various fields of activity. This aspect includes the development and implementation of emerging technologies such as artificial intelligence, machine learning, Big Data, blockchain, the Internet of Things, cloud computing, and others that enable the transition to more automated, intelligent, integrated, and specialized management systems.

Big data technologies make it possible to collect, store, process, and analyze huge amounts of unstructured and structured data. It provides insightful insights to improve decision-making, streamline processes, and develop new products and services.

Blockchain technologies offer a new approach to ensuring the security, transparency, and negotiability of data in various fields, including finance, logistics, law, and public administration. They can be used to create decentralized databases, smart contracts, and voting systems [49, 50].

The Internet of Things integrates physical objects with the Internet infrastructure, enabling real-time data collection, sharing, and analysis. It finds applications in smart homes, Industry 4.0, smart cities, and healthcare, contributing to improving efficiency and quality of life.

Cloud computing provides flexibility, scalability, and cost savings by providing Internet access to computing resources and services. They enable organizations to quickly adapt to changing market demands and optimize IT infrastructure costs.

The technological aspect of ICST will continue to focus on integrating these innovative technologies to create more intelligent, automated, and interconnected systems. The main areas of research and development are improving artificial intelligence algorithms, ensuring data security, developing standards for IoT, introducing the latest industrial technologies and IIoT, optimizing cloud platforms, and expanding blockchain capabilities.

4.3. Organizational aspect of the development of ICST programs

The organizational aspect of the development of ICTS programs encompasses a wide range of interrelated elements, including the management structure, decision-making processes, organizational culture, and the interaction between people and technology. The development of ICT requires an integrated approach, which includes the analysis and optimization of organizational processes, the adaptation of the culture and management structure to the new requirements of the digital era, as well as the development of strategies for the effective integration of information systems into all aspects of the organization's activities.

The development of ICT requires businesses to review and adapt their organizational structure and management processes. This includes creating agile structures that can quickly adapt to changes in technology and market conditions, as well as developing mechanisms to manage knowledge and information within the organization effectively. Successful implementation of ICT also depends on the culture of the organization. Organizations must foster a culture that fosters innovation, is open to change, and supports continuous learning. This includes developing training and development programs for employees to ensure they are prepared to handle new technologies and systems [51].

The development of ICT also requires organizations to manage knowledge effectively [52]. This includes the development of systems for collecting, storing, processing, and analyzing data and information, as well as mechanisms for sharing knowledge among employees.

The organizational aspect of the development of information management systems and technologies is key to achieving success in today's business environment.

Conclusions

1. A classification of information control systems has been carried out in the context of state programs of informatization, development, and implementation of innovative information technologies in the process of designing information control systems, where new promising classes of information control systems have been identified: intelligent information systems (hybrid systems) and specialized computer systems (Internet of Things).

2. Positive trends in the development and implementation of innovative information technologies, in particular artificial intelligence

technologies, cloud computing, «big data», and the Internet of Things in the architecture of information control systems in various organizations, manufacturing enterprises, technical facilities, higher education institutions, medicine, are highlighted. Despite the long-term war in the country, there are favorable conditions and the need for the organization of dynamic digitalization of all spheres of public relations and informatization of priority areas of high-tech production in the defense, social, and state spheres of management.

3. The informational, technological, and organizational aspects of the development and implementation of ICST programs in various sectors of the economy and technology are considered. Aspects aim to improve the efficiency, accessibility, and transparency of management of organizations, manufacturing enterprises, and the social sphere. The technological aspect of the development of ICT programs will continue to focus on the implementation of the principles of hybridization and integration of methods and the development of approaches to the use of innovative technologies to create more intelligent, automated, specialized, and interconnected systems. The main areas of research and development are the improvement of artificial intelligence algorithms, ensuring data security, and the introduction of the latest IIoT industrial technologies. Organizational architectural solutions for ICTS programs include the creation of flexible structures that can quickly adapt to changes in technology and market conditions, as well as the development of mechanisms for effective management of knowledge and information within the organization.

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INNOVATIVE TRENDS IN THE DEVELOPMENT OF DIGITAL EDUCATIONAL ACTIVITIES OF HIGHER EDUCATION INSTITUTIONS

In the context of innovative development of information control systems and technologies, education is undergoing global changes in the direction of digital transformation, including the creation of a safe electronic educational environment, providing the necessary digital infrastructure of educational institutions, increasing the level of digital competence, as well as automating data collection and analysis [1], which leads to an improvement in the quality of educational services.

It is also known that one of the goals of sustainable global development [2] is to ensure inclusive and equitable quality education and to promote lifelong learning opportunities for all. The quality of education affects the level of well-being of society, and the opportunity for lifelong learning of each person renews the capital of responses to the challenges of our time. In turn, equitable access to low-cost vocational training, elimination of gender and material disparities, and ensuring universal access to education are clear guidelines for businesses on the way to achieving the Sustainable Development Goals. The defined goals of global sustainable development in the field of education are:

- ensuring the accessibility of vocational education;
- improving the quality of higher education and ensuring its close connection with science, promoting the formation of cities of education and science in the country;
- increasing the prevalence of knowledge and skills necessary for decent work and entrepreneurship among the population;
- creation of modern learning conditions in HEIs, including inclusive, based on innovative approaches [3].

Digital transformation in the field of education and science is a comprehensive work on building an ecosystem of digital solutions in the field of education and science, including the creation of a safe electronic educational environment, providing the necessary digital infrastructure of educational and scientific institutions, increasing the level of digital competence, digital transformation of processes and services, as well as automating data collection and analysis [1].

The harmonization of Ukrainian and European educational spaces takes place according to the concepts of Education 4.0 and Industry 4.0, where one of the important steps on this path is to enter the pan-European qualifications space, the formation of joint institutions and the use of effective tools, ensuring educational and labor mobility. Education 4.0 is the fourth revolution in education, characterized by a new approach to education that is based on the use of technology to create more personalized and interactive learning [4]. Education 4.0 has several advantages over traditional education. It allows students to learn faster and more effectively, fosters critical thinking and creativity, and helps students become more adaptable to change.

The characteristic factors of the implementation of the concept of Education 4.0 include [5]:

- using technology to create more personalized learning;
- interactive learning that encourages students to collaborate and explore;
- lifelong learning;
- learning that builds on the skills that are essential for success in today's economy.

The purpose of this work is to analyze and identify key innovative trends in the development of digital educational activities in higher education institutions.

1. Learning Technologies

One of the key aspects is the widespread use of modern educational technologies and the introduction of progressive forms and methods of teaching. Evolving technologies are not only changing formal education and the structure of training, but they are also changing access to and relationship with information, which causes an inevitable change in the relationship between participants in the educational process. In the context of current challenges and threats to the national security of the state, the educational infrastructure is expanding, which should be aimed at the development of learning technologies, in particular new forms and approaches to adaptive learning, open education, game-based learning, and the implementation of online courses. These learning technologies are aimed at the introduction and implementation of competency-based and student-centered approaches, which allow you to build individual educational learning trajectories. Also, the Law «On Education» [6] regulates some additions, in which such concepts as «individual educational trajectory», «individual development program», and «individual curriculum» were expanded, which expands the direction of assistance in the formation of individualized education and takes into account individual needs, intellectual abilities and acquisition of the potential of professional knowledge of each applicant.

1.1. Adaptive learning

Adaptive learning is a technological pedagogical system of forms and methods that contributes to effective individual learning, and the combination of this technology with the capabilities of modern information and technical technologies has significant potential for education. The advantages of adaptive learning include individual pace, objectivity of assessment of learning outcomes, choice of individual learning trajectory, and growth of intellectual abilities [7, 8].

Varieties of systems and features of adaptive learning [9]:

A macro-adaptive system is a system that adapts educational material for applicants at the macro level, grouping applicants into groups based on test results. Participants have a common learning trajectory in a group, but this approach leads to a deterioration in the individual learning trajectory of each applicant.

A micro-adaptive system is a system that adapts education at the micro level, constantly reviewing and analyzing the profile of applicants based on their activities and providing personalized instructions. This approach is more effective since the individual learning trajectory of each applicant is formed.

An aptitude-treatment interaction system (ATI) is a system that is designed for a large number of people but forms individual instructional strategies that are built based on specific inclinations and characteristics of the applicant (for example, intellectual abilities and cognitive style, knowledge, and learning style). Such a system allows the applicant to partially or completely establish the process of their learning.

An intelligent learning system (ILS) is a system that is implemented with the help of adaptive intelligence and is a hybrid combination of a Micro-adaptive system and an Aptitude-treatment interaction system. Such a system for the formation of adaptive learning strategies takes into account both the inclination and needs of the applicant, applying a complex structured model of the applicant.

The Adaptive Hypermedia System (AHS) is a hypermedia system built using artificial intelligence (AI) and uses a user model that contains the applicant's personal information about knowledge, interests, and goals to adapt content and navigate the hypermedia space.

The Adaptive Educational Hypermedia System (AEHS) is a specific adaptive hypermedia system applied in the context of learning and consists of a document space, an applicant model, and observation and adaptation components.

1.2. Open Educational Resources

Open Educational Resources (OER), a term proposed at the 2002 UNESCO Forum, is educational content, materials, or open activities, meaning they are easily accessible to teachers and students. OER solutions include repositories for searching OER and software or other technologies that help create and distribute OER to students [9]. OER manifests itself as a trend, especially in scientific communities, conferences, round tables, trainings, workshops, and publications. OER can be an information source as an alternative to textbooks and allows you to reduce the cost of individual training of students. Opportunities for open educational resources include:

- Storage – the ability to download, store, and duplicate information;
- Reusability – the ability to use content in a variety of ways (in the lab, in the classroom, on the website, in video devices, etc.);
- Viewing – the ability to adapt, correct, change information (in particular, translate into other languages);
- Remix – the ability to combine original or modified content with other material to create something new (for example, include content in a mashup);
- Distribution means the right to share copies of the original content, your revisions, or your remixes with others (e.g., transfer a copy of the content to another applicant).

1.3. Gamification of learning

Gamification is defined as the integration of game elements into a non-game environment [10], it is the process of adding game elements or mechanics to an experience. In the process of gamification, game elements are differentiated from educational content. As a result, we get a non-game-based learning activity using game principles. Unlike game-based learning, in which the game is an experience, in the process of gamification, game components are integrated into traditional learning.

1.4. Massive Open Online Courses

Massive Open Online Course (MOOC) is a training course with mass interactive participation using e-learning technologies and open access via the Internet, as a form of distance education. They are intended for advanced training, retraining, and certification of specialists in various specialized areas of specialties [11].

2. Organizational Learning Models

Due to the challenges of today, the process of obtaining education has undergone many changes, and one of the most significant has been the emergence of various forms of education and the rapid transition from traditional face-to-face to online, distance, blended, and hybrid learning. This was an unexpected and quite serious test for all participants in the educational process: teachers, students, and masters. But at the same time, it has significantly expanded the opportunities for students and training has become available to all groups of applicants, regardless of individual characteristics, professional skills, and in life circumstances. Teachers had to accept this challenge and quickly adapt to new realities, and the issue of developing models for organizing the educational process has become very relevant.

To ensure a full-fledged educational process in today's conditions, we will consider several models for organizing the educational process, including distance, blended, and hybrid learning.

2.1. Distance education

Distance learning is a fundamentally different approach to the organization of the educational process, when the teacher may not meet with students in online broadcasts at all, but only accompany the lesson in the chat if necessary [12]. Such learning is asynchronous and operates in a separate mode, where a convenient time is chosen for studying the subject in the recording and performing individual tasks. Distance learning has a wide range of information and technical opportunities in the form of the use of educational products such as video lectures, online tests, and individual assignments. The main feature of this training is the careful monitoring of the applicants' progress, building their educational trajectory. Distance learning, as a combination of information technology and digital teaching methods, involves obtaining education without the mandatory presence of applicants in educational institutions. Also, the advantages of this learning model are interactive interaction with the allocation of time for independent mastering of the material, consulting support, convenient use of interactive technologies, and learning management systems. It allows you to better use the principle of visibility and transparency of teaching.

Online learning is a type of distance learning that largely follows the techniques of face-to-face learning. Online learning involves conducting classes in synchronous mode, that is, tasks are also performed simultaneously: «completed – sent – received feedback». Also, online learning involves an asynchronous mode, where the interaction between the subjects of distance learning is carried out with a time delay. The advantages of online learning include the convenience of demonstrating presentations and videos, conducting online testing, and assessing knowledge in real time. If online education tries to imitate face-to-face learning, then distance education has a model of a computer game, new levels of which can be opened only when the previous ones have been passed.

2.2. Blended Learning

Blended learning combines offline and online learning, where students interact with the teacher, material, and other applicants through both a physical classroom and an online platform. Usually, there may be an alternation of visits to educational institutions and distance learning outside the educational institution.

Blended learning is a type of hybrid methodology, where there is a combination of online learning, traditional and self-paced learning. This means not just the use of modern interactive technologies in addition to traditional ones, but a qualitatively new approach to learning that transforms and sometimes «flips» the audience [13].

There is a common thread between hybrid and blended learning. This is the use of modern computer and mobile technologies that facilitate the learning process. Hybrid learning allows you to uncover every kind of intelligence, depending on a person’s mindset. When conducting blended or hybrid learning, various training programs are used to facilitate the receipt and transfer of information. The most common are Blackboard and Moodle. These programs help students gain more information than they would in classroom classes. Students have the opportunity to communicate remotely with teachers, solve test tasks, process materials on their own, and conduct open access to video lectures.

There are four types of blended learning [14]:

1. ***Rotation model.*** This is the principle of rotation when students study in groups and also perform individual communication with teachers. Groups perform tasks at stations, one of them is distance learning.

2. ***Second model (Flex model).*** The main thing is online learning. Students work in classrooms, each is assigned a teacher who helps with assignments.

3. ***Third model (A la carte model).*** Online learning only. A student can work both at home and in the classroom, but communication with the teacher takes place only online.

4. ***Fourth model (Enriched Virtual model).*** It is carried out with the help of classical and distance learning. There is an opportunity to gain learning experience in the classroom and online learning.

2.3. Hybrid learning

Hybrid learning involves students attending offline and online classes at the same time. This method combines both synchronous and asynchronous methods to create a flexible learning environment. Students learn independently and work in groups during classes. The content of an asynchronous lesson presented in a learning environment allows students to interact with work content anytime they can. For example, a teacher can stream live in-person lectures so that students can listen both in the classroom and from home. A recording of this lecture can then be shared for other students to review later if they attended the class synchronously. Hybrid learning creates a single space between two formats: distance and face-to-face.

Some researchers often use the terms hybrid learning and blended learning interchangeably. If you also do this, you need to understand that both learning styles are different. The key difference between the two learning styles is that blended learning only works by combining two things: e-learning and traditional learning, while hybrid learning allows applicants to choose whether to study directly in a classroom or participate online. This enables training for applicants, who do not have the opportunity to be directly present in the classroom at a certain time due to objective reasons (consequences of external risks), illness, or other personal circumstances, as they have the opportunity to attend online and not miss training. Hybrid learning offers «face-to-face and remote» applicants the same access to classrooms.

Forms and methods of teaching are used in educational programs on the principles of a student-centered approach, the essence of which is primarily in the selection of the best organizational models of education, educational components, teaching practices, the maximum formation of competencies, and the achievement of program learning outcomes of educational programs.

3. Artificial Intelligence Technologies

Artificial intelligence (AI) as a direction of modern science is now being implemented in educational activities and is associated with the use of innovative technologies. AI is used to update and evaluate knowledge, develop an adaptive, individual, and differentiated approach to learning, virtualize learning, determine the rating of the teacher's activities, etc. Let's consider the trends in the use of AI technologies in educational activities.

3.1. ***Assessment of knowledge.*** AI provides an opportunity to analyze the response based on automatic assessment, provide individual feedback, and create an individual learning plan for everyone using the following forms:

- adaptive learning – provides an opportunity to track the individual process of each applicant, his communication, and the teacher related to solving problems that arise in the learning process;
- individual training – provides an opportunity for everyone to choose the pace of learning, the level and gradualness of completing tasks, taking into account the interests and preferences of each applicant (*tutoring*);
- differentiated learning – provides an opportunity to consolidate educational material, which with the help of AI can be carried out in stages.

3.2. ***Virtualization of learning.*** Important components of training are to ensure the appropriateness of learning by prioritizing learning over teaching; transmission of the activity type of learning; organization of self-sustaining educational activities; increasing the motivation of learning with the help of the use of means of complex presentation and manipulation of audiovisual information; raising the level of emotional perception of information and the formation of skills to realize various forms of self-sufficient activity about the processing and analysis of information. The virtual educational environment is a typical environment of human self-development. The prevailing method in the virtual educational environment is the method of interactive self-learning with the constant cooperation of the subjects of teaching and the subjects of learning in the presence of continuous irreversible connections between them [15]. It also provides support for students in obtaining education, for example, anthropomorphic presence, which includes virtual agents and persuasive intervention through digital applications. AI can complement human abilities. The idea of using technological systems to complement or enhance human abilities is not new, and it is referred to as increased intelligence (II). II focuses on the importance of presenting the learning process in real-time, in the efficiency of its presentation by the tools and means of AI used in the learning environment. For example, AI tools enable the enhancement and expansion of individualized and differentiated learning for all applicants. AI tools provide relevant and timely feedback to students.

3.3. ***Predicting the status of learning.*** It involves the process of dropping out students, forming risk groups, acquiring innovative abilities, career decisions, productivity or satisfaction, and improving the educational experience.

3.4. ***Automation of evaluation processes.*** AI systems can automate assessment and reporting processes, which reduces the burden on educators and allows them to focus on quality learning. Natural Language Processing (NLP) technologies can be used to assess written responses or automatically generate reports on learning progress. NLP technology allows you to process, analyze, and interpret natural language in the form of chatbots and digital assistants.

3.5. ***Machine learning and data analytics***. The use of machine learning and data analytics allows you to analyze large amounts of learning data to identify trends, understand student needs, and improve curricula. Machine learning is used to create interactive and innovative learning materials, such as virtual labs, game-based learning environments, and other effective learning methods.

3.6. ***Development of chatbots and virtual assistants.*** Chatbots and virtual assistants can provide students and teachers with access to information and round-the-clock support. They can answer questions about study material, provide study advice, and help solve problems.

3.7. ***The use of generative AI*** is an artificial intelligence model that is designed to create new content in the form of written text, audio, images, or video. Generative AI can be used to create educational and scientific products of information control systems, train modern specialists based on the introduction of non-formal education, conduct student scientific and practical conferences, round tables, professional circles, etc.

4. Virtual and augmented reality (VR/AR) technologies

4.1. **VR** is a computer-generated simulation that is a collection of images and sounds that represent a real-world place or situation that a person can interact with, either in a real or physical way, using special electronic equipment. VR can convey visual, audible, and different sensations to users through a headset to make them feel like they are in a virtual or imaginary environment. That is, the user becomes part of the virtual world or immerses himself in this environment and, while there, can manipulate objects or perform a series of actions to determine what is happening in the environment [16].

4.2. **AR** is an extended version of reality, where there are direct or indirect views of the physical environment of the real world complemented by superimposed computer images on the user's real world, thus improving the current perception of reality. Simply put, users see layers of digital information covering images of the real world and enhancing their overall experience of reality.

The most common versions of AR are classified as:

- location-based – This system provides users with additional information based on their or their geolocation. It has incredible potential for application, in particular in the automotive industry and transport in general;
- projection-based – in this case, the AR software sends light to a physical object to create an interactive dashboard in a real-time environment;
- overlay-based – this type of AR allows users to completely or partially replace the actual image by adding new elements to the viewpoint. This type of AR is ideal for the fashion, architecture, and design industries.

Teaching based on VR/AR technologies promotes personalized learning as a way to get the best out of each applicant. The technology offers a personalized learning experience, allowing applicants to learn at their own pace. Using AR or VR gadgets, anyone can conduct classes both inside and outside the educational institution. In terms of teaching methodology, it is possible to distinguish between two different systems – ***closed*** and ***open*** learning.

The closed learning system uses VR headsets as a means of learning. This method is called closed because it isolates the subject from external influences, emphasizing individual work.

The most important characteristics of a closed education system include the following factors:

- focus on one subject: VR headsets completely captivate students and make them concentrate on one subject of study by 100 %;
- combination of theory and practice: VR technology allows applicants to see or feel everything they have read about in theory;

- application of gamification elements: applicants learn well during the game, which makes VR equipment the most attractive learning tool in education.

The open learning system is based on context-controlled learning algorithms. AR is constantly improving learning processes and adapting according to the needs of each user individually. AR adds value to training courses because it takes into account the need to showcase contextual information related to the subject of study.

The most important characteristics of an open learning system are:

- learning support: unlike closed systems, these systems do not take full control over the learning process, instead, AR increases learning productivity by displaying a variety of contextual information when needed;
- improved engagement: while VR technology isolates users, AR does the opposite. The system improves interaction because it allows all users to engage and comment on the current topic that interests them.

AR and VR technologies can be used to create virtual classrooms with students within related educational and professional programs of specialties in IT industries. Features of learning with the help of AR and VR: advantages – the ability to test, and improve interaction with the audience, and the ability to use various forms and methods of teaching; *Disadvantages* are a decrease in interpersonal communication, lack of control over the actions of participants, and the need for specialized equipment.

The combination of VR/AR technologies and generative AI in the area of education forms a transformational synergy that improves the efficiency of the educational process. This integration fosters personalized learning, thanks to generative AI that tailors learning content and simulations in VR/AR environments to meet individual student needs and the pace of learning in modern educational systems. Dynamic scenario generation immerses applicants in interactive, engaging educational environments, providing an opportunity for hands-on study of subjects. Adaptive assessment, natural language interactions with virtual tutors, and the creation of additional resources improve engagement and comprehension.

5. E-learning platforms

E-learning is a way of e-learning, online learning, or online learning, which is implemented through digital tools, the Internet, satellite broadcasting, CD, or interactive television. Technological development requires modern approaches to modern educational education systems.

Education is becoming widespread due to the increase in online courses and the opportunity to gain knowledge from the best leading experts in Ukraine and the world. The question of technological characteristics of learning management systems. From an organizational and technical point of view and areas of use, the following systems have been developed: LMS – Learning Management System; CMS – Course Management System; LCMS – Learning Content Management System; VLE – Virtual Learning Environments; VC – Virtual Classroom (virtual classroom system).

Figure 1 depicts the traditional E-learning architecture of existing and most-used e-learning systems, consisting of three layers:

- Client who connects to the online learning platform (administrator, teacher, applicant);
- E-learning platform deployed on a web server (LMS, CMS, VLE, LCMS, VC);
- Database – Allows you to store data, learning resources, user activities, and more.

LMS are the most common learning management systems, which include means of organization, control of the use of courses and training, and administration of the educational process. Most LMSs allow administrators and teachers to create educational projects for conducting classes, and adjust and track the educational process flexibly by all its forms and methods. The most popular examples of learning management systems today are:

- MOODLE (Modular Object-Oriented Dynamic Learning Environment) is a modular object-oriented dynamic learning environment designed to organize interaction between a teacher and a student, to organize all forms of learning. Using the MOODLE system, the teacher can create courses, fill them with content in the form of texts, auxiliary files, presentations, and questionnaires, and conduct knowledge testing [17].
- CATS (Care About the Students) system allows you to implement all components and components of the educational process, keep an electronic log of attendance and defense of laboratory work, monitor the progress of course and diploma design, test students' knowledge, form electronic educational and methodological support [17].
- Google Classroom is a free learning monitoring system that is a blended learning platform developed by Google for higher education institutions. The platform today is no less popular than the above-mentioned one – Moodle, but it is characterized more as a CMS – course management system. The system is actively and successfully used during distance learning. It allows you to create courses and

assignments for them, and exchange information between course authors and participants in the educational process. Teachers can create video conferences, subject classes, and individual professional tasks, evaluate work according to the configured gradation, and set deadlines for work. Students, on the other hand, can keep track of the latest learning information, complete the necessary tasks, and receive feedback from course authors.

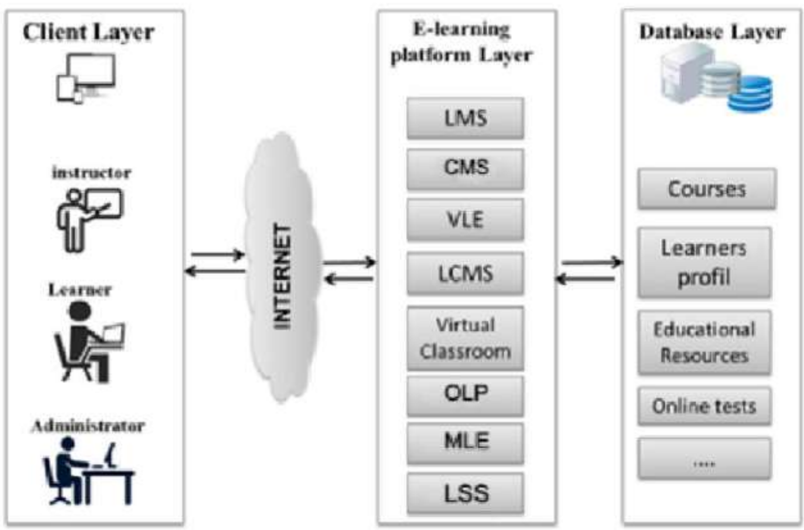

Figure 1. E-learning systems

Source: Developed by the Authors

Thus, LMSs are online platforms for posting, sharing, and mastering educational material, as well as for further tracking the progress and achievements of those who are directly involved in the educational process.

A CMS [17] is a set of software tools that provide an online environment for interacting with a training course. The CMS usually integrates with other databases at the university so that students enrolled in a particular course are automatically enrolled in the CMS as participants in that course. CMS is an enterprise software system designed to automate logistics and resource management, planning, administration, finance, reporting, etc. It may also include sales for for-profit training companies. Course management software is specifically designed for learning organizations, whether corporate training departments, for-profit training companies, or associations. In higher education institutions, this system is used in advanced training courses in various production areas.

LCMS shares the same basic functionality as an LMS, but LCMS can create and manage content [18]. LCMS provides a common environment for content writers and those who directly use the system: teachers, administrators, and applicants. That is, it is a system for managing educational content and, above all, a platform used to manage the development of educational content. LCMS allows you to play content, not just use it. The tools of such systems allow you to manage the accounts of students or teachers, create and manage new courses, and reproduce smart analytics based on the success of participants in educational activities. Examples of systems for controlling educational content are Blackboard Content System, ATutor, OpenCms, etc.

VLE is an online platform (virtual learning environment) that offers students and educators digital solutions that enhance the learning process, aimed at creating an interactive, active learning environment. Virtual learning environments are often part of an LMS used by HEIs. Unlike Virtual classrooms, which are designed to copy and replace the physical classroom environment for distance learners, VLE uses technology to Complement classroom experiences, such as through digital communication, interaction, and testing, surveys are conducted through VLEs.

The virtual classroom is a video conferencing tool where teachers and students interact with each other and study educational material. The difference from other video conferencing tools is that virtual classrooms offer an additional set of features that are essential to the learning environment. An added benefit of virtual classrooms is that they can be scaled to more students. Physical classrooms often limit the maximum number of seats, Virtual classrooms use virtual meeting solutions that have a larger number of participants, allowing more students to attend engaging classes at the same time. This ensures better and higher participation rates and ensures that knowledge is much more accessible. A virtual classroom platform helps to make the learning process interactive by providing an effective, controlled environment. Attendees can connect to virtual classroom platforms from any device that has access to the internet. This type of flexibility allows members to consume content regardless of their location. Another great advantage of the virtual classroom is that it makes it easier to track users' progress through online surveys and analytics, identify complex areas of discipline topics, and generally help the participant learn complex subjects using visual tools.

Finally, many virtual classroom platforms can be integrated into a university's learning management system (LMS). Advanced platforms support Learning Tools Interoperability (LTI) so that the virtual classroom system and LMS can communicate with each other, making the whole greater than the sum of its parts [19].

Systems are also used to support learning processes: OLP – Online Learning Platform (portal for educational content and resources); MLE – Managed Learning Environment; LSS – Learning Support System.

General advantages of e-learning platforms:

- flexibility – the ability to study regardless of time and place;
- diversity – the presence of a large number of tools for presenting information;
- certification – the possibility of obtaining a certificate of completion of training courses;
- monitoring is the ability to control the dynamics of success during training courses.

6. IoT Technologies

The Internet of Things (IoT) is an integrated part of the Internet of the future and can represent a dynamic global network with adaptive capabilities based on standard and interoperable communication protocols, where physical and virtual objects have matches, physical attributes, and virtual objects use intelligent interfaces and are seamlessly integrated into the information network [20]. IoT is a network of physical objects that have built-in technologies that allow them to interact with the external environment, transmit information about their state, and receive data from the outside. In the book Designing the Internet of Things, the elements of IoT are reduced to a simple formula:

Physical Objects + Controllers, Sensors, Actuators + Internet = IoT

This formula clearly describes the very essence of the Internet of Things. An IoT instance consists of a set of physical objects, each of which contains: a microcontroller that provides intelligence; a sensor that measures any physical parameter, and/or an actuator triggered by any physical parameter; it can communicate via the Internet or any other network. For example, a smart room installation consists of a set of things in the room that exchange information via Wi-Fi or Bluetooth with a central controller. Whether or not there is an Internet connection, a set of «smart» elements, combined with any other computing and storage devices, can be described as a «network of things» or IoT. In these architectural definitions, it is interesting to understand that a device with the Internet of Things (network of things) means a piece of equipment that has mandatory communication capabilities and additional capabilities for measuring, triggering, as well as input, storage, and processing of data. According to Recommendation Y.2060, IoT is characterized by adding the dimension of «communication between any THINGS» to information and communication technologies that already enable communication «at any TIME» and «at any PLACE» (Fig. 2) and an IoT reference model by Recommendations Y.2060[21] (Fig. 3).

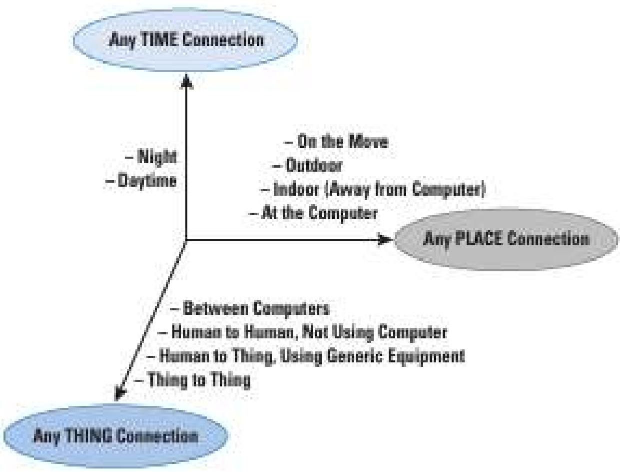

Figure 2. A New Dimension in the Internet of Things

Source [21]

The IoT reference model according to Recommendation Y.2060 (Fig. 3) consists of four layers plus management and security capabilities operating between the layers. Recommendation Y.2060 lists as examples of common management capabilities the functions of

- Device Management: Examples include device discovery, authentication, remote device activation and deactivation, configuration, diagnostics, device operational status management;
- LAN Topology Management: An example is network configuration management;

▪ Traffic and congestion management: for example, identifying network congestion conditions and implementing resource reservations for urgent and/or vital traffic flows.

The Internet of Things should not only replace traditional teaching methods but also bring changes to the infrastructure of educational institutions. The Internet of Things environment promotes the learning of academic disciplines through the use of images, objects, and videos in the classroom, and this contributes to the addition of new cultures. Aspirants can access resources using their devices, including mobile phones, laptops, and tablets, to create a dynamic learning environment. The learning process is automated with the help of e-learning platform software, by recording the data received from students, tracking courses, and managing reports.

Examples of the use of IoT technology in the educational process can be:

- automation of attendance accounting;
- security improvements;
- adaptive lighting systems;
- climate control systems;
- automation of material and technical support accounting;
- control of power consumption.

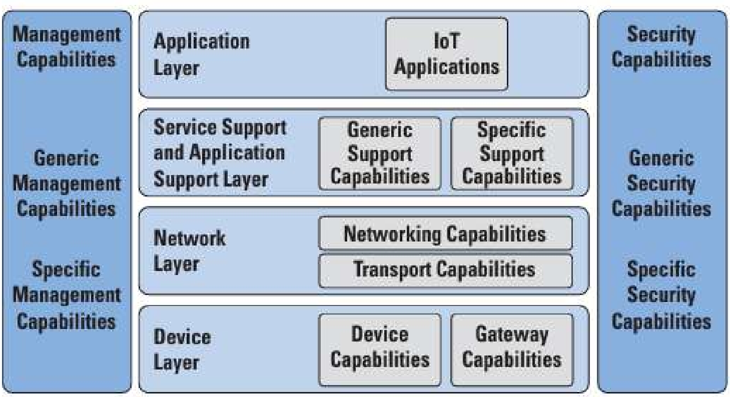

Figure 3. IoT Reference Model according to Recommendation Y.2060

Source: [21]

Based on the Internet of Things in education, a variety of «smart (smart)» systems can be implemented in various fields of student learning, these are «smart classrooms» for conducting lectures, «smart laboratories» for laboratory research, «smart campuses» for creating a comfortable living and leisure environment.

Smart classrooms. Usually, in a traditional classroom, their activities are not recorded in any form, since they only contain display aids such as a whiteboard and a projector connected to a PC. Whiteboarding has become less common in use due to the use of newer alternatives such as interactive whiteboards and flipcharts, LCD projectors used to display given graphic, textual, and tabular information. Thus, using improved tools, a display system, and a system for finding the necessary information, the general audience turns into a smart class. Also, the smart classroom provides the necessary information for both lengthening and repeating the learning of the necessary material, as well as for novice students who, for some valid reason, missed the given topics.

IoT-controlled facilities are equipped in a smart classroom to provide remote functions, such as lighting, room temperature, parameters of technical devices for conducting lecture material, accumulation of necessary material from network platforms, and collection of information on the interaction between users [22]. After the lesson, the necessary information is stored for future use. A smart e-learning app can be used by downloading this data in the required learning format [23].

Smart Labs. In smart laboratories, classes are also held in various formats, both in distance and online forms of learning. Directly in smart laboratories, students perform experimental research using existing equipment, specialized computer equipment, and prototyping of various physical processes, and phenomena with IoT devices [24]. In distance learning, interactive experiments and software simulators are conducted that can reproduce a physical experiment and assess the adequacy of its mathematical model. In laboratories, IoT devices can be used in different ways. It allows students to remotely control and access IoT devices through a learning management system (LMS). To experiment remotely, students can log in to their account, perform the specific experiment that is needed, select the architecture of the required laboratory work, and select the required laboratory. Students can use the IoT module to collect the data needed for the experiment if the experiment requires external data, and then save it to the experiment profile.

The results of the evaluation of the conducted classes are carried out by the E-learning system for each lesson and/or experiment with the distribution of grades according to the rules of assessment using IoT. The time it takes for students to complete each task completely, the calculation of the number of errors, and the number of attempts for each task are also analyzed by IoT.

Smart campuses, as a rule, are implemented on the campuses of higher education institutions on the initiative of the governing bodies of student self-government and are designed to create a comfortable student environment for the living, leisure, and recreation of students.

The main advantages of using IoT technologies in education include:

- Improved communication and collaboration. IoT devices, such as smart whiteboards, tablets, and laptops, can facilitate real-time communication and collaboration between teachers and students, as well as between students themselves.
- Personalized learning. With the help of IoT devices, teachers and administrators can collect data on a student's «successful» learning style, progress, and difficulties that arise in the learning process. This information can be used to create customized training plans tailored to the individual needs of each applicant.
- Improved interaction in smart classrooms. With the help of IoT devices, such as interactive whiteboards and tablets, educators can create more engaging and interactive classes that keep applicants engaged and motivated.
- Improved resource management. Thanks to IoT systems, teachers and administrators can more effectively control and manage classroom resources, as well as accumulate the necessary e-textbooks and e-materials for each topic conducted.
- Improved safety and security. With the help of IoT devices, can you monitor and protect your buildings, grounds, specialized computer devices, and tools? helping to ensure the safety and well-being of applicants and staff.
- Increased efficiency. Educators and administrators can streamline many of the administrative and organizational tasks that take up their time each time using IoT systems, such as automating attendance tracking and grading after each class. This can free up more time for teaching and learning and allow educators to focus on the core learning functions of their work.

7. The main trends and directions of research of the Research Institute «Institute of Information Systems in Economics» and the Department of Information Systems in Economics of KNEU named after Vadym Hetman in the field of education

One of the main directions of the strategic objectives of the KNEU named after Vadym Hetman is provided in the «Development Strategy of KNEU named after Vadym Hetman» and «Program of Innovative

Development of KNEU named after Vadym Hetman» are dominated by the following provisions:

- digitalization of the scientific and educational process;
- introduction of the latest educational technologies to improve the quality of educational services and adaptation of the educational process to the requests and needs of higher education applicants;
- intensification of competition between universities for leadership in the world market of educational services;
- deepening international scientific cooperation.

7.1. Trends and directions of research in educational activities:

- Formation and implementation of applied and initiative research. The subject of scientific research is focused on the design, creation, and implementation of information control systems (ICS) for complex objects, in particular at enterprises, firms, banks, universities, and other organizations using modern information technologies, the results of which are implemented in the educational process of the Department of Information Systems in Economics;
- Research of the conceptual and methodological foundations of ICS design, the use of modern information and communication technologies, and applied artificial intelligence tools for the construction of universal and specialized computer systems and tools in various fields of science, economics, technology, and education, the results of which are implemented in the educational process of the specialty 122 «Computer Science»;
- Development, improvement, and implementation of universal electronic document management systems in banking systems, and IT companies using machine learning technologies to build a semantic search result based on large Amazon Kendra services, which will increase the efficiency of individual banks, large IT companies, and the banking system as a whole [25, 26];
- Development, improvement, and prototyping of the latest ICS, specialized computer «smart» systems and tools in the social and applied sphere and educational activities based on modern microcontroller elements based on the Arduino platform, in particular, the development of the Smart Laboratory ICS, which consists of the following modules: module for accounting for the material and technical support of the laboratory, module for monitoring climatic indicators in the room, a module for monitoring electricity consumption, etc.;

▪ Organizational and technological improvement and updating of the material and technical base of the leading Educational and Scientific Laboratory «Information Control Systems and Technologies» of the Department of Information Systems in Economics and the Research Institute «Institute of Information Systems in Economics» of specialized computer equipment and hardware and technical devices on the platforms Arduino Uno, Arduino Mega, Arduino Nano, ESP8266, Orange Pi and Raspberry Pi allows:

– to increase the scientific and practical efficiency of high-quality training of specialists of all levels in the specialty «Computer Science»;

– to implement the provisions of the concept of Industry 4.0 industrial platforms, the main role of which is played by such technologies and concepts as high-tech production systems and technologies, applied artificial intelligence systems, intelligent technical systems, knowledge bases, IoT technologies, mobile and cloud technologies, specialized digital information processing systems, remote device management systems, intelligent «smart» laboratories and classrooms in education:

– conduct various laboratory scientific research and educational processes in technical, industrial, social, domestic, financial, and economic systems;

– Carry out prototyping of the developed devices on a 3D printer to improve and produce experimental functional models and finished components of various technical objects and systems in the educational process

– train student teams and projects and participate in competitions, IDEAFESTs, and startups;

▪ Introduction and implementation of organizational and technical aspects of the development of educational activities of the latest information and communication technologies and modernization of educational products, in particular, video products from the cycle of presentation of educational and professional programs; innovative specialized disciplines of specialties; performance of individual and independent work of students; scientific and educational nature of student projects; educational and scientific circles and master classes of educational and professional programs; branded accessories;

▪ Attraction and cooperation with leading Ukrainian and foreign IT companies for joint scientific cooperation with IT employers, which should be understood as customers of potential scientific products, business partners in the training of modern specialists based on the introduction of a dual form of education of our graduates in the specialty «Computer Science», employment of graduates and organization of scientific activities based on non-formal education of the OPP «Information Control Systems and technologies», expanding the participation of researchers in the implementation of international projects on the platforms of IT startups, grants, and programs, Industry 4.0 concepts;

- Implementation of real scientific projects at the University based on the development of qualifying master's theses of the OPP «Information Control Systems and Technologies» and initiative research work carried out at the Research Institute «IISE»;
- Introduction and development of new innovative educational products (systems) and technologies of distance education to provide relevant services to students, graduate students, and young scientists, including webinars, coaching, webcasts, lectures, and practices.

Conclusions

The current stage of development of the educational sector in Ukraine is characterized by increased competition and the desire of higher education institutions for even greater integration into the global market of educational services. Under such conditions, in this work, a study of the introduction of innovative trends in the development of digital educational activities was carried out, the results of which include:

1. The study showed that innovations in digital educational activities allow: to reduce in the costs of the educational process through the use of digital technologies, tools, and educational materials on a free or inexpensive basis; increasing the effectiveness of the study of basic training courses; and reduce the need to retake these courses; use convenient and flexible forms of conducting training courses and programs with remote access provided by mobile devices and applications; to receive high-quality preparation of the developed courses and training at the level of individual and independent work of students.

2. One of the most common modern trends in the education system is the search for new forms of education. The most common were distance learning, continuing education, transnational learning, and virtual education using network information technologies. Virtualization of education opens up fundamentally new opportunities to overcome the two most important and urgent problems of modern society, it is an increase in accessibility to openness of quality education and the continuity of the learning process throughout human life, which is already a universally recognized need and requirement proclaimed in UNESCO documents. At the same time, it should be remembered that

the virtual education system cannot be recognized as full-fledged because of its fundamental inability to completely replace the personal contact between the student and the teacher, the processes of their communication and interaction. The development of virtual reality, the transformation of communicative processes carried out within its framework into everyday life, is an essential prerequisite for the development of distance learning.

3. In the context of external challenges and threats to the national security of Ukraine, there is a constant expansion of the educational infrastructure aimed at the development of innovative learning technologies, such as the latest flexible forms and approaches to adaptive distance learning, open education, gamification of learning, the use of artificial intelligence and the Internet of Things, which contributes to wide access to information resources, the study of academic disciplines through the use of means of images, objects and videos in the classroom and this contributes to the formation of a new information culture of promoting and accumulating knowledge. Applicants can access resources using their devices, including mobile phones, laptops, and tablets to create a dynamic learning environment and implement online courses. The learning process is automated with the help of E-learning platform software, by recording data from applicants, tracking courses, and managing reports. All innovative learning technologies are aimed at the introduction and implementation of competency-based and student-centered approaches, which allows you to build individual educational learning trajectories. Institutional implementation of innovations requires proper infrastructure, including economic, personnel, technical, information, and marketing. It is also necessary to treat organizational support properly. The introduction of digital technologies requires careful planning and implementation of innovative technologies in various specialties of educational and professional programs with implementation in the basic training courses of higher education institutions.

4. A significant number of HEIs and teachers have been innovating in digital learning for a long time. E-learning platforms and mobile devices are considered the main learning technologies in most institutions throughout Ukraine, as well as abroad, in particular, the MOODLE system is effectively used at KNEU named after Vadym Hetman to ensure a continuous learning process at all levels of educational activities. Thanks to advancements in mobile technology and the compatibility of learning tools, allowing for the integration of course software into an LMS. Students can learn from their devices regardless of location and time, according to this, the determining factor

is the implementation of personal and individual forms of learning. The introduction of these innovative technologies, although redundant, creates the effect of a spiral of development and implementation of the main learning technologies located on the following trends.

5. With the rise of innovation in digital learning, it is evident that institutions, educators, and researchers are confronted with large amounts of teaching and learning data that they previously could not cover on a large scale in traditional face-to-face courses. Therefore, big data, machine learning, artificial intelligence, and the Internet of Things are becoming major trends in the field of educational technology. Also, in recent years, distance learning has acquired a single privileged trend, which has radically changed the educational process. Students now have to get used to remote learning with E-learning platforms due to social distancing. The most promising forms are blended and hybrid learning. Blended learning involves alternating offline and online classes, which allows you to conduct online lectures and consolidate knowledge in practice during offline classes. Hybrid learning involves a simultaneous combination of offline and online classes, which creates the effect of direct presence. Thus, as the study showed, it is impossible to single out only one or several identified innovative trends, since each of them directly affects the quality of education. In general, it can be noted that the use of innovative technologies in digital educational activities can significantly increase the efficiency of the educational process and ensure the quality of education in difficult conditions of internal and external challenges and uncertainties. Priority in further research of this issue should be given to the development of effective approaches, methods, and models for assessing the effectiveness of digital educational activities and determining the degree of expediency of introducing appropriate digital technologies at the existing risk.

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THEORY AND PRACTICE OF IDENTIFICATION OF CYBER THREATS IN THE INFORMATION SPACE

Even two millennia ago, influencing the enemy's psychology was considered more important than his physical destruction. As Sun Tzu wrote: «War is a path of deception. A person must show his adversary incompetence even when he is capable. If you need to bring some of your forces into battle, pretend to be inactive. When the goal is far, show as if it is close and vice versa» [14].

Information and communication technologies (ICT) are becoming a key factor in world politics, economy, and security systems. Information weapons are turning into an increasingly important element of the military potential of states, which complements conventional military means. Information sabotage in cyberspace has become a new tool for non-state, collective, and individual actors. And cyberwars of some states against others can turn out to be no less destructive and cruel than traditional ones.

ICT in warfare, including a long stage of information and psychological pressure and the integrated use of means of intelligence, control, communication, navigation, and radio-electronic warfare, were first used by the United States in the operation «Desert Storm» in 1991 in Iraq. After that, information influence was used on an increasing scale in operations in Yugoslavia (1999), Afghanistan (2001), Iraq (2003), and Libya (2011).

Destructive informational and psychological action was carried out with quite high efficiency by Western countries during the Georgian-South Ossetian conflict of 2008. At this time, the application of almost the entire spectrum of modern methods of information influence on the Ukrainian State is observed.

In the 21st century, there is an increase in the number of successful attacks on information resources not only of personal computers of citizens and organizations but also of state departments and critical infrastructure objects, which are turning into a tool of political and economic pressure.

Examples of cyberattacks recorded in all regions of the world, on various information carriers: from home personal computers to targeted attacks on large information agencies, banking and business structures, intelligence, government and government departments, international organizations, and large industrial objects of critical infrastructure, carried out since the beginning of the 21 century, prove the global level of threat, demonstrate the accelerated pace of expansion of the scale, geography and list of objects of cyberattacks.

One of the first examples of the impact on information and control systems of critical infrastructures is the use of the malicious software Stuxnet, Duqu, Flame, and Wiper in 2010–2012 aimed at causing physical damage to the Iranian uranium enrichment plant in Natanz, the Bushehr nuclear power plant and at inhibiting Iran’s nuclear program. One of the probable causes of damage is the simultaneous introduction of a large number of centrifuges into the resonance frequency due to the influence of the malicious software Stuxnet. Moreover, experts concluded that the software was created with the support of state structures by a team of extremely qualified specialists with large resources and significant financial support. Therefore, there was not a case of cybercrime, but an act of cyberwar.

Another similar incident occurred in 2013 in the energy sector and is related to the malicious software Shamoon, a virus that infected almost 30 thousand computers in the network of Saudi Arabia’s oil producers Aramco. According to experts, oil and gas companies in the Persian Gulf are very vulnerable to cyberattacks due to the high probability of penetration of harmful technologies into the infrastructure of critical processes. Experts believe that Shamoon was developed in Iran to defeat the energy industry. Note that the case of the Saudi company Aramco is not the only one, the company RasGas Company Limited — the largest supplier of liquefied gas was also subjected to cyberattacks by hackers in Qatar and the UAE.

Also, one example of cyberattacks is the malicious Trojan program Duqu 2.0, recorded in 2014. This is an extremely complex software that is a whole generation ahead of all known threats. Because of this, there were harmful infections, in particular, the sites of the Group of 5 + 1 activities to solve the Iranian nuclear problem, within the framework of which meetings of world leaders were held. In 2015, the cyber division of the banned Islamic State terrorist group managed to gain access to the personal data of an estimated 1,400 American troops, followed by a call to organize attacks on them. Among the published data are management and units, which are assigned to the military, email addresses, postal codes, phone numbers and other data.

In the spring of 2021, a cyberattack on the ICS of Ukrainian state authorities was discovered, and decoy documents on COVID-19 were used. Downloading the above-mentioned files led to the defeat of users' AWS and uploading files to the attackers' servers [15].

On January 14, 2022, hackers carried out a massive cyberattack on Ukrainian government sites. Whisper Gate was used to destroy the data.

Now the threat from a malicious cyberattack can be assessed as global.

Thus, the global information space has become the most important arena of confrontation in the 21st century.

In this regard, now fully there is a problem of ensuring information security as an important component of national and international security. Various projects of national concepts of information security, which appeared at the end of the last century, revealed the absence at the international level of a single conceptual apparatus and generally accepted methodology for assessing threats, and sometimes the inconsistency of their options with the current regulatory and legislative bases at the national and international levels. The formation of an appropriate intellectual and political base is an urgent task and an indispensable condition for the development of international political and legal norms, mechanisms of global management and regulation in this area.

The information threat is understood as the potential for violation of information security or a potentially possible event that carries a certain information phenomenon that could lead to harm to someone's interests.

Threats to information security are factors that create a danger to the individual, community, state, and their interests in information spacious [17, 18].

An attempt to implement an information threat is called an information attack.

Within the framework of the issue of information security threats, an important factor is information vulnerability – any characteristic of an information system, the use of which by the violator, can lead to the implementation of the threat.

The main types of information security threats are aimed at violating:

- availability of information resources (access blocking);
- privacy (unauthorized access to information);
- integrity (distortion of information).

Nowadays there are different classifications of information security threats, but in general, it is advisable to distinguish three main types:

1. The emergence and rapid spread of «meta technologies», that is, technologies that create the ability to control the consumer and collect information about him from the developer through various gadgets.

2. «Electronic-digital gap», that is, the emergence of the so-called elite, which has unlimited access to ICT, both at the domestic and international levels. As a result, the possibility of manipulating the opinion of certain people, social groups, and states increases dramatically.

3. Computer militarization, information terrorism, and crime, that is, the use of the colossal potential of ICT in favor of ensuring military-political superiority, power confrontation, and blackmail, which changes the idea of crises and conflicts, tactics and strategy of warfare and opens up qualitatively new directions through the rapprochement of civil and military technologies.

The main objectives of information threats are information resources, information infrastructure, and information, including its flows (document arrays, databases, and data banks, archives, libraries, museum funds, etc.) [17, 18].

Information infrastructure, as a set of information systems, contains:

information and telecommunication structures – corporate and state computer networks, telecommunication networks, networks, and data transmission channels, means of managing information flows;

- cyberspace;
- mass-media;
- structures that enable the functioning and development of cyberspace, in particular the search, collection, distribution, processing, transmission, and storage of information.

So, there is a fundamentally new environment of warfare – Information Space – the sphere of activity associated with the formation, creation, transformation, transmission, use, and storage of information that affects, among other things, individual and social consciousness, information infrastructure and, in fact, information [17, 18].

The most common type of information is information presented in the form of texts in the language of the country, so content analysis is one of the most common types of scientific and practical analysis.

In content analysis, evaluators classify the key ideas of a written message, such as a report, article, or film.

The growth of information in electronic form and the increase in the number of computer programs for analyzing text files make content analysis easier than ever before. Moreover, computerized programs can easily encode text data and combine it with quantitative data. Next, the evaluator can analyze both types of data using different statistical methods. However, content analysis can continue even when written information is not available in electronic format.

There is a real difference between data, information, and evidence. Researchers tend to talk about data as a mass of disordered raw materials from which information (knowledge) is extracted to provide evidence to support arguments and conclusions. The information keeps us informed, and the evidence confirms the conclusions. Therefore, it is advisable to consider the study in three stages:

1. Collection of output data.
2. Data is ordered and converted into information.
3. Evidence is extracted from information through analysis and testing processes.

But neither the information nor the evidence is obvious: the material «speaks for itself». Some interpretation is needed. However, when the interpretation is reinterpreted, a certain distortion of the original is inevitable. Therefore, differences, criteria, and tests must be present to weed out distortion of information and «falsehoods». There are distinguished primary and secondary sources of information. The criteria used are reliability, reliability, and accuracy.

The primary data are original, unedited, and «first-hand», while the secondary data are «from secondary», edited, and interpreted materials. However, the information obtained during the study, and the information that was extracted from other sources, are valuable. Where possible, analysts prefer to use primary eyewitness data recorded at that time by participants or privileged observers. There are four main sources of primary data that analysts use:

1. Documentary (written) records, such as minutes, letters, emails, and diaries.
2. Interviews with key individuals, «agents» and «actors».
3. Numerical records, for example, election results, and census data.
4. Own observations and recordings of interviews, as well as other events.

All records, however «primary» they are, contain a degree of bias, perception, interpretation, and editing, including contextual, curatorial, or intentional ones.

Written primary records include meeting reports, minutes, diaries, letters, reports, telephone transcripts, telegrams, emails, etc. It can be argued that all accounts are partial since they are functional, that is, intended to achieve the goal. Most public records reflect the interpretation of those with power.

As a general principle, all primary information in the form of records, in addition to those made using their observations, should be treated with caution. You should always ask the following questions:

– Who prepared the recording?
– For what reason?
– Who was he prepared for?
– Who was it intended for?
– For what purpose was this done?
– Who would «correct» or otherwise change the record before it was completed?

The most common misconception is that numerical information is more reliable than other formats because it is less vulnerable to spreading. However, since numerical records are generally considered reliable, they attract more attention. Therefore, numerical records should be checked for any changes in the definition and any selective use of periods to allow the worst records to be skipped.

Accordingly, data that are not primary should be secondary, but should not be discarded. Secondary information will include records collected from several separate primary sources and may contain authoritative comments and analyses. Interpretations and source bias are important, especially the evidence for how events were interpreted during the Christmas period, as well as the moral relativism of value judgments.

When using primary and secondary materials, you need to evaluate and analyze the documents themselves before extracting the contents. Evaluation of documents usually includes four criteria: authenticity, reliability, representativeness, and meaning [2].

Authenticity refers to whether materials are authentic or of dubious origin, and whether their creation is original and reliable and has not been subsequently modified. If a document has been transformed through text editing, marginalization, or other means, the researcher seeks to clearly identify these changes. Authenticity is considered the most fundamental criterion for all documentary research in the field of information protection since the confirmation of authorship, place, and date is determined before the analyst continues to work with the document.

The report or any form of qualitative data can be original and authentic, its content can be distorted in one way or another. Thus, the second criterion in the evaluation of materials is to determine the reliability and reliability of the information contained in the document.

Reliability of information is a property of information that determines the degree of objective, accurate reflection of events, and facts that took place [3].

The third criterion, representativeness, shows whether the analyzed data contains enough information to build a qualitative model, as well as whether the information can be used by the model-building algorithm. The representativeness of the document may be distorted over time as the usefulness of certain materials becomes greater. Documents that are considered less valuable are used after they are created and thus stored.

Acquisition process – analysts examine documents (removing what they consider optional), which can also distort the source and representativeness. Similarly, some important documents are not preserved because their use has led to degradation and subsequently destruction, while less important documents are preserved because they are little used.

Determining whether the documents are fully authentic and representative may never be confirmed by the investigator. Thus, the question arises whether the materials can be considered unreliable, not representative, and whether they are credible. This has led to the view that «methodological skepticism» is described when researchers take a general approach, questioning all materials and requiring that documents, before being used, confirm their authenticity, credibility, and representativeness. [2].

The last criterion is meaning. This is a textual analysis of the document, as well as an analysis of whether the evidence is clear and understandable. The combination of semiotic and intertextual research tests the proper arrangement of a document's content in its historical context; this is partly confirmed by the method by which the value is constructed and perceived by the originally appointed audience.

Although these four criteria are fundamental, there is a fifth criterion for analyzing documents: theorizing is the expected theoretical hermeneutical basis for interpreting material. Documentary studies emphasize an important aspect of theorizing and constructing the meaning of a document: reconstructing the content of a text as it moves from author to audience [4].

Relevant analysis and evaluation of documents occur when the materials are determined to be public or private, primary or secondary (the source does not have to be the only original document), and whether the researcher has direct contact (the ability to inspect the original or primary document) or indirect access (facsimile or scanned electronic version).

Content analysis is a qualitative and quantitative method of studying documents, which is characterized by the objectivity of conclusions and the rigor of the procedure and consists of the quantification processing of the text with the subsequent interpretation of the results [5]. Researchers use content analysis to quantify and analyze the presence, meaning, and relationships of certain words, topics, or concepts to learn about the goals, messages, and effects of communication content. They can also conclude the authors and audience of the analyzed texts.

Data sources can be:

– books, newspapers, and magazines;
– speeches and interviews;
– web content and social media posts;
– photos and movies.

One study can analyze different forms of text in its analysis. To analyze text using content analysis, it must be encoded or broken into manageable categories of code to analyze (i.e., codes). Once the text is coded into code categories, the codes can be classified into «categories» to further generalize the data.

Content analysis can be used to quantify certain words, phrases, objects, or concepts in a set of historical or modern texts, in particular:

– determination of intentions, orientation, or communicative tendency of an individual, group, or institution;
– a description of attitudes and behavioral responses to communication;
– determining the psychological or emotional state of individuals or groups;
– identification of international differences in the content of communication;
– identification of patterns in the content of communication
– identification of the regularity of the context in the content of information resources;
– analysis of focus group interviews and open-ended questions, to complement quantitative data.

To use content analysis in a study, you need to start with a clear, direct research question.

The analysis process includes five steps:

1. The content to be analyzed is selected.

Based on the research question, the texts to be analyzed are selected. Next, it is solved:

– medium (e.g. newspapers, speeches, or websites) and genre (e.g. articles, political campaign speeches, or marketing copies);
– inclusion criteria (for example, newspaper articles that mention the relevant event, speeches of a certain politician, or websites where certain information is posted);
– parameters by date range, location, etc.

If there are only a small number of texts that meet the specified criteria, you can analyze them all. If there is a large volume of text, you can select a sample encoding.

2. Define analysis units and categories.

It is necessary to determine the level at which the selected texts will be analyzed, in particular:

– units of value to be encoded. For example, fixing the frequency of individual words and phrases, the characteristics of people who created or appeared in texts, the presence and arrangement of images, or the interpretation of topics and concepts.

– a set of categories to be used for encoding. Categories can be objective or more conceptual.

3. Analysis of a set of coding rules.

Coding involves organizing value units into predefined categories. Especially for more conceptual categories, it is important to clearly define the rules regarding what to include/not include to ensure consistent coding of all texts.

Coding rules are especially important if several researchers are involved, but even if all the text is encoded independently, writing down the rules makes this method more transparent and reliable.

4. Text encoding according to rules.

Each text is reviewed and all necessary data is recorded in the appropriate categories.

5. Analysis of results and conclusions.

After the coding is completed, the collected data is checked to find patterns and draw conclusions in response to the research task. You can use statistical analysis to find correlations or trends and draw conclusions about the authors, context and audience of texts.

Content analysis is applied to textual information in the form of words. An analyst can classify text, such as a report, article, or journal. In subsequent statistical manipulations, categories are treated as numerical data. Statistical analysis allows the analyst to conclude the information contained in the text. This is a traditional form of content analysis.

Content analysis can be considered as one of the many methods of text data analysis. Under the name of qualitative content analysis, many possibilities for analyzing text data are described [6, 7]. Some of these alternatives classify text but do not give categories numerical labels in preparation for statistical processing. Analysis in other qualitative approaches involves manipulating graphics and displaying text segments as codes or actual words rather than statistical manipulations. Content analysis is usually limited to statistical analysis [8, 9].

It is best to consider some assessment issues using text data content analysis and other forms of qualitative analysis. To some extent, programs such as AQUAD can be used in any situation [10, 11, 12]. AQUAD was designed for a style of qualitative analysis that keeps segments of the text intact. It provides the ability to cut and paste encoded segments of computerized documents. The ability to count codes also provides it with certain content analysis capabilities.

When developing an assessment that will use qualitative data, different approaches should be considered, including content analysis. As always, the methods that the analyst chooses must correspond to valuation questions.

You can use statistical analysis to find correlations or trends and draw conclusions about the authors, context, and audience of texts.

Content analysis is applied to textual information in the form of words. An analyst can classify text, such as a report, article, or journal. In subsequent statistical manipulations, categories are treated as numerical data. Statistical analysis allows the analyst to conclude the information contained in the text. This is a traditional form of content analysis.

The content analyst must perform the following functions:

– editing: creating and editing recorded information, including creating ASCII files;

– encoding: designating recording units and adding category codes;

– search: defining specific words, phrases, and categories;

– counting: counting the number of specific words, phrases, or categories in each unit of record;

– getting: getting certain words, phrases, or categories;

– export: creating a computer file for analysis using statistical packages.

Thus, the software in Table 1 is described primarily about these functions, organized in such a way that the software with the most functions is at the top, and with the least is at the bottom.

Table 1

SOFTWARE CAPABILITIES RELATED TO CONTENT ANALYSIS

SW	Editing	Encoding	Search	Counting	Receipt	Export
AQUAD	0	+	+	+	+	–
Word-Cruncher	0	–	+	+	–	0
Word-Perfect	+	–	+	–	0	0

Source: [14]

The software function meets the requirements – «+». The function is a little limited, but not completely absent – «–». The function is missing – «0».

The AQUAD software was designed primarily to analyze qualitative data in conditions where there is no intention to convert results to numbers. However, AQUAD has several features that make it useful for content analysis.

Text material is prepared on a word processor and converted to ASCII files for processing by the AQUAD program. Each document consists of one file. For example, if 10 interviews are conducted, 10 ASCII files will be prepared.

Encoding in AQUAD can be performed with text material displayed on the screen, as well as in a word processor. The cursor moves to the line where the passage to be encoded begins and the code is entered. The code contains three types of information: the line where the segment begins, the line where it ends, and the category label. If the analyst prefers to mark the codes on a hard copy first, AQUAD provides a shortcut to enter them into the database.

Although AQUAD was not designed as a content analysis program, it can be used to count code frequencies and produce coded passages in full.

Word Cruncher indexes text files, elicits data from them and processes them for viewing or analysis. This software is primarily designed to display text associated with words or phrases (i.e., context). It also provides a count of the number of instances of each word and a way to create an autonomous thesaurus, making it easier to develop categories for content analysis.

Before using Word Cruncher for content analysis, analysts create text material and encode it in a word processor. In some cases, Word Cruncher automatically generates second and third-level codes. Codes consist of two parts: a symbol and a mark that determine the location of words in the text.

Once the text has been encoded, Word Cruncher is used to create an index – a list of words along with their frequencies. Then, when the analyst selects a word and presses the key «enter», the program finds each instance of the word and displays its context.

Word processing software WORDPERFECT is indispensable for content analysis. It can be used to create a text database for later use with other applications, edit an existing database, add codes needed to analyze content, and convert from a word processor format to ASCII format. Almost all word processors can perform these tasks, and their editing capabilities usually far exceed the primitive editing functions found in most specialized content analysis programs.

Some word processors have powerful search functions that are useful in the early stages of content analysis. WordPerfect has a Quick Finder that searches for words and phrases within files as well as between files. The analyst can then scroll through the text to find the words and phrases that QuickFinder has highlighted. The program thus used can be useful in determining variables and categories, as well as in deciding which material to encode.

The digital age has provided diverse opportunities for society and business in general. However, these opportunities are also associated with various types of risk, such as cyberattacks, data leakage, loss of intellectual property, financial fraud, etc. One approach to mitigate these risks is to share threat information through platforms such as closed and open communities to share information and threat channel providers. The idea of exchanging information about threats comes from the assumption that an enemy attacking a certain target can also attack similar targets shortly. While the popularity of information-sharing platforms was growing, the amount of threat information shared increased significantly, overwhelming analysts and undermining efforts to share threat information.

The need to process text information that is on the Internet still exists. Scientific articles are of particular interest since international relations and the foreign policy position of the state play a special role in the era of information and hybrid wars.

Information and psychological confrontation, as a certain methodology for changing the picture of the world in a given direction, today has become one of the forms of struggle of the most rapidly developing advanced states. In this case, the object of influence can be both individuals (or a group of persons) who make decisions at different levels, and the mass consciousness of the people as a whole.

Information and psychological confrontation in the political sphere – the use of information, diplomatic, military demonstration, economic, and other techniques to influence the opinion, mood, and, as a result, the behavior of the opposite side.

Fundamental features of information and psychological impact:

– is conducted, as a rule, on any territory, without restrictions crossing borders, penetrating, including, into the consciousness of the enemy;

– is conducted, leaving no visible traces. It seems to the object of influence that he makes decisions, but in fact, he is under the influence;

– relative economy for its initiators, since a small amount of input information can lead to the most significant result, for example, the formation of the necessary public opinion;

– the same fact in terms of information and psychological operation can receive different interpretations;

– the inability to block enemy actions based on the conditions of the presence of advanced ICTs, similar to how it is done by traditional weapons.

Information-psychological warfare is the most acute form of confrontation in the information-psychological direction, carried out by influencing the enemy to solve strategic problems. This includes purposeful and systematic use of tools of information and psychological influence on the opinion, mood, and, as a result, on the behavior of the enemy with the aim of destabilization and demoralization [19].

Information and psychological operation are complex of coordinated and coordinated actions related to the achievement of goals, and objectives, as well as to the place and time, objects, and procedures of types, forms, and methods of information influence [19].

Information and psychological operations are divided into:

– long-term;

– medium-term;

– short-term.

By the time of implementation of information and psychological operations are divided into:

– operations that are conducted before the transition of the conflict into the active-power phase;

– operations that are carried out in the context of the conflict.

Direction is divided into operations carried out:

– against the recipient;

– in the interests of the subject carrying out communicative actions;

– against third parties for whom there are intentions to persuade them in their direction.

Information and psychological methods and means of psycho-technologies are divided into open and hidden, positive and with shortcomings.

Secret information and psychological operations are aimed at creating conditions for making profitable decisions in various fields, in particular political, in countries that are objects of information and psychological influence. To create such conditions, the developed information is brought to the attention of the object of influence through electronic, printed, and other means of mass communication, means of electronic and postal communication, audio, video, and film production, open telecommunication networks, and visual and demonstration means.

In general, it is possible to predict the improvement of methods and expansion of the spheres of application of information and psychological warfare, which can not only affect the strategic balance of forces prevailing in the world but also change the existing criteria for assessing such a balance based on the ratio of geopolitical, economic and military factors.

Content analysis is an analysis based on the study of messages, topics, words, etc., which focuses the researcher's attention on content text [20].

This method allows us to draw important conclusions, as well as scientifically confirm assumptions and hypotheses regarding the effectiveness of informational and psychological influence methods.

To conduct a content analysis of the mention of words with the prefix «cyber» (cybersecurity, cyberspace, cyber weapons, cyberattack, cyber war, cyber swim, etc.), scientific articles were chosen in the public domain:

– Ukraine, as the main entity that protects national security from cyber threats (59 articles);

– USA, as an advanced state in the development and protection cyberspace (212 articles).

A total of 271 articles were analyzed.

The list of interested countries and their scientific articles can certainly be expanded.

Using the Python programming language and using the pandas and matplotlib libraries, you can analyze and visualize data from an information and psychological impact file (Fig. 1).

The first step is to import the pandas and matplotlib libraries for working with data and visualization and load the data from the information and psychological impact file using the «read_csv» function from pandas and save it to a DataFrame named «df».

```
# Import libraries
import pandas as pd
import matplotlib.pyplot as plt
# Load data
```

```
data_url = «/content/Data_4.csv»
df = pd.read_csv(data_url)
# Display information about columns in the dataset
print(df.columns)
```

	A
1	sphere,country,topic,words,year
2	State and law,USA,вЂњHelp IвЂ™ve Been HackedвЂќ: Insights from a Corpus of User-Reported Cyber Victimization Cases on Twitter,21,2019
3	Computer Engineering,USA,A Bi-objective Hyper-Heuristic Support Vector Machines for Big Data Cyber-Security,34,2018
4	Computer Engineering,USA,A Brute-Force Black-Box Method to Attack Machine Learning-Based Systems in Cybersecurity,57,2020
5	Economics,USA,A Clustering Method of Asset Cybersecurity Classification,32,2019
6	Economics,USA,A Comprehensive Study of the IoT Cybersecurity in Smart Cities,150,2020
7	Computer Engineering,USA,A Conversation with Xiaokui Shu: The pursuit of speed in cybersecurity,46,2021
8	Politics,USA,A Crisis of Trust in Transatlantic Cybersecurity Relations in the Post-Snowden Era,135,2018
9	Computer Engineering,USA,A critical review of intrusion detection systems in the internet of things: techniques deployment strategy validation strategy attacks public datasets and challenges,18,2021
10	Politics,USA,A cyber-security framework for development defense and innovation at NATO,264,2019
11	State and law,USA,A Cyber-Security Methodology for a Cyber-Physical Industrial Control System Testbed,118,2021
12	Computer Engineering,USA,A Deep Learning Architecture for Psychometric Natural Language Processing,4,2020
13	Computer Engineering,USA,A DGA domain names detection modeling method based on integrating an attention mechanism and deep neural network,5,2020
14	Computer Engineering,USA,A Holistic Review of Cybersecurity and Reliability Perspectives in Smart Airports,161,2020
15	Economics,USA,A Maussian bargain: Accumulation by gift in the digital economy,10,2020
16	Computer Engineering,USA,A Methodology forВ Runtime Detection andВ Extraction ofВ Threat Patterns,8,2020
17	Economics,USA,A Monte-Carlo Analysis of Monetary Impact of Mega Data Breaches,20,2021
18	Economics,USA,A Moving Target Defense Strategy for Internet of Things Cybersecurity,18,2021
19	Computer Engineering,USA,A novel feature extraction methodology using Siamese convolutional neural networks for intrusion detection,3,2020
20	Computer Engineering,USA,A novel risk assessment process: Application to an autonomous inland waterways ship,58,2021
21	Computer Engineering,USA,A Review of Cybersecurity Guidelines for Manufacturing Factories in Industry 4.0,194,2021
22	Computer Engineering,USA,A selective ensemble model for cognitive cybersecurity analysis,83,2021
23	Computer Engineering,USA,A Survey of Cybersecurity of Digital Manufacturing,42,2021
24	Computer Engineering,USA,A survey of methods supporting cyber situational awareness in the context of smart cities,100,2020
25	Computer Engineering,USA,A survey of new orientations in the field of vehicular cybersecurity applying artificial intelligence based methods,17,2021
26	Politics,USA,A Systematic Framework to Understand Transnational Governance for Cybersecurity Risks from Digital Trade,76,2021
27	Politics,USA,A Systematic Framework to Understand Transnational Governance for Cybersecurity Risks from Digital Trade,287,2021
28	Computer Engineering,USA,A Systems and Control Perspective of CPS Security,51,2019
29	Computer Engineering,USA,A Test-Driven Approach for Security Designs of Automated Vehicles,44,2020
30	Computer Engineering,USA,A Threat Hunting Framework for Industrial Control Systems,64,2021
31	Computer Engineering,USA,About the cybersecurity of automated process control systems,18,2021
32	Computer Engineering,USA,Access control technologies for Big Data management systems: literature review and future trends,1,2019
33	Computer Engineering,USA,Actual TDoA-based augmentation system for enhancing cybersecurity in ADS-B,13,2021
34	Computer Engineering,USA,Additive Manufacturing Cyber-Physical System: Supply Chain Cybersecurity and Risks,22,2020
35	Computer Engineering,USA,Addressing Cybersecurity in the Next Generation Mobility Ecosystem with CARAMEL,22,2021
36	Computer Engineering,USA,Adversarial attacks on machine learning cybersecurity defences in Industrial Control Systems,11,2021
37	Computer Engineering,USA,Adversarial XAI Methods in Cybersecurity,13,2021

Figure 1. Sample data from informational
and psychological influence file

Source: developed by the authors

The next step was to analyze and output information (Fig. 2).

```
Index(['sphere', 'country', 'topic', 'words', 'year'], dtype='object')
    year               sphere  country  words
0   2018  Computer Engineering      USA    274
1   2018  Computer Engineering  Ukraine    266
2   2018            Economics      USA    511
3   2018            Economics  Ukraine     46
4   2018             Politics      USA    179
5   2018             Politics  Ukraine     15
6   2018        State and law      USA    164
7   2018        State and law  Ukraine    193
8   2019  Computer Engineering      USA    394
9   2019  Computer Engineering  Ukraine    218
10  2019            Economics      USA    948
11  2019            Economics  Ukraine    213
12  2019             Politics      USA    716
13  2019             Politics  Ukraine     98
14  2019        State and law      USA    216
15  2019        State and law  Ukraine     55
16  2020  Computer Engineering      USA   1574
17  2020  Computer Engineering  Ukraine    102
18  2020            Economics      USA    494
19  2020            Economics  Ukraine    111
20  2020             Politics      USA    435
21  2020             Politics  Ukraine      5
22  2020        State and law      USA    999
23  2020        State and law  Ukraine    162
24  2021  Computer Engineering      USA   1898
25  2021  Computer Engineering  Ukraine    265
26  2021            Economics      USA   1831
27  2021            Economics  Ukraine     65
28  2021             Politics      USA   1058
29  2021             Politics  Ukraine     88
30  2021        State and law      USA   1111
31  2021        State and law  Ukraine    287
```

Figure 2. Sum of words for the period 2018–2021
for each area of countries

Source: developed by the authors

Code (Fig. 3):
# 1. Finding the number of words for each year in each sphere for each country
sum_words_by_year_sphere_country = df.groupby([‘year’, ‘sphere’, ‘country’])[‘words’].sum().reset_index()
print(sum_words_by_year_sphere_country)
# 1.1. Calculating the number of articles
sum_articles_by_country = df.groupby([‘country’])[‘topic’].count()
print(«\nSum of Articles:»)
print(sum_articles_by_country)
# 1.2. Calculating the sum of words
sum_words_by_country = df.groupby([‘country’])[‘words’].sum()
print(«\nSum of Words:»)

```
print(sum_words_by_country)
# 1.3. Calculating the ratio of words to articles
coefficient_by_country = sum_words_by_country / sum_articles_by_country
print(«\nCoefficients of Words to Articles:»)
print(coefficient_by_country)
```

```
Sum of Articles:
country
USA        212
Ukraine     59
Name: topic, dtype: int64

Sum of Words:
country
USA        12802
Ukraine     2189
Name: words, dtype: int64

Coefficients of Words to Articles:
country
USA        60.386792
Ukraine    37.101695
dtype: float64
```

Figure 3. Number of articles and words and their ratio

Source: developed by the authors

Code:

```
# 2. Constructing comparative graphs for two countries in each sphere
countries_to_compare = [‘USA’, ‘Ukraine’]
# Filtering data for selected countries
df_comparison = df[df[‘country’].isin(countries_to_compare)]
# Grouping by year, sphere, and country
grouped_comparison = df_comparison.groupby([‘year’, ‘sphere’, ‘country’])[‘words’].sum().unstack()
# Constructing graphs
for sphere in df[‘sphere’].unique():
 data_for_sphere = df[df[‘sphere’] == sphere]
 if not data_for_sphere.empty:
 plt.figure(figsize=(10, 6))
 data_for_sphere.groupby([‘year’, ‘country’])[‘words’].sum().unstack().plot(kind=‘bar’, stacked=True)
```

```
plt.xlabel('Year')
plt.ylabel('Sum of Word Count')
plt.title(f'Comparative Graph of Word Count for Sphere
«{sphere}» for Selected Countries')
plt.legend(title='Country')
plt.show()
plt.close()

# 3.1. Constructing a line graph for the number of scientific articles
of two countries for each year
df_articles_by_year = df.groupby(['year',
'country'])['topic'].count().unstack()
df_articles_by_year[countries_to_compare].plot(kind='line',
marker='o')
plt.xlabel('Year')
plt.ylabel('Number of Scientific Articles')
plt.title('Line Graph of Number of Scientific Articles for Selected
Countries Each Year')
plt.legend(title='Country')
plt.show()
# 3.2. Constructing a line graph for the number of words of two
countries for each year
df_words_by_year = df.groupby(['year',
'country'])['words'].sum().unstack()
df_words_by_year[countries_to_compare].plot(kind='line',
marker='o')
plt.xlabel('Year')
plt.ylabel('Number of Words')
plt.title('Line Graph of Number of Words for Selected Countries
Each Year')
plt.legend(title='Country')
plt.show()
# 4. Displaying on screen the top three article topics with the
highest word count for each year
top_topics_by_year = df.groupby(['year',
'topic'])['words'].sum().reset_index()
top_topics_by_year = top_topics_by_year.sort_values(by=['year',
'words'], ascending=[True, False])
top_topics_by_year = top_topics_by_year.groupby('year').head(3)
print(«Top Article Topics with the Highest Word Count for Each
Year:»)
print(top_topics_by_year)
```

In the third step, comparative graphs for each area were built, and dynamics regarding the number of scientific articles and words for selected countries were presented (Fig. 4–9).

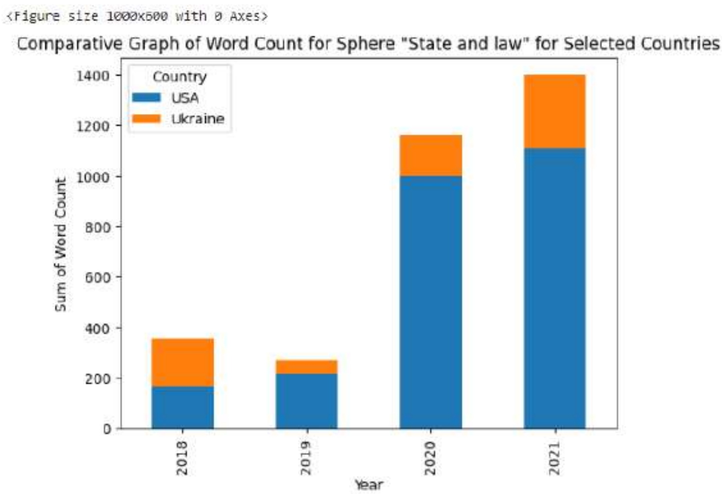

Figure 4. Theme «State and Law»

Source: developed by the authors

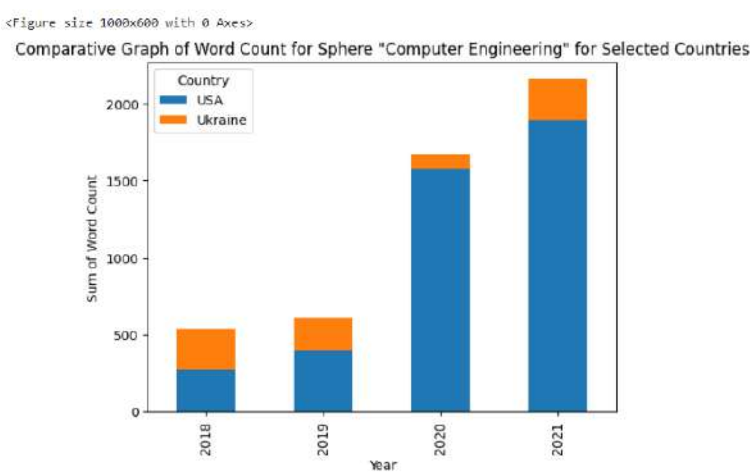

Figure 5. Theme «Computer Engineering»

Source: developed by the authors

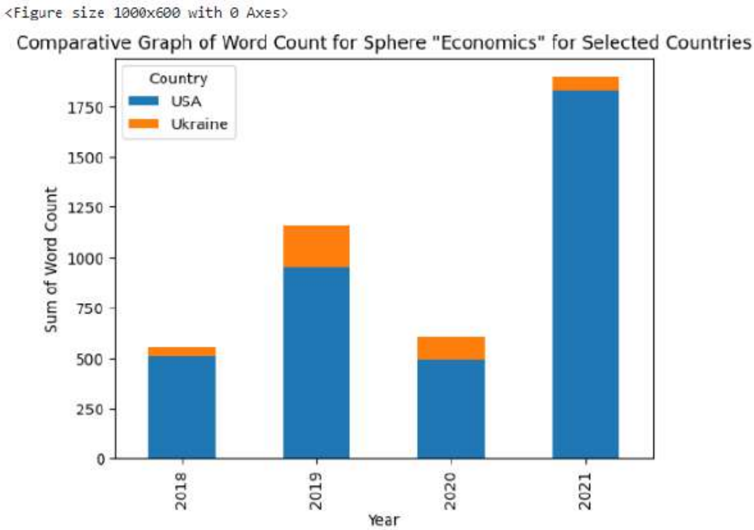

Figure 6. Theme «Economy»

Source: developed by the authors

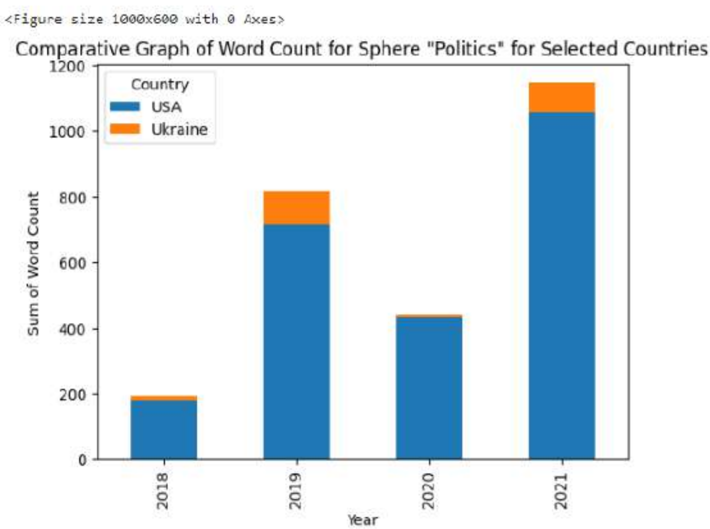

Figure 7. Theme «Politics»

Source: developed by the authors

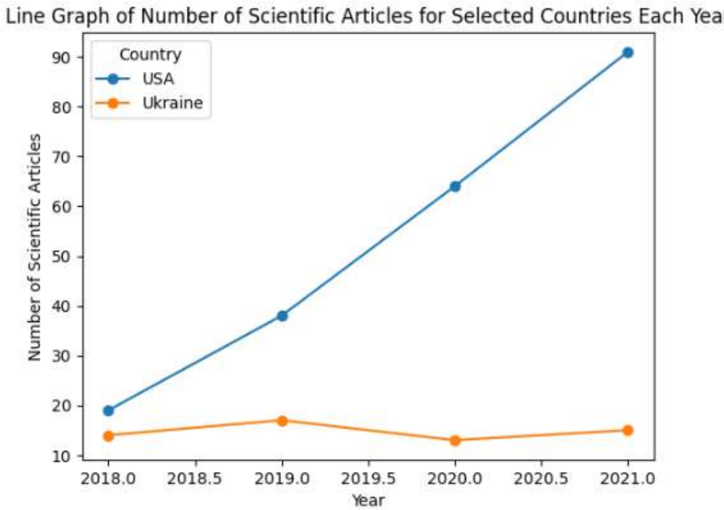

Figure 8. Dynamics of scientific articles related to cybersecurity

Source: developed by the authors

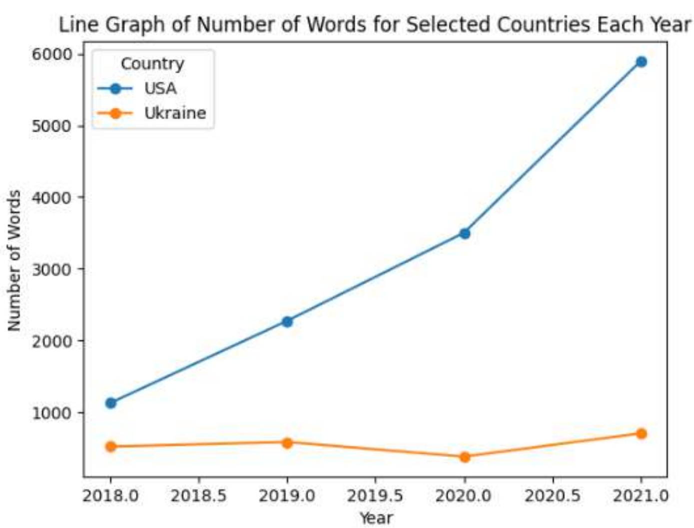

Figure 9. Dynamics of the number of mentioned words with the prefix «cyber» in scientific articles

Source: developed by the authors

The final step is to identify the top 3 topics with the most words with the prefix «cyber» for each year (Fig. 10).

```
Top Article Topics with the Highest Word Count for Each Year:
     year                                              topic  words
8    2018  Empirical Evidence on the Determinants of Cybe...    305
21   2018  АКТУАЛЬНІ КІБЕРЗАГРОЗИ СУЧАСНОГО БЕЗПЕКОВОГО С...    166
2    2018    An Options Approach to Cybersecurity Investment    150
65   2019  Systematically Understanding the Cyber Attack ...    436
35   2019  A cyber-security framework for development  de...    264
78   2019       КІБЕРБЕЗПЕКА УКРАЇНИ: АНАЛІЗ СУЧАСНОГО СТАНУ    166
118  2020  Cybersecurity data science: an overview from m...    254
136  2020                      Privatized Cybersecurity Law    220
155  2020  War  Health and Ecosystem: Generative Metaphor...    164
214  2021  Economic model for evaluating the value creati...    731
186  2021  Analysis of cybersecurity competencies: Recomm...    369
171  2021  A Systematic Framework to Understand Transnati...    363
```

Figure 10. Topics of articles with the most words for each year

Source: developed by the authors

Based on the data obtained on the number of mentions of words with the prefix «cyber» in scientific articles for the period 2018–2021 in the USA and Ukraine, several conclusions can be drawn:

General growth trend. In general, there is a general trend in the number of mentions of words with the prefix «cyber» during the period under review in both countries, but especially in the United States.

Difference in volumes. There is a big difference in the volume of research between the USA and Ukraine, in particular in the spheres of economy and politics. In the United States, the number of mentions significantly exceeds the corresponding figures in Ukraine.

Spheric specificity. In each of the areas considered (Computer Engineering, Economics, Politics, State and law), there are excellent dynamics. For example, in the field of Computer Engineering, the number of mentions in both countries increased significantly in 2020 and 2021. In the fields of «Politics» and «Economy», high indicators are found in the United States compared to Ukraine, especially in 2019 and 2021.

Features in Ukraine. In Ukraine, the dynamics of growth in all spheres are expressed, but the volumes remain much smaller than in the USA.

Increased focus on cybersecurity. The increase in the number of mentions of words with the prefix «cyber» may indicate an increase in attention to this issue in scientific research in both countries, which may be associated with an increase in the number of cyberattacks and cybersecurity threats.

In general, the data indicate the relevance of the topic of cybersecurity in scientific research of both countries, but different volumes and dynamics indicate a difference in the levels of development of this direction in the United States and Ukraine.

By analyzing scientific articles on topics and collecting statistical information, you can identify threats of certain or random actions, or much wider actions.

By analyzing scientific articles on topics and collecting statistical information, you can identify threats of certain or random actions, or much wider actions.

The best practices for preventing and detecting cybercrime include, in particular, the adoption of laws, the creation of effective leadership, conducting information and educational activities, increasing the powers of criminal justice bodies, cooperation between certain executive authorities, communities, as well as at the world level.

So, each of the above topics makes it possible to form an idea about certain aspects of the phenomena studied:

Economy. Ensuring economic security in states is impossible without an appropriate cyber component. Questions about cyber defense have turned from a local threat to the functioning of business units into a world-class task.

State and law. Cybersecurity is considered one of the most pressing topics of modern international law, extremely important for ensuring the national security of the state. However, a single approach to solving this problem in the international arena has not yet been developed, since the complexity of the legal regulation of cyberspace is due to the virtual characteristic of the relations developing in this area.

Policies. The fight against cybercrime has become not only a personal matter of certain states but also a number of international organizations that, in order to protect against the encroachment of cybercriminals, focus more on the development of effective international regulatory documents as a fundamental basis for the development of their legislation by participating states. One such international act is the Convention on Computer Crime ETS No. 185 (Budapest, November 23, 2001).

Computer engineering. The main problem for the cybersecurity departments is the insufficient level of cybernetization and visual control over the cyber environment. The lack of automated data collection mechanisms, as well as a meaningful understanding of cybersecurity and visual control over cyber threats hidden in the network significantly increases the risk of cyberattacks on organizations.

Also, to ensure situational awareness, the analyst must be able to identify information related to cyber threats specifically applied to his environment in order to actively monitor and prevent possible intrusion and control possible risks.

Conclusions

The results of the study allow the analysis and assessment of threats in terms of risk levels for vital areas of economic activity. Recommendations for strengthening the national security of Ukraine obtained as a result of the study, can be sent to government agencies. The results of the study can be used for strategic analysis of cybersecurity threats now.

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TRENDS IN USE AND DEVELOPMENT OF NOVEL TECHNOLOGIES IN HEALTHCARE SYSTEM FOR EFFICIENT DIAGNOSIS AND TREATMENT IN NEUROLOGY AND INTERNAL MEDICINE

Healthcare in the field of neurology and internal medicine continues to evolve and has dramatically changed in the last decade with the emergence and integration of new technologies to enhance patient care and outcomes. Neurology is a specialized branch of healthcare focused on diagnosing, treating, and managing disorders of the nervous system. This encompasses a wide range of conditions affecting the brain, spinal cord, nerves, and muscles, including stroke, epilepsy, Alzheimer's disease, Parkinson's disease, multiple sclerosis, and peripheral neuropathy, among others [1]. From machine learning algorithms assisting in diagnostics and treatment planning to the development of new medications and data mining systems enabling proactive healthcare management, the landscape of healthcare delivery is constantly being reshaped [1]. Furthermore, advancements in telemedicine platforms facilitate virtual consultations and remote patient monitoring, breaking down geographical barriers and improving access to healthcare services. Additionally, innovations in medical devices and procedures, such as 3D printing for customized implants and minimally invasive surgeries, contribute to improved patient experiences and shorter recovery times [1]. As technology continues to advance, healthcare providers remain committed to embracing these innovations to provide more efficient, effective, and patient-centered care. This article provides a summary on the current use of artificial intelligence (AI) in the healthcare in the United States. The author provides a thorough review about the use of AI assisted diagnostic tools, electronic health records with data mining functionality, nanotechnology, and genomics in healthcare settings. Even though these novel technological advancements offer numerous benefits suggesting promising future developments, artificial intelligence is not replacing human specialists and physicians but only serves as a supplemental tool.

Present Use of AI

The innovative technologies that currently utilize artificial intelligence (AI) and are implemented in the United States include AI assisted diagnostics, electronic health records with data mining functionality, nanotechnology, and genomics [2]. Some of the benefits of using AI is enabling predictive analytics for personalized treatment plans, improving diagnostic accuracy through advanced imaging analysis, and streamlining administrative tasks to enhance operational efficiency in healthcare facilities. Data mining techniques are being utilized to extract valuable insights from large datasets, facilitating evidence-based decision-making for disease prevention, diagnosis, and treatment optimization in healthcare [2]. Nanotechnology is offering novel solutions in drug delivery systems, allowing for targeted and controlled release of medications, as well as the development of miniature devices for real-time monitoring of patient health parameters [3]. Genomics is playing a pivotal role in precision medicine by providing insights into individuals' genetic makeup, enabling tailored therapies and interventions based on genetic predispositions and variations [4]. The integration of these innovative artificial intelligence technologies in modern healthcare is not only enhancing patient outcomes but also driving advancements in research, healthcare delivery, and cost-effective healthcare solutions.

Artificial Intelligence in Diagnostics

Artificial intelligence (AI) is being used more frequently since it offers immense benefits to transform healthcare through enhanced diagnostic techniques and improved efficiency and productivity. It is gaining more popularity as a diagnostic tool but there are still many challenges due to the complexity of diseases and underlying mechanisms. AI driven applications are utilized in different types of cancer diagnosis. Studies demonstrate that using an AI system to interpret mammograms results in a reduction in false positives by 5.7 % and false negatives by 9.4 % [5]. Utilizing AI system has shown to have more sensitive results compared to radiologists, 90 % vs. 78 %, respectively, and better detection rates of early breast cancer than radiologists by 12 % [5]. Studies also show that AI-utilized diagnosis was more sensitive to diagnose breast cancer with mass compared to radiologists, 90 % vs. 78 %, respectively [5]. AI applications are also used in diagnostics for other disease processes such as diabetic retinopathy, EKG abnormalities, pneumonia, appendicitis, and many others.

One of the innovative applications is RapidAI, an imaging recognition system that represents an advanced artificial intelligence platform designed to assist healthcare providers in rapidly interpreting medical imaging scans, such as CT scans and MRI images, particularly in the context of stroke assessment and management. The Rapid AI algorithms can analyze medical images, such as X-rays, MRIs, and CT scans faster and more precisely compared to traditional methods [5]. The use of AI is rapidly growing in neurology since acute ischemic or hemorrhagic cerebrovascular accidents require urgent detection and treatment decisions. Utilizing cutting-edge AI algorithms, the RapidAI system can quickly and accurately analyze medical images to identify signs of acute ischemic stroke, intracranial hemorrhage, and other neurological conditions [6].

The system employs deep learning techniques to analyze imaging data and detect subtle abnormalities, such as blocked blood vessels or hemorrhagic lesions, that may indicate a stroke or other critical neurological event. By rapidly identifying these abnormalities, the RapidAI system provides clinicians with timely insights to guide diagnosis and treatment decisions, potentially saving valuable time in critical situations where every minute counts [6].

RapidAI imaging recognition system is integrated seamlessly into existing medical imaging workflows, allowing healthcare providers to upload imaging scans directly to the platform for analysis. The system then generates detailed reports and visualizations highlighting key findings, facilitating rapid communication and collaboration among multidisciplinary care teams. Moreover, the RapidAI system is continuously updated and refined through ongoing training with large datasets of medical images, ensuring its performance and accuracy improve over time. This iterative learning process enhances the system’s ability to detect and classify neurological abnormalities with high sensitivity and specificity, ultimately improving patient outcomes and reducing the burden on healthcare providers [6].

The RapidAI imaging recognition system is a state-of-the-art tool that leverages artificial intelligence to enhance the interpretation of medical imaging scans, particularly in the assessment and management of stroke and other neurological conditions. By providing rapid, accurate insights into imaging data, the system empowers healthcare providers to make informed decisions and deliver timely interventions, ultimately improving patient care and outcomes [6].

Even though RapidAI brings multiple benefits, this application continues to only serve as a supplemental tool due to contradictory study results on its accuracy. For example, the most recent studies demonstrated that sensitivity for large vessel occlusion (0.65–0.96) and for medium vessel occlusion (0.62–0.94) was higher for all physicians compared with RapidAI (0.62 and 0.39, respectively). Additionally, most readers had superior specificity compared to RapidAI for LVO (0.75–0.98 versus 0.93) and MVO (0.55–0.95 versus 0.92) [6]. Other studies show that the AI algorithm of using three-dimensional deep convolutional neural network results an increased detection of intracranial hemorrhage by 12.2 % [1]. Even though RapidAI is susceptible to programming-related systematic errors, this system is superior to humans in relation to no possibility of making errors from fatigue, clinical load, and lapses in concentration [6].

One of the main advantages of RapidAI is its quick reading time and immediate remote access by external readers. This reduces delays in reading and initiation of treatment which can be as long as 50 minutes. The read time for RapidAI averages five minutes, which is faster than any experienced reader, which expedites and improves the workflow by alerting neurologists and neuro-interventional radiologists to abnormal findings and leading to timely insights to guide diagnosis and treatment decisions [6]. By accelerating the interpretation process, AI helps reduce diagnostic delays, improve patient outcomes, and optimize workflow efficiency in healthcare settings.

AI-powered decision support systems are transforming clinical decision-making by synthesizing vast amounts of patient data, including medical records, lab results, and genetic information, to assist healthcare providers in making evidence-based treatment recommendations. These systems can analyze complex datasets, detect patterns, and generate personalized treatment plans tailored to individual patient needs. By augmenting clinicians' expertise with AI-driven insights, healthcare delivery becomes more precise, proactive, and patient-centered, ultimately leading to better outcomes and higher quality of care.

Data Mining and Quality Improvement

Data mining is an important process for workflow mapping in healthcare companies because it helps analyze large amounts of data and discover hidden patterns [7]. Leadership is responsible for making informed decisions and considering all available data sifted to validate assumptions about the suggested workflow process. Data mining results direct the workflow design uncovering complex relationships of multiple processes within the healthcare industry and individual hospitals. Data mining technology is now also suggesting new approaches to help build workflow processes and workflow design creation. Healthcare leaders use these approaches to discover new knowledge which contributes to research development, brings financial stability, and provides a perspective on quality improvement. Data mining functionality plays an important role in workflow design and contributes to quality improvement decisions.

Data Mining Role in Workflow Design

Data mining helps in workflow design because the healthcare industry produces a large amount of data and uses workflow design to help improve performance and optimize the functioning of the companies in light of the massive amount of data. Data mining is the practice of examining large amounts of data to generate new knowledge [7]. This practice is used in different industries and becoming more popular in the medical field because of the enormous amount of data that the healthcare industry generates.

Data mining tools are used to collect, process, and analyze that data and use this information to discover patterns and trends, and make informed decisions [7]. Having a large amount of big data makes it more complicated to design workflows for healthcare companies. Connecting multiple heterogeneous tasks generated from data mining with third-party codes, different versions of programs and services may be time-consuming and error-prone [8]. To overcome the dependency on the individual skills of scientists to connect tasks and design a workflow, new mining tools are being created which use sequence mining techniques in workflows, which is a successful technique for finding frequent sequential events in a dataset [8]. So, data mining provides ways to handle big data and can be useful in actual workflow design creation.

Quality Improvement Decisions

To make adequate quality improvement decisions, healthcare administrators must have close work relationships with advanced analytics professionals capable of analyzing and managing massive amounts of data and using data mining tools and techniques. Advanced analytics professionals are data scientists who are at least master's-prepared nursing informaticists with a solid base as a mathematician and have extensive training in computer science, statistics, biomedical and clinical informatics [7].

Data collection and analysis are an integral part of quality improvement initiatives. Using accurate data at each phase of the quality improvement process helps inform the progress guiding it to achieve the best outcomes. Data mining provides accurate data from a variety of sources ensuring that the new strategies are developed based on the most recent evidence-based practice. The data serves as a catalyst for change and a crucial element of the change process leading to the implementation of new processes [9].

Accurate data collection and processing are extremely important in the quality improvement projects directed towards disparities, for example. Quality improvement approaches addressing disparities consist of systematic data-guided interventions that have the goal of improving healthcare services and the health status of specific patient groups through the implementation of best practices in clinical care. Quality improvement interventions require ongoing data collection, analysis, and evaluation of the intervention effects [10]. One of the examples of how data mining is used in healthcare for quality improvement is error, abuse, and fraud prevention. Healthcare fraud is defined as an intentional deception that has the goal of obtaining unauthorized benefits. Healthcare abuse results from any practice that contradicts the goals of providing medically necessary services to the patients, fails to meet recognized standards or leads to unnecessary costs to the payers [11].

The growing use of electronic health records and other computerized systems makes it very time-consuming and difficult to use traditional methods for fraud detection. Data mining becomes very useful and proves to be a more efficient approach as an information technology-based auditing system that uses Knowledge Discovery from Databases [11]. Studies show that three to ten percent of healthcare expenditure is lost to fraud, which constitutes about three hundred billion dollars every year. So, this problem is costly and contributes to increased premiums and harm to beneficiaries. Using modern approaches of data mining for fraud detection in healthcare helps combat this societal threat efficiently and fast [12].

Advanced Analytics Professional’s Role

It is important for the healthcare executives to work closely with advanced analytics professionals because they offer continuous feedback on the workflow processes. The primary mission of healthcare executives and advanced analytics specialists is to get accurate information from data mining to ensure the translation of the complex data into actionable information which eventually leads to the implementation of evidence-based practices, improved safety, and better outcomes for patients. Since data mining assists in identifying actionable insights, healthcare leaders have to work closely with people who work with the data mining technology to ensure prompt delivery of the data mining findings to the appropriate providers and users of the data [7].

Healthcare executives work closely with advanced analytics professionals also because data mining leads to significant cost savings. Prompt identification of issues and implementation of interventions to fix the problems leads to improved quality metrics and better reimbursement for hospitals. It also leads to increased patient satisfaction because they have better outcomes, reduced preventable adverse events, improved comfort, etc. [7]. Improved results from data mining are only possible if healthcare executives work closely with data scientists.

Conclusions on Using Data Mining in Healthcare

Data mining plays an important role in a variety of healthcare processes. Just like any other industry, healthcare is becoming increasingly complex because it generates a vast amount of data from a variety of sources. Data mining provides modern approaches to creating workflow design and finding efficient ways of constructing the processes in hospitals and clinics. Knowledge discovery from databases allows to find and implement multiple quality improvement projects, keep data safe and prevent fraudulent activity. By working closely with advanced analytics professionals, healthcare executives find the most efficient ways to lead the healthcare industry and provide the best care to the patients.

AI is driving innovation in disease management and holds promise in drug discovery and development, streamlining the drug discovery process by predicting the efficacy and safety of potential drug candidates through computational modeling and simulation. By analyzing vast datasets of biological, chemical, and clinical information, AI algorithms can identify novel drug targets, design optimized drug molecules, and accelerate preclinical and clinical trials. This convergence of AI and pharmaceutical research has the potential to accelerate the pace of drug discovery, reduce development costs, and bring life-saving medications to market more efficiently.

Nanotechnology

Nanotechnology is still considered a new concept but its principles have been utilized for many centuries. The initial use of nanoscience concepts dates back to medieval times when the church artists used alternate-sized gold and silver particles to create beautiful works of art in stained-glass windows or decorate glasses and cups using nano-sized metals. American physicist Richard Feynman was one of the first scientists who extrapolated on the processes and ideas of manipulating and controlling individual atoms and molecules directly related to nanotechnology concepts [13]. In his paper «There's Plenty of Room at the Bottom», he raised questions such as creating an electric motor of the size of a nail, writing all of the twenty-four volumes of the Encyclopedia Britannica on the head of a pin, and other similar ideas related to manipulating and controlling things on a small scale [14].

The first time the term nanotechnology was used was in 1974 by professor Norio Taniguchi during a scientific conference, but there are many other scientists who contributed to the development of the field of science. He defined nanotechnology as the process of separation, consolidation, and deformation of materials by a single atom or molecule [15]. Nanotechnology is a promising field of study which is rapidly developing and evolving but still needs a lot of special attention due to its novel nature. It has a huge impact on health information technology, but requires careful handling and consideration of bioethical checklist while dealing with ethical principles related to nanotechnology use.

The Impact of Nanotechnology on Health Information Technology

Nanomedicine represents one of the branches of nanotechnology that focuses on diagnostic testing and treatment of diseases. There are a few ways in which health information technology' roles are impacted by nanotechnology and nanomedicine. One of the ways is the improved diagnostics of the diseases. Dr. Chad Mirkin is a famous nanomedicine researcher, who developed Verigene ID SystemtS as a part of Nanosphere company, which can simultaneously test patients for a multitude of markers in less than an hour. His system can help detect traces of proteins associated with Alzheimer's disease, as well as help diagnose oncological and cardiovascular conditions [16].

Another way how health information technology is impacted by nanotechnology and nanomedicine is through drug delivery. Nanotechnology provides new opportunities for improved drug delivery through enhanced bioavailability, reduced toxicity, and increased solubility [7]. There are studies that investigate the use of nanotechnology methods to use nano-sized particles for common treatment of asthma and chronic obstructive pulmonary disorders as well as delivering less toxic chemotherapeutic drugs to target tumor cells [16].

The development of nanotechnology leads to improved and personalized medicine tailored to each patient. The use of nanotechnology allows scientists to select appropriate therapies for specific groups of patients and makes it possible to predict whether a particular therapy will be sufficient for a given patient [16]. The right medicine for the right patient at the right time will be the future of diagnosing and treating every patient.

Nanomedicine as the emerging and developing field of science brings up questions related to its use. Dissemination of new devices requires the implementation of appropriate policies and procedures for their safe use by the patients to address any legal, system design, and bioethical issues that can impede the introduction of these novel devices [17].

One of the applications of nanotechnology advancements is nano tattoos. This ancient form of art is now combined with the latest technology to diagnose and monitor certain conditions providing valuable information to patients and their physicians. Nano tattoos represent a form of emerging bio-integrated intelligent sensing system (BISS), that is able to process data and perform multimodal human-centered sensing [18]. While this technological advancement offers multiple benefits, there might be concerns related to the ethical issues of practical implementation and its novel nature. To address the implementation of these novel devices, the researchers propose using a bioethical checklist consisting of the questions of patent scope and thicket potential, as well as ethical principles of autonomy, justice, beneficence, and confidentiality [17].

Patient Education on Nanotechnology Including Common Treatments

The patients have to be treated based on ethical principles and presented with extensive information about the novel treatments. The patients have to be provided with the purpose of the new device, and its risks and benefits. All of the concerns have to be addressed and the patients need detailed information about how nanotechnology works and the involvement of humans in this process [19].

The use of nano-tattoos can be compared to some of the common treatments of smoking cessation and cardiac monitoring. Nicotine replacement therapy has a similar approach. Nicotine patches are applied to the skin to allow a steady rate of delivering nicotine through the skin. The main principle is that this treatment allows a simple approach to help patients quit smoking. The patients simply apply a patch to the skin and allow it to work throughout the day. By applying a nano-tattoo, the patient can monitor the blood sugar throughout the day instead of actively checking it multiple times with other devices [18].

Another similar approach is the Holter monitor. Patients with arrhythmias can have that device implanted for a few weeks. This device records the heart rhythm and allows providers to make more informed decisions about the patient's condition. Nano-tattoos have similar approaches but more advanced technology. The most important aspect of patient education is to assess the patient's education to see if he or she fully understood the presented information and is ready to make an informed decision [20].

Conclusions on Utilizing Nanotechnology in Healthcare

Nanotechnology is new and the information about the nano-devices can be scary and confusing. Providers have the responsibility to use the advances in technology to improve patient outcomes but ensure that the patients make their own informed decisions. Nanotechnology provides many novel ways of diagnosing and treating diseases. It generates an increased amount of data and requires a careful approach to data collection to ensure patient confidentiality. Researchers and healthcare workers have to follow ethical principles in medicine to respect patients' rights. Special attention has to be paid to assessing patient understanding of the provided information to ensure the patients are making informed decisions about their treatments.

Genomics

Genomics is defined as the study of the complete set of DNA in a person or other organism. Studying genetic makeup and genomes helps researchers understand how genes interact with each other and with the environment and how certain diseases form. Genetic testing is becoming increasingly popular since it can provide valuable information about inherited chromosomal disorders and identify risk for diseases such as heart disease, cancer, diabetes, and others. Advancements in genomic science made this industry more accessible for patients, who now have access to tests that help them learn about their personal risks. Research is being done about new ways how to use this information to diagnose, treat and prevent inherited conditions. This essay will discuss ethical issues in the genomic industry and how they are addressed, the role of genomics and personalized medicine in the shaping of healthcare, the complexity of technical issues related to managing and utilizing genomic data, as well as the issues related to genetic testing and management of personalized data [7].

Ethical Issues and How They Are Being Addressed

Ethical issues related to genetic testing include health insurance reimbursement and genetic discrimination. Advances in genomic science bring a lot of opportunities including diagnosing, preventing the diseases, finding the optimal regimen for treating them, and predicting the likelihood of the medication response as well as avoiding potentially ineffective and toxic drugs. These advancements led to a large number of new genetic and sequencing tests coming to the market. The large volume of these tests makes it difficult for the insurance companies to evaluate which tests should be covered and which should not, and under which circumstances they could be covered. Reimbursement of genetic testing continues to be a problem but the policy and scientific experts created a few reports which advise federal agencies on the reimbursement issues. These reports include «An Evidence Framework for Genetic Testing» and «Coverage and Reimbursement of Genetic Tests and Services, which contain detailed recommendations for the Department of Health and Human Services to improve appropriate access to genetic testing and services for the public utilizing insurance programs [21].

Another ethical issue related to genetic testing is genetic discrimination. The questions are raised about the potential denial of coverage from the insurance companies or increased premiums for the patients who test positive for certain diseases. Another issue is keeping the information safe and private since genetic information requires a large storage capacity. For example, one fully sequenced genome requires about one hundred gigabytes, and a fully analyzed genome may need up to one terabyte of storage space. Not all companies have such capabilities. Patient information safety becomes a problem because if the companies cannot keep these large volumes of data, they might not be able to protect it as well [21].

To solve the problem of genetic discrimination, the Genetic Information Nondiscrimination Act was issued in 2008. This act prohibits insurance companies to use genetic information or request genetic testing to be done in order to determine coverage, underwriting and set the amount of premiums. This act also extends into employment decisions and prevents employers from using genetic information to make decisions about hiring, promotions, salaries, job assignments, and firing [21].

Informed Consent

Informed consent is an important part of any type of research and genomics is not an exception. Informed consent refers to the process when patients are given information about their care, procedures, treatments, genetic testing, clinical trial, etc., which includes the possible risks and benefits so that the patients could make informed and voluntary decisions [22]. Genomic research requires special considerations because sequencing the human genome may have implications related to identity and privacy. These special considerations include the personal and unique character of the information of every individual genomic information, privacy concerns, relevance for the family members and reproductive decision-making, the uncertainty of the results and potential risks, long-term storage and use of data, etc. [21].

To protect participants and human rights in large-scale genomic research, the National Institutes of Health set forth expectations and rules for using and sharing genomic research data which are outlined in the NIH Genomic Data Sharing Policy. Researchers are required to share with participants how the information is collected, how it is stored and shared, what information participants would get from the study, the risks and benefits of generating large-scale genomic data, etc. [21].

The Role of Genomics and Personalized Medicine in the Landscape of Healthcare

Genomics and genetic testing are becoming an integral part of the development of personalized medicine in the landscape of modern healthcare. The patients now have access to genetic testing not only for inherited chromosomal disorders but also for their potential risks of developing common diseases. Having the knowledge of personal risks provides valuable insight and a stimulus to make appropriate changes in life. If a person knows that he or she is predisposed to diabetes, for example, they might be more prone to having regular screenings, start preventative interventions, lead a healthier lifestyle such as appropriate diet and exercise, not smoking or using drugs, etc. Having this knowledge also provides an opportunity to join support groups of people in similar situations. On the other hand, there might also be some negative implications about knowing that you are at risk for certain diseases such as increased levels of stress and even developing depression [23]. Studies show that chronic stress can endanger the health and promote the development of certain diseases such as cancer [24].

The Complexity of Technical Issues Related to Managing and Utilizing Genomic Data

A large amount of data generated by genomics create complex issues in relation to the management and utilization of that data. The cost of genomic services continues to become more affordable leading to the increasing demand for genetic information that drives the development of sequencing instruments requiring increasing storage databases for all produced data. Every year, over two thousand DNA sequencing instruments produce more than fifteen quadrillion nucleotides a year, equaling 15 petabytes of data. To be able to use and analyze this massive amount of data, the companies require specialized technology with multi-functionality. New and more efficient electronic health records and decision support tools are yet to be developed to allow providers to use the genomic data and quickly interpret it by linking genomic, clinical, and personal information in a meaningful and personalized way [7].

Genetic Testing and Management of Personalized Data

Since genetic testing is becoming more popular, accessible and affordable, the issues of appropriate management of personalized data are becoming more crucial. More and more people are being tested which generates massive amounts of genetic data. As discussed earlier, the information one individual receives might also be relevant to his or her blood relatives. This leads to the new type of ethical, social, legal issues that have to be addressed. Policies regarding the sharing of genomic information among related individuals have to be created to protect the rights of patients, consumers and providers [7].

Increasing number of companies providing genetic testing also create the risks for the consumers to receive information that is not accurate or misinterpreted. Genetic testing is now regulated under Clinical Laboratory Improvement Amendments program, which outlines federal standards applicable to all United States facilities that test human specimens for the purposes of health assessment, diagnosis, prevention, or treatment of diseases [25]. It is also very important for the genetic testing results to be interpreted by genetic specialists [23].

Conclusions on Using Genomics in Healthcare

Ethical considerations in genomics are becoming a serious topic for discussion since this industry is rapidly growing and developing. Genetic testing is becoming more popular since it can reveal an important information for families about their risks for common diseases, raising the issue of whether or not these tests should become a part of insurance reimbursement because not everyone can afford them. Large amounts of data generated by the genomic industry require the companies to continue looking for better technology for processing and storing that data. The concept of truly personalized healthcare will become a reality when genetic information becomes a routine part of care for every patient because genetic data will be available for better assessment, diagnosis and finding optimal treatment options.

Health Information Technology and Implications for Patient Safety

Health Information Technology advancements such as the implementation of Electronic Health Records (EHR) made a significant transition in improving quality care, boosting efficiency, and cutting health care costs. Communication technologies enhanced coordination of care delivered by interprofessional teams by decreasing the time gaps and eliminating or reducing the number of potential errors [26].

Even though the advancements in technology have the potential to drastically reduce medication errors, order duplications, etc., the errors continue happening. Studies show that hospitals with CPOE don't reduce all mistakes associated with drug delivery. Researchers reviewed a random sampling of all admissions in a twenty-week period at Veterans Admission hospital which uses CPOE and they found that medication errors contributed to more than 25 % of all inpatient adverse drug events [27].

These studies demonstrate that CPOE or other computerized system does not make hospitals error-free and clinicians have to be vigilant in checking for correct drug ordering and administration process. In fact, medical errors account for about 251,000 deaths annually which makes them the third leading cause of death. Studies show that medical errors are underreported and their rates in the United States are significantly higher than in developed countries like Canada, the United Kingdom, Germany, etc. [27]. These reports demonstrate the urgent need to implement healthcare changes directed at improving patient safety. There have been multiple efforts with specific action plans directed at optimizing patient safety in the healthcare system.

Multifaceted Efforts to Optimize Safety

There have been multiple efforts proposed and implemented in the healthcare system directed toward safety optimization. The Institute of Medicine's report from 1999 *To Err is Human* revealed that nearly 100,000 lives are lost every year due to preventable medical errors with subsequent research suggesting the number is twice as high [28]. Medical errors contribute to increased healthcare costs including the expense of additional care necessitated by the errors resulting in about twenty-nine billion dollars per year. These errors also contribute to the lower population health status, reduced school attendance by children, psychological discomfort, and lower trust in the healthcare system. The worst part is that these deaths could be prevented but they continue happening [29].

However, progress is being made, and based on the analysis by the Johns Hopkins Armstrong Institute for Patient Safety and Quality there are 45,000 fewer deaths in 2019 than in 2016 [30]. Many new programs and safety practices have been developed and implemented by healthcare organizations, in addition to national organizations, such as the National Patient Safety Foundation, Agency for Healthcare Research and Quality (AHRQ), the Institute for Healthcare Improvement, the Joint Commission, etc. [31].

The SAFER Guides

In response to the catastrophic numbers of medical errors in the healthcare system, the SAFER Guides have been created as one of the options to improve safety in organizations. SAFER Guides is an acronym that stands for The Safety Assurance Factors for Electronic Health Records Resilience Guides. These guides represent the tools with certain checklists and recommended evidence-based practice guidelines which are designed to help healthcare organizations and providers assess their use and safety of electronic healthcare records and implement appropriate improvements if necessary. In addition to the existing health information technology (IT) safety tools developed by the Office of the National Coordinator for Health IT and the Agency for Healthcare Research and Quality, the SAFER Guides provide extensive support and guidance for organizations regarding safe EHR use. Health IT is considered one of the highest priority areas for the Agency for Healthcare Research and Quality because it significantly impacts patient safety [32].

The Office of the National Coordinator for Health IT recommends all organizations to start with the foundational guides such as High Priority Practices and Organizational Responsibilities and then select additional guides relevant to the organizational needs which might include contingency planning, system configuration, system interfaces, patient identification, computer provider order entry with decision support, test results reporting, and clinician communication [7].

Recommended Action Steps and the Role of Informatics Nurse

The first step is defining the goal for using the guide. The goal of using the Clinical Communication guide is usually to increase awareness of practices within an organization that can improve the safety of EHR-based communication. It can also help identify potential risks and communication breakdowns, specifically targeting high-risk processes such as patient-related messaging between clinicians, consultations and referrals, and discharge-related communications. The informatics nurse will serve as a support person who will be educating staff about the guide, how to use it, and ensuring it is used appropriately. The second step is the assessment which is accomplished through data collection and conducting a thorough analysis. The informatics nurse will facilitate data collection and data analysis [33].

The third step is identifying potential risks. The role of the informatics nurse will include data analysis and presentation of the information in meaningful and clear ways. The fourth step includes developing and implementing the plan. Each domain provides a number of examples of potentially useful practices and scenarios that can be used and tailored toward the needs of each organization. Step five is evaluation of the success and plan adjustment for sustained success. Informatics nurses can be useful in providing data analysis and designing and adjusting processes for improved safety [33].

An informatics nurse is a graduate nurse with an emphasis in informatics. It is a specialty that integrates nursing science with information science to manage and communicate data, knowledge, and wisdom in nursing practice. Utilizing informatics in nursing is the fifth core competency of the Institute of Medicine which can lead to safer quality care. The informatics nurse is responsible for developing and supporting applications, tools, and processes that help health care workers to manage data in the direct care of patients [34]. A safe and reliable system has to be created by the informatics nurses to facilitate the work of the rest of the team.

Action Plan for TeamSTEPPS Implementation

TeamSTEPPS is an evidence-based teamwork system that provides ready-to-use materials, education tools, and simulations to improve patient safety within healthcare organizations [7]. The action plan for implementing TeamSTEPPS to ensure correct orders are placed will include ten steps: creating a change team, identifying the problem, defining the intervention, designing an intervention, developing a plan for testing the effectiveness of the intervention, developing an implementation plan, developing a plan for sustained continuous improvement, selecting a communication plan, writing a complete plan, and reviewing the plan with key personnel [35].

There are also many innovative information technologies for the diagnosis, treatment and rehabilitation of patients, which are constantly evolving in order to improve the quality of medical care, in particular:

Virtual reality (VR) therapy. With the help of IoT, it is possible to create virtual reality systems for rehabilitation sessions. For example, stroke patients can use VR to train movement and restore coordination. Sensors built into VR devices can track patient movements and send data to software to analyze and adapt training programs.

Neural Interfaces and Brain Computer Interfaces (BCI). Technologies that allow signals to be read from the brain and used to control devices or restore functions lost due to injury or disease.

Biomedical implants. The use of implants to replace lost organs or tissues, as well as to enhance body functions (e.g., electronic prostheses, pacemakers, etc.).

Internet of Things (IoT). It is used to monitor health, create interactive rehabilitation programs, automate medical processes, and support patient self-care in order to improve the effectiveness and outcomes of treatment.

Innovative IoT technologies are a new technology that provides improvements and better solutions in the field of medicine that allow for proper medical record keeping, medical sampling, device integration, and efficient identification of the causes of diseases.

Let’s take a look at some specific applications of the IoT for the treatment and rehabilitation of patients:

Monitoring of chronic diseases. The Internet of Things makes it possible to create monitoring systems for patients with chronic diseases such as diabetes, cardiovascular disease, or Parkinson's disease. For example, sensors can read blood sugar, blood pressure, or tremors and then transmit this data to a cloud server, where it can be analyzed and alerted to doctors if abnormalities are detected.

Medical implants and communication devices. IoT can be used to monitor patients with medical implants, such as pacemakers or implanted sensors. These devices can automatically transmit heart rate, blood pressure, or blood oxygen level data to medical systems for analysis and timely intervention.

Rehabilitation through games and interactive applications. Sensor devices, such as Microsoft Kinect or motion sensors, can be used to create playful applications for patient rehabilitation. These games can promote the recovery of body functions through active movement and provide patients with motivation to exercise.

Self-service support systems. IoT can be used to create self-care support systems for patients with limited mobility or disabilities. For example, smart home devices can automatically adapt the environment for patients with different needs, ensuring accessibility and ease of use.

Combining the capabilities of IoT with medical equipment can significantly improve the quality and efficiency of services and create better conditions for patients who require constant medical supervision and/or preventive intervention, such as the elderly or patients with chronic diseases. Therefore, a type of IoT, the Internet of Medical Things (IoMT – Internet of Medical Things) makes a significant contribution to creating more personalized and patient-centered healthcare. Doctors and patients will be able to get remote access to expensive medical equipment or electronic medical records in any place where a remote health monitoring system, automated dispensing of medicines to patients, etc., will be implemented. The Internet of Things (IoMT) is a concept that involves two-way communication between physical objects and computer systems in the medical field [36].

The medical field of IoT is developing at a rapid pace. The latest report by Grand View Research, Inc., a research and consulting company from India and the United States, registered in the state of California and headquartered in San Francisco, conducting research containing thousands of statistics and detailed analysis on 46 industries in 25 major countries around the world), showed that the global market size of the Internet of Things in healthcare will reach 534.3 billion US dollars by 2025, increasing by an average of 19.9 %. This sector is one of the key factors driving technological transformations in the medical field. The growing penetration of connected devices in various healthcare settings and the adoption of IoT systems and software solutions in healthcare operations are among the key factors driving digital transformation in this industry [37].

IoMT sensor technology, due to the widespread use of biosensors embedded in clothing or attached to the skin or implanted in the patient's body, closely monitors the dynamics of the disease, while providing complete freedom of movement [38]. This technology enables direct contact of portable smart devices with patients who monitor (diagnose) human health parameters and provides an excellent opportunity to reduce risk during complex cases, in particular when determining the patient's diagnosis. IoMT focuses on helping to accurately diagnose and treat various cases of the disease, facilitates the work of the surgeon, cardiologist, neurologist, minimizing risks and increasing the overall productivity of treatment. Using IoT technology, doctors can easily detect changes in critical patient parameters, such as cardiology. Therefore, this information service opens up new opportunities for health care, as it advances towards the best way to use the information system, which is the adaptation of the medical field to world-class results, as it allows the improvement of treatment systems in the hospital.

Architecture of the automated system for remote monitoring of patient parameters.

The medical ecosystem has evolved significantly due to the rapid advancements in science, technology, and medicine and the proliferation of smart medical devices. In addition, advances in communication technology have transformed various healthcare services into accessible virtual systems and remote care applications.

The Internet of Medical Things (IoMT) is a practical application of IoT devices combined with MedTech tools used in healthcare. With the ability to connect medical devices using networked technology, healthcare professionals can monitor key patient biometric data in real-time.

Researchers are working on the application of the Internet of Medical Things (IoMT) to provide better, cheaper, and more accessible medical care. A traditional medical ecosystem typically includes a patient, a doctor, a medication (pharmacist), and a treatment. In addition to this, the IoMT medical ecosystem includes cloud data, applications (online, mobile, real-time, and non-real-time), and wearable sensors. Fig. 1 compares a traditional medical ecosystem with a more advanced IoMT-based ecosystem [39].

The researchers come up with many interesting and feasible ideas for improving and transforming the traditional medical ecosystem into an IoMT ecosystem. In general, these improvements relate to –

applications, architecture, technology, communications, and security components. The structure of the medical ecosystem generally follows the Open Systems Interconnection (OSI) model, but with corresponding changes made to include communication and IoT technologies. IoMT technology refers to Hardware (Firmware), middleware, and cloud platform (Software) [40].

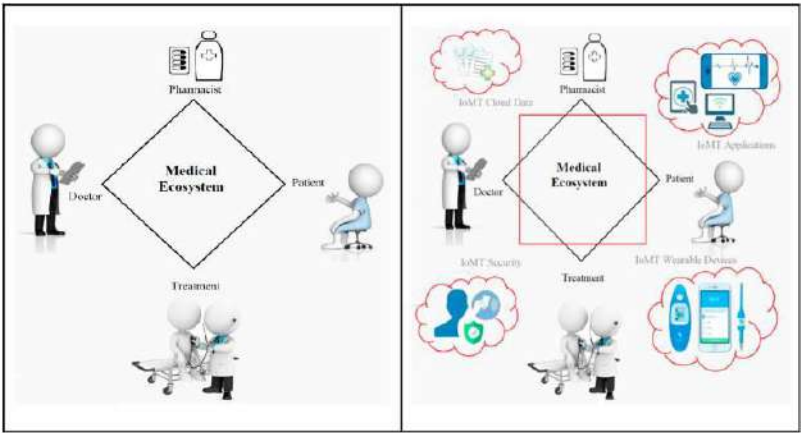

Figure 1. Traditional and IoMT medical ecosystem

Source: [39]

Communication in the medical ecosystem is a protocol used to interconnect IoT devices, or communication over short or long distances. Medical ecosystem security includes vulnerability to attacks, protection, and mitigation, Fig. 2 illustrates the core communications and technologies of the IoMT ecosystem.

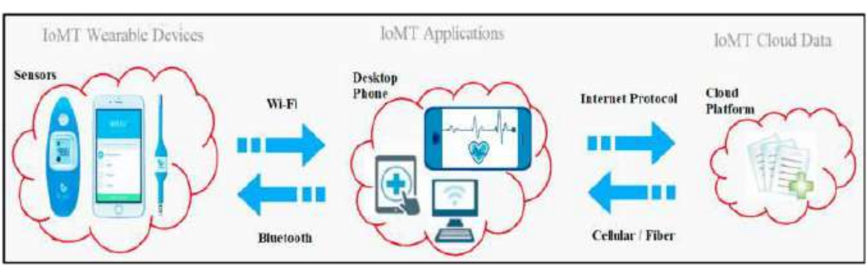

Figure 2. Core communications and technologies of the IoMT ecosystem

Source: [39]

Due to the numerous non-standardized IoT frameworks proposed by researchers and industry, the IEEE recently announced a new IoT architectural standard to promote heterogeneous interoperability, system interoperability, and support further industry scalability. Consider the IoT architecture standard P2413.1 RASC.

The RASC standard defines four layers of architecture:

- Device level
- communication network layer;
- IoT platform layer;
- application layer.

The standard incorporates an Intelligent Operations Center (IoC) relationship specific to big data, cloud computing, and edge computing technologies with unified security aspects. The specific architecture of IoMT is shown in Fig. 3.

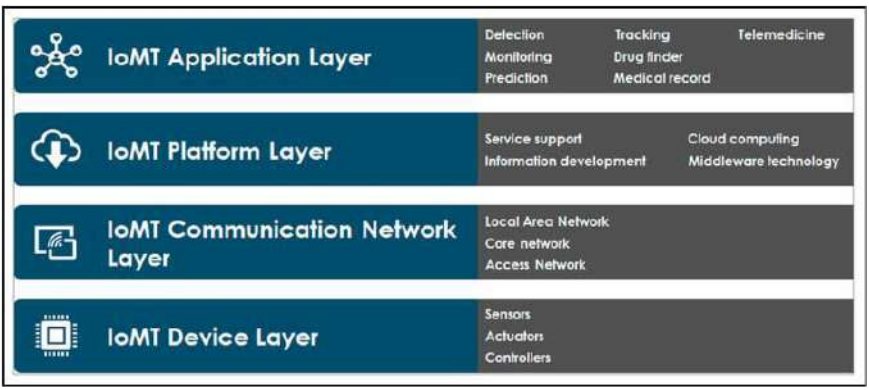

Figure 3. IoMT architecture

Source: [39]

The device layer consists of hardware such as sensors, controllers, and starters. RFID reader/tag, facial recognition camera, fitness smartwatches, health monitoring sensors, insulin pumps, and infrared temperature sensors are some of the machines currently in use. Sensors can be classified as wearable sensors, implantable sensor devices, and environmental sensors.

The next level is the communication network layer. Some of the latest communication technologies used are Wireless Sensor Networks (WSN), Bluetooth, ZigBee, WiFi, NB-IoT, LTE, 4G, and 5G. These are lightweight protocols that are suitable for low-power devices in wireless networks such as Body Area Network (BAN) and Personal Area Network (PAN). Another important element is the aggregator, such as WiFi routers, which act as gateways that enable multi-party communication. The new paradigm of IoT communication is the Information Oriented Network (ICN), the data-driven nature of ICN, enabling data-driven communication of IoT networks where content is a key element in the infrastructure. ICN offers scalability, efficient routing mobility, caching strategy, and IoMT security elements.

The IoT platform layer is another baseline layer that provides service support, information development, cloud computing, and middleware technology. A cloud platform such as Microsoft Azure, Oracle Cloud, Amazon Web Services, Google Cloud, IBM Cloud, and Alibaba Cloud provides services such as messaging, storage, data processing, and analytics for IoMT applications.

The highest level of IoT architecture is the application layer. This level includes any number of devices such as monitoring system, tracking/locator system, fitness/health system, medical electronic record, remote diagnostic system, telemedicine, etc.

Massachusetts/Israel-based EarlySense is a global leader in contactless continuous healthcare monitoring solutions. EarlySense has developed a dedicated platform for monitoring inpatient patients using sensors. They read the patient's readings, such as heart rate and respiratory rate, around the clock, allowing the medical staff to respond instantly to deterioration. In the future, it is planned to provide patients of the cardiology and intensive care department with such devices [41].

The main components of the system are:

- Non-contact sensor
- Information module
- Metrics monitor.

The non-contact continuous monitoring system tracks breathing rate, heart rate, and movement without touching the patient. A sensor placed under the patient's mattress transmits real-time patient data for early detection of clinical changes to a display outside the patient's room, limiting the need for staff to dress and enter isolation areas. The EarlySense system is clinically proven to help prevent adverse events, including code blue cases resulting from cardiac or respiratory arrest, patient falls, high blood pressure, intensive care, and hospital admissions.

According to the analysis of the subject area, the main goals of the development of this system were identified and include the following:

- Automation of control of the patient's medical indicators;
- Continuous monitoring of the patient's medical parameters;

• Formation of a database of norms of medical indicators, patients, doctors, devices, diagnoses;

• Formation of a knowledge base containing rules and algorithms (training) for determining the diagnosis;

• Automatic diagnosis based on the obtained indicators and recommendations of the knowledge base.

On the basis of the defined goals, the architecture of the automated system for remote monitoring of patients' medical indicators has been developed, which is shown in Fig. 4.

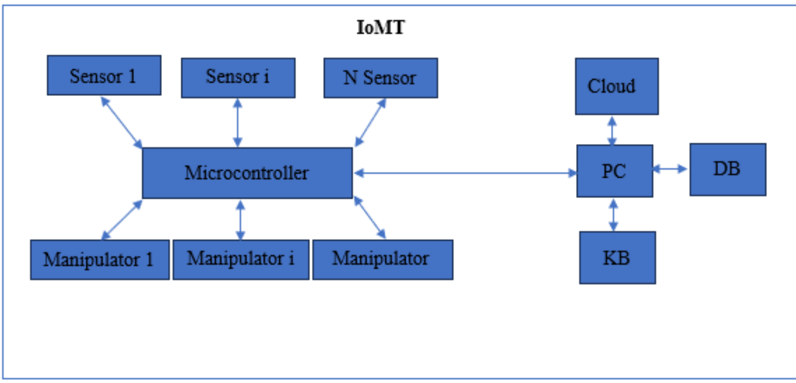

Figure 4. Automated system for remote monitoring of medical indicators

Source: developed by the author

In accordance with this architecture, the following elements are allocated:

• Sensors (biosensors) provide reading of the patient's medical indicators.

• Manipulators – ensures the performance of the result of checking compliance with critical indicators (infusion control).

• Microcontroller – provides data transfer from sensors to professional computers (PC), and transmission of commands from PCs to manipulators.

• PC – contains software that compares the values received from the microcontroller and compares them with the normative values recorded in the database, in case of discrepancy, makes a request to the KB to receive instructions and make an effective decision. Additionally, it records the received data to cloud storage.

• DB – contains reference books with normative indicators of medical indicators of patients depending on the diagnosis of the disease.

• KB is a set of instructions that store the basic commands for accumulating knowledge and making decisions depending on the diagnosis and their deviation.

All defined components of the architecture of the automated system for monitoring medical indicators form a single automated software and hardware complex that allows monitoring patients in the hospital, both an individual patient and the entire department. This system also provides constant monitoring, management of the treatment and rehabilitation process based on the provision of practical recommendations.

Conclusions

The author provides a thorough overview of the use of diagnostic tools using artificial intelligence, electronic medical records with the functionality of data mining, nanotechnology, and genomics in healthcare institutions in the United States of America. While these latest technological advancements offer numerous benefits that suggest promising future developments, AI does not replace human specialists and doctors, but only serves as an additional effective tool.

The healthcare system is evolving and changing with the rest of the world. Everything is moving to an online and paperless world. Many hospitals opt for flexible software that allows them to have a better communication system within the hospital as well as between different facilities. It's certainly convenient, but mistakes keep happening, prompting the creation of numerous systems and guides designed to help healthcare organizations improve their safety. Some of the tools available to healthcare organizations include the SAFER and TeamSTEPPS guides. Thanks to numerous efforts to improve security, the error rate is gradually decreasing. Healthcare organizations should be encouraged to use these evidence-based tools to evaluate their practices and optimize their safety.

The paper also analyzes innovative technologies for the treatment and rehabilitation of patients, in particular such breakthrough technologies as virtual reality (VR) therapy, neural interfaces and brain computer interfaces (BCI), biomedical implants and the Internet of Things. Particular attention is paid to the Internet of Things, which is designed for better management of chronic diseases, emergency medical care, better patient care, fitness, monitoring blood pressure, health screening systems, measurement and control systems, heart rate checking systems, and hearing aids. IoT-enabled devices can facilitate the digital storage of personal health information of patients with various medical conditions and connect to the accumulation of a database and knowledge base. This technology can help minimize manual record-keeping. With an evidence-based solution, it reduces errors and delivers timely results. With this technology, medical devices and networks are becoming smarter and more efficient during pandemics. In this way, these technologies considered provide immediate information and enhance communication to improve the patient's quality of life. A particularly important factor in the introduction of IoT technologies is the ability to implement the principle of personalization and predictiveness in medicine, as an individual approach to disease prevention, improvement of diagnostic and treatment methods, and, ultimately, an increase in healthy life expectancy.

An automated system for remote control of medical parameters is proposed, which provides constant monitoring, management of the process of treatment and rehabilitation based on the provision of practical recommendations.

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SECTION 2
CONCEPTUAL AND METHODOLOGICAL BASES OF DESIGN OF DIFFERENT CLASSES OF INFORMATION CONTROL SYSTEMS

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CONCEPTS OF INDUSTRY 4.0 AND INDUSTRY 5.0 BASED ON THE USE OF MODERN INFORMATION TECHNOLOGIES IN APPLIED INFORMATION SYSTEMS

1. Introduction

The concepts of Industry 4.0 and Industry 5.0 reflect the evolution of approaches to the use of modern information technologies in production and management. Industry 4.0 refers to the transition to digital transformation, where automation, the Internet of Things (IoT), artificial intelligence (AI) and data big data analysis play a key role in improving efficiency and optimizing production processes. In contrast to the Industry 4.0 concept, Industry 5.0 is defined by human-centeredness and emphasizes the importance of cooperation between humans and machines, where AI and robots complement human labor.

In applied information systems, these concepts are realized through the development of intelligent control systems that combine the power of data analytics, advanced artificial intelligence algorithms, and IoT capabilities to optimize production processes. However, the success of these concepts depends on the ability of companies to adapt to new technologies, train staff to use them properly, and ensure effective cooperation between people and information systems.

2. Evolution of the industrial revolutions concepts

The history of industrial revolutions has been going on for the past three centuries, but their intensity has been increasing dramatically over time and causing fundamental changes in the socio-economic space of human life [1–3], as shown in Figure 1.

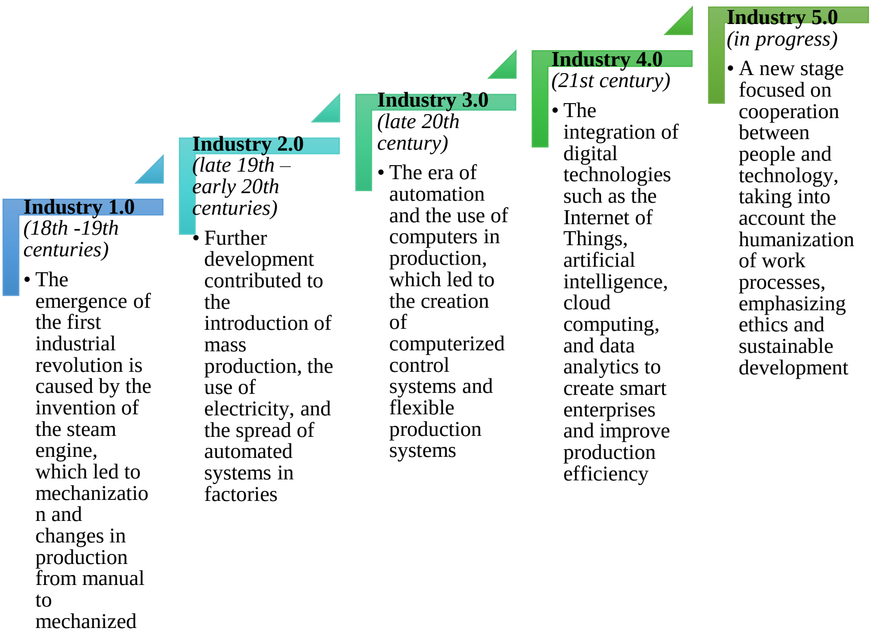

Figure 1. Evolution of industrial revolutions

Source: compiled by the authors based on [1–3].

Today, the fourth industrial system is dominated by the main technological achievements of which are additive manufacturing (AM), artificial intelligence (AI), augmented reality, cyber-physical systems, blockchain technologies, cybersecurity, smart manufacturing, smart products, the Internet of Things, cloud services, smart supply chains, and much more. It should be noted that although Industry 4.0 has enormous potential for industrial growth, it poses many challenges, including the potential to negatively affect the sustainability of existing information systems used in various sectors of the economy; requires increased consumption of energy and other resources, which causes climate problems, leads to deterioration of safety standards, etc. The interconnection of machines and resources generates a lot of data, and analyzing this data is one of the new challenges of Industry 4.0, especially in the field of quality management, where this generated data can be used in a variety of ways to track the quality of products resulting from production processes, to optimize the supply chain, etc.

Despite the fact that Industry 4.0 considers sustainable development as one of the most important factors, African countries have little chance of benefiting, as it is believed that the Industrial Revolution 4.0 is unlikely to benefit low- and middle-income countries [1]. There are some examples of Industry 4.0 being more energy efficient [6] but some researchers have found that this concept does not fully meet the goals of sustainable development [7]. But the main problem of Industry 4.0 is not providing the necessary basis to achieve the global goals of Europe and the whole world by 2030, as it creates a technological monopoly in the market and does not consider the needs of individual industries, countries, people, and for effective socio-economic development, it is necessary to take into account future shocks that humanity may face, such as the war in Ukraine, the war in Israel, the Covid-19 pandemic and others, and to increase the focus on the real needs of people in the context of following the principles of sustainable development [7]. Under such conditions, Industry 5.0 can significantly help overcome the challenges faced by Industry 4.0.

3. Industry 4.0 concept: technologies and applied information systems

In this part, we will focus on the concept of Industry 4.0 and its inherent technological features.

Industry 4.0 is primarily based on data-driven cyber-physical systems and their use for knowledge integration, so the digitalization of industries is commonly referred to as Industry 4.0 [8]. Industry 4.0 has led to the introduction of many new and advanced technologies, which can be divided into two main classes: basic technologies – technologies that emerged and are inherent in the fourth industrial revolution, and applied technologies – technologies that support functional tasks on the user side (Table 1).

Many different applied information systems have been created and are currently being actively used on the basis of Industry 4.0 technologies, as shown in Fig. 2–6.

Table 1

INDUSTRY 4.0 TECHNOLOGIES

Basic technologies	Applied technologies
1. Internet of Things (IoT). IoT is the interconnection of computing capabilities and network communication with sensors and objects. It uses various communication models, such as device-to-device and device-to-gateway. The maximum potential of IoT can only be utilized if security and privacy issues are addressed [9].	**1. Smart manufacturing.** The continuous development of computers and information processing technologies has led to the introduction of smart manufacturing. Automated systems provide information support for material processing. Smart manufacturing promotes the integration of production systems with communication technologies, sensors and modeling [15].
2. Artificial intelligence (AI). AI is the use of computers to simulate intelligent behavior with minimal need for human intervention. It is also often defined as a scientific technique for creating intelligent machines that can make decisions without human intervention [10].	
3. Computer Aided Design (CAD). CAD is a technology used to digitally design and manufacture the final product. CAD software is used to create the geometry of an object or product. Parts manufactured using CAD can be produced using subtractive or additive manufacturing [11].	**2. Smart products.** A smart product can be defined as a tangible service or software created and capable of self-organize into different intelligent environments throughout its life cycle. This is achieved by improving the interaction between the product and the user and between products through contextual awareness, self-description, proactivity, artificial intelligence-based planning, and machine learning concepts [16].
4. Additive manufacturing (AM). The need for mass customization of products in Industry 4.0 has led to the introduction of additive manufacturing. AB can produce more complex products with advanced features. It can also help in the production of product prototypes [12].	
5. Augmented Reality. It is a technology that focuses on enhancing the real-world experience of using a display by making the display environment more interactive and reality-based. It also focuses on improving sound quality and helps to combine virtual and real objects [3].	
6. Cloud services are a new technology that can eliminate the need for industry to maintain computer hardware. Thanks to virtualization and time-sharing between resources, clouds meet the needs of a large number of users with diverse needs using a single set of physical resources. Thus, clouds have the potential to provide their owners with economies of scale and become an alternative to in-house clusters and parallel production environments for both industry and academia [13].	**3. Smart supply chain. The** overall efficiency of an organization can be improved by better supply chain management. Integrating IoT with the supply chain can help significantly as it allows for real-time tracking of the supply chain. Location tracking can be greatly improved by integrating the supply chain with the Internet of Things, known as the smart supply chain [17].

Basic technologies	Applied technologies
7. Cyber-physical systems (CPS) are a new generation of systems integrated with computational and physical capabilities that can interact with humans in various new ways. Thanks to computing capabilities, the ability to interact with the physical world extends the capabilities of the physical world through the use of computing and communication. Communication and control are crucial for future technological progress [14].	
8. Global positioning systems (GPS). They help GPS receivers to make accurate location calculations and display them. For this purpose, satellites are used to transmit signals [5]. This has significantly improved the ability to determine time and perform complex calculations related to navigation.	**4. Smart buildings.** This technology uses a variety of sensors, communication devices, and other smart devices to automate and control various aspects of the building's interior environment to improve comfort, safety, energy efficiency, and convenience for people, allowing them to manage various aspects of their home or building from anywhere using modern technology [18].
9. Nanotechnology. The control over individual atoms or molecules involved in the formation of a macroscale object has improved significantly thanks to nanotechnology, often known as molecular nanotechnology [6]. They have helped improve medical equipment, such as drug delivery systems. They have also helped improve shelf life as well as manufacturing processes.	
10. Sensors and accelerators. These are devices capable of responding to external stimuli in the form of light, sound, heat, magnetism, and many others and, in turn, producing a response [12]. Sensors perceive physical gestures from the environment and convert them into electrical signals. In contrast, accelerators receive electrical signals and facilitate the transformation of this signal into a specific physical gesture.	**5. Smart work.** Smart work is the flexibility of the work environment and adaptation to various changes that may occur in the work environment. Flexibility of work is the central point of smart work [19].

Compiled by the authors based on [3, 5, 6, 9–19].

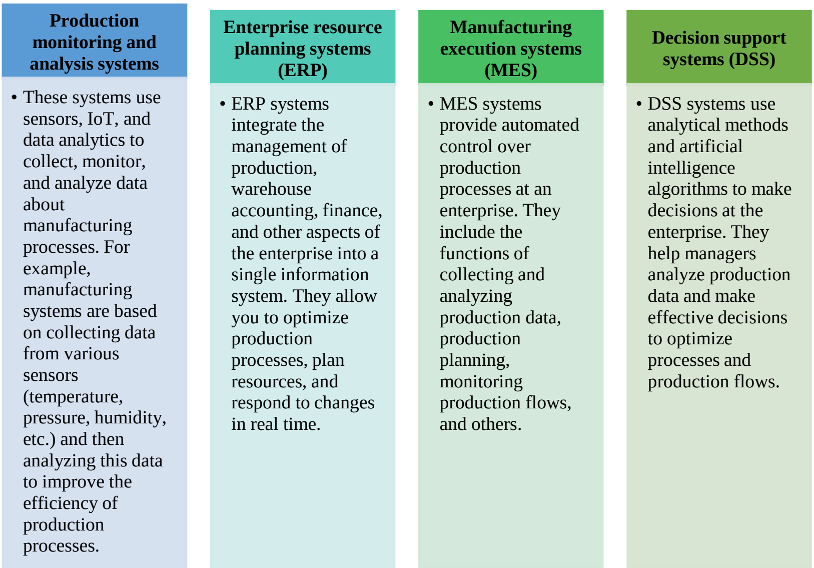

Figure 2. Applied information systems related to smart manufacturing technology

Source: systematized and compiled by the authors based on [20, 21].

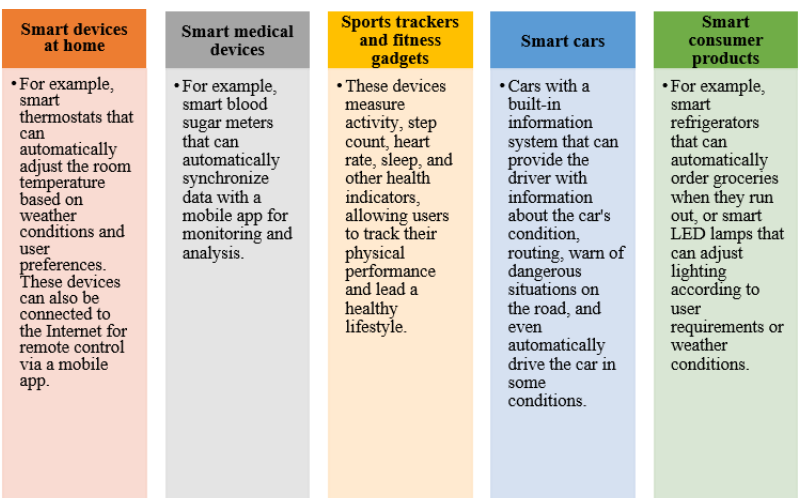

Figure 3. Applied information systems related to smart product technology

Source: systematized and compiled by the authors based on [22–24].

RFID tracking systems	Demand forecasting systems	Inventory management systems	Systems for monitoring and analyzing supplier data	Transportation and logistics management systems
• These systems use RFID tags to track the movement of goods from suppliers to end users. They allow you to accurately track the location of goods at each stage of the supply chain and ensure on-time delivery.	• These systems use data on sales, weather, consumption trends, and other factors to predict the demand for goods. They help businesses optimize inventory and plan production based on expected demand.	• These systems are used to optimize the inventory of goods in warehouses and stores. They automate the processes of ordering, receiving goods, inventory, and stock allocation, allowing businesses to manage inventory efficiently and reduce costs.	• These systems allow you to track and analyze supplier data, including their reliability, product quality, delivery times, and other parameters. They help businesses select the best suppliers and optimize their supply chain.	• These systems help plan and track transportation routes, track cargo, and monitor its delivery. They ensure efficient management of transportation resources and reduce logistics costs.

Figure 4. Applied information systems related to smart supply chain technology

Source: systematized and compiled by the authors based on [25–26].

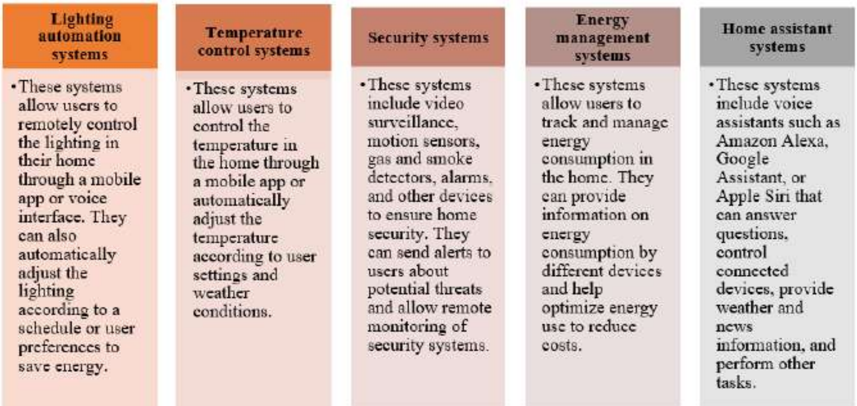

Figure 5. Applied information systems related
to smart building technology

Source: systematized and compiled by the authors based on [17, 27].

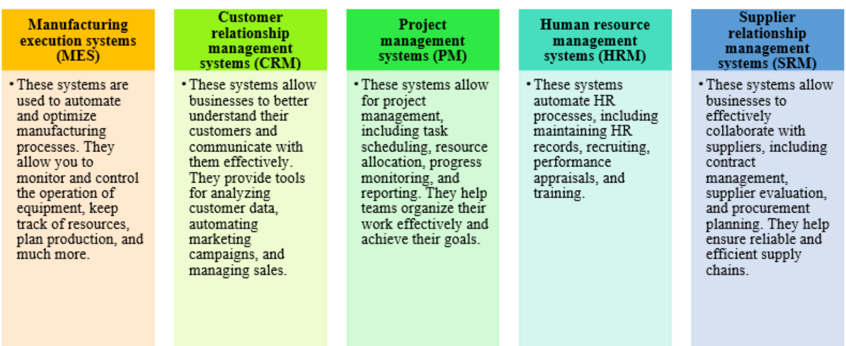

Figure 6. Applied information systems related
to smart work technology

Source: systematized and compiled by the authors based on [28].

Along with its high potential for development and positive impact on the organization of global socio-economic processes, Industry 4.0 faces serious challenges, including the problem of technical integration, data and information security, human resources, supply chain management, and threats to product safety and quality (Fig. 7).

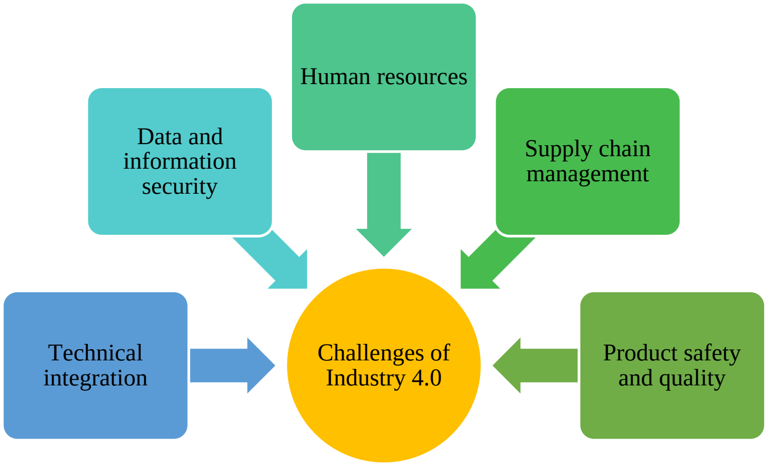

Figure 7. Challenges of Industry 4.0

Source: developed by the authors

Thus, one of the important challenges faced by Industry 4.0 is the technical integration. The use of technologies that do not have a potential to cope with digitalization can lead to the manufacturing of low-quality products. Moreover, the introduction of new IT solutions requires additional costs. In addition, standard protocols need to be developed to ensure efficient communication between machines [29].

Data and information security is another major challenge that organizations are facing. IoT can make industries vulnerable to industrial espionage and unauthorized access [29]. In 2016, about 75 % of companies involved in the oil, gas, and energy sectors faced at least one cyberattack, and the continuous monitoring of patients in the healthcare sector also increases the risk of data breaches [30]. The cargo transportation and storage sector also faces threats to data privacy. As shown by B.C. Ervural, B. Ervural (2018), data privacy is one of the most important issues in the freight transportation industry [31]. Consequently, it can be argued that Internet-connected systems, especially IoT-based systems, are more susceptible to cyberattacks [31].

Another challenge faced by Industry 4.0 is the problem of human resources. Employees need to be properly trained to work in rapidly changing environment [29]. It requires good management practices for workers to have the appropriate competencies and professional skills to cope with smart manufacturing. Effective policies can enhance dynamic capabilities, leading to more innovation [32].

Industry 4.0 has also led to specific challenges in supply chains. Supply chains are becoming increasingly digitalized and automated. The accuracy of market forecasting has increased significantly as well as the ability to track products [33]. This has led to shorter planning cycles. However, the results of the study by A.I. Aljumah, H. Shahroor, M.T. Nuseir and G. A. El Refae (2022) show that managing data privacy and integration remains the biggest challenge in supply chain management [26].

The increasing complexity of systems and the use of new technologies sometimes demand on using more capacity and poses a threat to **product safety and quality,** which is another challenge faced by organizations [29].

4. Transition from Industry 4.0 to Industry 5.0

The recent changes known as the fifth industrial revolution are intended to address the existing challenges and problems posed by the Industry 4.0 concept and improve its useful technologies and approaches. Some Industry 4.0 technologies remain unchanged, some are being improved, and fundamentally new ones, known as Industry 5.0 technologies, are emerging (Fig. 8).

Thus, the Industry 4.0 supply chain considers strategies as disruptive technologies and various implications for supply chain efficiency and is generally technology-oriented while the Industry 5.0 supply chain considers the balance between people and technology. The Industry 4.0 supply chain is based on mass customization and improvement of the supply chain efficiency through greater transparency, flexibility, reduced waste, and responsiveness. Industry 5.0 aims to maintain these benefits while adding more value through hyper-customization. The supply chain in Industry 4.0 mostly uses the Internet of Things, artificial intelligence, and blockchain technologies while Industry 5.0 uses these technologies with more advanced technological capabilities, especially in the field of AI and the use of cobots [1]. Industry 5.0 also focuses on sustainability in supply chain management [34].

IoT in Industry 4.0 has caused many problems, such as data piracy, hacking, and information leakage. These problems are conceptually solved in Industry 5.0. For example, blockchain technologies are used for the decentralized industrial Internet of Things (IIoT), which integrates data from various resources and services used in smart manufacturing. These individual resources are then used to support the targeted value chain. Thus, it helps to somewhat reduce the intensity of problems associated with network failures and error resolution. Proper use of blockchain in smart contracts can help eliminate the need for third-party registrations or documentation [35]. Smart contracts implemented with blockchain technology can increase the autonomy of Industry 5.0 systems and make them more resilient, as these contracts can reduce dependence on third parties and the requirement for different documentation. Resilient manufacturing strategies can help improve data security, as IIoT contains a lot of critical and sensitive data that needs to be protected [36].

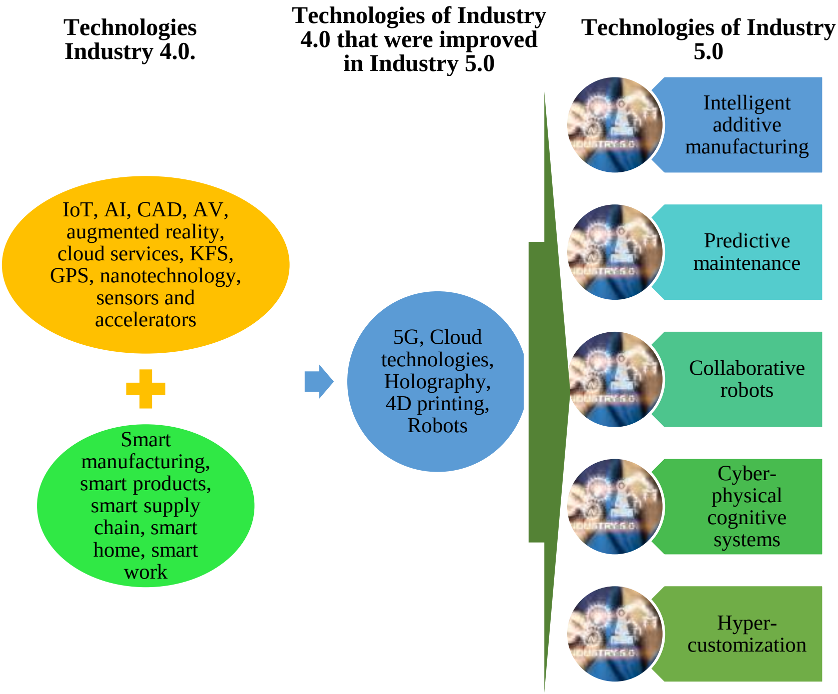

Figure 8. Transition from Industry 4.0 to Industry 5.0 technologies

Source: generalized and compiled by the authors based on [33–38].

One of the important challenges of Industry 4.0 is also the issue of technical integration, as technologies will have to cope with the increasing level of digitalization. Nevertheless, Industry 5.0 is human-centered and combines human creativity with machine precision to improve productivity and efficiency. It can also help improve product quality by using robots to perform repetitive tasks [37].

An equally significant challenge of the fourth industrial revolution is the issue of human resources. Industry 4.0 has led to the automation of existing production technologies. Thus, employees need to be trained accordingly. At the same time, Industry 5.0 focuses on human-centeredness and is based on proper communication between humans and robots to achieve the best results in accordance with the given tasks. In this way, they help to increase employee productivity. In addition, workers can be involved in higher value-added tasks without having to perform monotonous work or be involved in dangerous jobs. However, preventive maintenance is a necessary to protect these machines from potential malfunctions [38].

5. Development of Society 5.0

The development of industry and technology driven by the fourth and fifth industrial revolutions is actively influencing the social aspects of human development, which are centered on the concept of Society 5.0.

Society 5.0 is a concept that describes the future stage of development of society that actively uses technology to ensure sustainable development and solve social problems; it is aimed at balanced development of people and technology, creation of a favorable environment for living and working, and improvement of the quality of life. The main principles of the Society 5.0 concept are shown in Fig. 9.

Along with the positive changes that the concept of Society 5.0 brings to our lives, there are also challenges that we must properly address, including the following:

– ethical issues, as the development of new technologies such as artificial intelligence, genetic editing, and automation, raise~~s~~ complex ethical questions for society about their use [39];

– inequality due to the uneven distribution of benefits from technological development, which is extremely important to eliminate in order not to deepen the level of inequality in society;

– data privacy and security issues due to the emergence of new threats with the growing level of digitalization, which requires the development and application of effective protection methods;

– environmental challenges caused by the destruction of natural resources and environmental pollution to achieve the goals of technological development [40];

– inaccessibility of digital technologies for less affluent and remote groups of people.

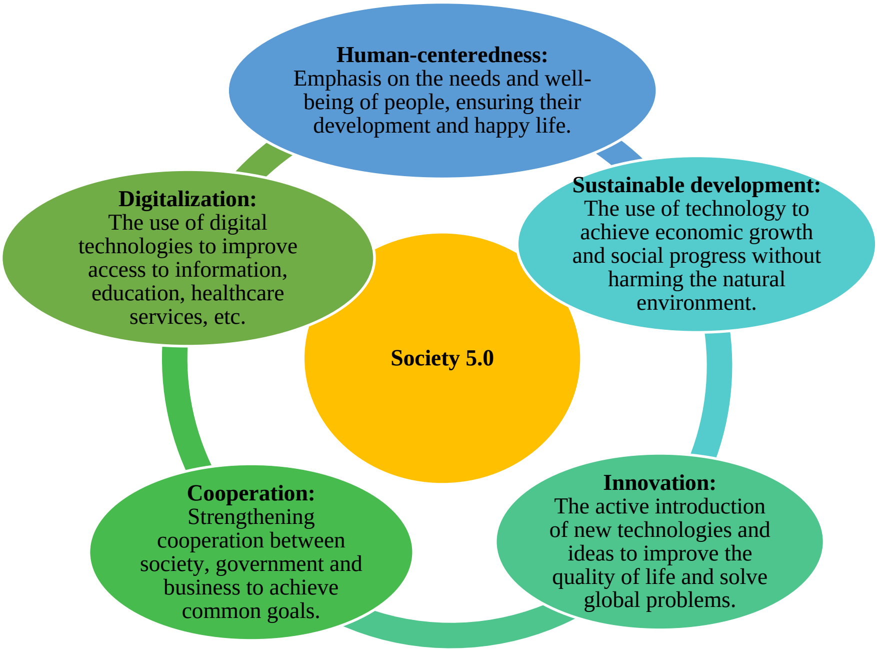

Figure 9. Basic principles of the Society 5.0 concept

Source: compiled by the authors based on [39, 40].

6. Industry 5.0 concept: advanced information technologies and systems

Industry 5.0 is an attempt to revive the presence of human labor in factories, where humans and machines will work together to increase process efficiency by fully utilizing human intelligence and creativity through their integration with modern intelligent systems [40]. One of the main goals of Industry 5.0 is waste management through recycling. Industry 5.0 includes the interoperability of networked sensor data, an improved version of Industry 4.0 with new additional features. Some of these are intelligent additive manufacturing (AM), predictive maintenance, hyper-customization in industry, cyber-physical cognitive systems, and the introduction of collaborative robots [41]. Let us consider these technologies in more detail.

Smart additive manufacturing (AM). Thanks to the potential of artificial intelligence, its use has spread to additive manufacturing. The implementation of AM is a complex process that includes design, parameter selection, planning and control. Information and communication technologies have greatly contributed to the development of additive manufacturing. As noted by Y. Wang, P. Zheng, T. Peng, H. Yang, J. Zou (2020), smart AM can be considered at three levels: market, system, and technological [42].

At the market level, AM can be combined with cloud technologies, and several companies have started selling 3D printing services online. Customers can access resources using AI technologies directly via the Internet. However, this requires the customer to have enough knowledge to make the right decisions and, accordingly, print the right parts needed [43].

At the system level, cyber-physical systems (CPSs) are presented, which have enormous potential. CPSs have been developed for various 3D printers. Data can be processed and optimized in real time to improve the printing process. 3D printers can use previous data to adjust to the task and automatically generate different solutions [44].

At the technological level, the key parameters are the development of information and communication technologies, including cloud computing, 5G, the Internet of Things, and edge computing, which facilitate the collection of large amounts of data and its processing. Humans cannot process such a huge amount of data, so it is necessary to study and research learning agents. These self-learning agents include data collection and efficient computing [42].

Predictable maintenance. Maintenance accounts for 15 to 60 % of the costs associated with operating a production facility [45]. Data collected from various sensors can be used to predict the life of an asset. Predictive maintenance can create a schedule of actions according to the performance of the equipment. Thus, it can help reduce maintenance costs and improve productivity and quality [36]. Industry 5.0 also takes into account human factors. People demand that decisions made in the framework of predictive maintenance are based on forecasting. Predictive maintenance focuses on operational decision-making and should also focus on implementation issues through the Work System model. Predictive maintenance has five stages: signal processing, diagnostics, prognosis, maintenance, decision-making, and actions [38].

Collaborative robots, or cobots, can work with humans and help perform repetitive or dangerous work while humans can do more creative and challenging work. Instead of replacing humans, cobots take over monotonous tasks and help manufacturers increase production. In this way, cobots help to increase productivity and worker safety. In 2014, out of 422,000 robots installed in industry, about

14,000 were cobots. They can be used to automate parts of a production line with minimal changes [46].

The introduction of robots can also face specific challenges, while the acceptance of cobots by workers can only be achieved if they are introduced at the initial stage of the production system [47]. Another challenge faced by cobots is their design. Different aspects that need to be considered when designing cobots are actions, type of robot, interaction technologies, and sensors. The third challenge faced by cobots is the development of an appropriate software architecture. The fourth challenge is to create a user-friendly interface between humans and cobots. In addition, cobots need to be able to detect collisions and be easy enough to control according to the user's needs. There are many infrastructure challenges, as described in detail by V.G. Ivancevic, D.J. Reid, M.J. Pilling (2018), and cobots need to know their workspace well [48].

Cyber-physical cognitive systems. Cyber-physical cognitive systems are a subset of trusted autonomy. Furthermore, they fall into three broad categories: physical autonomy, cybernetic autonomy, and cognitive autonomy. It offers many benefits to humans, such as better decision-making, product classification, and various defense applications [49].

Autonomous systems that are trusted can have a significant positive impact on society, including providing assistance to the elderly and helping robots increase the level of trust in them by people. Trust between humans and machines can help increase productivity in various challenging situations [50]. Cognitive-cybernetic symbiosis can help improve the manufacturability of production. They achieve this either by enabling human abilities and skills to interact with machines in the cyber-physical world through an intelligent human-machine interface, meeting the physical and cognitive needs of the operator, or by enhancing the physical senses of the human and their cognitive abilities [51].

Hyper-customization. Industry 4.0 has proven to be able to meet the ever-growing demand for customization. Hypercustomization is a concept that uses real-time data to prepare more specific products according to user needs using artificial intelligence and big data. This customization of robot-human integration makes it easier to produce products in large quantities. Hyper-customization and personalization require a shift to flexible manufacturing. Yoram Koren and his team suggest that we are witnessing the emergence of a new manufacturing paradigm, which they call «mass individualization» [41]. This is a concept in which large numbers of individualized products can be manufactured, and each of these products will meet the needs of individuals. This involves developing an open platform for products with defined interfaces for each module [52]. Individualization of production improves the flexibility of both hardware and software components by decoupling physical systems from logical ones [41, 53].

The growing demand for individualization is driving the need for flexible production systems. Introducing modularization into the production line can help meet these requirements. To improve modularity, an open architecture model is used, for example, a relatively new class of machine tools based on fixed standard platforms and customized modules that also follow open architecture models. Also, to achieve the best results, as shown by M. Khan, A. Haleem, M. Javaid (2023), it is necessary to transform the Industry 4.0 manufacturing paradigm into a more decentralized and socialized version of Industry 5.0 to improve the idea of crowdsourcing [1].

Conclusions

The study analyzes the features of the concepts of Industry 4.0 and Industry 5.0, identifies the challenges facing the fourth industrial revolution, and outlines approaches to addressing them within the next industrial order. It is shown how Industry 5.0 uses new technological advances, such as predictive maintenance, hyper-customization in industry, cyber-physical cognitive systems, and collaborative robots to overcome the challenges of Industry 4.0. Furthermore, Industry 5.0 provides enormous opportunities for research, especially in the areas of security and data integration, which is considered the most significant challenge in IoT.

The main results of this paper are as follows: having considered the evolutionary paths of different industrial revolutions, we can observe the movement of humanity towards total digitalization and human-centeredness, which is confirmed by the modern modes of Industry 4.0 and Industry 5.0. While the Industry 4.0 concept is at the stage of implementing and overcoming the existing problems of this way of life, the Industry 5.0 concept is currently a more theoretical development that only determines the direction of movement in the development of industry, economy and humanity as a whole.

This paper demonstrates how these issues are being addressed in the concept of Industry 5.0, which has introduced more advanced technologies such as predictive maintenance, hyper-customization in industry, cyber-physical cognitive systems, and collaborative robots.

The study categorizes Industry 4.0 technologies and characterizes the challenges associated with them; demonstrates that Industry 4.0 is technology-oriented, while Industry 5.0 implements these technologies through human-centeredness. For example, in the supply chain, where Industry 5.0 retains the benefits of Industry 4.0 and at the same time adds the benefits of robots and cobots, while people remain an integral part of the supply chain.

Another important aspect of this paper is the consideration of the concept of Society 5.0, which is driven by the development of industry and technology based on the fourth and fifth industrial modes and allows combining human creativity and intelligence with the precision and accuracy of machines and technologies.

The study also systematizes and summarizes the applied information systems based on technologies that characterize the achievements of Industry 4.0, as well as shows their limitations and approaches to address them in the context of Industry 5.0 development. Industry 5.0 actually puts the Industry 4.0 approach into a broader context, providing a restorative purpose and focus for the technological transformation of industrial production for the prosperity of people and humanity as a whole, rather than just the growth of economic indicators such as GNP or a company's financial capitalization.

The findings are intended to help researchers and practitioners in various sectors of the economy learn about the various challenges faced by Industry 4.0 and how these challenges can be overcome with the help of Industry 5.0.

Prospects for further research may be focused on work aimed at addressing the existing challenges of Industry 4.0 related to human-centeredness, data security, improvement of technologies for human-robot interaction, and 4D printing technologies. Thus, ensuring the prominent role of human-centeredness will help to increase human productivity and provide meaningful work for employees. If data security issues are overcome, organizations will be able to implement Industry 5.0 principles and technologies more quickly and efficiently, and this will also provide increasing trust in digitalization, which will help employees do their jobs with cobots. As human-machine interaction increases, future work could also focus on developing intelligent control by improving existing pattern recognition algorithms. 4D printing technologies can be improved to provide better print quality, given their huge potential in the prosthetics industry and other industries.

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CONCEPT FOR THE DEVELOPMENT OF GOVERNMENTAL INFORMATION SYSTEMS

In recent years, Ukraine, in line with global trends, has witnessed rapid development of governmental information systems. This growth is a fundamental part of a broader digital transformation, which not only modernizes public services but also introduces advanced approaches in e-governance, the advancement of digital education, and enhances cybersecurity literacy among the population. These initiatives aim to improve the accessibility and quality of public services, ensuring transparency and openness in governmental activities. A significant facet of this transformation is Ukraine's integration into the global digital landscape, achieved through active participation in international cyber programs and cooperation with the European Union and other leading international organizations focused on digitalization and cybersecurity. This engagement not only promotes knowledge exchange and better international understanding but also opens new avenues for technological innovation development. In this context, establishing a strategic vision for digitalization and cybersecurity in government administration becomes a priority, necessitated by the need to adapt to a rapidly evolving technological environment and to effectively address the contemporary challenges posed by the digital age in the 21st century.

We are exploring two key areas in the development of governmental information systems. Firstly, internal digital transformation, which entails the modernization of infrastructure, improving the efficiency of data processing, and the adoption of advanced technologies to tackle administrative challenges. Secondly, the enhancement of digital governance, which focuses on expanding online services for citizens, improving public information access, and establishing transparent interaction mechanisms between the state and society.

To systematize approaches to organizing and analyzing issues associated with the use of these information systems in governmental administration, it is prudent to consider them at both the macro and micro levels.

At the **macro level**, governmental information systems (IS) are designed to create both long-term and current plans for the country, determine outcomes, regulate activities across different economic sectors, and develop and monitor the execution of the state budget [1]. These systems comprise numerous functional subsystems that can be categorized both vertically and horizontally within the framework of state administration. Vertically, subsystems are organized according to the administrative-territorial hierarchy, including at the national, regional, district, or community levels – for instance, the information systems of the Ministry of Finance, regional financial management, or district finance departments. In cases where an institution is not structured by territorial principles, such as the State Customs Service, functional subsystems are defined according to its organizational structure. Horizontally, subsystems are identified based on the list of functions or functional departments that are typical of the institution. For example, within the information system of the Ministry of Finance of Ukraine, distinct subsystems are identified for developing the state budget draft, detailing it, and accounting and analyzing budget execution, along with a subsystem for reporting. Within these subsystems, automated functions are specified for revenue and expenditure categories, as outlined in the Budget Code. It’s important to note that the list of functional subsystems and departments is consistent across all levels of the Ministry of Finance. Further decomposition of functional tasks may be performed by identifying separate technological processes needed to execute classic administrative functions such as forecasting, planning, accounting, analysis, and regulation. Each function is executed following specific algorithms at the designated workstations of specialists.

The **micro-level** of state governance includes state-owned production enterprises and state institutions under regional and district subordination. The digital transformation of these state-owned enterprises involves several aspects such as aligning with national or regional digitalization strategies, support through state investments and regulation, adherence to state safety and privacy standards, higher social responsibility and transparency, and cooperation with other state enterprises and institutions to coordinate efforts and organize collaboration. Additionally, the heterogeneity in the structures of regional and local government bodies poses a significant challenge for their integration. Other challenges include differences in the level of technical equipment, access to qualified IT specialists, and internet connectivity across various regions and districts, limitations in budgets and resources, and the need to modernize obsolete infrastructure to deploy modern information systems and integrate them with existing, often outdated systems. From the perspective of delineating interconnected functions, defining shared information resources, organizing informational links, and optimizing decision-making processes, information systems of state governance are considered within three spheres: financial-economic, social, and administrative-legal. The information systems functioning within the financial-economic sphere include systems such as the Information-Analytical System of the Ministry of Economy, the Automated Information-Analytical System of the Ministry of Finance, the Automated System of the State Treasury Service, the Information-Analytical System of the State Tax Service, the Unified Information-Analytical System of the State Customs Service, the Information System of the National Bank of Ukraine, the Information-Electronic System of the Central Depository of the National Securities and Stock Market Commission, the Information-Computational System of the State Statistics Service, and the Information-Analytical System of the Accounting Chamber. These information systems can be unified on a sectoral basis to create a unified information space for functions such as budget planning and forecasting, budget control and audit, public debt management, effective resource allocation, reporting, ensuring transparency of processes, analysis, and strategic management within the Public Financial Management System. This system maintains a strictly regulated exchange of information in accordance with regulatory documents [2].

A key strategic direction for the modernization of the Public Financial Management System's information systems is the transition from a distributed to a centralized model. This approach includes creating a unified information space for state-level corporate use and ensuring reliable centralized storage of crucial financial services information in Kyiv and at regional financial administrations. Information from district databases is currently being consolidated at regional levels, establishing data centers that support state financial management and enhance cloud-based integration. This involves creating a comprehensive pool of configurable computing resources (networks, servers, storage systems, applications, and services) that can be rapidly deployed with minimal effort and without the need for direct interaction with the service provider. By migrating information interactions to the cloud, the model not only minimizes material costs but also expands user accessibility. This transition boosts operational efficiency, reduces corruption risks, and utilizes Internet technologies to ensure public transparency in the management of state and local budgets. The benefits of this model extend beyond financial management to other areas of state governance, particularly in the **social sector**, where digital transformation includes developing and supporting information systems for the Ministry of Labor and Social Policy, the Ministry of Education and Science, the Pension Fund of Ukraine, and healthcare analytics, thereby promoting a comprehensive and transparent governance environment.

Within the third sector of state governance, specifically in the sphere of **administrative-legal** bodies' operations, several information systems have been established: the computer system for information-analytical support of legislative and legal enforcement activities, the corporate information system of the Ukrainian Prosecutor's Office, information support systems for the Ministry of Internal Affairs of Ukraine, the information system for justice bodies, and the information system for courts. The operation of these entities relies on a unified information space for legislative and legal protection activities, characterized by strictly regulated processes for information exchange.

The advancement of information and communication technologies and their broad implementation have catalyzed the emergence of digital governance, identified by experts [3] as evolving through three key stages. The first stage involved the development of e-government applications aimed at management and service delivery (e-services) to reduce transaction costs, transform public service methods, and enhance public service efficiency. This fostered Government-to-Citizen (G2C), Government-to-Business (G2B), and Government-to-Government (G2G) models. G2C systems have facilitated easier and cheaper access for citizens to essential information and services, such as tax payments and other bureaucratic processes. In Ukraine, all state authorities, ministries, agencies, and other entities maintain online presence. Through their websites, citizens can access official information, such as on the Verkhovna Rada of Ukraine's site and the official portal of the Cabinet of Ministers of Ukraine, and interact with government bodies, notably through the state electronic services portal «Diia» and the electronic taxpayer office. The State Statistics Service of Ukraine provides a significant volume of public statistical information. In 2011, Ukraine adopted the «Law on Access to Public Information», and in 2016, the term «open data» was introduced, significantly increasing the number and use of related services [4]. In October 2016, Ukraine officially joined the International Open Data Charter, committing to the international community to implement a national open data policy in accordance with the principles of the charter. Open data also provides a powerful anti-corruption effect, promotes government transparency, and positively impacts economic development. The citizens show significant interest in public information, particularly that released by the Ministry of Social Policy, the State Tax Service, and the Ministry of Finance. Although the state policy in this area is quite effective, only a portion of the tens of thousands of open data providers fulfil their publication duties. The incompleteness of data, inconsistency of formats, and non-compliance with update procedures complicate their aggregation and use. Consequently, the procedures for data publication, along with the monitoring and control systems, require further refinement.

An example of a Ukrainian B2G e-commerce platform is «Prozorro», an online system where public and municipal buyers announce tenders for goods, works, and services, and business representatives compete to supply these. Since April 2016, «Prozorro» has become mandatory for all public entities, connecting over 35,000 government and municipal bodies and enterprises (buyers) with approximately 250,000 commercial suppliers. The adoption of «Prozorro» has eliminated many corrupt procurement schemes and resulted in significant public fund savings. However, the lack of detailed regulations for certain tender procedures and the exclusion of specific items or types of subcontracted works from bids limit its effectiveness. Overall, the main challenges in the initial stage are cybersecurity vulnerabilities and the legislative inadequacy to fully manage the risks associated with using ICT.

The second stage of digital governance development is characterized by the adoption of open government models, enhancing transparency and promoting collaboration with various stakeholders. At this stage, Web 2.0 technologies play a crucial role in improving service delivery, accountability, and citizen participation. These technologies have transformed the ways citizens interact, facilitating collaboration in creation, organization, connection, and sharing of content, which in turn creates public value. Social networks and specialized platforms are instrumental in supporting people's mobilization and social activities, contributing significantly to the development and resilience of civil society. During the Revolution of Dignity, social networks not only expedited the dissemination of information and coordinated protester actions but also provided a platform for international media coverage. With the onset of military actions, social networks have become vital for timely informing citizens about events and warning about dangers. They also serve as arenas for information warfare and tools for public support, including fundraising for the Armed Forces, assisting victims and displaced persons, organizing volunteer initiatives, coordinating humanitarian aid, and distributing resources. In these challenging times, social networks also offer psychological support and mutual aid among Ukrainians and act as essential tools for documenting war crimes and human rights violations. These practices are integral to the development of digital diplomacy and are vital components of Ukraine's national security and cybersecurity strategies, as well as its foreign policy strategy [5–7].

The third stage of e-government development is centered on data utilization. This stage involves collecting data through technologies such as the Internet of Things devices, social media, cloud computing, and blockchain, and employing data analytics to support policy formulation and decision-making. The aim is to enable automated decision-making processes and empower citizens to drive these processes themselves. The implementation of this stage is a current priority for Ukrainian government authorities.

The adoption of advanced technologies and innovative approaches by government institutions to optimize public service delivery, enhance internal process efficiency, and encourage public engagement has become so significant that it has been coined as GovTech (from «government technology»). This encompasses a broad spectrum of technologies, including artificial intelligence, blockchain, cloud computing, and the Internet of Things (IoT). GovTech initiatives may involve developing digital platforms for citizen engagement, utilizing data analytics to refine decision-making processes, and deploying smart city solutions to improve urban living. A key benchmark for strategies and policies in this area is the GovTech Maturity Index (GTMI), developed by the World Bank to measure the level of digital transformation within the public sector. In 2022, the GTMI included 40 indicators to assess the maturity of four main GovTech directions, along with several external indicators from other relevant indices such as the United Nations E-Government Development Index (EGDI), the UN E-Participation Index (EPI), the International Telecommunication Union's Global Cybersecurity Index (GCI), and Identification for Development (ID4D) [8–12]. The GTMI represents the average of normalized scores across these four components:

– CGSI (The Core Government Systems Index) – this index evaluates core management systems across seventeen key indicators, including one external indicator. It reflects essential aspects of a «comprehensive government» approach, encompassing government cloud technologies, interoperability frameworks, and other platforms;

– PSDI (The Public Service Delivery Index) – an index of public service delivery, PSDI assesses nine key indicators, including two external indicators. It measures the maturity of online public service portals with a focus on citizen-centric design and universal accessibility;

– DCEI (The Digital Citizen Engagement Index) – this index measures digital citizen engagement through six key indicators, including one external indicator. It evaluates public participation platforms, citizen feedback mechanisms, open data, and open government portals;

– GTEI (The GovTech Enablers Index) – the index includes sixteen key indicators, four of which are external. It reflects strategies, institutions, laws and regulations, digital skills, and policies and programs that promote GovTech.

In 2022, Ukraine was classified into Group «A» of countries with a high level of maturity in governmental technologies [12]. Unlike many fragile and conflict-affected economies where investments in GovTech are primarily aimed at improving core public financial management systems and ICT infrastructure to support essential functions, Ukraine channels investments into other areas of state management, shared platforms, and public online services as well. There is also considerable focus on enhancing citizen engagement and strengthening the necessary institutional and regulatory framework. However, there are gaps in monitoring and increasing the efficiency of existing platforms, ensuring their interoperability, implementing open-source software in the public sector, supporting GovTech startups and SMEs, refining policies and practices related to digital skills, innovating in public management, disruptive technologies, and developing local GovTech ecosystems. The digital transformation program for public administration must become a crucial component of the national strategy to build the country's digital economy, marking a significant factor in its development [13].

The study identified key directions for creating a competitive, innovative, and sustainable digital environment for public administration in Ukraine. The foundation should be an advanced digital infrastructure, which includes ensuring universal access to high-speed internet, particularly in remote and rural areas, to foster digital equity. Important elements include the deployment of next-generation networks, particularly 5G, across all regions of the country, and the construction and modernization of infrastructure to support digital services and applications. The development of digital platforms is also crucial, as they facilitate the integration of various services and provide easier access to both public and private services.

The further digitalization of Ukrainian state institutions and departments involves enhancing both state and sector-specific information systems. These include the integrated information-analytical system «Transparent Budget», the multifunctional system «Electronic Customs», and automated systems like «Treasury» and «Taxes», all based on cutting-edge information and communication technologies. This initiative aims not only to update technology but also to significantly improve business processes within these domains. An example of such modernization is the Electronic Payments System of Ukraine, which, starting April 1, 2023, processes interbank payment operations continuously in a 24/7 mode. This system operates on the international message exchange standard ISO 20022, marking one of the first steps in the project «Development of Ukraine's Payment Infrastructure», aligned with Ukraine's Payment Infrastructure Development Strategy and the European Central Bank's strategy within the framework of Ukraine's integration into the EU [14–16]. Future plans include harmonizing Ukraine's payment space with global standards to join the Single Euro Payments Area (SEPA) and enable cross-border transfers via the SEPA Instant Credit Transfer system (connected to TIPS). Additionally, the transition to flexible and standardized XML-based information exchange formats, the introduction of instant payments, multi-currency functionality, payment tracking services, and other tools are anticipated.

The improvement of public administration information systems is closely tied to the development of a unified information space in the country – a complex of databases, data repositories, technologies for their management and use, information-telecommunication systems, and networks. These operate on unified principles and common rules to ensure the informational interaction of organizations and citizens, as well as to meet their information needs. At the heart of this infrastructure should be a registry system—a collection of information and communication systems. These systems function and interact to create, store, process, and use information for licensing activities, delivering administrative, social, and other public services, conducting other management activities, and implementing state regulation [17]. Key Ukrainian registries include: «The Unified State Demographic Registry», «Unified State Registry of Legal Entities, Individual Entrepreneurs, and Public Organizations», «State Land Cadaster», «Unified State Registry of Vehicles», «Registry of Buildings and Structures», «Unified State Address Registry», «State Registry of Real Property Rights». Other registries are maintained by state authorities, local governments, and legal entities of public law, as defined by law. For instance, the Ministry of Justice of Ukraine develops and supports unified and legal registries, including the «Unified State Registry of

Normative Legal Acts», «The Unified Registry of Notaries of Ukraine», «Inheritance Registry», «Unified Registry of Powers of Attorney», and more than twenty other registries. The State Statistics Service maintains the «Unified State Registry of Enterprises, Organizations, and Institutions of Ukraine», among other registries and classifiers. The State Tax Service administers the «State Registry of Individual Taxpayers. The State Enforcement Service manages the «Unified State Registry of Enforcement Proceedings», and the State Service of Ukraine for the Protection of Personal Data oversees the «State Registry of Personal Data Databases». A number of state registries are operated by the State Enterprise «Diia». The operation of these registries is governed by Ukrainian laws including «On Public Electronic Registries», «On the Specifics of Providing Public (Electronic Public) Services», «On the Protection of Personal Data», «On Access to Public Information», «On Electronic Trust Services», «On Administrative Services», and other relevant laws and regulatory acts. The large number of registries and their custodians lead to data dispersion and usage difficulties, which can be addressed by the electronic office for accessing state registries. This office would offer capabilities for searching data in registries, obtaining extracts, searching for normative legal documents and related information, performing registration actions, and accessing a reporting system for individuals engaged in specialized professional activities, among other features. Additionally, the challenge of integrating information systems at both state and regional levels necessitates further research and the direct design of information processes.

To ensure swift, seamless, and reliable access to information needed by state authorities and local governments to perform their duties, a national electronic interaction system has been developed. This system integrates unified state information resources, electronic registries, and the information systems «Trembita» [18, 19]. It is designed to enable the use of standardized access to the nation's information resources, reduce data duplication across registries, and enhance the interoperability of information systems. The implementation of electronic interaction among priority state electronic information resources is governed by a Resolution of the Cabinet of Ministers of Ukraine [20].

The foundation of the «Trembita» system is the Estonian data exchange platform «X-ROAD». The system consists of a core and local components (Fig. 1). The core components manage a directory of entities participating in electronic interactions within the «Trembita» system, distribute updated details about them across secure exchange gateways, and accumulate statistical data on system usage, such as the exchange of electronic messages. The local components are secure exchange gateways-software tools that provide access to web services using SOAP and REST technologies, and control access to them. These components ensure the integrity and confidentiality of data, record exchange activities, and support data processing tools. The latter include web services and web clients that are integrated with departmental information systems, including electronic registries. Legal significance is imparted to messages using trust services provided by qualified electronic trust service providers. The exchange of legally significant data adheres to principles of technological neutrality, using unified rules for electronic information interaction, open data formats, exchange protocols and standards, informing individuals about inquiries into their personal data, reusing data and software tools, and avoiding data redundancy and duplication.

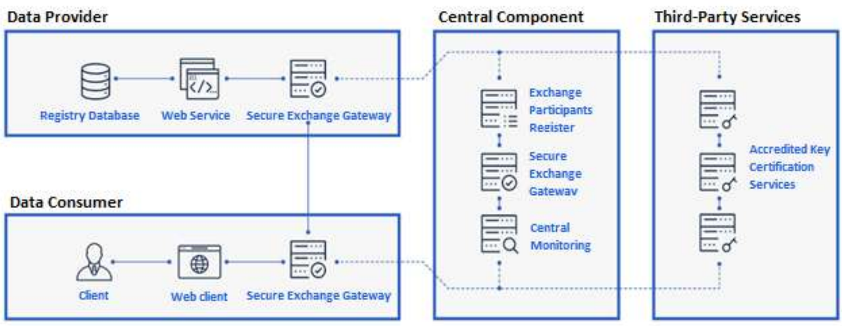

Figure 1. Components of the e-Interaction System «Trembita»

Source: [egov.dp.gov.ua site]

To provide administrative services to citizens with access to state registries, an information system for administrative service centers called «Vulyk» has been implemented, facilitating online data exchanges through the «Trembita» system [21]. Administrative service centers connected to «Vulyk» can interact with the «Diia» mobile app, which allows users to access services without requiring an identity card or taxpayer number and enables online payment via QR code or email. The system's capabilities include comprehensive processing of applications, involving the reception, sending, and receiving of documents, as well as their immediate scanning and automatic linkage to the corresponding electronic case file. The system also automates the archiving of processed applications, thus enhancing the management of administrative services. Additionally, it allows for the creation and printing of necessary application forms, document lists and their descriptions, collects detailed internal statistics and reference information, and provides the ability to check the status of applications via the website.

Applications from the IS «Vulyk» are transferred to external government bodies via the «System of Electronic Interaction of Executive Authorities» (SEI EA) – a state telecommunications system designed for the automation of processes including creation, sending, transfer, receipt, processing, usage, storage, and destruction of electronic documents that do not contain restricted access information. This system utilizes qualified electronic signatures and/or seals and also facilitates interdepartmental monitoring of the implementation of administrative decisions [22]. The SEI EA operates according to regulations governing the electronic interaction of executive authorities.

The laws of Ukraine «On Electronic Documents and Electronic Document Management» and «On Electronic Trust Services» [23, 24] have established the groundwork for organizing electronic document management in Ukraine. However, ensuring the standardization and interoperability of information systems in state institutions also requires the establishment of universally accepted standards for data formats, information exchange protocols, and user interfaces. This involves ensuring system compatibility, standardizing data processing procedures, using open standards for flexibility, broader compatibility, and independence from specific software manufacturers, integrating security and privacy measures across all levels of information systems, and supporting continuous integration and updates. Examples of approaches to data format standardization include the adoption of the standard XML format for banking reporting through the National Bank of Ukraine's web portal and the introduction of a unified electronic financial reporting format according to the Financial Reporting Taxonomy based on international standards, specifically the UA XBRL IFRS taxonomy [25]. The use of the iXBRL format helps raise the standards of information disclosure in the domestic financial market. A practical example of software implementation for integrating electronic document management systems is the «Ptah» roaming platform, which has integrated with the SEI EA platform. «Ptah» also establishes a unified standard for exchanging, verifying, and protecting legally significant documents signed with a qualified electronic signature [26].

As a result, electronic document management systems such as «Vchasno», «Paperless», «M.E.Doc», and SEI EA can exchange electronic documents without the need for additional software – «Ptah» operates as a universal delivery system.

In the context of digital government evolution and increasing cyber threats, the issue of digital identification of individuals is becoming increasingly critical. A digital identifier is not just a key to modernizing state services like healthcare, social payments, certifications, and licensing but also a crucial element for the security of a digital society. Given the importance of this issue and the sensitivity of the technologies involved, the government needs to retain control in this area rather than outsourcing decisions to large tech companies [27]. Ukraine has become the first country in the world to legalize electronic passports and give them the same legal status as paper ones. The Ukrainian citizen's e-passport is a digital replica of passport information formatted as a card, issued through the Unified State Demographic Registry, complete with a unique electronic identifier (QR code, barcode, digital code), and includes residency information [28]. When personal and biometric data are embedded in a contactless integrated circuit implanted in the passport, it enables identity verification and can serve as a qualified electronic signature. Currently, the use of the banking identifier, BankID, which was adopted for identifying individuals for the remote opening of personal bank accounts, is seen as a temporary solution for digitally integrating Ukrainian citizens. This approach faces challenges such as insufficient privacy protection and potential risks arising from close integration with banking systems, which may be vulnerable to failures, technical malfunctions, or cyberattacks on financial institutions. Additionally, this approach can create barriers for people without bank accounts, those who do not use internet banking, or those who lack extensive IT knowledge. Limitations on the use of BankID for international transactions or services due to the legal and regulatory norms of other countries should also be considered. The transition to a state-centralized digital identification system is feasible with the readiness of the necessary infrastructure and the implementation of a comprehensive set of laws, regulatory acts, and policies that define rights and responsibilities regarding the collection, preservation, processing, and use of relevant information. Citizens' adoption of this system depends on their overall trust in it and the range of services it provides. Looking forward, digital identity should not only cover individuals but also devices, software systems, artificial intelligence systems, robots, and other potential participants in digital interactions.

The accumulation of digital data resulting from the operation of information systems and electronic document flows creates opportunities for expanding the scope of analytical tasks. Previously, some of these tasks were addressed using economic-mathematical methods, particularly within the information systems of state-owned industrial enterprises for optimizing the load on production capacities, assessing the profitability of individual departments or the enterprise as a whole, and for developing product supply chains. While administrative data can be used for quantitative evaluations of resources and processes, obtaining qualitative assessments is beneficial when supplemented with results from surveys of government officials and external evaluations (for example, household surveys or anthropological studies) [29]. Integrating data from various sources and updating it in real-time, and employing Big Data technologies, machine learning, and artificial intelligence enable the undertaking of new tasks, including:

– enhancing automation in administrative tasks and public service delivery – employing computer vision and natural language processing systems to manage document workflows, utilizing chatbots and virtual assistants for personalizing government services, providing 24/7 support, and preventing corruption and misuse;

– supporting decision-making and policy development – utilizing big data analytics to identify community needs, demographic layers, regional demands, and other characteristics, along with predictive analytics and automated analysis of legal and regulatory documents;

– risk management – identifying and assessing risks, classifying «risk objects» which could include individuals or categories thereof, as well as entities such as organizations, buildings, river states, residential areas, vehicles, and energy consumption processes;

– optimizing dynamic capacity and coordinating mobile units – addressing bottlenecks in operational processes, including scheduling, route planning, or managing resources under constraints;

– resource and infrastructure management – monitoring assets, analyzing expenditure patterns, forecasting revenue, and identifying opportunities for cost savings;

– enhancing public safety – detecting fraud and ensuring compliance through automated monitoring, identification, and classification of objects and individuals, characterizing their behavior, and modeling scenarios.

Although Ukraine is making progress in each identified the critical direction of information systems development for public administration and is implementing numerous individual projects that enhance transparency and efficiency, enable sound decision-making, and improve access to public information and services, the absence of a coordinated systemic strategic approach, formalized as the National Concept of Digital Development, significantly hampers the potential for further development. It is essential to acknowledge that the effective deployment of advanced information and communication technologies, and consequently, the development of information systems in public administration, depend on a broad spectrum of factors, among which some are particularly significant:

– stimulating research and development – innovative ICT emerges from scientific research and technological developments. Investments in this area open new opportunities and technologies that can later be utilized to create new products and services. These processes require contributions not only from private investors and venture capital but also from governmental support;

– infrastructure development – the growth in computing power, advances in sensors, increased network speeds, and expanded memory capacities facilitate the implementation of more complex and powerful technologies and systems;

– demand for innovation – the market and societal needs for new solutions and opportunities drive enterprises and research groups to develop technologies that meet these demands;

– legislation and regulation – constructive and supportive legal frameworks can stimulate innovation by facilitating the development of new technologies and providing legal protection for them;

– education and workforce – the development and application of ICT require highly skilled professionals from various fields who are capable of developing, managing, and supporting innovative technologies;

– cultural changes – introducing new technologies may necessitate shifts in thinking and work practices, as well as adaptations to new methods of interaction and communication among all potential users.

The government should not only actively engage with national digital ecosystems but also take an active part in international initiatives aimed at addressing global challenges. These initiatives focus on strengthening digital connections between governments, economies, and societies through coordinated strategies, standards, and principles of digital transformation management. In particular, enhancing Ukraine's cybersecurity involves collaboration with organizations such as the European Union Agency for Cybersecurity (ENISA), the NATO StratCom Centre of Excellence, the NATO Cooperative Cyber Defence Centre of Excellence, the European Cybersecurity Competence Centre, and the EU Cyber Academia and Innovation Hub (EU CAIH), etc. Ukraine's participation in the EU eGovernment Action Plan and the EU Digital Decade policy program is crucial for its integration into digital Europe.

Conclusions

This study provides a detailed analysis of the strategic development of state information systems in Ukraine within the context of global digital transformation trends. It assesses the current status and future prospects of these systems across financial-economic, social, and administrative-legal dimensions, both at macro and micro levels. The research outlines three phases in the evolution of GovTech in Ukraine and delineates strategies for creating a competitive, innovative, and sustainable digital environment. The critical need for establishing an effective legislative framework and standardization to ensure data compatibility and security, which are essential for successful digital transformation in public administration, is emphasized. Moreover, the importance of integrating Ukraine into the global digital space through collaboration with international organizations and the European Union is highlighted, which aids in the exchange of knowledge and technological innovations crucial for developing digital governance strategies.

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CONCEPT OF IMPLEMENTATION RESEARCH OF INNOVATIVE TECHNOLOGIES IN THE HIGHER EDUCATION INSTITUTIONS` DIGITAL EDUCATIONAL ACTIVITIES

The National Economic Strategy for the period up to 2030 [1] defines one of the barriers to achieving Goal 3 «Transformation of spheres of life into efficient, modern and comfortable ones» of direction 18 «Digital Economy» – the lack of comprehensive approaches to the implementation of digital transformations. The issues of education and science in the National Economic Strategy are given key, cross-cutting positions in several areas of economic development, in particular in direction 8 «Information and Communication Technologies» in terms of the introduction of IT education and STEM education and the Draft Concept of Digital Transformation of Education and Science for the period up to 2026 [2], which presents a comprehensive strategic vision of the digital transformation of education and science, which corresponds to the principles of implementation of the principles by executive authorities State Policy of Digital Development, approved by the Resolution of the Cabinet of Ministers of Ukraine dated January 30, 2019 No. 56.

The system of education and science must undergo radical digital changes and comply with global trends in digital development for the successful realization of each person's professional potential. Today, more and more professions require the acquisition of a high level of digital skills and mastery of new technologies. This need is also exacerbated by external factors related to the hostilities in Ukraine, which has exacerbated the problem of introducing innovative technologies into the education system to ensure quality education.

Therefore, the Ukrainian education system should ensure the formation of digital competencies and the necessary knowledge and skills of students, scientific and pedagogical staff and the development of digital infrastructure in HEIs, in general.

Purpose and objectives of the study. The Concept of Research on the Introduction of Innovative Technologies in Digital Educational Activities (DPC) (hereinafter referred to as the Concept) considers the theoretical, methodological and practical foundations (components) to improve the efficiency of the processes of introducing innovative technologies, the development of a holistic set of interrelated models, methods and approaches for evaluating the effectiveness of the data center, their practical application for the development of digitalization processes of HEIs.

The purpose of the work necessitates the solution of the following complex problems and tasks:

1. Analysis of the patterns and principles of learning that provide data center processes.
2. Determination of the required resource potential of the HEI.
3. Definition of legislative and legal aspects of data center support.
4. Analysis and implementation of innovative data center technologies.
5. Analysis of methods, approaches, and models of activity and evaluation of data center efficiency.
6. Formation of methodological tools for studying the process of evaluating the efficiency of the data center.
7. Formation of information and technical and information technology support of the data center.
8. Identification of organizational problems in the implementation of innovative data center technologies.
9. Analysis of effective e-learning systems and submission of the necessary reports to HEIs.
10. Formation of the Eco-system of HEIs.
11. Creation of an integrated information system for monitoring and managing the quality of education.
12. Determination of architectural, information-analytical and management solutions of the data center of higher education institutions in the face of complex external risks and uncertainties.

The implementation of the Concept creates opportunities to improve the efficiency of the quality of education at the following levels, Fig. 1.

1. Theoretical component. The goal is to provide a theoretical justification for the implementation of the HEI's data center implementation.

Theoretical provisions include:

1.1. Learning Patterns:

- Conditionality of education by social needs – reflects the state of development of the state, which materializes in the part of national income allocated by the state for the development of education;
- Dependence on the conditions of study and the state of the educational and scientific base – the specifics of training and the scope of professional activity of specialists is the need to use the current state of the educational and scientific base, the use of electronic digital platforms and systems for various purposes, and the introduction of innovative digital technologies, projects and programs of digitalization, software products, tools for the development of information infrastructure, taking into account modern challenges and principles of humanization of the digital sphere;

1. Theoretical component	**1.1 Learning Patterns**	**1.2 General Principles of Learning**	**1.3 General principles of development**
	Conditionality of needs Dependence on learning conditions Interdependence of learning processes Interdependence of tasks, content, methods, and forms Regularity of management of the educational and scientific process Regularity of management of the educational process	Scientificity Systematic and consistent Accessibility and comprehensibility Visibility and transparency Thoroughness Sustainability of knowledge Individual approach Democratization Differentiation Optimization and Unconventionality	Digitalization Quality of education Integrity Resistance International cooperation Cooperation with industry and society Financing Academic Freedom Adaptability
	1.4 Formation of resource potential: financial, educational and scientific, personnel, information and technical, innovative, marketing, external	**1.5 Compliance of program learning outcomes with the requirements of the National Qualifications Framework**	**1.6 Compliance with the legal framework and the interests of the academic community**
2. Methodological component	**2.1 Innovative learning technologies**	**2.2 Organizational Learning Models**	**2.3 Disruptive technologies**
	Traditional technologies: explanatory and illustrative, problem-based, programmable, and differentiated. New technologies: adaptive, open educational resources, gamification, massive open online courses	Offline learning Online learning Distance learning Blended Learning Hybrid learning	Analysis of the impact of AI, ML, IoT, AR, and VR technologies on the educational process and determination of their life cycle
	2.4 Models of Organization of HEIs	**2.5 Classical methods and models for evaluating the activities of HEIs**	**2.6 Methods and models for evaluating the effectiveness of digitalization**
	Determination of the basic subsystems of the HEI: financial and economic, educational and scientific,	Classical approach to the analysis of the economic efficiency of VO according to the models of cost minimization.	Fuzzy model of decision-making according to the Belman-Zadeh principle

	information and technical, personnel, and marketing. Formation of criteria for evaluation of certain subsystems	Methods of marginal analysis of economic efficiency. Model for Evaluating the Effectiveness of Competency-Based Management of Professional Training Organizational model of quality assurance of education	Fuzzy risk-based decision-making model Decision-making model using the mechanism of fuzzy logical inference Unclear model for assessing the effectiveness of digitalization of educational activities
3. Practical component	**3.1 Model studies for evaluating the effectiveness of information technology implementation processes**	**3.2 Architectural Information Technology and Information Technology Approaches and Solutions**	**3.3 Modeling of accounting processes**
	Modeling and analysis of the results of the study of financial, economic, educational, scientific, technical, informational, personnel, and marketing subsystems	Architectural solutions for the implementation of breakthrough technologies	Analysis of the results of accounting for the material and technical support of the educational and scientific work of the HEI
	3.4 Modeling of the processes of characteristics of the smart infrastructure of HEIs	**3.5 Introduction and development of new innovative educational products and technologies of education**	**3.6 Development of an eco-system of HEIs for education quality management**
	Architectural solutions and software for the implementation of smart classrooms, smart laboratories, smart campuses, in general – the functioning of a smart University	Provision of relevant services (e-learning system) to applicants, including webinars, coaching, webcasts, lectures, practices, etc.	Development of an information system for education quality management as part of the eco-system of higher education institutions
	3.7 Provision of referral services		

Figure 1. Concept of research on the implementation of innovative technologies in the digital educational activities of higher education institutions

Source: Developed by the author

- Interdependence of the processes of training, education, upbringing, personal development – allows you to acquire professional skills, both through educational components that form general and professional competencies «Hard skills» – «hard» skills related to the knowledge of mandatory and optional components of professional training, and through social skills «Soft skills» – «soft skills», which involve the formation of various social skills, in particular – oratorical and communication skills, participation in debates, preparation and conduct of presentations, teamwork, high self-organization;
- Interdependence of tasks, content, methods and forms of the educational process – methods and forms of teaching, the introduction of digital technologies stimulate the development of logical thinking, the ability to apply theoretical knowledge in practice, to show one's initiative and non-standard decision-making. The forms and methods of teaching are chosen by teachers by the content of educational components, so their student-centeredness lies primarily in the selection of the best teaching practices, the maximum formation of competencies and achievement of program learning outcomes, as well as compliance with the standards and recommendations for entering the European Higher Education Area.
- The regularity of management of the educational and scientific process is objectively existing, repetitive, stable, essential connections between various elements of the educational system, which reflect the content of managerial influences and ensure the stable functioning of the system. Regular monitoring, revision and updating of educational programs guarantee the appropriate level of educational services, as well as create a favorable and effective learning environment for updating the content of educational components based on scientific achievements and modern practices;
- The regularity of management of the educational process in modern education depends on the efficiency and organization of the system of student self-government of the HEI.

1.2. General principles of learning:

- Scientificity – consists in the formation of theoretical and practical knowledge, skills, and abilities in the subject, the specifics of its sections and topics on the basis of verified scientific data, the disclosure of cause-and-effect relationships of phenomena, processes, events, the latest achievements of science and connections with other sciences;
- Systematization and consistency of teaching – based on a specific system of training and the sequence of knowledge formation according to the structural and logical schemes of educational and professional programs;

- Accessibility and intelligibility of teaching – implements the appropriate rules of accessibility and consistency: from simple to complex;
- Visibility and transparency of teaching involve the acquisition of knowledge in various transparent forms of education;
- Thoroughness implies the connection of materials with professional activity;
- Stability of knowledge, skills, and abilities implies long-term preservation of acquired knowledge, skills, and abilities;
- Individual approach – takes into account the individual level of mental development, knowledge and skills, ability to work, cognitive and practical independence of applicants;
- Democratization means the organization of the educational process by the conditions of the development of society and trends in the development of civilization, taking into account the peculiarities of learning depending on the development of the applicant and the use of effective forms of influence on it;
- Differentiation of the educational process involves the adaptive dosage of educational material to applicants, taking into account their general development;
- Optimization of the educational and scientific process is based on the achievement of a high level of knowledge, skills, and abilities, the development of their intellectual, psychological functions, the improvement of ways and means of educational and cognitive activity;
- The non-traditional nature of the education system involves non-traditional forms of practical knowledge acquisition, in particular, dual.

We will also note the principles on which social and network partnership is based: inclusiveness and accessibility; security and confidentiality; multilingualism; the principle of creating an educational space as a favorable social environment, etc.

The general principles of training in combination with the use of the latest digital technologies ensure: the implementation of the exchange of professional information; simplification of teachers' activities, management of learning processes (monitoring, visibility, accessibility, reporting, etc.); orientation in the information space; establishing constructive and partnership interaction in the information space.

1.3. General principles of development:

- Digitalization is a paradigm shift in communication with the outside world and a high-quality internal digital tool for optimizing the educational and scientific environment through technological and digital modernization of the infrastructure of an educational institution, creating a safe digital educational environment, developing digital competence of pedagogical, scientific, pedagogical and administrative personnel who are able to effectively use digital technologies in the educational process [3].

- The quality of education is achieved through the development of relevant curricula, modern methods of teaching and assessment, as well as the involvement of highly qualified teachers and researchers.
- Integrity – the creation of an integrated and holistic system of higher education covering all aspects of teaching, research, information technology support, and social development.
- Resilience – involves recognizing and adapting to unforeseen challenges, the ability to counteract internal and external influences, overcome unpredictable disturbances in the information environment, and also means taking into account environmental aspects and implementing practices aimed at conserving natural resources and sustainable development [4].
- International cooperation – strengthening ties with the world higher education environment through the exchange of students, teachers, and researchers, as well as participation in international research projects and exchange programs.
- Cooperation with industry and society – interaction with the private sector, public organizations, and government agencies to adapt curricula to the requirements of the labor market and solve current social problems.
- Funding – Providing effective funding for higher education to provide infrastructure, access to scholarships, and other student and research support programs.
- Academic freedom is the protection and promotion of freedom of thought, the expression of innovative ideas, and the independence of higher education institutions from external pressures.
- Adaptability – the ability to adapt to systematic changes to achieve the goals of the HEI, taking into account global trends in changes in the educational sector; challenges and development trends in the field of technological, economic, and information changes; strategies for the development of HEIs; compliance with international qualification requirements for the quality of education, etc.; development of flexible curricula capable of adapting to market requirements and individual needs of students.

1.4. Definition and formation of resource potential:

- Financial capacity – providing stable funding for staff salaries, infrastructure improvements, development of new programs and research. This can include government appropriations, grants, sponsorships, and other sources of funding.

- Educational and scientific potential is determined by the ability to provide quality education and create favorable conditions for scientific research. This aspect encompasses various resources and opportunities that contribute to the development of students and the scientific community.
- Human resources are determined by their ability to provide quality training and create favorable conditions for scientific research. This aspect encompasses various resources and opportunities that contribute to the development of students and the scientific community;
- Information and technical potential – covers all aspects related to information technologies and systems that are used to support educational, scientific and administrative processes in HEIs (IT infrastructure, E-learning, information management systems, technical means, «smart» classrooms).
- Innovative potential – activities, support for startups and entrepreneurial initiatives among students and teachers. Promoting the introduction of innovative ideas and the latest technologies.
- Marketing potential – covers strategies and tools used to position and promote HEIs in the educational market, attract students, maintain reputation and interact with stakeholders (branding, marketing strategies and campaigns, media and public relations, international partnerships, competition monitoring, cooperation with the business environment).
- External potential is determined by the interaction of the HEI with the external environment, which includes relations with the public, regulatory bodies, business environment, social and cultural organizations. This aspect is important for creating a positive impact on society and the development of the university.

1.5. Compliance of program learning outcomes with the requirements of the National Qualification Framework:

- program learning outcomes meet the requirements of the National Qualifications Framework, as a result of the ability to solve complex tasks and practical problems in the field of «Information Technology», in the process of learning and professional activity, which involves the use of certain concepts, theories, methods, technologies for designing various classes of information systems, conducting scientific research, implementing innovations and is characterized by complexity and uncertainty of conditions based on approved Standard of Higher Education in Specialty 122 Computer Science [5].

1.6. Compliance with the legal framework and the interests of the academic community:

- compliance with the norms of current legislation in the field of education and science and intellectual property [6];
- compliance with corporate culture and respect for other employees and students;
- academic responsibility for violation of the principles of academic integrity and ethical ethics;
- observance of the interests of the academic community of the University, which consist in the formulation of goals and program learning outcomes, which are taken into account by their maximum relevance and intensification of teaching activities to achieve them, the accuracy of formulation to specify learning outcomes, and in general – the creation of conditions for cooperation with representatives of other HEIs, stakeholders, scientific institutions.

2. Methodological component. The purpose is to substantiate, provide and implement innovative learning technologies, organizational learning models, breakthrough technologies, models of organization of HEIs, methods and models for evaluating the effectiveness of digitalization of HEIs.

Methodological components 2.1–2.4 are discussed in detail in the article [7]:

2.1. Innovative learning technologies: analysis of traditional learning technologies (explanatory and illustrative, problem-based, programmable, differentiated) and the latest learning technologies (adaptive learning, open educational resources, gamification of learning, massive open online courses);

2.2. Organizational Learning Models (Offline Learning, Online Learning, Distance Learning, Blended Learning, Hybrid Learning)

2.3. Disruptive technologies. Analysis of the impact of AI, ML, IoT, AR, and VR technologies on the educational process and determination of their life cycle.

2.4. Models of organization of HEIs.

In the work, we will determine the basic subsystems of the organization of the activities of the HEI, they include:

- financial and economic;
- educational and scientific;
- information and technical;

- personnel;
- marketing subsystem.

Formation of criteria for evaluation of certain subsystems.

Financial and economic subsystem:

1. The amount of revenues to the special fund based on the results of scientific and scientific-technical work on international cooperation projects, on the results of scientific and scientific-technical work on economic contracts, and the results of the provision of scientific services, thousand UAH, x_{11}.
2. The amount of expenses for the renewal of scientific and laboratory equipment (including the book value of equipment received as a gift, lease, or lease) in the cost estimate of the HEI (excluding institutions of professional pre-higher education in its structure), thousand UAH, x_{12}.
3. The amount of funds for the implementation of research and development of HEIs, which, according to the results of the competitive selection, are financed from the general fund of the budget (in absolute values and/or as a percentage of the amount of relevant funding), thousand UAH, x_{13}.
4. Receipt of funds from the general fund of the budget, thousand UAH, x_{14}.
5. Receipt of funds from the special fund of the budget (payment for services provided by budgetary institutions by the legislation, with their main activities, from additional (economic) activities, payment for the lease of property of budgetary institutions), thousand UAH, x_{15}.
6. Expenditures and provision of loans, thousand UAH, x_{16}.
7. Use of goods and services, thousand UAH, x_{17}.
8. Research and development, individual measures for the implementation of state (regional) programs, thousand UAH, x_{18}.
9. Cost of training, thousand rubles UAH, x_{19}.
10. Expenditures for the educational process per student, UAH/person, x_{110}.
11. The cost of educational services for higher education applicants with full reimbursement of costs, thousand rubles UAH, x_{111}.
12. Cost of postgraduate educational services, thus. UAH, x_{112}.
13. The cost of educational services for retraining and advanced training is, a thousand rubles UAH, x_{113}.
14. The cost of educational services for graduate students with full reimbursement of expenses is, a thousand rubles UAH, x_{114}.
15. The cost of educational services for doctoral students with full reimbursement of expenses, thousand rubles UAH, x_{115}.
16. Labor costs of performers of research work commissioned by enterprises, institutions, organizations, and citizens, thus. UAH, x_{116}.

17. Expenses for the provision of the necessary working capital and intangible assets for the implementation of research work, thousand rubles UAH, x_{117}.

Educational and scientific subsystem:

1. A number of higher education students who participated in international academic mobility programs (lasting at least 1 month, per calendar year), x_{21}.
2. The number of interdisciplinary educational (educational and scientific) programs and the number of students enrolled in them, x_{22}.
3. Number of hours of training sessions for higher education applicants of higher education institutions, which are conducted in English (except for language disciplines), x_{23}.
4. The number of scientific journals of category «A» (by the Procedure for the formation of the List of Scientific Professional Publications of Ukraine, approved by the order of the Ministry of Education and Science of Ukraine dated 15.01.2018, No. 32) published by HEIs, x_{24}.
5. The number of publications in professional scientific journals of Ukraine of category «A» (or categories «A», «B») made by scientific and pedagogical, scientific and pedagogical workers who work at the main place of work in the HEI, x_{25}.
6. The number of scientific, pedagogical, and scientific workers who have at least one patent for an invention or five declarative patents for an invention or utility model, including secret ones, or the presence of at least five certificates of copyright registration for a work, x_{26}.
7. The number of scientific, pedagogical, and scientific employees of the HEI, who have been working at the main place of work in the HEI for at least six months and have prizes at International Olympiads and conferences, x_{27}.
8. The number of full-time scientific, pedagogical, and scientific staff of the HEI, who have been working at the main place of work in the HEI for at least six months and under their leadership over the past five years have received diplomas (documents) of winners and prize-winners (laureates) of international projects, x_{28}.
9. Number of full-time scientific, pedagogical, and scientific staff who participated in international academic mobility programs, x_{29}.
10. Ensuring «zero tolerance» for the facts of violation of academic integrity by checking each appeal for the violation of academic integrity and bringing to academic responsibility persons whose actions (inaction) are recognized as a violation of academic integrity, x_{210}.
11. Share of subjects taught using innovative methods, %, x_{211}.
12. Qualitative performance at the end of the year, %, x_{212}.
13. Qualitative performance of graduates, %, x_{213}.

14. Availability of a published textbook or textbook (including electronic) or a monograph (with a total volume of at least 5 author's sheets), including those published in co-authorship (at least 1.5 author's sheets for each co-author), x_{214}.

15. Availability of published teaching aids/manuals for independent work of higher education applicants and distance learning, electronic courses on the educational platforms of licensees, lecture notes/workshops/guidelines/recommendations/work programs, and other printed educational and methodological works with a total of three titles, x_{215}.

16. Number of grants received, x_{216}.

17. Number of dissertations defended for a scientific degree, x_{217}.

18. The number of scientists performing the functions (powers, duties) of the scientific supervisor or responsible executor of the scientific topic (project), or the editor-in-chief/member of the editorial board/expert (reviewer) of a scientific publication included in the list of professional publications of Ukraine, or a foreign scientific publication indexed in bibliographic databases, x_{218}.

19. Number of participants in international scientific and/or educational projects, x_{219}.

20. The number of students who won prizes in domestic and international competitions, x_{220}.

Information and technical subsystem:

1. Availability of an electronic Learning Management System (stages of design, development, implementation, maintenance, and the assessment of its quality), x_{31}.

2. Availability of a comprehensive system for automating the management of higher education institutions, an electronic document management system, x_{32}.

3. Availability of a system of internal quality assurance of higher education, based on the information system of quality management of higher education, x_{33}.

4. Introduction of a system of key performance indicators in the contracts of deputy heads of HEIs and heads of structural subdivisions (if it has not been introduced before), x_{34}.

5. The number of classrooms equipped with multimedia equipment or other special equipment that ensures the performance of the functions of multimedia equipment, x_{35}.

6. The coefficient of involvement of the digitalization process (the use of innovative digital technologies), x_{36}.

Personnel subsystem:

1. Staffing for the provision of specialties, %, x_{41}.

2. Number of students per 1st teacher, x_{42}.

3. Number of foreigners and stateless persons among higher education students of higher education institutions (as of January 1 of each year), including citizens of OECD member countries, x_{43}.

Marketing subsystem:

1. Image indicator of the HEI's activities (Availability of the Strategy, Concept, Digitalization Program, and strategic plan for the development of the HEI), x_{51}.
2. Inclusion of HEIs in the International Comparative Ranking of HEIs U-Multirank (if it has not been done before), x_{52}.
3. Advertising and marketing costs, UAH (Marketing System Efficiency Ratio = Costs/Net Revenue), x_{53}.
4. The proportion of graduates of higher education institutions who pay taxes in Ukraine as entrepreneurs or employees, and 2 years after graduation work in positions that require higher education (except for persons who have continued their studies, serve in law enforcement agencies or are on social leave), %, x_{54}.

2.5. Classical Methods and Models for Evaluating the Activities of HEIs

The complexity of the tasks of modeling the activities of higher education institutions, which is associated with digitalization, the use of innovative digital technologies and the requirements for their solution, is increasing every year. The vast majority of tasks are multi-criteria and multi-purpose tasks of managerial decision-making, which require simultaneous implementation and coordination of different, sometimes conflicting goals, and taking into account a fairly large number of criteria when choosing alternatives. Often you have to make decisions both in conditions of insufficient information and conditions of redundant data, among which it is difficult to single out the necessary ones (useful, correct, reliable, etc.). Modern decision-making tasks can be weakly structured or completely unstructured, poorly formalized, etc. These problems can be overcome, in particular, through the use of adequate mathematical apparatus in the form of economic and mathematical methods and models implemented in the relevant monitoring systems for assessing the effectiveness of higher education.

To solve the structured problems of the HEI's activities, in which the relations between the elements can acquire numerical values or symbols, it is advisable to use quantitative methods of analysis: linear, nonlinear, dynamic programming, queuing theory, as well as game theory. Scientists distinguish the following approaches, methods, and models:

1. The classical approach to the analysis of the economic efficiency of higher education according to the models of cost minimization, «costs – effectiveness», «costs – benefits», the method «costs – utility» [8], as well as the financial and economic model of development of higher education institutions in conditions of risks and uncertainty [9];

2. Methods of marginal analysis of economic efficiency, including parametric and non-parametric methods. Parametric methods are based on the econometric estimation of the analytical function. Nonparametric methods use linear programming methods [10].

3. Models for evaluating the effectiveness of competence-oriented management of vocational training (weighted arithmetic mean dependence of the criterion assessment of the quality of education) [11].

4. The organizational model for ensuring the quality of education is defined at the legislative level by the Law of Ukraine «On Higher Education». The educational process is «a system of scientific, methodological and pedagogical activities aimed at the development of the individual through the formation and application of his/her competencies» [12]. The quality of higher education is defined as «compliance of the conditions for the implementation of educational activities and learning outcomes with the requirements of legislation and higher education standards, professional and/or international standards (if any), as well as the needs of stakeholders and society, which is ensured through the implementation of internal and external quality assurance procedures» [6]. To guarantee, maintain and improve quality, HEIs build an internal quality assurance system, which is regulated by the Law of Ukraine «On Higher Education», the Concept of Digital Transformation of Education and Science, Education Standards, EP accreditation, EP license, requests from the academic community and stakeholders. The HEI carries out continuous improvement of the quality of the educational process, educational information environment and resource potential, in which educational programs, the learning process and learning outcomes are constantly being improved, which meet the regulatory requirements for the quality of education of the external support system. The whole range of functionality of the educational information environment in practice can be implemented in the information system of quality management of higher education.

2.6. Methods and models of assessment of HEIs.

To solve semi-structured problems characterized primarily by qualitative (verbal), as well as quantitative dependencies between the elements of the studied HEI and the external environment, it is advisable to apply mathematical models based on the use of fuzzy sets and fuzzy logic tools, neural networks, the use of artificial intelligence tools, including collective artificial intelligence approaches. In addition, hybrid systems are widely used, in particular, fuzzy logic and artificial neural networks; genetic algorithms and artificial neural networks, etc. Multi-purpose multi-criteria decision-making tasks under fuzzy conditions, decision-making using fuzzy sets, fuzzy multi-criteria hierarchical decision-making model are used.

- Fuzzy model of decision-making according to the Belman-Zadeh principle
- Fuzzy risk-based decision-making model [13].
- Decision-making model using the mechanism of fuzzy logical inference
- Unclear model for assessing the effectiveness of digitalization of educational activities.

The paper proposes a fuzzy model for assessing the effectiveness of digitalization of educational activities based on modeling the basic subsystems: financial and economic, educational and scientific, information and technical, personnel and marketing.

To construct fuzzy models based on the use of the fuzzy set apparatus, the following development algorithm is usually used [14–16]:

Stage 1: Selection of indicators to be taken into account in the model;

Stage 2: Description of linguistic variables;

Stage 3: Determination of the types of membership functions and their construction;

Stage 4: Building a base of fuzzy knowledge;

Stage 5: Configuring the model parameters and determining the output characteristics.

Stage 1**.** Discussed in section 1.2. – Models of organization of HEIs.

Stage 2**.** The initial parameter of the model, as a result of modeling the system for evaluating the effectiveness of HEIs, is calculated based on assessing the parameters of the states of financial and economic (X_1), educational-scientific (X_2), informational-technical (X_3), personnel (X_4) and marketing (X_5) subsystems of educational activities of HEIs:

$$R = f(X_1 \ldots X_m),\ S_i = f(x_{i1} \ldots x_{in}),\ i = \overline{1,m},\ j = \overline{1,n} \quad (1)$$

where is R an integral indicator of the level of effectiveness of educational activities of the HEI, X_i– generalizing features of subsystem states, i – subsystem number; m – number of subsystems $m = 5$, x_{ij} – generalizing features of the assessment of the parameters of the states of subsystems, j – the number of the parameter i, n – the number of parameters that characterize the state.x_{i*}

The first step in the implementation of the model is the formation of parameters x_i based on input data x_{ij}, which can be characterized both quantitatively and qualitatively. In the second step of the model implementation, the state of the subsystem X_i is determined. The last step in implementing the model is to determine the integral performance indicator R.

To reflect the relationship between the input and output parameters of the model with the help of the linguistic rules «If-then», we form the linguistic characteristics of the qualitative terms of the state of the financial-economic, educational-scientific, information-technical, personnel and marketing subsystems of the educational activities of the HEI: $\{VL,\ L,\ M,\ H,\ VH\}$

VL – very low, *L* – low, *M* – medium, *H* – high, *VH* – very high. Let us denote the given term sets as follows:

$$S_{i*} = \left\{s_{i*}^1,\ s_{i*}^2,\ s_{i*}^3,\ s_{i*}^4,\ s_{i*}^5\right\} = \left\{s_{i*}^1 = \text{«}VL\text{»},\ s_{i*}^2 = \text{«}L\text{»},\ s_{i*}^3 = \text{«}M\text{»},\ s_{i*}^4 = \text{«}H\text{»},\ s_{i*}^5 = \text{«}VH\text{»}\right\},$$

where $s_{i*}^p - p$ is the linguistic term of the $i*$-th variable, $p = \overline{1{,}5}$, $i* = \overline{1{,}5}$,

$i*$is the end-to-end number of the input linguistic variables.

The resulting parameter makes it possible to assess the level of efficiency of educational activities of HEIs on the following scale of term sets: $R\{P,\ S,\ U,\ C\}\,P$ – positive, *ST* – satisfactory, U – unsatisfactory, *C* – critical. Let us denote this term set as follows:

$$G = \{g^1,\ g^2,\ g^3,\ g^4\} = \begin{Bmatrix} g^1 = \text{«}P\text{»},\ g^2 = \text{«}S\text{»}, \\ g^3 = \text{»}U\text{»},\ g^4 = \text{»}C\text{»} \end{Bmatrix},$$

where is the linguistic term of the original variable

Table 1 shows the values of the fuzzy terms of the input and output variables described above.

Stage 3. The membership function performs the task of averaging the values of expert assessments relative to the distribution of elements over sets.

Suppose there is some universal set (which includes a set of possible values of the $i*$th variable), then there is a fuzzy subset S of, describing the constraints on the possible values of the variable s_{i*}. Then it is possible to define as $S = \left\{x_{ij}, \mu^{s_{i*}^p}(x_{ij});\ x_{ij} \in Q\right\}$ and

$S = \{X_i, \mu^{s_{i*}^p}(X_i);\ X_i \in Q\}$ where $\mu^{s_{i*}^p}(x_{ij})$and $\mu^{s_{i*}^p}(X_i)$ are the characteristic functions of belonging, which acquire a value in the interval from 0 to 1, whereby:

$$\mu^{s_{i*}^p}(X_i) > 0,\ \forall X_i \in Q$$
$$\mu^{s_{i*}^p}(X_i) = 0,\ \forall X_i \notin Q$$
$$sup_{X_i \in Q}\left[\mu^{s_{i*}^p}(X_i)\right] = 1 \quad (2)$$

The same is true for$\mu^{s_{i*}^p}(X_{ij})$.

Thus, the function $\mu^{s_{i*}^p}(X_i)$ determines the degree of belonging of the elements X_i and x_{ij} the subset of x_{ij}. To determine the parameters $\mu^{s_{i*}^p}(X_i)$ and $\mu^{s_{i*}^p}(x_{ij})$, it is expedient to use bell-shaped membership functions [14–16], since they are smooth over the entire domain of definition and take non-zero values (Table 1).

The analytical form of writing bell-shaped (or *U-shaped*) membership functions of fuzzy terms of input variables has the form for X_i and x_{ij} respectively [16]:

$$\mu^{s_{i*}^p}(X_i) = \frac{1}{1+\left|\frac{X_i - c}{w}\right|^{2b}}, \quad (3)$$

$$\mu^{s_{i*}^p}(x_{ij}) = \frac{1}{1+\left|\frac{x_{ij} - c}{w}\right|^{2b}}, \quad (4)$$

where w – concentration-stretch coefficient See–like membership function (bell-shaped); *c* is the coordinate of the maximum of the function; *b* – Customization option.

Accordingly, the characteristic membership function $\mu^{g^k}(R)$ fuzzy terms g^k output variable *R*, takes on a value between 0 and 1:

$$\mu^{g^k}(R) = \frac{1}{1+\left|\frac{R - c}{w}\right|^{2b}}\ , \quad (5)$$

Stage 4. Let's form a set of rules – a fuzzy knowledge base (KB), which is an expert-logical conclusion for the basic evaluation criteria for assessing the states of the subsystem (Tables 2, 3).

We will present the KB to determine the level of effectiveness of educational activities of higher education institutions in the form of Tables 2, 3.

Table 1

PARAMETRIC CHARACTERISTICS OF THE MODEL FOR ASSESSING THE EDUCATIONAL ACTIVITIES OF HEIS

Linguistic Variable Number	Notation of linguistic variables	Name of linguistic variables	Base term set of a linguistic variable	Syntactic description of the values of a linguistic variable
Input Variables				
$i *= 1$	X_1	Level of operation of the financial and economic subsystem	S_1	$s_1^1,\ s_1^2,\ s_1^3,\ s_1^4,\ s_1^5$
$i *= 2$	X_2	The level of work of the educational and scientific subsystem	S_2	$s_2^1,\ s_2^2,\ s_2^3,\ s_2^4,\ s_2^5$
$i *= 3$	X_3	The level of operation of the information and technical subsystem	S_3	$s_3^1\ s_3^2,\ s_3^3,\ s_3^4,\ s_3^5$
$i *= 4$	X_4	The level of work of the personnel subsystem	S_4	$s_4^1,\ s_4^2,\ s_4^3,\ s_4^4,\ s_4^5$
$i *= 5$	X_5	The level of work of the marketing subsystem	S_5	$s_5^1,\ s_5^2,\ s_5^3,\ s_5^4,\ s_5^5$
Output Variables				
-	R	Integral indicator of the effectiveness of educational activities of higher education institutions	G	$g^1,\ g^2,\ g^3,\ g^4$

Source: compiled by the author

Table 2

KNOWLEDGE BASE FOR DETERMINING THE EFFECTIVENESS OF EDUCATIONAL ACTIVITIES OF HEIS

Meaning of System States					Output Variable
X_1	X_2	X_3	X_4	X_5	R
VH	*VH*	*VH*	*VH*	*VH*	
H	*H*	*VH*	*H*	*H*	*P*
M	*VH*	*H*	*VH*	*H*	
H	*M*	*H*	*M*	*M*	
M	*H*	*H*	*M*	*H*	*ST*
M	*H*	*H*	*H*	*M*	

End of the table 2

Meaning of System States					Output Variable
X_1	X_2	X_3	X_4	X_5	R
L	*L*	*M*	*M*	*M*	
H	*M*	*VL*	*VL*	*VL*	*U*
L	*L*	*L*	*L*	*L*	
M	*VL*	*L*	*VL*	*L*	
VL	VL	M	M	L	*C*
VL	VL	VL	VL	VL	

Source: compiled by the author

The result of a positive overall level of efficiency of educational activities of HEIs in an analytical form can be formulated as follows:

$$\begin{gathered}\mu^{P}(X_1 \dots X_5) = \mu^{VH}(X_1) \cdot \mu^{\mathrm{VH}}(X_2) \cdot \mu^{\mathrm{VH}}(X_3) \cdot \mu^{\mathrm{VH}}(X_4) \cdot \mu^{\mathrm{VH}}(X_5) \vee \\ \mu^{H}(X_1) \cdot \mu^{H}(X_2) \cdot \mu^{VH}(X_3) \cdot \mu^{\mathrm{H}}(X_4) \cdot \mu^{\mathrm{H}}(X_5) \vee \\ \mu^{M}(X_1) \cdot \mu^{\mathrm{VH}}(X_2) \cdot \mu^{H}(X_3) \cdot \mu^{\mathrm{VH}}(X_4) \cdot \mu^{H}(X_5)\end{gathered} \qquad (6)$$

where through is denoted by a logical disjunction operation such that∨

$$\mu^{s_{\mathrm{i}*}^{\mathrm{p}}}(X_i) \vee \mu^{s_{\mathrm{i}*}^{\mathrm{p}}}(X_{i+1}) = max\left(\mu^{s_{\mathrm{i}*}^{\mathrm{p}}}(X_i), \mu^{s_{\mathrm{i}*}^{\mathrm{p}}}(X_{i+1})\right),$$

(∧) – logical conjunction

$$\mu^{s_{\mathrm{i}*}^{\mathrm{p}}}(X_i) \wedge \mu^{s_{\mathrm{i}*}^{\mathrm{p}}}(X_{i+1}) = min\left(\mu^{s_{\mathrm{i}*}^{\mathrm{p}}}(X_i), \mu^{s_{\mathrm{i}*}^{\mathrm{p}}}(X_{i+1})\right).$$

Similarly, the final rules for the other three terms (C, NZ, K) can be presented:

$$\begin{gathered}\mu^{ST}(X_1 \dots X_5) = \mu^{H}(X_1) \cdot \mu^{M}(X_2) \cdot \mu^{H}(X_3) \cdot \mu^{M}(X_4) \cdot \mu^{M}(X_5) \vee \\ \mu^{M}(X_1) \cdot \mu^{H}(X_2) \cdot \mu^{H}(X_3) \cdot \mu^{M}(X_4) \cdot \mu^{H}(X_5) \vee \\ \mu^{M}(X_1) \cdot \mu^{H}(X_2) \cdot \mu^{\mathrm{H}}(X_3) \cdot \mu^{H}(X_4) \cdot \mu^{M}(X_5),\end{gathered} \qquad (7)$$

$$\begin{gathered}\mu^{U}(X_1 \dots X_5) = \mu^{L}(X_1) \cdot \mu^{L}(X_2) \cdot \mu^{M}(X_3) \cdot \mu^{M}(X_4) \cdot \mu^{M}(X_5) \vee \\ \mu^{H}(X_1) \cdot \mu^{M}(X_2) \cdot \mu^{VL}(X_3) \cdot \mu^{VL}(X_4) \cdot \mu^{VL}(X_5) \vee \\ \mu^{L}(X_1) \cdot \mu^{L}(X_2) \cdot \mu^{\mathrm{L}}(X_3) \cdot \mu^{L}(X_4) \cdot \mu^{L}(X_5),\end{gathered} \qquad (8)$$

$$\begin{gathered}\mu^{C}(X_1 \dots X_5) = \mu^{M}(X_1) \cdot \mu^{VL}(X_2) \cdot \mu^{L}(X_3) \cdot \mu^{VL}(X_4) \cdot \mu^{L}(X_5) \vee \\ \mu^{VL}(X_1) \cdot \mu^{VL}(X_2) \cdot \mu^{M}(X_3) \cdot \mu^{M}(X_4) \cdot \mu^{L}(X_5) \vee \\ \mu^{VL}(X_1) \cdot \mu^{VL}(X_2) \cdot \mu^{\mathrm{VL}}(X_3) \cdot \mu^{VL}(X_4) \cdot \mu^{VL}(X_5),\end{gathered} \qquad (9)$$

Let's consider how the BZ is formed to assess the state of educational activities of the HEI. The final rules for assessing the operating states of X_1, X_2, X_3, X_4, X_5 are presented in Table 3.

The analytical form of recording the final rules for the state of the financial and economic subsystem for a limited number of indicators, for example, *n* = 3, has the following form:

$$\mu^{VH}(x_{11}, x_{12}, x_{13}) = \mu^{VH}(x_{11}) \cdot \mu^{\mathrm{VH}}(x_{12}) \cdot \mu^{\mathrm{VH}}(x_{13}) \vee \\ \mu^{H}(x_{11}) \cdot \mu^{VH}(x_{12}) \cdot \mu^{\mathrm{VH}}(x_{13}), \tag{10}$$

$$\mu^{H}(x_{11}, x_{12}, x_{13}) = \mu^{H}(x_{11}) \cdot \mu^{\mathrm{H}}(x_{12}) \cdot \mu^{\mathrm{H}}(x_{13}) \vee \\ \mu^{M}(x_{11}) \cdot \mu^{VH}(x_{12}) \cdot \mu^{\mathrm{VH}}(x_{13}), \tag{11}$$

$$\mu^{M}(x_{11}, x_{12}, x_{13}) = \mu^{M}(x_{11}) \cdot \mu^{\mathrm{M}}(x_{12}) \cdot \mu^{\mathrm{M}}(x_{13}) \vee \\ \mu^{L}(x_{11}) \cdot \mu^{H}(x_{12}) \cdot \mu^{\mathrm{H}}(x_{13}), \tag{12}$$

$$\mu^{L}(x_{11}, x_{12}, x_{13}) = \mu^{L}(x_{11}) \cdot \mu^{\mathrm{L}}(x_{12}) \cdot \mu^{\mathrm{L}}(x_{13}) \vee \\ \mu^{VL}(x_{11}) \cdot \mu^{M}(x_{12}) \cdot \mu^{\mathrm{M}}(x_{13}), \tag{13}$$

$$\mu^{VL}(x_{11}, x_{12}, x_{13}) = \mu^{VL}(x_{11}) \cdot \mu^{\mathrm{VL}}(x_{12}) \cdot \mu^{\mathrm{VL}}(x_{13}) \vee \\ \mu^{L}(x_{11}) \cdot \mu^{VL}(x_{12}) \cdot \mu^{\mathrm{VL}}(x_{13}), \tag{14}$$

Similarly, the analytical form of recording the final rules for the states of educational and scientific (X_2), information and technical (X_3), personnel (X_4) and marketing (X_5) subsystems of educational activities of higher education institutions is constructed.

Table 3

FORMATION OF BZ TO DETERMINE THE STATES OF FIVE SUBSYSTEMS OF EDUCATIONAL ACTIVITIES OF HEIS AND A LIMITED NUMBER OF PARAMETERS FOR EACH SUBSYSTEM (*n* = 3 is taken for example)

Values of state parameters			Status Value
x_{11}	x_{12}	x_{13}	X_1
VH	VH	VH	VH
H	VH	VH	
H	H	H	H
M	VH	VH	
M	M	M	M
L	H	H	
L	L	L	L

Continuation of the table 3

Values of state parameters			Status Value
x_{11}	x_{12}	x_{13}	X_1
VL	M	M	
VL	VL	VL	VL
L	VL	VL	
x_{21}	x_{22}	x_{23}	X_2
VH	VH	VH	VH
H	VH	VH	
H	H	H	H
M	VH	VH	
M	M	M	M
L	H	H	
L	L	L	L
VL	M	M	
VL	VL	VL	VL
L	VL	VL	
x_{31}	x_{32}	x_{33}	X_3
VH	VH	VH	VH
H	VH	VH	
H	H	H	H
M	VH	VH	
M	M	M	M
L	H	H	
L	L	L	L
VL	M	M	
VL	VL	VL	VL
L	VL	VL	
x_{41}	x_{42}	x_{43}	X_4
VH	VH	VH	VH

End of the table 3

Values of state parameters			Status Value
H	VH	VH	
H	H	H	H
M	VH	VH	
M	M	M	M
L	H	H	
L	L	L	L
VL	M	M	
VL	VL	VL	VL
L	VL	VL	
x_{51}	x_{52}	x_{53}	X_5
VH	VH	VH	VH
H	VH	VH	
H	H	H	H
M	VH	VH	
M	M	M	M
L	H	H	
L	L	L	L
VL	M	M	
VL	VL	VL	VL
L	VL	VL	

Source: compiled by the author

Stage 5. At the final stage of building a model for evaluating the effectiveness of educational activities of higher education institutions, we will determine the parameters for setting up the system and deriving a logical conclusion, since it is necessary to determine the decision-making algorithm that will allow the vector of input variables to match the possible value of the output variable.

To express the degree of connection between the output variable and the input variables, the function of belonging of the input variables X_i to the value of the output variable R can be represented as:

$$\mu^{g^k}(X_1,\ X_2,\ X_3,\ X_2,\ X_3) = \vee_{p=1}^{5}\left[\wedge_{i*=1}^{5}\mu^{s_{i*}^{p}}(X_i)\right] \tag{15}$$

Then, based on the provisions of the theory of fuzzy sets, on the basis of equation (15) it is possible to form a fuzzy set of the original variable R:

$$\mu^{g^k}(R) = \max_{p=\overline{1,5}}\left(\max_{i=\overline{1,5}}\mu^{s_{i*}^{p}}(X_i)\right) \tag{16}$$

Where $\mu^{s_{i*}^{p}}(X_i)$ is the function of belonging of the input variable X_i to the term s_{i*}^{p};

$\mu^{g^k}(R)$ is the function of belonging of the input variable R to the term g^k.

Equation (16) is based on the method of identifying the linguistic term, which is called the maximum of the membership function.

3. **Practical component.** The goal is to provide practical recommendations, advice, and innovative services for the implementation of information support for the data center. Practical results and recommendations include:

3.1. Model studies for evaluating the effectiveness of information technology implementation processes. Modeling and analysis of the results of the study of financial and economic, educational and scientific, information and technical, personnel, and marketing subsystems on the examples of higher education institutions.

3.2. Architectural information-technical and information-technological approaches and solutions to the creation and implementation of breakthrough technologies in the educational process.

3.3. Modeling of accounting processes for material and technical support of educational and scientific work of higher education institutions.

3.4. Modeling of the processes of characteristics of the smart infrastructure of the HEI, in particular architectural solutions and software for the implementation of smart classrooms, smart laboratories, smart campuses, in general – the functioning of a smart University.

3.5. Implementation and development of innovative educational products (systems) and educational technologies in order to provide relevant services (e-learning system) to students, masters, graduate students and young scientists, including webinars, coaching, webcasts, lectures, practices, etc.

3.6. Development of an eco-system of higher education institutions for education quality management based on platforms of universal, intelligent and specialized information management systems.

3.7. Provision of advisory services on the process of assessing the effectiveness of the quality of education of a given HEI based on the introduction and use of a fuzzy model of rating assessment of the quality of education; introduction of innovative technologies and data center products; on the creation of an architecture of information and technical support for the activities of higher education institutions on the terms of cooperation with leading Ukrainian and foreign IT companies for joint scientific and educational cooperation; for the inclusion of applicants in the work with IT employers, customers of potential scientific products, business partners in organizing and conducting open forms of training for our graduates in the specialty «Computer Science», for the implementation of international projects on the platforms of IT startups, grants and programs, concepts Industry 4.0., 5.0.

Conclusions

A concept for researching the introduction of innovative technologies in the digital educational activities of higher education institutions has been developed, which, unlike the existing ones, comprehensively describes and takes into account the triad of the following components: theoretical includes patterns of learning, general principles of learning and their development, formation of the resource potential of an educational institution, analysis of the compliance of program learning outcomes with the requirements of the National Qualifications Framework and the legislative framework; methodological uses approaches to the analysis, implementation of innovative learning technologies, in particular breakthrough technologies (AI, ML, IoT, AR, VR), organizational learning models, basic subsystems of the institution's activities (financial and economic, educational and scientific, information and technical, personnel, marketing) and the formation of evaluation criteria for each of the subsystems; classical methods and models for evaluating the effectiveness of the process based on the use of fuzzy set theory; practical includes the process of modeling and analysis of the study of certain subsystems on the basis of the proposed fuzzy model for assessing the effectiveness of digitalization of educational activities; architectural solutions for the development of an information system for managing the quality of education as part of the eco-system of a higher education institution.

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DIGITAL TRANSFORMATION OF ENTERPRISE ARCHITECTURE

Enterprise architecture, defined as its fundamental organization or properties within its environment, along with the guiding principles for its implementation and evolution and the related lifecycle processes [1], is largely determined by the information systems and technologies employed. These information systems form a crucial part of the technological infrastructure and, along with other architectural elements, are designed to support the enterprise in achieving its short-term and long-term business objectives. Digital technologies and tools are integrated into various aspects of enterprise operations to enhance productivity, efficiency, and competitiveness [2]. Terms such as «digitization», «digitalization», and «digital transformation» (DT) [3] are used to describe the extent of these changes. «Digital transformation» refers to the profound changes in the business and operational models of the enterprise, creating new opportunities for generating added value. Enterprises across various sectors, such as automotive, energy, healthcare, banking, logistics, aviation, and tourism, are adopting new high-tech solutions to transform business practices and secure competitive advantages.

While digital transformation is increasingly capturing the attention of scholars, practitioners, governments, and ICT providers, most enterprises recognize its potential impact. However, many of these enterprises do not have a clear action plan to restructure existing processes to align with new technologies. Although 74 % of enterprises consider digital transformation a priority, only 35 % of these initiatives are successful [4], and, on average, 87.5 % of digital transformations fail to meet their initial goals [5]. The success of transformation efforts largely depends on addressing a comprehensive set of strategic and operational organizational, managerial, technical, and cultural challenges, as well as executing a sufficient number of actionable steps [6]. The primary challenges in implementing digital transformation include the complexity of planning, resistance to organizational changes, skill shortages, outdated infrastructure, lack of a clear strategy and vision, security and privacy issues, resource limitations, rapid changes in technology, trends, and expectations, and the difficulty in quantitatively assessing the effectiveness of relevant investments due to their intangible and hard-to-measure outcomes [7, 8]. Recent studies [9–11] indicate that using a structured and standardized model to delineate processes and development pathways for digital transformation can enhance the return on investment. Enterprise architecture models such as TOGAF, the Zachman framework, Gartner, FEAF, DoDAF, the NIST enterprise architecture model, and the ISO 19439 enterprise modeling standard, among others, can be utilized to reduce uncertainty and accelerate transformation. These models help achieve a comprehensive understanding of processes, support the development of a transformation roadmap, and ensure alignment with business objectives while managing challenges and risks [12].

Each enterprise architecture framework has its strengths and weaknesses, prompting many enterprises to adopt a hybrid approach. A viable alternative is the Unified Architecture Framework (UAF), an architectural model that offers a standardized and consistent methodology based on UML and SysML languages, the DoDAF Unified Architectural Framework Profile, and the UK Ministry of Defence Architectural Framework [13]. UAF is designed to support the modelling of a wide range of complex systems, which may include hardware, software, data, personnel, and infrastructure elements, as well as modelling for systems that incorporate other systems (system of systems, SoS). It provides methods for presenting enterprise architecture that enable stakeholders to concentrate on specific business processes, operational and business requirements, and the system integration of commercial and industrial enterprises.

The UAF comprises three main components: the Domain Metamodel (DMM), the UAF Profile (UAFP), and the UAF Grid. The standard facilitates the development of various model types: Taxonomy (Tx), Structure (Sr), Connectivity (Cn), Processes (Pr), States (St), Interaction Scenarios (Is), Information (If), Parameters (Pm), Constraints (Ct), Roadmap (Rm), Traceability (Tr), as well as Metadata. It also includes models for the Strategic, Operational, Services, Personnel, Resources, Security, Projects, Standards, Actual Resources, Dictionary, Summary and Overview, and Requirements domains. These models are employed to represent different elements and their interrelations within the enterprise architecture. For example, the taxonomy organizes all elements as an independent structure, whereas connectivity details the connections, relationships, and interactions among various elements. Specifically, the UAF Operational Domain depicts the enterprise’s logical architecture, including its requirements, operational behaviours, structures, and exchanges needed to support functionality. Meanwhile, the Resources

Domain outlines how resource configurations meet operational requirements and enhance overall functionality.

One of the advantages of UAF is its built-in integration with system modelling tools and support for Model-Based Systems Engineering (MBSE) [14, 15]. While UAF does not prescribe a specific graphical notation for modelling, it provides guidelines for utilizing various types of SysML diagrams to generate specialized views. Additionally, UAF addresses the absence of pragmatism and a standardized methodology in modelling languages for systems of systems [16]. The UAF framework aims to enhance the quality, productivity, and efficiency of modelling for enterprise architectures and systems of systems. It promotes the reuse of architectural models, supports their maintenance, and improves the compatibility of various modelling tools.

One of the limitations of UAF is its lack of a defined method for architectural development. This limitation can be addressed by leveraging the compatibility between UAF and TOGAF, whose metamodels serve as alternative options within the same class, and by implementing the TOGAF Architecture Development Method (ADM). Additionally, the incorporation of Model-Based Systems Engineering (MBSE) into enterprise architecture development significantly enhances the success of digital transformation (DT) [17]. Specifically, the model-based approach enhances requirement management practices by using models as the central element in change management, providing a foundation for collaboration and communication among all stakeholders, and facilitating the tracking of requirements throughout the design and implementation phases. SysML requirements diagrams, in particular, help organize and visualize all types of requirements and their interconnections, and establish links between requirements and project elements. However, neither the architectural framework nor the MBSE methodology inherently supports the processes of goal setting and requirements definition, whereas developing a clear and comprehensive digital strategy is crucial for successful DT.

A benchmark for evaluating the vision and business objectives pursued during DT, as well as the goals of specific digital initiatives, is the digital maturity level of the enterprise. This level reflects the enterprise's capability to create value using digital technologies and processes. To determine this, models and tools that are widely available on the market can be utilized. The characteristics of the most popular digital maturity models, developed by international consulting firms, are summarized in Table 1. Analysis of these models reveals a consensus among experts: digital transformation exceeds the mere implementation of individual technologies; it necessitates the creation of a complex of technologically interconnected assets and the expansion of business capabilities. The models typically include components such as technology, digital culture, digital skills, operations, and processes (Table 2). The digital maturity assessment framework under the European Commission's program «Digital Europe» introduces fundamentally new components [18]. According to this model, the digital maturity of enterprises, particularly small and medium-sized ones, as well as public sector organizations, should be measured across specific dimensions:

– digital strategy and investments – the overall status of the enterprise's digitalization strategy, its readiness to embrace digital changes that may require substantial organizational and economic efforts, and investments in digital initiatives across all operational areas;

– digital readiness – the current use of digital technologies, encompassing both foundational and advanced technologies;

– human-centric digitalization – the skills of the staff, their engagement with digital technologies, and the enhancement of employee capabilities that contribute to improved productivity and well-being;

– data management and security – the digital storage of data, its organization, accessibility, and use for business objectives, all while ensuring adequate data protection;

– green digitalization – the organization's ability to undertake long-term digital initiatives with a responsible approach to conserving and sustaining natural resources and the environment.

An additional dimension for public sector organizations under this framework is interoperability – the adherence to standards and shared technical specifications that enable various systems and services to interact with each other, following the European Interoperability Framework. For enterprises, the degree of automation and intelligence provided by digital tools integrated into business processes should also be evaluated.

Digital maturity models are used to evaluate the digital capabilities of enterprises, identify gaps, and prioritize digital initiatives for both short-term and long-term periods, as well as for benchmarking purposes. Given the ever-changing technological landscape and business environment, one of the most critical attributes for enterprises remains their agility – their ability to quickly and effectively respond to changes. In this context, there is a need for a generalized framework to structure the components of existing models. This framework would ensure flexibility and adaptability in measuring digital maturity, facilitate the comparison of different models and the assessment results derived from them, establish goals, and prioritize digital transformation efforts, all while maintaining a comprehensive approach to DT.

Table 1

CHARACTERISTICS OF DIGITAL MATURITY MODELS, DEVELOPED BY CONSULTING COMPANIES

Digital Maturity Model	Features	Key Components or Assessment Areas	Maturity Stages
Deloitte-TM Forum Digital Maturity Model	Offers a holistic view on digital transformation efforts	Customer, Strategy, Technology, Operations, Organization, and Culture	Early, Developing, Maturing
Gartner Digital Business Maturity Model	Pinpoints essential competencies for organizations to focus on for digital business success	Digital Strategy, Leadership, Culture, Capabilities, Ecosystem, Customer Experience, Innovation, Operations, and Management	Initial, Experimentation, Scaling, Transformation, Digital Leadership
Google and Boston Consulting Group Digital Maturity Model	Concentrates on the capabilities for digital marketing	Strategy, Process, Organization, Technology, Customer	Nascent, Emerging, Connected, Multi-Moment
Capgemini Digital Transformation Maturity Model	Categorizes organizations by their digital practices	Transformation Management Intensity, Digitization Intensity	Digital Beginner, Conservative, Fashionista, Digital Elite («Digirati»)
BCG Digital Acceleration Index (Boston Consulting Group)	Evaluates strengths and weaknesses of enterprises relative to competitors, digital leaders, and industry averages	Digital-based Strategy, Core Value Chain Digitization, Digital Growth Stimulation, Work Method Changes via Digital Technologies, Data and Technology Management, Future Readiness, Integrated Ecosystems	Digital Beginner, Knowledgeable, Performer, Leader
The Digital Maturity Model 5.0 (Forrester)	Assesses the systematic application of best digital practices	Culture, Organization, Technology, Insights	Sceptics, Adherents, Partners, Change Agents

Source: Compiled by the author based on [19–27]

Table 2

COMPONENTS OF ACADEMIC MODELS OF DIGITAL MATURITY

Rank by frequency of mention	Key Components	
	Models for a specific field of activity	General-purpose models
1	Technologies	Digital Culture
2	Digital Skills	Technologies
3	Operations and Processes	Operations and Processes
4	Products and Services	Digital Strategy
5	Compliance and Security	Organization
6	Digital Culture	Digital Skills
7	Digital Strategy	Innovations
8	Organization	Customer Understanding and Experience
9	Management	Management
10	Digital Ecosystem	Vision
11	Innovations	Digital Ecosystem
12	Customer Understanding and Experience	Leadership
13	Digital Business Model	Compliance and Security
14	Vision	Products and Services
15	Leadership	Digital Business Model

Source: Compiled by the author based on [28]

Deloitte's expert groups propose several alternative options for defining such a framework. The Deloitte Digital Maturity Index is structured into two sub-indices, which correspond to management and planning levels [29]. The first, a strategic index, encompasses aspects of digital business including parameters like the organization's network of connections, its value creation structure, investments in digitalization, and software services. It also takes into account dynamic capabilities related to managing the life cycle of a company's products, investments in new assets, technology monitoring, and adaptability. The second, an operational index, focuses on digital activities such as the enterprise's investments in smart devices and equipment, smart planning, connected client applications, and efficient logistics. It further includes digital capabilities that emerge from the integration of digital technologies into business processes, operations, and corporate culture, support from top management, clear roadmaps, and a focus on intelligent key performance indicators. Deloitte China's Risk Advisory group identifies three key pillars for evaluating an organization's digital maturity: digital strategy, technological processes, and agile organization [30]. Meanwhile, Deloitte Digital's Austrian team suggests a comprehensive approach to assessing the digital maturity of enterprises, incorporating several key aspects:

– dimensions – digital human resources, digital processes, digital technologies;

– focus areas – strategy and transformation, organization, distribution, marketing, customer service, digital products, data and reporting, front-end technology, back-end infrastructure;

– core processes – IT, HR, procurement, finance, and technical processes [31].

Each of the mentioned approaches is well-founded and emphasizes important areas for applying digital technologies, yet it is the architecture of the enterprise that enables their orderly integration. Based on the analysis of existing maturity models within the context of enterprise architecture levels, the following key digital technology aspects were identified: digital infrastructure, data management, and digital intelligence, the digitization of operations, as well as digital marketing and digital business. Each of these aspects requires investments and a holistic approach to decision-making, planning, and design. This involves engaging qualified professionals, training staff, implementing organizational and managerial changes, reengineering business processes, and developing a specific corporate culture. Particular attention should be paid to digital alignment.

Table 2

DIGITAL TRANSFORMATION ACROSS ENTERPRISE ARCHITECTURE LEVELS

<table>
<tr><th>Enterprise architecture levels</th><th colspan="2">Key aspects of digital transformation</th></tr>
<tr><td>Business Architecture</td><td>Digital business models, digital business</td><td rowspan="4">Digital development and alignment</td></tr>
<tr><td>Application Architecture</td><td>Digital operations, digital marketing</td></tr>
<tr><td>Information Architecture</td><td>Information asset management</td></tr>
<tr><td>Technology Architecture</td><td>Digital infrastructure</td></tr>
</table>

Source: Developed by the author

For many companies, digital transformation starts with modernizing their **IT infrastructure**. This process equips enterprises with the latest tools to enhance economic efficiency, accelerate operations, boost employee satisfaction, improve customer service, and reduce maintenance costs. Managing digital infrastructure involves deploying and administering technological components, systems, and services that support an enterprise's digital activities. The goals of rapidly and adaptably meeting business demands and providing necessary technological resources, such as computing power and data storage, are accomplished through the implementation of on-demand services using cloud platforms such as Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform, combined with virtualized infrastructure. This configuration enables the provisioning of virtual instances of computing resources, like servers and networks, on physical servers. Federated access management secures and controls access to corporate resources, while digital continuity management ensures the stability and reliability of digital services. Distributed computing technologies enable the sharing, selection, and aggregation of various resources, including computing power, storage, and data, across a network, typically the Internet. Parallel processing services, especially those using grid computing, are applied to process large data volumes and address complex computational tasks. Other types of services enhance interactions with users and between business processes and systems, improving operational efficiency and optimization. In sectors such as manufacturing, healthcare, and smart city development, where quick and efficient data processing is crucial, creating a flexible and highly effective system that integrates cloud computing with edge computing technologies is ideal. This combination significantly reduces data transmission delays and decreases the overall strain on network resources, optimizing data processing and expanding the system's capabilities.

Digital infrastructure creates a foundation for the effective management of **digital informational assets** – such as data, content, and knowledge – that are crucial for an enterprise and can be leveraged to support strategic development and enhance operational efficiency. Digital data management is a vital component of contemporary business strategies and encompasses a comprehensive set of policies and technologies for managing the large volumes of data generated and stored by enterprises. Specifically, the management of non-relational data involves handling data in various formats, including text, multimedia files, and data in JSON and XML formats, among others. Primarily, this data is used to enhance analytical capabilities, uncovering valuable insights, trends, and relationships that can improve business strategies. It also facilitates the personalization of products and services, forecasting, risk analysis, marketing and advertising enhancements, supply chain optimization, security enhancement, fraud detection, and acceleration of market-responsive actions. Additionally, it supports the development of new products and services and enhances collaboration and communication.

Large enterprises dealing with large data volumes use distributed data storage systems to organize secure storage and collective access to data. Enterprise search systems assist in locating relevant information within vast data pools. To achieve a unified, consistent view of data, Master Data Management (MDM) is employed-dealing with critical data, typically involving customers, products, employees, suppliers, and other aggregated enterprise data used across various departments and systems. MDM solutions and practices are essential for organizations to ensure data accuracy, facilitate informed decision-making, enhance operational processes, improve data quality, and meet regulatory requirements. Data quality management ensures the accuracy, consistency, and reliability of data. The development and implementation of data management policies and standards lead to processes for validation, quality control, and data cleansing. Enterprises must establish policies for data privacy, access, storage, security, backup, archiving, restoration, and deletion, as well as standards for data processing and exchange.

Enterprise content management encompasses a comprehensive set of activities aimed at creating, managing, storing, distributing, and archiving valuable information, including text, graphics, audio, and video materials. Content plays a key role in various management tasks such as corporate communications, public relations, brand building, promoting products and services, attracting potential customers, maintaining consumer relationships, providing service and support, disseminating corporate news, policies, and procedures, and facilitating training and staff development. It also enhances collaboration on projects. The initial step in content management involves defining the goals and target audience of the content, which helps ensure its relevance, followed by planning a content strategy that encompasses production, editing, publication, and monitoring. Content management systems simplify the creation, editing, and publication of content, as well as version control, ensuring the content remains current, compliant, and effective. The aggregation and syndication of content allow for its distribution across various platforms and channels, significantly extending its reach. Simultaneously, it is crucial to ensure the protection of copyright and intellectual property, as well as adherence to regulatory requirements related to the publication and distribution of content. Collecting and analysing feedback from users and audiences is an essential part of the process, enabling the evaluation of content effectiveness and its impact on achieving the enterprise's business objectives.

Knowledge management within an enterprise encompasses a wide range of tasks focused on the effective use of intellectual capital. This process aims not only to enhance the company's innovative potential and adaptability in response to market changes but also to improve the productivity and professional skills of its employees. It starts with identifying and gathering key knowledge that is valuable to the business from various sources, including internal documents, processes, and the experiences of employees. Key tasks in knowledge management include organizing and consolidating relevant knowledge, ensuring that all employees have access to the company's accumulated knowledge or 'collective memory,' conducting semantic searches and filtering knowledge across corporate and global information resources, and fostering collaboration among high-performing professionals in the idea generation and decision-making processes. Additionally, it is crucial to establish an environment for online interaction among distributed project and business teams, professional communities, and experts. Equally important is creating a networking environment that enhances professional development and fosters a corporate culture supportive of management and business processes.

Artificial intelligence technologies are opening new frontiers for knowledge management within enterprises, offering substantial advantages compared to traditional methods. AI-based systems provide a high level of personalization, adapting knowledge according to the unique preferences and needs of each user. Additionally, they maintain the relevance of knowledge by automatically detecting and updating it across various sources and integrating this knowledge into the enterprise's unified repository. The automation of processes for searching knowledge, analysis, and decision-making not only reduces system maintenance costs but also enhances resource efficiency. Moreover, artificial intelligence introduces adaptability and autonomy into the management of organizational knowledge, thereby transforming traditional practices in management, utilization, and value derivation from knowledge assets. This enhancement aids in leveraging gathered knowledge to support decision-making, stimulate innovation, enable strategic planning, and optimize business processes.

The digitalization of enterprise operations typically begins with the transition from analog to digital methods. However, businesses gain more significant benefits when they begin to optimize and simplify their business processes using modern technologies. This approach fosters the development of digitally intensive enterprises, which incorporate digital tools and data analytics into their daily operations. According to the OECD, digital sectors, particularly those that are highly digital-intensive, are more dynamic than other economic sectors and are major drivers of economic growth and employment [32–34]. Enterprises whose employees actively use digital tools, including in interactions with customers and suppliers, gain advantages that stimulate innovation, productivity, and growth. This shift demands a special focus on a range of entirely new challenges, such as digital marketing, managing digital customer experiences, customization and personalization in customer interactions, managing digital channels, fostering social interactions, and harnessing digital intelligence.

Digital marketing encompasses a broad set of strategies and techniques aimed at boosting brand visibility in the digital space and attracting customers. This approach includes digital brand marketing, focused on creating a strong digital image of the brand through innovative content and leveraging online platforms. Search engine optimization (SEO) plays a key role in increasing website traffic and enhancing search engine rankings. Tools such as paid search and targeted content are used to attract specific audiences through contextual advertising and personalized offers. Affiliate marketing and online advertising significantly contribute to broadening reach and capturing new customers. Managing digital campaigns, leads, and marketing offers is aimed at optimizing marketing efforts. Email and mobile marketing open new horizons for customer engagement, and marketing automation along with conversion optimization enhances the overall effectiveness of marketing initiatives and the accuracy of measuring their results.

Managing the digital customer experience requires a thorough examination and optimization of all interaction points between customers and the company in a digital environment. This approach encompasses the development of strategies from the initial brand interaction to fostering long-term engagement, aiming to ensure a consistently positive user experience throughout their digital journey. It is crucial to focus on understanding users' needs and preferences, analyzing their behavior, and assessing their responses to various digital products and services. The design of intuitive interfaces, rigorous functionality testing, and usability assessments, as well as ongoing improvements based on data collection and user feedback, are essential tasks. These efforts are key to cultivating a seamless and rewarding digital experience, ultimately building customer loyalty to the brand.

Customization and personalization are crucial in customer engagement. Managing these interactions involves tracking individual customer behaviors, analyzing their needs and preferences in depth, and creating of individual user experiences. This continuous improvement process helps maintain customer loyalty. A vital aspect of this approach is managing customer communications, which focuses on enabling effective feedback mechanisms to enhance interaction and information sharing. Furthermore, overseeing social behavior is essential for understanding the impact of social networks and digital interactions on customer decision-making. Digital services for customers also form a core part of this strategy, making interactions with the company more convenient and accessible, ultimately boosting overall customer satisfaction.

Digital channel management entails developing strategies and techniques that enhance the efficiency of various distribution and communication channels, along with optimizing their combinations for increasing outcomes. Utilizing analytical tools allows for the measurement and optimization of each channel's performance to maximize resource efficiency. Digital integration facilitates seamless connections and interactions between diverse business structures and channels, thus enhancing the overall customer experience. This integration also enables consumers to have continuous and consistent interactions across different devices. Collectively, these elements contribute to establishing a robust and cohesive digital presence. Managing user feedback across platforms is crucial for maintaining service quality and enhancing products or services. Moreover, integrating social media and other digital platforms creates a comprehensive communication environment where customers can find information, engage with the brand, and make purchases. Collaborating with influencers and other brands on joint marketing campaigns can effectively broaden the audience and boost sales. This strategy not only extends the brand's digital footprint but also helps achieve strategic business objectives.

Social interaction is pivotal in cultivating customer relationships in the digital world, beginning with social monitoring — the tracking and analysis of user activities. This approach enables companies to adapt to evolving trends and consumer preferences, facilitating timely responses to their needs. Marketing through social networks and digital customer service platforms enhances active engagement and retention, fostering long-term relationships. Managing online communities, as well as addressing ratings and feedback, is critical in maintaining a positive brand image and fostering a platform for dialogue and customer engagement. Additionally, content moderation and crisis management in social media are essential for sustaining a positive reputation. Prompt and effective handling of negative situations is crucial for maintaining customer trust and loyalty.

Digital intelligence encompasses a broad range of analytical tools and methodologies designed to enhance the effectiveness of digital strategies. For instance, product similarity analysis can identify and recommend products that align with customer interests and needs. Customer reviews and client segmentation provide deeper insights into distinct user groups and their preferences, enabling companies to tailor their offerings more effectively. Analytics on conversion rates and digital marketing effectiveness help assess the success of marketing campaigns and guide adjustments to improve profitability. Big data and web analytics offer valuable insights into client behavior and their interaction with digital content. Additionally, Internet of Things (IoT) technologies allow for data collection from a variety of sensors, devices, and equipment, facilitating remote monitoring and management of connected assets. This data can be leveraged to optimize business processes, such as maintenance scheduling for equipment or managing the supply chain. Dashboards and reports visualize data and trends, supporting well-informed management decisions.

While digitization of operations focuses on supporting and enhancing key business processes, **digital transformation of business models** lays the groundwork for companies to secure unique competitive advantages by altering these models. Changes can occur at the level of individual components, the entire business model, the value chain, or the integration method of various stakeholders into a value-added network. The most significant business model transformations are often linked to the development of digital platforms, which establish the technological basis for creating an e-business ecosystem with these main characteristics:

− it features an open environment with clearly defined formal and informal rules and guidelines;

− the roles of participants are not fixed and can vary.

− algorithmic management is employed, where the right and responsibility for assigning tasks and making decisions are granted to platform control algorithms with minimal human intervention. These algorithms are capable of self-learning from accumulated data.

− there is mutual benefit (not exclusively economic) for all participants, which operates on a win-win principle and is proportional to the number of participants involved (scale of the platform).

Service business models and marketplaces are increasingly common and show great promise. Service business models, particularly those operating under the Everything-as-a-Service (XaaS) concept, utilize resources rather than purchasing them outright. Offerings include Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Data Center-as-a-Service (DCaaS), Software-as-a-Service (SaaS), Desktop-as-a-Service (DaaS), Banking-as-a-Service (BaaS), and artificial intelligence solutions. These are variations of the traditional subscription business model where clients pay a fixed fee, monthly or annually, for access to a product or service tailored to their needs. Currently, the most prevalent model is SaaS (Software-as-a-Service or «Software on Demand»), which allows multiple clients to remotely use an application hosted in the cloud, completely managed by the provider. Ownership of the product stays with the supplier company, which is responsible for selecting and managing the products, providing service maintenance, and monitoring user experience, usage parameters, and characteristics to enhance products and services. The «economy of scale» achieved through a single software core used by all clients helps save resources and reduce service costs. Another advantage is the prevention of unauthorized software usage. For consumers, this model is attractive because it eliminates the need to invest heavily in hardware and software, replacing substantial upfront costs with more manageable periodic payments and offering the flexibility to adjust resource consumption dynamically. This model is generally not suitable for applications requiring highly specific customizations or tasks that involve the accumulation and processing of sensitive information.

Product-as-a-Service (PaaS) models provide customers with a comprehensive suite of products and services. Alongside the product itself, customers receive instructional support, advice, or other assistance to enhance their product experience, as well as service maintenance and product updates. One of the services may be the opportunity to learn from the experience of using the product or contacting the company based on customer feedback. In certain scenarios, this model is designed to create a complex array of products and services that motivates customers to make new purchases or further engage with the company. As a result, the company can implement various pricing strategies. Under the Freemium Model, the product or service is available at no cost, with charges applied only for advanced functionalities or additional products and services. Alternatively, the payment could be in the form of agreeing to view advertisements, which generates revenue for the provider. In the Free Model, the provider offers the product or service for free but earns revenue from advertising or by selling data about customer preferences, which can later be used for targeted advertising.

A marketplace is a digital platform that serves as an intermediary between suppliers (sellers) and consumers (buyers). This model enables the platform to earn revenue through advertising, transaction fees (commissions), charges for additional services provided to participants, or fixed membership fees. Additionally, the data collected are utilized to enhance services. A specific example of this business model includes hypermarkets, which offer a broad range of products and services, some of which are exclusive, and pyramids that facilitate cooperation with third parties, especially goods sellers. Companies may also integrate elements from multiple business models. For consumers, a marketplace offers a broader selection of products at potentially lower prices. For suppliers, it offers a quick way to start selling and to enter both local and international markets, all within a supportive and secure environment. The owning company manages the website and mobile apps for accessing the marketplace, conducts marketing activities, strives to attract users (both buyers and sellers), acts as a market operator, ensures transaction security, and handles various administrative tasks.

Digital platforms have become the foundation for new business models across various industries. They encompass a broad spectrum of sectors, including transportation, exemplified by Uber, and delivery, highlighted by Glovo. In tourism, platforms like Airbnb and Booking have redefined accommodation booking practices. The financial sector is also experiencing a digital transformation with platforms such as Afluenta, KiaKia, and Lending Club, which deliver innovative financial services. The entertainment industry has been transformed by services like Netflix and Spotify, while media giants such as Bloomberg and Reuters leverage digital technologies for news distribution. The advertising and marketing sectors have undergone significant changes due to platforms like Baidu, Facebook, Google, and OLX. The review and recommendation industry is being reshaped, as demonstrated by Tripadvisor. In education, platforms such as Coursera, edX, and Udacity are creating new opportunities for learning and development. Meanwhile, Upwork and TaskRabbit are pioneering new horizons for the labour market and freelancing.

Conclusions

The development of digital platforms underscores the critical importance of aligning digitalization initiatives with the strategic business objectives of a company. Digital infrastructure and digital information assets, essential for achieving digital transformation goals, must be seamlessly integrated into all business operations. The digitization of operations and the shift towards new business models should be carried out with consideration of both the short-term and long-term strategic goals of the company. In this context, managing digital programs and projects involves detailed planning and control over complex digital initiatives, as well as the coordination of all digital resources and processes. It also requires effective knowledge exchange with partners and stakeholders. Furthermore, it is crucial to ensure the ongoing innovation in digital technologies to enhance products, services, and processes, boost competitiveness, exploit new digital opportunities, and adapt to changing market conditions and customer expectations.

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CONCEPTUAL PRINCIPLES FOR RESILIENT DEVELOPMENT OF ENERGY INFRASTRUCTURE

1. State of the Energy Sector and Contemporary Challenges

The war has significantly impacted the functioning of the Ukrainian energy sector. Due to their economic, humanitarian, and geopolitical significance, energy infrastructure facilities are frequent targets of Russian aggression. Despite this, the Ukrainian power system has demonstrated remarkable resilience, and energy professionals have shown exceptional skill in maintaining the sector's stability even during wartime. As of July 2022, the «Energy Security» working group's materials for the Ukraine Recovery Plan noted that approximately 4 % of generating capacity was destroyed in combat, with another 35 % located in occupied territories. Notably, the largest nuclear power plant in Europe (Zaporizhzhia) operates within the Ukrainian power system but remains under constant pressure from Russian occupiers. The plant's production capacity is 6000 MW, which accounts for 43 % of the total capacity of all Ukrainian nuclear power stations.

Since October 2022, extensive attacks on energy infrastructure have posed new challenges not only for the stable operation of Ukraine's energy sector but also for the European energy system ENTSO-E, which Ukraine joined on March 16, 2022. Against this backdrop, research on enhancing and ensuring the resilience of Ukraine's energy sector is critically important. Moreover, the relevance of research in this field is underscored by a clear trend in the increase of relevant scientific publications worldwide (from ten publications in the Scopus database in 2013 to over one hundred in 2023). Therefore, the conceptual principles of economic, ecological, and technological functioning and development of energy facilities must consider and rely on the concept of resilience.

The timeliness and prospective nature of research in this area are also evidenced by the fact that the introduction and a specific section (Strengthening Cybersecurity and Resilience in the Energy System) of the EU action plan for digitalizing the energy system (Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions, Strasbourg, 18.10.2022) are linked specifically to enhancing energy resilience.

Although there is currently no universally accepted definition of «resilience» in scientific publications and normative documents worldwide, one of the most comprehensive definitions can be considered as proposed based on publication [1]: resilience of a particular system is its ability to counter hybrid threats, absorb disruptions, reorganize, maintain essentially the same functions and feedback over time, and continue to evolve along a certain trajectory. This ability arises from the nature, diversity, redundancy, and interaction among components involved in creating various functions. Resilience is a system attribute and applies to various subsystems.

The practical significance and importance of this direction are further emphasized by the fact that ensuring the resilience of Ukraine’s electrical power as a component of the country’s national stability is among the main strategic tasks, as noted in the national report «National Resilience of Ukraine: Strategy for Responding to Challenges and Preempting Hybrid Threats» [2].

2. General Concept of Resilience

«Resilience» is a term that has become the subject of active discussion and is used in various contexts, sometimes being misinterpreted. This ambiguity can lead to poor outcomes and distort the fundamental concept underlying the management of diverse complex systems such as ecosystems, businesses, societies, rivers, cities, communities, and energy sectors.

In general terms, resilience is defined as the ability of a system to withstand impacts and maintain its functionality at a roughly equivalent level. It is measured by the extent to which a system can experience significant changes without crossing a critical threshold and shifting into a state from which it would need to recover. Based on the analysis of publications, particularly drawing on research [3], let us consider the general concept of resilience.

The concept of resilience comprises two important aspects: firstly, the system should be able to recognize and avoid (or, if necessary, adapt to) critical points or barriers; secondly, it should have the ability to avoid crossing unknown and unexpected barriers by exploring the attributes of the system that provide its overall resilience.

It is important to note that resilience is not always a desirable quality. For example, dictatorial regimes, degraded landscapes, and pathological states of individuals can be highly resilient. However, the main challenge lies in knowing how to reduce resilience in such cases [3].

The most common misinterpretation of resilience is perceiving it as «recovery». In reality, resilience involves the ability to adapt and change, reorganize while maintaining functionality. It's about changing to remain stable. A resilient system responds to disturbances by altering the interaction of its components and how it functions. It remains a learning system that adapts from its mistakes to better handle similar challenges in the future. It does not return to its previous state. Resilient systems are learning and evolving systems.

Moreover, it is important to distinguish resilience from reliability. Reliability typically indicates the ability of a system to withstand impacts while remaining unchanged, sometimes referred to as «technical robustness». This significantly differs from the idea of resilience, which involves change and adaptation in response to impacts. However, variations in interpretations exist where these two concepts are distinguished. But in environments of decision-makers who are not researchers, there is a tendency to perceive resilience as «hardening», as the ability to remain unchanged and robust against changes and stress. Overall, this can lead to a deterioration in resilience.

Equally important is the necessity to create resilience not only to specific threats but generally to all aspects of a system in the face of any disturbances. Excessive resilience in one aspect can lead to a loss of resilience in another. For instance, attempts to increase a forest's resilience to fires through extensive use of controlled burning can decrease the resilience of small animal species during droughts. Forests with high spatial diversity, featuring various stages of post-fire recovery, are generally more resilient to diverse disturbances than forests focused solely on creating fire resistance. Let us consider more aspects that contribute to overall resilience, and below are some of the key attributes that often remain unnoticed or misunderstood [3]:

1. Diversity of Responses: The first attribute on the resilience list is recognizing the importance of diverse methods to achieve the same result, considering different possibilities for responding to various types of disturbances. For example, in some ecosystems, plants, particularly legumes, have the ability to remove nitrogen from the air, which is crucial for the health and productivity of the entire ecosystem. In a resilient ecosystem, this function can be performed by various plant species, each capable of responding differently to external influences such as drought, frost, fire, disease, etc. Regardless of changes in the

environment, a resilient ecosystem can continue to fix nitrogen. However, in modern society, the management of corporations, public sector agencies, and various complex structures often dominates the paradigm of «efficiency» and «minimizing the unnecessary», which can lead to a lack of response diversity. At the same time, investments in maintaining response diversity, which is important for supporting resilience, are undervalued or not properly considered.

2. Impact of Disturbances: An ecosystem always protected from fire gradually loses its ability to withstand fire, although some species may need fire for seed sowing. Where fires are a natural part of the environment, it is necessary to periodically allow fire to maintain resilience. However, it is important to know the limits that cannot be crossed; too intense or insufficiently intense fire can cause serious damage and lead to the loss of other species. A comparison can be made that children who are forbidden to play in the dirt may grow up with a weakened immune system and develop allergies later in life. Attempts to completely prevent one type of disturbance for the sake of safety can worsen resilience. To ensure resilience to various types of disturbances, access to a full spectrum of ecological (natural and social) conditions is necessary. This can be compared to a probing process in which it is necessary to avoid crossing the boundary of stresses and disturbances.

3. Modularity: This is the ability of a system to be neither too strongly nor too weakly connected. Too strongly connected systems are vulnerable to the rapid spread of diseases (such as the coronavirus), cascading failures (for example, the global financial crisis), improper task performance, bad ideas, etc. On the other hand, insufficiently connected systems may be inadequately efficient in management, learning, and responding to crises and other challenges. The correct modularity of a system depends on the specific context and requires a careful balance between the level of connections and separateness. This balance requires constant monitoring and adjustment, as changes in one aspect can affect others.

4. Speed of Response to Shocks and Changes in the System: The ability to quickly respond to unexpected events and changes in the system is crucial for resilience. Having too many stages in the reporting and approval procedure can significantly slow down the response to events. The widespread tendency to add more checks and approval processes to ensure safety and legal compliance can reduce resilience and lead to bureaucracy. Therefore, it is important to ensure the efficiency of regulated processes and simplify the response to crises.

5. Capacity for Transformation When Necessary: Sometimes it is necessary to make fundamental changes to the system if it is threatened

by catastrophic change or due to changes in the environment. Resilience includes understanding when transformation is inevitable and the ability to rethink the system or its components in such a way that the new system provides what is most valued and necessary. Transformation may require changes in goals and approaches and may occur under changed environmental conditions. It is important to recognize the need for such a capacity for transformation to maintain the resilience of the system. The resilience of systems is a critical aspect of ensuring their stability and ability to withstand various challenges and disturbances. Resilience and transformation are not opposites; they can be complementary. Maintaining resilience at one level may require transformative changes at other levels.

6. Thinking, Planning, and Managing at Various Levels: One of the most common reasons for undesirable outcomes in planning and management is focusing only on the level of the perceived problem. A resilient complex system cannot be understood or managed at a single level. All complex systems operate at multiple levels, and the interaction between levels is critical for resilience. In some cases, cross-level effects reduce resilience at the focus level, in others, they enhance it.

7. Leadership, Not Management: The future environment and future states of all complex systems are inherently uncertain. Attempts to design and manage them towards some desired state are doomed to fail. Resilience involves maintaining capabilities, learning how to manage the system within a set of «good» states, and avoiding transition to «bad» states. This involves learning where not to go, rather than ideally managing where to go.

In the context of resilience, it is important to consider various attributes and aspects that contribute to a system's ability to survive and function in conditions of uncertainty and change.

First, it is important to consider the diversity of responses, which means recognizing the importance of different methods of achieving the same result, considering different types of disturbances. A resilient system must be able to respond to various external influences, such as drought, frost, fire, diseases, etc. A lack of response diversity can lead to a loss of system resilience.

Second, systems should be modular, i.e., capable of being neither too strongly nor too weakly connected. Too strong connectivity can make the system vulnerable to the rapid spread of failures, while insufficient connectivity can impair its management and coordination.

Third, the speed of response to shocks and changes in the system is important for resilience. Systems should be able to quickly adapt to unexpected events and changes in conditions.

Fourth, the ability to transform the system when necessary is also important for resilience. Sometimes fundamental changes need to be made to the system to ensure its ability to adapt to new conditions and challenges.

In addition, systems must be capable of thinking, planning, and managing at various scales, as all complex systems operate at multiple scales, and the interaction between them is crucial for stability. Managing and learning how to manage the system within a set of «good» states is an important aspect of resilience, as well as avoiding the transition to «bad» states.

It should also be noted that attempts to protect the system by maintaining it in a constant state can impair its resilience. It is important to consider the impact of the full spectrum of changes and take into account all resilience attributes for proper assessment and support of system stability.

3. Resilience of Systems

The guidance framework for resilience includes risk analysis as a central component. Risk analysis depends on characterizing threats, vulnerabilities, and the consequences of adverse events to determine the expected loss of critical functionality. The definition of resilience by the U.S. National Academy of Sciences incorporates risk within a broader context of a system's ability to plan, recover, and adapt to adverse events over time. Within the system's functionality profile, risk is interpreted as a general reduction in critical functionality, and system resilience is associated with the slope of the absorption curve and the shape of the recovery curve—indicating the temporal effect of the adverse event on the system. The dashed line indicates that highly resilient systems may adapt in such a way that the system's functionality may improve relative to its initial performance, thereby enhancing the system's resilience to future adverse events. A roadmap for enhancing the resilience of any complex system should include the following [4]:

– Specific methods for defining and measuring resilience;

– New modeling and simulation techniques for highly complex systems;

– Development of resilience engineering;

– Approaches to stakeholder engagement.

Necessary strategies for engaging with policy receivers to support the transition to resilience management through legislative, regulatory, and other means are essential.

The U.S. National Academy of Sciences defines resilience as «the ability to prepare and plan for, absorb, recover from, and successfully adapt to adverse events». Conceptually, risk analysis quantitatively assesses the probability that a system will reach the lowest point of its critical functionality profile. Risk management helps the system prepare and plan for adverse events, while resilience management goes further by integrating the system's temporal potential to absorb and recover from adverse events, and then adapt (Fig. 1).

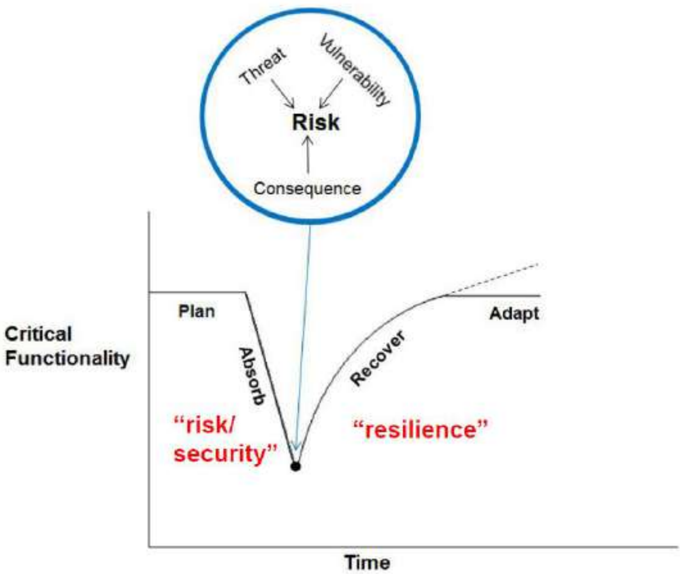

Figure 1. Illustration of System Resilience

Source:[4]

Resilience is not a substitute for fundamental system design or risk management. Instead, resilience is a complementary attribute that utilizes strategies of adaptation and mitigation to enhance traditional risk management. Strategies for enhancing resilience can take the form of flexible response, decentralized decision-making, modularity, redundancy, ensuring component interaction independence, or a combination of adaptive strategies to minimize functionality loss and enhance the steepness of the recovery curve (Fig. 2).

The magnitude of the initial disturbance reflects the overall risk to the system, while the shape of the recovery curve is controlled by the system's resilience. The area under the curve is an indicator of the system's overall functionality. Systems facing high risks and high resilience perform better than those facing similar risks but with low resilience. Systems with low risk but also low resilience may perform as well as systems with high risk and high resilience.

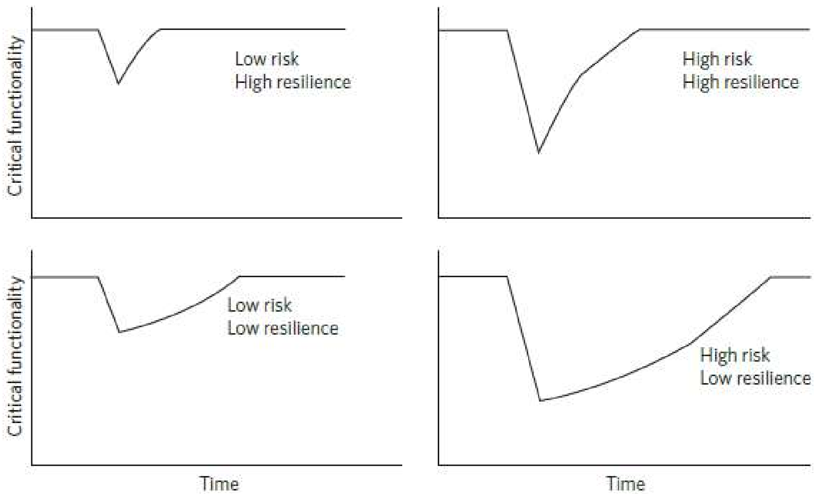

Figure 2. Schematic Representation of Changes in Critical Functionality Over Time Demonstrates the Interaction of Risk and Resilience in System Performance During an Adverse Event

Source: [4]

4. Taxonomy for Energy Resilience

Overall, a review of the literature allows for the determination of a suitable taxonomy for energy resilience. The most useful classification can be obtained by considering key terms extracted and derived through textual analysis [5, 6]:

1. Resilience in Systems: Utilizing flexibility and adaptability to adverse impacts [7, 8].

2. Approaches to Energy Resilience that emphasize and explore the concept of assessment and metrics. Assessment is fundamental for ensuring appropriate resilience measures [9]. These measures should be aimed at improving economic performance and environmental sustainability.

3. Approaches to Energy Resilience that emphasize the concept of security and analyze potential sources of risk management [10,11]. The diversity of energy supply sources and sustainable resources is a fundamental issue in this context [12].

4. Urban or Regional Approaches to Energy Resilience – where resilience is emphasized and based on the spatial level [13].

5. Community-based Approach to Energy Resilience, focused on specific and active support of local communities [14]. The community approach to energy resilience aims to balance social values and environmental impact.

6. Policy-based Approach to Energy Resilience, involving national-level interventions [15].

7. Sectoral Approaches to Energy Resilience (biofuels, bioenergy, etc. [16]).

5. Indicators of Energy Resilience

Based on a review of the literature, 20 key indicators have been identified that can be used to assess the resilience of the power sector:

1. Reliability of Energy Supply: Frequency and duration of energy supply interruptions.

2. Diversification of Energy Sources: Variety and distribution of energy sources.

3. Energy Reserve Capacity: Level of strategic energy reserves.

4. Flexibility of the Energy System: The ability of the system to adapt to changes in consumption (demand) and generation (supply).

5. Recovery Efficiency: Speed of the energy system’s recovery after disruptions.

6. Renewability of Energy: Percentage of renewable sources in the overall energy balance.

7. Energy Independence: Degree of dependence on imported energy sources.

8. Financial Stability of the Energy Sector: Ability of the sector to withstand financial fluctuations.

9. Level of Technological Advancement: Use of advanced technologies in the energy sector.

10. Cybersecurity: Protection of energy infrastructure from cyberattacks.

11. Environmental Sustainability: Impact of energy activities on the environment.

12. Market Integration: Ability to operate effectively under market conditions.

13. Social Support: Level of public support for energy policy.

14. Institutional Stability: Stability and efficiency of energy legislation and policy.

15. Climate Change Resilience: Ability of the system to adapt to the effects of climate change.

16. Energy Accessibility for the Population: Level of accessibility and price dynamics of energy for consumers.

17. Infrastructure Reliability: Condition and efficiency of energy infrastructure.

18. Innovativeness: Level of implementation of new technologies and innovative solutions.

19. International Cooperation: Collaboration in the international energy sector.

20. Regulatory Adaptiveness: Ability of legislation to quickly adapt to changes in the sector.

6. Components of Resilience

The resilience of the power sector is defined by several key components that allow the system to withstand, adapt to, and recover from various types of disruptions or challenges (Fig. 3). Analysis of contemporary scientific approaches has identified the following main components of power sector resilience:

1. Modularity: The system’s structure is divided into independent modules that can function separately. This allows for isolating issues and preventing their spread throughout the system.

2. Flexibility: The system’s ability to quickly adapt to changes in energy demand and supply, as well as new operating conditions.

3. Reliability: The system’s stability during designed and emergency conditions, capable of preventing or minimizing supply interruptions.

4. Recoverability: The system’s ability to quickly recover from interruptions and damages.

5. Diversification of Energy Sources: Utilizing a variety of energy sources (renewable, fossil, nuclear) to reduce dependence on any single type of resource.

6. Cybersecurity: Protection of systems from cyberattacks and other forms of cyber threats.

7. Infrastructure Robustness: The physical robustness of the energy infrastructure, capable of withstanding natural disasters and other physical challenges.

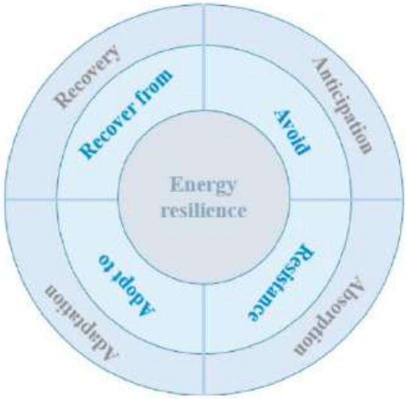

Figure 3. Main Components of Energy System Resilience

Source:[1]

8. Environmental Sustainability: Minimizing negative environmental impacts, ensuring sustainable resource use.

9. Innovativeness: Implementation of new technologies and solutions to enhance the efficiency and resilience of the system.

10. Regulatory Support: Presence of legislative and regulatory frameworks that facilitate the development and support of resilience.

11. Social Responsibility: Considering the needs and interests of local communities and consumers.

12. International Cooperation: Collaboration with other countries and international organizations for knowledge and resource exchange.

13. Risk Management: Identification, analysis, and management of potential risks to the system.

14. Integration of Renewable Sources: Incorporation of renewable energy sources, such as solar and wind, to provide additional resilience.

15. Organizational Structure: Effective management, organizational structures, and procedures that facilitate response to challenges and ensure resilience.

7. Assessing the Resilience of Power Systems

Authors [17] have proposed a framework of approaches for measuring resilience (Fig. 4), divided into two main categories: «Metric-Based» (individual metrics, indices, dashboard analytics, and decision analytics) and «Model-Based» (processes, statistical/Bayesian, networks, game-theoretic approaches, and simulations/agent-based). Each subcategory pertains to different methods of analysis and tools that can be used to assess the system's resilience.

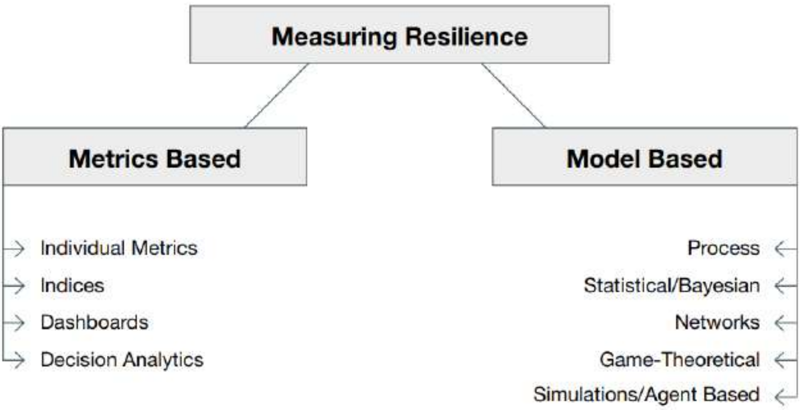

Figure 4. Metric and Model Approaches
to Resilience Assessment

Source:[17]

The graph (Fig. 5) depicts two trajectories of system value over time: one with resilience (green line) and another without resilience (red line). The stages of system development are marked as «Diagnosis and Conceptualization», «Design and Implementation», and «Operation and Maintenance». The green line illustrates an increase in value over time due to resilience, whereas the red line shows lesser value growth and a potential collapse of the system. The difference between the two curves illustrates the «value of resilience».

Table 1 presents a set of characteristics and factors affecting the resilience of energy systems, including references to sources that have explored them. Robustness and speed are considered in the context of infrastructure systems and were discussed in [18]. Adaptiveness, anticipation of unexpected events, response, and recovery in supply chains were explored in [19]. Planning/preparation, recovery, absorption, and adaptation regarding energy systems are discussed in [20].

Article [21] proposes a multi-criteria decision-making (MCDA) approach to assess the resilience of electricity supply, considering the interaction of criteria. The study evaluated 35 European countries using 17 interrelated assessment criteria through two complementary MCDA methods. Choquet integrals were used as importance measures to adequately account for interactions among criteria.

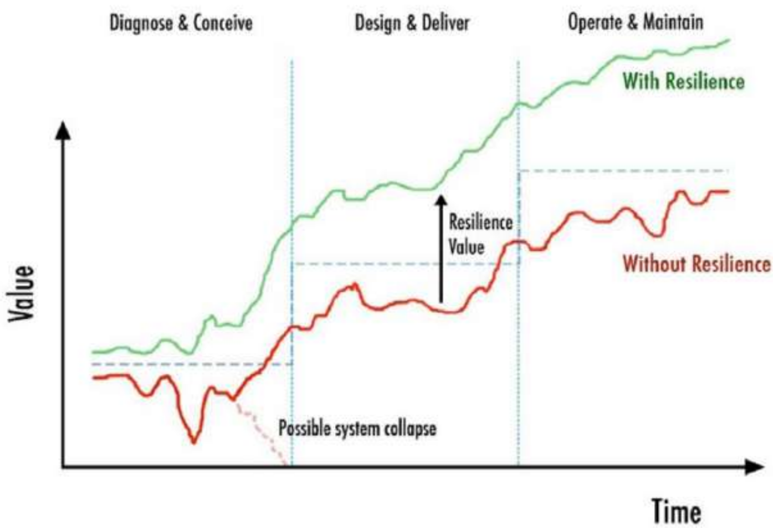

Figure 5. Illustrative Example of Value Generation under the Impact of Shocks and Stressors

Source: [17]

A detailed analysis of indicators and models for assessing the resilience of power systems is presented in [1]. Specifically, the Resilience Indicator (RC) as a measure for calculating system resilience. They divided the cost of resilience into two categories: costs associated with reduced system performance (SI), and costs associated with recovery measures (TRE). Thus, the cost of resilience is calculated as a function of System Impact Cost (SIC), Market Recovery Cost (MREC), Transport Recovery Cost (TREC), and Target Market Value of Production (TMV):

$$RC = \frac{SIC + MREC + TREC}{TMV}$$

Table 1

SET OF CHARACTERISTICS AND FACTORS OF ENERGY SYSTEM RESILIENCE

Characteristics and Factors	Considered Systems	Source
Robustness, Speed	Infrastructure Systems	McDaniels et al. (2008) [18]
Adaptiveness, Anticipation of Unexpected Events, Response, Recovery, System Control	Supply Chains	Ponomarov and Holcomb (2009) [19]
Anticipation of Unexpected Events, Adaptive Response, System Control, Robustness	Supply Chains	Ponis and Koronis (2012) [22]
Planning/Preparation, Recovery, Absorption, Adaptation	Energy Systems	Roege et al. (2014) [20]
Resilience, Recoverability	Supply Chains	Melnyk et al. (2014) [23]
Robustness, Speed	Engineering Systems	Zobel and Khansa (2014) [24]
Durability	Engineering Systems	Woods (2015) [25]
Preparation, Recovery, Mitigation, Response	Energy Systems	Philieps et al. (2016) [26]
Anticipation of Unexpected Events, Resilience, Recoverability, Flexibility, Redundancy	Supply Chains	Kamalahmadi and Melatparast (2016) [5]
Diversity	Energy Systems	Sato et al. (2017) [21]
Resource Efficiency, Durability	Energy Systems	Schlor et al. (2018) [27]
Absorption, Recovery	Solar Energy Installations	Wang et al. (2019) [28]
Preparedness, Recovery Capability, Adaptive Capacity	Microgrid Systems	Akhtar et al. (2019) [29]
Adaptive Capacity	Microgrid Systems	Ajaz (2019) [30]

Source: [1]

Conclusions

1. Definition of Resilience: Resilience is defined as the ability to prepare and plan for, absorb, recover from, and successfully adapt to adverse events.

2. Contextual Importance of Resilience: In the context of resilience, it is crucial to consider various attributes and aspects that contribute to a system's ability to survive and function under uncertainty and change. Firstly, the diversity of responses, which highlights the importance of different methods to achieve the same result while considering various types of disturbances. Secondly, systems must be modular, meaning they should not be too tightly or too loosely interconnected. Thirdly, the speed of response to shocks and changes within the system is critical for resilience. Systems must be able to quickly adapt to unexpected events and changes in conditions. Fourthly, the capacity for system transformation when necessary is also crucial for resilience. Sometimes, fundamental changes are needed within the system to ensure it can adapt to new conditions and challenges.

3. Key Indicators for Assessing Power System Resilience: Based on the literature review, 20 primary indicators have been identified for assessing the resilience of power systems. These include the reliability of energy supply; diversification of energy sources; energy reserve capacity; flexibility of the energy system; efficiency of recovery; renewability of energy; energy independence; financial stability of the energy sector; level of technological advancement; cybersecurity; environmental sustainability; market integration; social support; institutional stability; resilience to climate changes; energy accessibility for the population; infrastructure reliability; innovativeness; international cooperation; and regulatory adaptiveness.

4. Methods of Resilience Assessment: Assessment methods can be divided into two main categories: «Metric-Based» (individual metrics, indices, dashboard analytics, and decision analytics) and «Model-Based» (processes, statistical/Bayesian, networks, game-theoretic approaches, and simulations/agent-based).

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SECTION 3
METHODS, MODELS AND PROCESSES OF MODELING OBJECTS OF STUDY IN INFORMATION CONTROL SYSTEMS

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OPTIMIZATION MODELS OF TRANSPORT AND NETWORK FLOWS IN THE PROBLEMS OF SUPPORTING DECISION-MAKING IN INFORMATION MANAGEMENT SYSTEMS

Modern problems of traffic flow optimization

Most of the world's companies face disruptions in the field of logistics caused by various subjective and objective conditions. The world market is suffering from the deterioration of the political and economic situation in the world. Due to changes in communications and important world events, most managers of logistics companies have experienced first-hand serious disruptions in planning and ensuring transport flows, as all this has revealed the weaknesses of traditional work processes in existing supply chain logistics.

Lack of vertical visibility across processes, outdated demand management processes, insufficient resilience to changes in demand, and unexpected disruptions due to reliance on manual effort in logistics operations have disrupted typical supply chains.

Logistics companies were forced to analyze their logistics processes. It became clear that changes in customer behavior and expectations are unlikely to eliminate these unexpected logistics problems, even under conditions of stabilization of the situation in the economic sphere.

There was an urgent need to quickly optimize logistics management processes. Depending on the task, mathematical approaches can be used to solve logistics problems, including linear programming, network optimization, decision analysis, genetic algorithms, and others.

However, without understanding the essence of the main problems of the logistics industry and directions for their solution, optimization approaches will not be able to give a qualitative effect.

Among the current problems of the logistics industry, it is necessary to single out [1–3] the increase in transport costs; inconsistency of tracking due to the use of manual processes for tracking the movement of goods; limited transparency of shipments and monitoring of the flow of goods; fragmented communication; the presence of empty miles, which lead to increased costs, a negative impact on the environment and negatively affect the efficiency of both carriers and shippers; delays in delivery terms; objective events and circumstances that cannot be predicted in the processes of performing logistics tasks.

Each of the above problems has its own difficulties to overcome, some of them are solved thanks to an experienced management department, while others require the use of mathematical models and optimization methods, and the development of approaches to solving various non-typical problems [4]. It is clear that the specific approach will depend on the nature of the problem and the available data. In this work, the task of the traveling salesman is considered as the main direction of research.

Statement of the traveling salesman problem

The salesman's task was first formulated by the Irish mathematician V. R. Hamilton in the 19th century, the content of which is the need to draw up a route within a given set of interconnected points (cities) that form the transport network of a specific region. A traveling salesman needs to draw up a route by which he must visit all the cities of the network, taking into account the condition that the distance to be covered or the time to be covered is minimal. The peculiarity of the problem is that the route must contain all the points specified in the problem, and each of the points must be visited no more than once.

The salesman's problem is a combinatorial problem that can be solved using mathematical programming methods. For certainty, you can number the cities with numbers $(1,2,3,\dots,n)$, then the route of the traveling salesman will be described by a cyclic permutation of numbers $t=(j_1,j_2,\dots,j_n,j_1)$, and all of them $j_1,\dots,j_n$ are different numbers. Any permutation of numbers presented in this form represents a possible solution to the problem, and therefore there are $(n-1)!$ possible ways to construct its route. The traveling salesman's problem is to choose the route that is optimal in terms of the length or duration of the trip, which satisfies some given constraints.

Let's formulate the mathematical formulation of the problem. The set of cities of the network can be viewed as vertices of some graph with given distances (or travel time) between all pairs of vertices t_{ij} that form the matrix $T=\{t_{ij}\}$, $i,j=\overline{1,n}$. We consider the matrix to be symmetric. Then the formal task is to find the shortest route t (in terms of time or length) that passes through each city and ends at the departure point [5]. In this formulation, the problem is called the closed traveling salesman problem (TSP), which is a well-known mathematical integer programming problem.

The variables of the problem are the elements of the binary matrix of transitions between vertices $X = \{\boldsymbol{x_{ij}}\}$, $i, j \in \boldsymbol{I}$, which are equal to 1 if there is an edge $(\boldsymbol{v_i}, \boldsymbol{v_j})$ in the constructed route for the problem, 0 – otherwise [6]. The shortest route in terms of distance or time is optimal:

$$\boldsymbol{E} = \sum_{i\in I}\sum_{j\in I, j\neq i} \boldsymbol{t_{ij} x_{ij}} \rightarrow \boldsymbol{min} \tag{1}$$

with constraints

$$\begin{gathered} \sum_{j\in I, j\neq i} \boldsymbol{x_{ij}} = \boldsymbol{1},\ i \in \boldsymbol{I}, \\ \sum_{i\in I, j\neq i} \boldsymbol{x_{ij}} = \boldsymbol{1},\ j \in \boldsymbol{I}, \\ \boldsymbol{v_i} - \boldsymbol{v_j} + \boldsymbol{n x_{ij}} \leq \boldsymbol{n} - \boldsymbol{1},\ \boldsymbol{1} \leq \boldsymbol{i} \neq \boldsymbol{j} \leq \boldsymbol{n}. \end{gathered} \tag{2}$$

The last inequality ensures the connectivity of the route around the vertices, it cannot consist of two or more unconnected parts.

In the real world, the concept of the duration or cost of travel between individual points of the transport network cannot be fixed, they are determined approximately, often with the influence of subjective factors on estimates of time periods or the cost of moving along the route. This leads to the need to take into account the conditions of uncertainty, and its formalization on the basis of various methods.

Algorithms that allow solving the problem of finding the optimal route are divided into exact and heuristic. Exact methods guarantee to find the optimal solution to a problem in a certain time or take into account certain resource constraints. In this case, the search for solutions is performed on the basis of optimization methods, such as linear programming, dynamic programming, or the method of branches and bounds [7]. However, it is advisable to use exact methods only for small-scale tasks (for example, for the purpose of the initial design of a small transport network), since their implementation requires large computing power.

On the other hand, heuristic methods are algorithms that do not guarantee finding the optimal solution, but, instead, are aimed at quickly finding a locally optimal solution. Traditionally, trial-and-error approaches, such as random search or a greedy algorithm, are used to quickly explore the solution space and find a promising solution [8]. Heuristic methods are more flexible and can be applied to larger-scale problems, but the solution they offer may not be optimal. Among such heuristic methods, methods imitating biological (ant algorithm and genetic algorithm [9, 10]) or physical processes (method of annealing simulation [11]) deserve attention.

Generalized traveling salesman problem with additional precedence constraint

The generalized traveling salesman problem (GTSP) is an extension of the classical problem, in which a set of cities is divided into non-intersecting metropolises (clusters), and each cluster must be visited only once along the route. The problem has a wide range of applications, including, for example, routing problems, rescue planning, etc.

This formulation of the problem requires determining the order of visiting megacities, as a result of which the search for the optimal route through all the cities of the network will depend on the quality of the chosen order. In this case, we get a problem with an advanced constraint.

Suppose that there are n sets $M_1, \dots, M_n$, which we will call megacities, and a starting point x_0 that does not belong to any of them. Without limitation of generality, we can consider multiples of the same power defined by interrelations $M_k = \{m_{k1}, \dots, m_{kp}\},\ k = \overline{1,n}$.

Together with the costs $c(m_{lu}, m_{kv})$, which for arbitrary indices $l \neq k,\ l,k = \overline{1,n},\ u,v = \overline{1,p},$ can be determined in the form of time periods for moving or distances between cities or transport costs, the corresponding costs $\bar{c}(x_0, m_{kv})$ i $\bar{c}(m_{kv}, x_0)$ for moving from a point x_0 to each of the points m_{kv} and back are set. If the costs of visiting each metropolis $c'(m_{kv})$ are known, then the goal of the problem is to find the least expensive route that starts and ends at a point x_0 and passes through all megacities only once [12].

From a mathematical point of view, it is necessary to find a permutation $(j(1), j(2), \dots, j(n))$, called a route, which determines the order of visiting megacities, and a finite sequence $m_{j(1)u(1)}, m_{j(2)u(2)}, \dots, m_{j(n)u(n)}$, called a route, such that

$$\bar{c}\left(x_0, m_{j(1)v(1)}\right) + \sum_{i=1}^{n-1} \left(c'\left(m_{j(i)u(i)}\right) + c\left(m_{j(i)u(i)}, m_{j(i+1)u(i+1)}\right)\right) + \\ + \bar{c}(m_{j(n)u(n)}, x_0) \to \min.$$

Modern problems of distribution of data streams

Distribution of data streams is a critical aspect of today, the problems of which can be easily encountered when solving problems of optimization of data warehouses, business and data analysis, and others. These areas use data stored and processed on several nodes or servers that can be geographically distributed in different parts of the world. Problems with the distribution of data flows arise in the process of finding an efficient and effective solution in the distribution of the volume of data transmission channels between these nodes, ensuring data consistency and availability.

Currently, the main problems of data flow distribution can be identified. These include uneven data distribution, which can be caused, for example, by using a suboptimal data distribution algorithm or inefficient network topology [13]; data asymmetry, which can severely affect processing speed and reduce network bandwidth [14]; irrational placement of data; complexity of data replication [15, 16], etc.

As the volume of data transmission continues to increase and the need for distributed computing systems increases, the problem of data flow distribution remains a critical area of research and development. In the process of practical implementation of the results of this work, it was often necessary to deal with these problems, which was especially evident in the training of linguistic models, where a large amount of annotated data was used to obtain the result, which, without a proper understanding of the problems of data flow distribution, could significantly complicate the learning process, reducing it efficiency and speed.

One of the problems that needs to be solved is the determination of the maximum bandwidth of user data transmission channels in a three-level information and communication network based on the change in the total capacity of routing servers (intermediate link) taking into account both the needs and wishes of subscribers (users) and the capabilities of the service provider.

Let's formulate a mathematical model. Let information and computer networks include N_1 data transmission channels (global network providers), N_2 communication servers, and N_3 end users (subscribers). We denote by A_i^+, $i = \overline{1, N_1}$, the values of the maximum bandwidth of the data transmission channel that provider i, $i = \overline{1, N_1}$, is able to provide; B_j^+, $j = \overline{1, N_2}$, – the value of the maximum bandwidth of the data transmission channel that the communication node j, $j = \overline{1, N_2}$, can provide; C_k^-, C_k^+, $k = \overline{1, N_3}$, – values of the minimum and maximum bandwidth of the data transmission channel, which must be provided to the subscriber k, $k = \overline{1, N_3}$; t_k – throughput of the k-th subscriber station, $k = \overline{1, N_3}$. Then, assuming that the power distribution of communication channels satisfies the conditions of additivity and proportionality, we can consider the problem of distributing a limited homogeneous resource (bandwidth of communication channels) with transport-type constraints in order to find the optimal data transmission plan. This ensures the effective functioning of the system for providing users with Internet access, which consists in finding the optimal values of data transmission bandwidths T_i of the i-th information provider (provider), $i = \overline{1, N_1}$, and the optimal values of the bandwidths t_k of using local communication channels of the k-th user, $k = \overline{1, N_3}$.

Formally, the formulation of this problem can be written in the form [17]:

$$max t_1; max t_2; \dots max t_{N_3}, \tag{3}$$

under the following conditions

$$\sum_{k=1}^{N_3} t_k = \sum_{i=1}^{N_1} A_i^+ ; \tag{4}$$

$$T_i \leq A_i^+, i = \overline{1, N_1}, \tag{5}$$

$$\tau_j \leq B_j^+, j = \overline{1, N_2}, \tag{6}$$

$$C_k^- \leq t_k \leq C_k^+, k = \overline{1, N_3}, \tag{7}$$

and with the next constraints

$$\sum_{k=1}^{N_3} C_k^- \leq \sum_{i=1}^{N_1} A_i^+ \leq \sum_{k=1}^{N_3} C_k^+ ; \tag{8}$$

where τ_j– values of the bandwidth of the communication channels provided by the j-th communication node, $j = \overline{1, N_2}$.

Fuzzy optimization problems

Most of the traditional tools for conducting modeling, experimental, and computational studies are precise, deterministic, and precise. Clarity refers to the dichotomous nature of information. In traditional binary logic, a statement can be true or false, in set theory an element can either belong to a set or not.

But far from all objects, events, and models can be described deterministically, uncertainty is manifested in many areas of everyday life, such as engineering, medicine, meteorology, production, etc. However, conditions of uncertainty are especially often characteristic of problem-solving situations in which subjective judgments, evaluations, and decisions are important. These include the tasks of supporting decision-making, optimization of processes and systems, formalization of reasoning processes, training, etc. One of the methods of formal description of uncertainty is based on the theory of fuzzy sets and fuzzy numbers [18].

Theory of fuzzy sets and fuzzy numbers

The traditional theory of sets (crisp sets theory) can be considered as a partial case of the theory of fuzzy sets (fuzzy sets). In classical applied mathematics, the concept of a set is presented as a collection of elements (objects) that have some common property. For example, a set of numbers whose value is not less than a given number, a set of vectors, the sum of the components of each of which does not exceed one, etc.

In accordance with the idea of Zadeh [19], the definition of a fuzzy set as a subset of a given universal set X is given as follows.

Definition 1. A fuzzy subset $\tilde{A}$ of the universal set X, is a collection of pairs $\tilde{A} = \{(\mu_{\tilde{A}}(x), x)\}$, where $\mu_{\tilde{A}}(x): X \to [0,1]$ is the mapping of the set X into the unit segment [0,1], which is called the membership function of the fuzzy set.

The value of the membership function $\mu_{\tilde{A}}(x)$ for an element $x \in X$is called the degree of membership (fig. 1). The interpretation of the degree of membership $\mu_{\tilde{A}}(x)$ is a subjective measure of how much an element $x \in X$ corresponds to a concept, the meaning of which is formalized by a fuzzy set $\tilde{A}$.

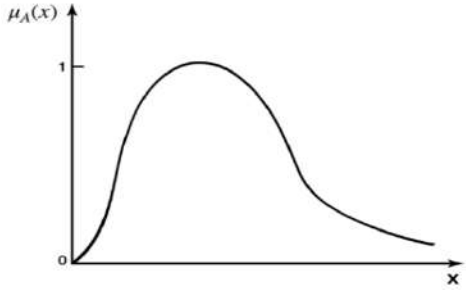

Figure 1. An example of a membership function

Source: [19]

Note that for arbitrary fuzzy sets $\tilde{A}$ and $\tilde{B}$ we have $\mu_{\tilde{A}\cup\tilde{B}}(x) =$
$= max(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x))$ та $\mu_{\tilde{A}\cap\tilde{B}}(x) = min(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x))$.

Definition 2. [20] A fuzzy set $\tilde{A}$ is called convex if

$\mu_{\tilde{A}}(\lambda x + (1-\lambda)y) \geq min(\mu_{\tilde{A}}(x), \mu_{\tilde{A}}(y))$, to all $x, y \in X$, $\lambda \in [0,1]$.

A fuzzy set $\tilde{A}$ is said to be normal if there exists such $x \in X$ that $\mu_{\tilde{A}}(x) = 1$. The clear sets $\tilde{A}_\alpha$ are called the sets of the level $\alpha > 0$ of the fuzzy set $\tilde{A}$, the magnitude $h = max\, \mu_{\tilde{A}}(x)$ is the height of the fuzzy set $\tilde{A}$, and supp $\tilde{A}$={$x \in X: \mu_{\tilde{A}}(x) > 0$} is the carrier of the fuzzy set $\tilde{A}$.

A fuzzy set $\tilde{A}$ is said to be unimodal if there is only one element $x \in X$, for which $\mu_{\tilde{A}}(x) = h$.

Let's consider the set of real numbers as a universal set, i.e. $X = R^1$.

Definition 3. [20] A fuzzy triangular number (triplet) $\tilde{A}$ is an ordered triplet of numbers (a, b, c), $a \leq b \leq c$, defining a membership function $\mu_{\tilde{A}}(x)$ of the form:

$$\mu_{\tilde{A}}(x) = \frac{x-a}{b-a}, x \in [a,b]; \; \mu_{\tilde{A}}(x) = \frac{c-x}{c-b}, x \in [b,c];$$

$$\mu_{\tilde{A}}(x) = 0, x \notin [a,c]. \qquad (9)$$

It is clear that the fuzzy triangular number (*a, b, c*) is a partial case of an unimodal fuzzy set with a height equal to one [7].

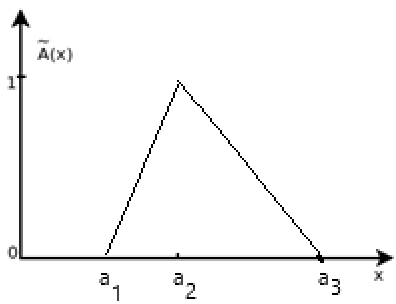

Figure 2. An example of a triangular fuzzy number $\tilde{A} = (a_1, a_2, a_3)$

Source: [20]

If an approach based on a Gaussian distribution with appropriate characteristics is applied to the presentation of a triangular fuzzy number, then in the generalized case a triangular fuzzy number can be presented in a slightly different form:

$$\tilde{A} = (a_1, a_2, a_3) = (m, \alpha, \beta), \qquad (10)$$

where $m = \frac{a_1+a_3}{2}$ – the middle point, and the coefficients $\alpha = a_2 - a_1$ and $\beta = a_3 - a_2$ define the left and right distributions of the fuzzy number $\tilde{A} = (a_1, a_2, a_3)$, respectively.

A fuzzy triangular number of the form (*a, b, b*), called a left fuzzy triangular number, is determined by the membership function of the form

$$\mu_{\tilde{A}}(x) = 0, x < a; \mu_{\tilde{A}}(x) = \frac{x-a}{b-a}, x \in [a, b]; \mu_{\tilde{A}}(x) = 1, x > b, \quad (11)$$

and the fuzzy triangular number of the form *(b, b, c)*, called the right fuzzy triangular number, by the membership function (fig. 3)

$$\mu_{\tilde{A}}(x) = 1, x < b; \mu_{\tilde{A}}(x) = \frac{c-x}{c-b}, x \in [b, c]; \mu_{\tilde{A}}(x) = 0, x > c. \quad (12)$$

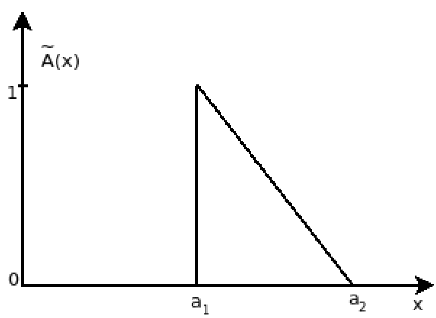

Figure 3. An example
of a right fuzzy triangular number $\tilde{A} = (a_1, a_1, a_2)$

Source: [20]

For a fuzzy number $\tilde{A}$ supp $\tilde{A}$={$x \in X$: $\mu_{\tilde{A}}(x) > 0$} is an interval. In this case, for a fuzzy triangular number, $\tilde{A} = (a, b, c)$ the support will be an interval (a, c), for a right fuzzy triangular number – an interval $[b, c)$, for a left fuzzy triangular number – an interval $(a, b]$.

It is clear that ordinary crisp sets form a subset of fuzzy sets. In fig. 4 shows the membership function of a clear set $B \subseteq X$, which is its characteristic function $\mu_B(x)$:

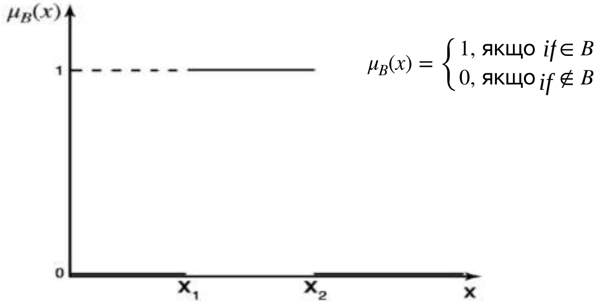

Figure 4. The membership function of a definite set (characteristic function)

Source: [19]

Arithmetic operations with triangular fuzzy numbers

To operate with the above fuzzy numbers, we define the rules for performing arithmetic operations based on their presentation in Gaussian-like form. Let's define operations with fuzzy numbers based on the above description. As the middle point, the usual arithmetic mean value of the carrier boundaries is taken, and the left and right distributions are considered according to the lattice rule, according to which for arbitrary real numbers a, b we put $a \cup b = max\{a, b\}$ and $a \cap b = min\{a, b\}$.

For arbitrary trapezoidal fuzzy numbers $\tilde{A} = \left(m(\tilde{A}), \alpha_1, \beta_1\right)$ and $\tilde{B} = \left(m(\tilde{B}), \alpha_2, \beta_2\right)$ we define the following operations of addition, subtraction, multiplication, and division, which in the general case are denoted by the symbol $\circ$:

$$\tilde{A} \circ \tilde{B} = \left(m(\tilde{A}) \circ m(\tilde{B}), \alpha_1 \cup \alpha_2, \beta_1 \cup \beta_2\right) =$$
$$= \left(m(\tilde{A}) \circ m(\tilde{B}), max(\alpha_1, \alpha_2), max(\beta_1, \beta_2)\right). \tag{13}$$

Finally, we have

$$\tilde{A} + \tilde{B} = \left(m(\tilde{A}) + m(\tilde{B}), \alpha_1 \cup \alpha_2, \beta_1 \cup \beta_2\right) =$$
$$= \left(m(\tilde{A}) + m(\tilde{B}), max(\alpha_1, \alpha_2), max(\beta_1, \beta_2)\right)$$
$$\tilde{A} - \tilde{B} = \left(m(\tilde{A}) - m(\tilde{B}), \alpha_1 \cup \alpha_2, \beta_1 \cup \beta_2\right) =$$
$$= \left(m(\tilde{A}) - m(\tilde{B}), max(\alpha_1, \alpha_2), max(\beta_1, \beta_2)\right)$$
$$\tilde{A} \times \tilde{B} = \left(m(\tilde{A}) \times m(\tilde{B}), \alpha_1 \cup \alpha_2, \beta_1 \cup \beta_2\right) =$$
$$= \left(m(\tilde{A}) \times m(\tilde{B}), max(\alpha_1, \alpha_2), max(\beta_1, \beta_2)\right)$$

$$\tilde{A} \div \tilde{B} = \left(m(\tilde{A}) \div m(\tilde{B}), \alpha_1 \cup \alpha_2, \beta_1 \cup \beta_2\right) =$$
$$= \left(m(\tilde{A}) \div m(\tilde{B}), max(\alpha_1, \alpha_2), max(\beta_1, \beta_2)\right)$$

It is natural to use a method based on the median average value to perform comparison operations and rank fuzzy numbers. In other words, if a ranking function $\Re: F(R) \to R$ with a median average value of the form $\Re(\tilde{A}) = \left[m + \left(\frac{\beta-\alpha}{4}\right)\right]$ is defined for each $\tilde{A} = (a_1, a_2, a_3) \in F(R)$, then for any two triangular fuzzy numbers $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$ we have the following possible comparison options:

– $\tilde{A} \succ \tilde{B}$ if and only if $\Re(\tilde{A}) > \Re(\tilde{B})$;
– $\tilde{A} \prec \tilde{B}$ if and only if $\Re(\tilde{A}) < \Re(\tilde{B})$;
– $\tilde{A} \approx \tilde{B}$ if and only if $\Re(\tilde{A}) = \Re(\tilde{B})$.

Defuzzification of triangular fuzzy numbers

The processes of processing fuzzy numbers involve the stage of defuzzification – the transformation of a fuzzy result into a clear (numerical) value. This is an important step in the methodology of applying the fuzzy approach, for the implementation of which it is necessary to transform the fuzzy solutions into concrete facts or numerical values. There are different methods of performing the defuzzification procedure, among which the most common is the Center of Gravity (CoG) or centroid method, the average maximum method, and the maximum method. To ensure the comparison of research results, we will use the center of gravity method [21]. In this method, the defuzzification result is calculated as the center of gravity of the fuzzy set, which for a discrete fuzzy number $\tilde{A} = \{(\mu(x_1), x_1), (\mu(x_2), x_2), \dots, (\mu(x_i), x_n)\}$ is determined by the formula:

$$CoG = \frac{\sum_{i=1}^{n} \mu(x_i) \cdot x_i}{\sum_{i=1}^{n} \mu(x_i)}, \qquad (14)$$

where x_i – elements of the universal space (set), and $\mu(x_i)$ is the degree of membership of each element of the fuzzy set.

It is easy to check that for a right fuzzy triangular number to $\tilde{A} = (a_1, a_1, a_2)$ the defuzzification point is equal $CoG(\tilde{A}) = \frac{a_2 + 2a_1}{3}$.

Formulation of the problem of fuzzy linear programming

In 1970, Bellman and Zadeh [22] reviewed the classic model of solving optimization problems and proposed a decision-making model in a fuzzy environment, which provided the impetus for most of the results of the theory of «fuzzy» decisions. Analyzing the processes of finding solutions to optimization problems under conditions of uncertainty, it can be noted that the objective function and constraints may be fuzzy, for which appropriate membership functions are defined. Since the main goal of optimization problems is to find solutions at which the objective function acquires an optimal value taking into account the given constraints, the solution in fuzzy conditions is determined similarly. To obtain an optimal solution, it is necessary to find such an element in the domain of admissible values that simultaneously corresponds to the best value of the objective function and satisfies the constraints. Thus, the «solution» in fuzzy conditions can be considered as the intersection of the definition regions of fuzzy constraints and a fuzzy objective function. In fig. 5 shows an example of a method of determining a solution to a fuzzy optimization problem.

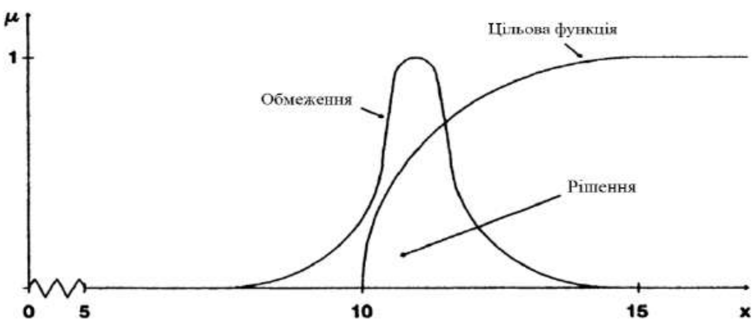

Figure 5. An example of determining a solution
in a fuzzy optimization problem

Source: [21]

Before developing a specific model of a linear programming problem (LPP) in a fuzzy environment, it is necessary to understand that, unlike a classical linear programming problem, a «fuzzy linear programming» model is an ambiguously defined type of model and that different variants of its implementation are possible depending on the assumptions or features of the real situation, which are to be simulated.

Let’s first formulate the basic model of the «fuzzy linear programming» problem. To do this, consider the standard formulation of the linear programming problem: find a solution $x \in R^n$ that achieves the optimal (maximum) value of the objective function:

$$c^T x \to max, \tag{15}$$

in the domain of admissible solutions, which is determined by the system of constraints

$$Ax \leq b, x \geq 0, \tag{16}$$

where $x = (x_1, \ldots, x_n)^T$- vector of unknown variables, $c = (c_1, \ldots, c_n)^T$- vector of the objective function coefficients, $A = (a_{ij}), i = \overline{1, n}, j = \overline{1, m},$ – the matrix of the system of linear constraints, $b = (b_1, \ldots, b_m)^T$- column of free elements.

We will assume that there is a decision-maker (DM) who can set the values of the objective function of the model (15)–(16) the level of reliability Z that must be achieved. Let us also assume that each of the constraints in the problem is formed on the basis of the data of the fuzzy set. In this case, we get the general appearance of a fuzzy LPP:
find a vector x such that

$$c^T x \gtrsim Z, \tag{18}$$

$$Ax \lesssim b, x \geq 0. \tag{19}$$

Here the sign «$\lesssim$» is used to indicate a fuzzy variant of the non-strict relation «≤« and can be linguistically interpreted as «essentially less than or equal to». The sign «$\gtrsim$», accordingly, denotes a fuzzy version of the relation «≥», which linguistically can be expressed as «significantly more than greater than or equal to». Formally, the fuzzy relations «$\lesssim$» and «$\gtrsim$» can be formulated as partial cases of the fuzzy relations «non-strictly less» and «non-strictly greater» on the set $X = R^1$, respectively [23].

In this case, the target function is given in the form of maximizing the value of the linear function (15), for which the value of Z is considered as the lower limit of the optimal solution. Let's enter the notation $\binom{-c}{A} = D$, $\binom{-Z}{b} = p$, rewrite constraints (18)–(19) in the form:

$$Dx \lesssim p, x \geq 0. \tag{20}$$

Suppose that the value Z and the elements of the vector b are given in the form of fuzzy numbers. Taking into account the uncertainty in the formalization of Z and b, the right-hand part of the system of inequalities (20) is a vector, the elements of which can be some values of the supports for the given fuzzy values. At the same time, each of the (m + 1) inequalities (20) for specific values of the vector p has a set of solutions characterized by the value of the corresponding membership function, each of which is denoted by $\mu_i(x),\ i = \overline{1, m+1}$. Without limiting the general statement, we can assume that all values of the membership function are monotonically increasing. Then, with arbitrary $\alpha \in [0,1]$ values $\mu_i(x) = \alpha$, $i = \overline{1, m+1}$, can be interpreted as the values of degrees of reliability with which the vector x satisfies distinct inequalities $\sum_{j=1}^{n} d_{ij}x_j \leq \tilde{p}_i(\alpha)$, $i = \overline{1, m+1}$ (here d_{ij}- matrix elements D, and $\tilde{p}_i(\alpha)$ – values obtained on the basis of α–equal sets for fuzzy elements of the vector p). Based on the definition of the solution of the LPP, the membership function of the fuzzy set of the «solution» $\tilde{P}$ of the fuzzy model (20) will be defined in the form

$$\mu_{\tilde{P}}(x) = \min_{i=\overline{1,m+1}} \mu_i(x). \tag{21}$$

If we assume that DM is interested not in a fuzzy set of solutions, but in a clear «optimal» solution of the original problem, then one can propose to «improve the solution» in (21) by solving a nonlinear programming problem

$$\max_{x \geq 0} \min_{i=\overline{1,m+1}} \mu_i(x) = \max_{x \geq 0} \mu_{\tilde{P}}(x). \tag{22}$$

Now we need to clarify the form of the membership functions $\mu_i(x)$, $i = \overline{1, m+1}$. The quantities $\mu_i(x)$ should be 0 if the constraints and objective function are strongly violated, and 1 if they are fully satisfied (in the usual clear sense). In addition, $\mu_i(x)$ should grow monotonically from 0 to 1 on the interval [0,1] (here x is determined by the permissible level of violation of constraints and the objective function, which is given by the value from [0,1]), i.e.:

$$\mu_i(x) = \begin{cases} 1, & \sum_{j=1}^{n} d_{ij}x_j \leq p_i, \\ \in [0,1], & p_i < \sum_{j=1}^{n} d_{ij}x_j \leq p_i + q_i, \\ 0, & \sum_{j=1}^{n} d_{ij}x_j > p_i + q_i, \end{cases} \quad i = \overline{1, m+1}, \tag{23}$$

where q_i, $i = \overline{1, m+1}$, are subjectively determined values of permissible violations in the constraints and the objective function.

Under our assumption about fuzzy numbers, we have that the membership functions will be linearly decreasing on the corresponding «admissibility intervals» $[p_i, p_i + q_i]$, $i = \overline{1, m+1}$:

$$\mu_i(x) = \begin{cases} 1, & \sum_{j=1}^{n} d_{ij}x_j \le p_i, \\ 1 - (\sum_{j=1}^{n} d_{ij}x_j - p_i)/q_i, & p_i < \sum_{j=1}^{n} d_{ij}x_j \le p_i + q_i, \\ 0, & \sum_{j=1}^{n} d_{ij}x_j > p_i + q_i, \end{cases}$$

$$i = \overline{1, m+1}. \tag{24}$$

Substituting (24) into (22), after simple transformations we obtain the criterion for choosing the optimal solution

$$\max_{x \ge 0} \min_{i=\overline{1,m+1}} \left(1 - (\textstyle\sum_{j=1}^{n} d_{ij}x_j - p_i)/q_i\right). \tag{25}$$

We will use a new variable $\lambda \in [0,1]$, which will correspond to the smallest level of the membership function of the fuzzy set «solution» $\tilde{P}$ (21) of the fuzzy model (20): $1 - (\sum_{j=1}^{n} d_{ij}x_j - p_i)/q_i \ge \lambda$.

Then we get an optimization model

$$\max_{x \ge 0} \lambda \tag{26}$$

$$\lambda q_i + \textstyle\sum_{j=1}^{n} d_{ij}x_j \le p_i + q_i,\ i = \overline{1, m+1},\ x \ge 0. \tag{27}$$

If the optimal solution of the problem (26)–(27) is written in the form of a vector (λ, x^O), then x^O will be the solution of the maximization problem (22) for the model (15)–(16) taking into account the assumption that the membership function of a fuzzy defined objective function has the form (23).

It is obvious that this optimal solution can be found by solving a standard (exact) LPP with an additional variable and an additional constraint with respect to the model (15)–(16). This scheme makes it possible to consider such an approach as quite constructive algorithmically and effectively from a computational point of view.

The general statement of a fuzzy linear programming problem can be detailed in various cases of situations with uncertainty, in which the description of the parameters of the problem is given in the form of fuzzy numbers. Additional information in the form of membership functions of these fuzzy numbers is introduced into the model. These functions can be considered as a way of an approximate reflection by the expert of the non-formalized attitude he has in estimating the real value of a specific parameter. Values of membership functions should be perceived as weighting factors that experts assign to different possible values of one or another parameter.

After this clarification, you can proceed to the formulation of the fuzzy linear programming problem of the following form. A linear model is given

$$\sum_{j=1}^{n} \tilde{c}_j x_j \to max, \tag{28}$$

in which the values of the coefficients $\tilde{c}_j$ are presented in the form of fuzzy numbers. In addition, there are constraints

$$\sum_{j=1}^{n} \tilde{a}_{ij} x_j \leq \tilde{b}_i,\ i = \overline{1,m},\ x_j \geq 0,\ j = \overline{1,n}\ , \tag{29}$$

and the values of the coefficients $\tilde{a}_{ij}$, $\tilde{b}_i$ are also given in the form of corresponding fuzzy numbers. It is necessary to make a rational choice of the solution $x \in R^n$, which in some sense maximizes the fuzzy given linear form (28) [24].

The formulation of a linear programming problem with fuzzy parameters will be called a fuzzy linear optimization problem.

Each type of fuzzy linear programming model requires different methods and technologies to solve. The choice of a specific model of fuzzy linear programming depends on the nature of the problem and the available information. In the case of the fuzzy problem of the traveling salesman, the application of fuzzy time estimates to determine the duration of movements at each stage of the route is considered.

A fuzzy model of the traveling salesman problem

In the case of setting a fuzzy task for the traveling salesman, it is necessary to find a cyclic permutation of the numbers of the cities that the traveling salesman must visit, according to which the time consumption will be minimal, taking into account the restriction on visiting each of the points no more than once. The mathematical formulation of the fuzzy problem of the traveling salesman can be written as follows: it is necessary to minimize, taking into account the above method of comparing fuzzy numbers, the objective function

$$\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{t}_{ij} x_{ij}, \tag{30}$$

where the time costs for movement between points are given in the form of a matrix $\tilde{T}$={$\tilde{t}_{ij}$}, $i, j = \overline{1,n}$, with elements in the form of fuzzy numbers, and the possible paths of movement between cities are determined by the matrix X, subject to the fulfillment of the constraints:

$$\sum_{i=1}^{n} x_{ij} = 1 \text{ for all } j = 1,2,\ldots,n,$$
$$\sum_{j=1}^{n} x_{ij} = 1 \text{ for all } i = 1,2,\ldots,n, \quad (31)$$
$$v_i - v_j + nx_{ij} \leq n - 1,\ 1 \leq i \neq j \leq n,$$
$$x_{ij} = 0 \text{ or } 1 \text{ for all } i,j = 1,2,\ldots,n.$$

For software implementation in the matrix $\tilde{T}$, the diagonal elements $\tilde{t}_{ii}$ must be set with large positive numbers in order to obtain in the solution the values $x_{ii} = 0$ for all $i = 1,2,\ldots.,n$.

Fuzzy values of the duration of movement between arbitrary cities will be set in the form of triangular fuzzy numbers.

A model of fuzzy distribution of data flows in a communication network

Another significant problem that relates to the traveling salesman problem is the consideration of fuzziness or uncertainty in the needs of network users. Ensuring the demand of end users in conditions of the limited bandwidth of data transmission channels, there is a need for the formation and research of optimization models and methods for solving the problems of effective distribution of available resources of the information and communication network.

Let us assume that in the formulation of the problem of distribution of the power of data transmission channels (3–8) the current values of the bandwidth of the communication channels of each subscriber k, $C_k, k = \overline{1, N_3}$, are known, and the values of $C_k^+, k = \overline{1, N_3}$, determine the values of the bandwidths that are planned by users as a result of updating communication equipment. The values of user needs are formulated as right fuzzy triangular numbers with linear membership functions and supports $\left[C_k, C_k^+\right]$, $k = \overline{1, N_3}$. The available capacity and resources of routing facilities are not sufficient to fully satisfy the expansion of the bandwidth of subscriber channels, which is possible only under the condition $\sum_{j=1}^{N_2} B_j^+ \geq \sum_{k=1}^{N_3} C_k^+$.

Formally, the formulation of this problem can be written in the form:

$$max t_1; max t_2; \ldots max t_{N_3}, \quad (32)$$

with the following constraints

$$t_k \in \operatorname{supp}\tilde{t}_k = \left[C_k, C_k^+\right],\ k = \overline{1, N_3};$$

$$\sum_{k=1}^{N_3} t_k \le \sum_{i=1}^{N_1} A_i^+ ;$$
$$t_k \le B_j^+,\ j = \overline{1, N_2},\ k = \overline{1, N_3}; \tag{33}$$
$$\sum_{j=1}^{N_2} B_j^+ \le \sum_{i=1}^{N_1} A_i^+ \le \sum_{k=1}^{N_3} C_k^+ .$$

We will assume that the current capacities of user data transmission channels satisfy the conditions $\sum_{k=1}^{N_3} C_k \le \sum_{k=1}^{N_3} t_k \le \sum_{i=1}^{N_1} A_i^+$ and that the values of the maximum expansion of the bandwidth of the channels exceed the network capacity of the communication servers $\sum_{j=1}^{N_2} B_j^+ < \sum_{k=1}^{N_3} C_k^+$.

This problem is a multiobjective optimization problem. To solve it, methods are used that allow finding a compromise (effective) solution by reducing the problem to a single-criterion one in the form of a convolution of criteria or a sequence of one-criterion optimization problems [25]. In the case of fuzzy specified constraints, each such problem can be reduced to a linear optimization problem with the following solution by the method proposed above (see problem (26–27)).

Let us give some numerical calculations. Let us first consider the clear task of a traveling salesman, which is set on a network of cities with the duration of movements (see Fig. 6).

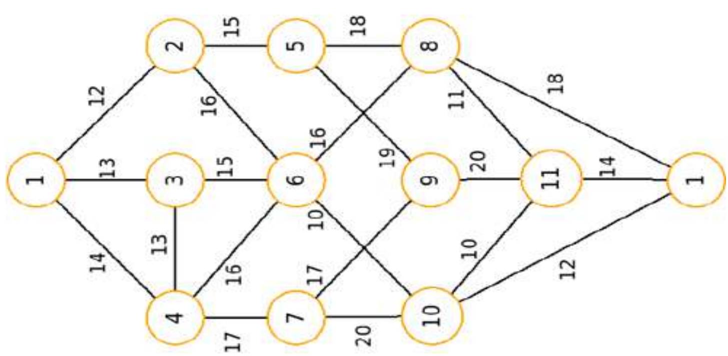

Figure 6. An example of a clear task of a traveling salesman

Source: [26]

For this problem, the optimal solution is a route

$$1 \to 2 \to 6 \to 10 \to 11 \to 8 \to 5 \to 9 \to 7 \to 4 \to 3 \to 1, \tag{34}$$

for which the duration of the shortest path is 156 units.

Let's introduce the fuzziness of the duration of movement between cities according to the rules

$$\tilde{t}_{ij} = (t_{ij}, t_{ij}, t_{ij} \cdot 1.8 + (i + j) \cdot 0.75),$$

where i, j – city numbers, t_{ij} – clearly given duration of movement.

Then the fuzzy values of the duration of moving between cities will be determined by the values given in Table 1. Applying the method of dynamic programming based on the Held-Karp algorithm [27] and the genetic algorithm [28] to solve the traveling salesman problem, a fuzzy solution is obtained, according to which the best value of the fuzzy duration of the total trip is determined (for both methods) by:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{t}_{ij} x_{ij} = (156.0, 156.0, 188.59),$$

for which, respectively, $CoG = 166.86$. This result is achieved on the basis of choosing a sequence of travel in the form (34), which was obtained for a clear problem of a traveling salesman.

In another way, if each distance is defuzzified and the traveling salesman problem is solved with the duration given in the column CoG in Table 1, then the minimum duration will be $\sum CoG = 188.59$, which is achieved on the sequence

$$1 \to 3 \to 4 \to 7 \to 9 \to 5 \to 8 \to 11 \to 10 \to 6 \to 2 \to 1. \quad (35)$$

Thus, it can be concluded that when ambiguity is introduced into the clear task of the traveling salesman, the optimal route in the task can change significantly. But, despite this, the conducted numerical experiments allow us to talk about the expediency of using a fuzzy formulation of the traveling salesman's problem, as a result of which it is possible to obtain meaningful results in situations with uncertainty.

Similar results were obtained for the problem of distribution of data flows in a communication network with fuzzily defined values of end-user needs. As an example, we consider a real computer network that uses one of 2 alternative external connections to the Internet (2 providers) and 2 or 3 communication servers, the total bandwidth of which is the same. The value of bandwidth is currently 2 Gb/s but can be increased to 3 Gb/s. Internal network channels with a bandwidth of 1 Gb/s are used to service network devices of 17 dormitories. Communication servers provide the connection of users to external channels, the bandwidth of which is 10 Gb/s.

Table 1

FUZZY VALUES OF THE DURATION OF MOVEMENTS BETWEEN THE CITIES OF THE NETWORK

i	j	a_1	a_2	CoG
1	2	12	18.9	14.3
1	3	13	20.5	15.5
1	4	14	22.1	16.7
1	8	18	28.5	21.5
1	10	13	19.7	15.23
1	11	14	22.8	16.93
2	5	15	23.8	17.93
2	6	16	25.4	19.13
3	4	13	20.8	15.6
3	6	15	24.0	18
4	6	16	25.6	19.2
4	7	17	27.2	20.4
5	8	18	28.9	21.63
5	9	19	30.5	22.83
6	8	16	26.0	19.33
6	10	10	17.2	12.4
7	9	17	27.7	20.56
7	10	20	32.3	24.1
8	11	11	19.0	13.67
9	11	20	32.6	24.2
10	11	10	17.7	12.57

Source: [29]

At the initial stage of the study, 2 communicators with a bandwidth of 1 Gb/s were used for service. As a result of monitoring the amount of traffic received by network equipment by user groups, it was established that the maximum bandwidth of connections to communication servers for 17 user groups is 260, 165, 150, 190, 275, 115, 175, 275, 155, 195, 125, 145, 90, 370, 180, 90, 150 Mb / s, respectively, (total traffic = 3105 Mb / s), which exceeds the total bandwidth of the server equipment.

It is impossible to provide the specified levels of bandwidth for all users at the same time in this configuration of network equipment.

The real bandwidth, which was implemented based on the specified bandwidth of each communicator, is obtained when group routers № 8, 14, 15, and 17 are connected to 1 server, and others – to server 2. Bandwidth values of local connections are equal to 0; 99; 129; 0; 0; 122; 28; 284; 150; 0; 130; 150; 99; 378; 192; 93; 146 Mb/s. The solution to the problem in the form of disconnecting Internet access to users whose channel capacity is 0 is unacceptable. As an innovative solution to the problem, it is proposed to improve the network equipment available at the ICC. This can be done by increasing the park of communication servers with a network computer with a capacity equal to two existing ones. Another way to increase the bandwidth of network channels is to purchase two new, more powerful servers.

When using 2 identical communication servers with a total bandwidth of 3 Gb/s, the bandwidth of local connections is equal to 259, 159, 149, 166, 273, 115, 163, 274, 152, 148, 125, 144, 90, 365, 180, 89, 149 Mb/s, respectively, which in total is 3 Гб/с. The use of 3 communicators with a total bandwidth of 3 Gb/s (1 Gb/s each) gives the value of the power of local connections 260, 148, 146, 190, 258, 114, 175, 266, 146, 195, 124, 143, 90, 335, 180, 89, 141 Mb/s, respectively, which also adds up to 3 Gb/s.

To speed up access to the Internet, there was a need to increase the bandwidth of data transmission channels. Based on the analysis of the existing traffic and equipment capabilities, the following maximum bandwidth values of local connections were proposed: 280, 180, 170, 200, 290, 125, 190, 290, 170, 210, 135, 160, 100, 390, 195, 95, 165 Mb/s.

For this, the use of two communication servers with a total bandwidth of 3 Gb/s provides local connection speeds that are equal to 128, 161, 160, 124, 284, 124, 152, 287, 165, 208, 134, 158, 100, 378, 194, 94, 149 Mb/s, respectively, (groups № 5; 8; 10; 14; 15 and 17 connect to server 1; others – to server 2). The use of 3 communicators gives the values of the power of local connections 271, 146, 153, 65, 273, 123, 123, 284, 162, 206, 131, 158, 97, 378, 192, 92, 146 Mb/s, respectively, (groups № 1; 5, 10, 12 and 16 connect to server 1; groups № 2; 3; 4; 6; 7; 9; 11 and 13 – to server 2; groups № 8; 14; 15; 17 – to server 3).

It should be noted that the results obtained in the process of practical application of the proposed approach for effective distribution of the power of data transmission channels were fully confirmed as a result of the reorganization of the server park of the Internet service provider, which once again confirms the constructiveness of the developed algorithms.

Conclusions

In the process of researching decision-making support tasks for the purpose of optimizing transport and network flows, models of the logistic problem of the traveling salesman and the problem of distributing the power of data transmission channels under conditions of uncertainty were considered and proposed. The concept of fuzzy numbers of a special form is used to formalize uncertainty. In the considered problems, it is proposed to use fuzzy numbers to describe the timing and volume of users' needs. Analysis of models and methods for solving problems was performed, actions on fuzzy numbers were formalized, and the procedure for defuzzification of fuzzy results was formalized. A mathematical model and algorithm for solving the problem of a traveling salesman with an uncertain duration of movements between cities have been formulated.

An approach is proposed to solve the problem of improving the distribution of the power of communication channels to increase the efficiency of organizational management in network structures based on modern methods of distribution and processing of information flows.

The results of numerical calculations for the considered problems and models are demonstrated. The conducted analysis and developed approaches provide an opportunity for the development and implementation of constructive architectures of innovative information systems in the management of logistics and flow processes, especially now in wartime conditions.

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TECHNIQUES FOR INFORMATION TRANSMISSION DEVICES' ADAPTATION TO COMMUNICATION CHANNEL PARAMETERS

Rapid and reliable transmission of large volumes of information is one of the most important tasks for the vast majority of technical and informational systems. In this regard, when transmitting information, it is important to minimize the impact of disturbances in the communication channel.

The efficiency of information exchange primarily depends on the reliability and speed of data transmission. Mathematical models describing the process of information exchange in the application domain generally involve partial approaches. However, reproducing a holistic picture of the modeled phenomenon allows for achieving sufficient generalization of research results and extending them to a range of similar phenomena.

To enhance the efficiency of the information exchange process, it is advisable to use a unified methodological framework and a systematic approach at all stages of establishing information transmission principles, starting from the formation of a mathematical model to their practical implementation. The application of generalizing methods of information transmission theory proves to be quite productive at all levels of solving this problem.

Considering the above, it is evident that constructing universal principles of information transmission with adaptation to communication channel parameters is a relevant scientific and applied task, as the need to increase the reliability and speed of information transmission processes through various communication lines is unquestionable.

1. Analysis of Systems from the Viewpoint of Information Transmission

The development of information technologies in all spheres of activities has clearly determined the transition from technologies aimed only at processing digital data to technologies that incorporate the possibility for automatic obtaining of quantitatively determined information from a material-world object, its entering into computing equipment with further processing in accordance with the procedures specified by the application software operator.

This technology's crucial elements are automatic measurements, as a result of which, with the help of specialized technical tools, numerical values of physical quantities characterizing the investigated object or phenomenon are found experimentally [1, 2].

Processes of automatic measurements have common features primarily including technical tools' perception of investigated (measured, controlled) values, the transformation of these values into intermediate values, their experimental comparison with known values, generation, and presentation of results in the form of named numbers, their dependencies, based on quantitative ratios.

A functionally combined set of computing tools and auxiliary devices, as well as communication channels (lines) designed to generate information signals in a form convenient for direct perception by the operator or for automatic processing, transmission, and use in automated control systems, is usually called the computing system (CS) [3]. A typical generalized CS structure is schematically presented in Fig. 1.

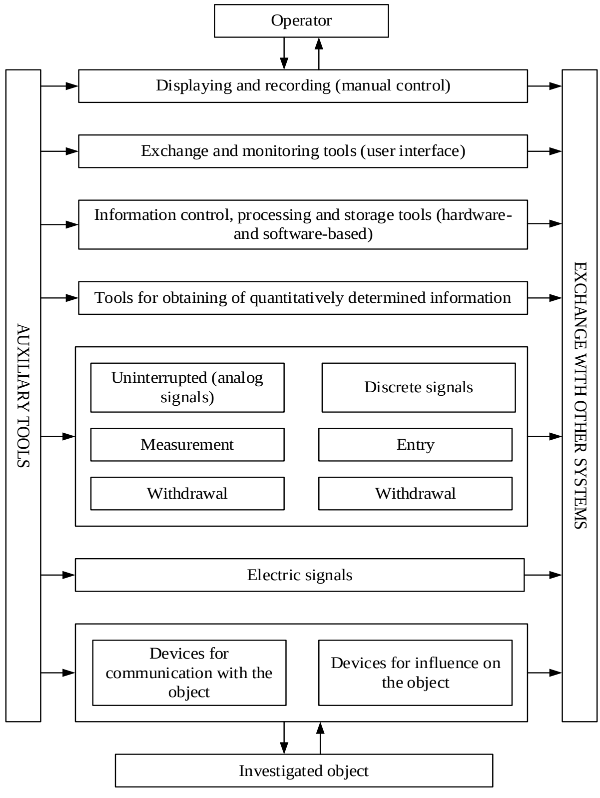

Figure 1. Generalized structure of the computing system

Source: [3]

Depending on the principles of information generation and transmission, one can use the CS classification shown in Table 1. The most interesting class of CSs comprises systems that include software-controlled computing tools.

Such systems are usually called control systems (CS), their core includes a programmable computing device (computer or microcontroller), and there also being devices for connection with communication channels, connection to input-output channels of analog signals, analog converters, measuring switchboards, analog-to-digital and digital-to-analog converters, devices forming the impact on the object and some other devices designed to perform CS functions.

Table 1

CLASSIFICATION OF COMPUTING SYSTEMS ACCORDING TO CONSTRUCTION PRINCIPLES

A sign of classification	Class	
	I	II
Availability of special-purpose communication channel	Missing	Available
Procedure for information acquisition operations	Sequential	Parallel
Use of standard interfaces	Not in use	In use
Availability of software-controlled computing devices	Missing	Available
Use of standard primary and applied mathematical support	Not in use	In use
Availability of information feedback loops	Missing (unlocked systems)	Available (single- and multi-circuit compensation systems)
Changing the speed of information receipt and issue	No changes (real-time system)	Changes available
Type of information signals used	Analog	Digital

Source: [3]

Complexes of tools for CS generation SC are called computational control complexes (CCCs).

In this case, the transmission medium may be different: electric communication lines, telephone and radio channels, fiber optic lines, etc. But nowadays, information processing goes on with the help of electrical signals, so it is absolutely necessary to provide for the presence of respective signal nature converters both on the system's transmitting and receiving parts. The generalized structure of a multi-channel information transmission system is shown in Fig. 2.

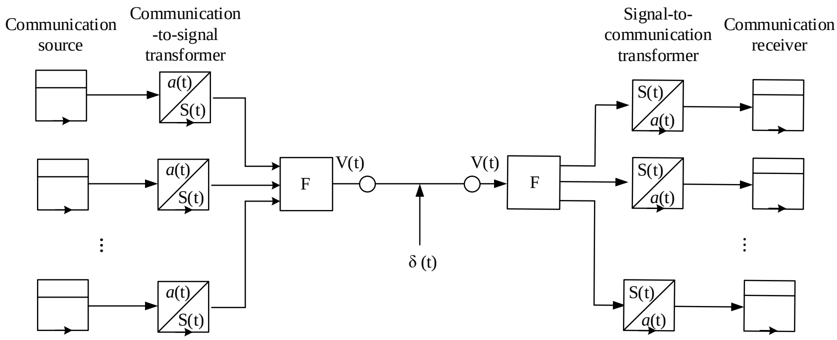

Figure 2. Generalized structure of multi-channel information transmission system

Source: developed by the author

Sources of messages on the transmission side are represented by end devices of one or many computing systems. With the help of respective converters, messages $a_i(t)$ are transformed into signals $S_i(t)$, the nature of which corresponds to the transmission environment. With the help of the generator, group $V(t)$ is formed from the channel signals to be further fed to the communication line. During transmission, it is affected by disturbances $\delta(t)$, with group signal $\overline{V(t)}$ having been already received at the input of the receiving part, which signal is distributed to respective channels $\overline{S_i(t)}$. In accordance with the principle of reverse conversion, the channel signal $\overline{S_i(t)}$ is converted into the message $\overline{a_i(t)}$.

CS creation requires the combining of various elements, blocks, and devices into a single structure. These components are usually developed and produced by different manufacturers. It is clear that the manufacturer, when creating both hardware and software, is obliged to comply with certain requirements and standards, compliance with which guarantees the possibility of such a combination. First of all, such requirements and standards should be established in relation to the properties and signs of the data being exchanged among themselves during the system's and its various components' operation.

The best way to solve the above-mentioned problems lies in the use of existing national and international standards. From the viewpoint of the importance of their application in information systems, a particular place is occupied by the model of open systems' interaction.

The model of network and inter-network interaction of the OSI (ISO) defines the hierarchy of 7 levels of interaction between network components [4]: applied, representative, session, transport, network, channel or data link level, and physical ones.

When considering these 7 levels, one should pay attention to the fact that, within the framework of such consideration, it is possible to establish uniform general rules and standards, with the help of which it is necessary to manufacture various devices, to develop programs so that various integral technology elements manufactured by different manufacturers would operate together and be connected.

In order to solve this problem, ISO developed the reference model of OSI (open systems interaction) [4, 5]. The international standard was published in 1983.

For differentiation purposes, in the course of processing each level adds its own protocolary control information to the data in the form of a header and so-called trailer. Moreover, the headers appear at all stages, while the trailer is a control sequence of bits that is used to check the correctness of message receipt, only adding the second level. The physical level does not form the title.

It is clear that in addition to the general standard, it is necessary to have standards for each level, so today there exist up to 20 standards for one level. Despite this, the OSI reference model facilitates further development.

2. Development and Research of the Communication Channel Model Using the Testing Method

2.1. Selecting the Test Sequence's Implementation Length When Calculating the Correlation Function of Random Processes

Proposed is the method for choosing the required implementation length for the experimental determination of correlation functions in one class of standard stationary random processes. The method is based on the connection of parameters of statistical process characteristics with the average number of maxima and minima per time unit.

The input value of the control system can, of course, be considered as a random process, the statistical properties of which change little over the final implementation length [6, 7]. At the same time, there is reason to assume that the random process is formed from the sum of components after multiple filtering by linear operators. Such a random process may be considered distributed according to the standard law, and after relatively simple statistical transformations it be reduced to a stationary one with sufficient practical accuracy.

Assessment of stationary correlation function of stationary ergodic random processes for finite implementation time T is defined by the following expression:

$$R^{\bullet}(\tau,T)=\frac{1}{T-\tau}\int_{0}^{T-\tau}\overset{0}{x}(t)\overset{0}{x}(t+\tau)dt\,, \tag{1}$$

where $\overset{0}{x}(t)$ is the centered random process.

Such being the case, there arises the task of choosing the implementation length T based on the estimation of expected statistical errors due to the final implementation time. It is natural to take mean square deviation (MSD) $\sigma^2(\tau,T)$ as the characteristic of estimation accuracy (1).

MSD is determined at the point of the correlation function's maximum, i.e. at $\tau = 0$. MSD value in other points $R(\tau)$ is most fully considered only for simple correlation functions of the following form:

$$R(\tau)=De^{-\gamma|\tau|},R(\tau)=De^{-\gamma|\tau|}\cos^{-1}\beta\tau\,, \tag{2}$$

where D – the dispersion,

γ , β – the constant.

The required implementation length is determined by the required accuracy of calculation of the correlation function and its properties. Correlation functions (2) also describe random processes, in which there is no derivative. At the same time, most of the random processes in industrial systems are such that they are differentiable, so when determining T value, expression (2) may only be used as a very rough approximation of the real correlation function.

To choose the implementation length, the investigated process must be referred to a certain class of random processes with a known structure of correlation function, that is, its mathematical model should be specified. If the adopted model sufficiently fully reflects the process, then the method for calculation of estimates of correlation function $R(\tau)$ would be optimal in terms of the minimum difference between the a priori given value of MSD and MSD value obtained by $R(\tau)$.

For the analysis, it is advisable to examine standard stationary differentiated random processes, the correlation function of which is of a monotonous nature. Such correlation functions may be approximated by a linear combination of exponents. Satisfactory results can be obtained if you limit yourself to the sum of two exponents. Then:

$$R^{\bullet}(\tau)=\begin{cases}\dfrac{D^{\bullet}}{a-1}(ae^{-\gamma|\tau|}-e^{-a\gamma|\tau|}) & \text{when} \quad a>1\\ D^{\bullet}(1+\gamma|\tau|)e^{-\gamma|\tau|} & \text{when} \quad a=1\end{cases}, \tag{3}$$

where a and γ are constants.

Such an approximation is devoid of the drawbacks inevitable in the case of using (2), and confers the correlation function to a «physical» character.

It will be shown below that the implementation length required to obtain correlation function (3) to specified accuracy may be directly estimated for the segment of random process implementation. For evaluation purposes, is the connection between the average number of maxima and zeros of the random process per time unit with correlation function parameters α and γ.

To select the required MSD implementation, the estimates of correlation function (1) of centered random processes with standard distribution is determined by the following formula

$$\sigma^2(\tau,T)=\frac{2}{T^2}\int_0^T(T-\theta)[R^2(\theta)+R(\tau+\theta)R(\theta-\tau)]d\theta. \tag{4}$$

It is clear that formula (4) may be applied to a standardized correlation function $\rho^{\bullet}(\tau)$. From (3), one can obtain

$$\rho^{\bullet}(\tau)=\begin{cases}\dfrac{1}{a-1}(ae^{-\gamma|\tau|}-e^{-a\gamma|\tau|}) & \text{when} \quad a>1\\ (1+\gamma|\tau|)e^{-\gamma|\tau|} & \text{when} \quad a=1\end{cases}. \tag{5}$$

By substituting (5) into (4) and introducing dimensionless parameters $\mu=\lambda T, \lambda=\gamma\tau$, at μ >10, the following relation may be obtained for $\sigma^2(\lambda,\mu)$:

$$\sigma^2(\lambda,\mu)=\frac{2}{\mu(a-1)^2}\left\{\left[\frac{a^2(2\lambda+1)}{2}+\frac{2a^2}{1-a^2}\right]e^{-2\lambda}+\right.$$
$$\left.+\left[\frac{2a\lambda+1}{2a}-\frac{2a}{1-a^2}\right]e^{-2a\lambda}+\frac{a^2}{2}+\frac{1}{2a}-\frac{2a}{1+a}\right\} \qquad \text{if} \qquad a>1 \tag{6}$$

$$\sigma^2(\lambda,\mu)=\frac{2}{\mu}\left\{\left[\frac{5}{4}+\frac{5\lambda}{2}+2\lambda^2+\lambda^3\right]e^{-2\lambda}+\frac{5}{4}\right\} \qquad \text{if} \qquad a=1. \tag{7}$$

Ratios (6) and (7) were obtained after discarding the terms of higher smallness order $e^{-\mu}$, $1/\mu^2$, λ/μ^2, λ^2/μ^2 in comparison with $e^{-\lambda}$, $e^{-a\lambda}$, $1/\mu$, λ/μ.

The accuracy of calculated values of estimates $\rho^{\bullet}(\lambda)$, as it can be seen from (6) and (7), depends on values λ and μ. The magnitude of the correlation function tends to zero as the argument λ increases, which cannot be said about MSD with fixed implementation length μ. MSD value tends to be a constant value with growth λ.

Interest arises about the boundaries of change in MSD value for correlation functions (3) when λ and a change. It is clear from expressions (6) and (7) that $\sigma^2(\lambda,\mu)$ growth $\lambda$from 0 to ∞ is halved for any a and is reduced by the factor of 2.5 with a change a from 1 to ∞at any λ. Thus, the error of calculating the correlation function significantly depends not only on μ, but also on λ and a.

MSD only characterizes the accuracy of correlation function values in the case when this very value has been defined. Therefore, it is advisable to introduce another accuracy characteristic – variability coefficient F of a random variable $\rho^{\bullet}(\lambda)$:

$$F=\frac{\sigma^2(\lambda,\mu)}{E\left\{\rho^{\bullet}(\lambda)\right\}}=\frac{\sigma^2(\lambda,\mu)}{\rho(\lambda)}, \tag{8}$$

where $E\{\rho^{\bullet}(\lambda)\}$is the mathematical expectation.

The variability coefficient increases with growth λ, and the value$\rho^{\bullet}(\lambda)$ with larger λ giving practically no information about the random process.

The value of the required implementation length may be determined proceeding from confidence intervals for $\rho(\lambda)$ at points λ_i. However, random processes at industrial facilities may only relatively be considered standard. Therefore, finding a finite dependence for the distribution of various calculated values of correlation function is a very clear condition. Obviously, distribution $\rho^{\bullet}(\lambda)$ is asymmetric with respect to its means at small values of the argument. But with growing λ, $\rho^{\bullet}(\lambda)$ distribution strives for the standard.

Further on, within the limits of acceptable accuracy, $\rho^{\bullet}(\lambda)$ larger λ will be considered distributed in a standard manner. Then the probability that the result of $\rho^{\bullet}(\lambda)$ measurement at λ >0 does not differ by more than ε from the real value, will

$$P\left\{|\rho^{\bullet}(\lambda)-\rho(\lambda)|\le\varepsilon\right\}=2\Phi(u), \tag{9}$$

where is the Laplace function.

Using (9), we can write the expression for the coefficient variability as follows:

$$\Phi(u)=\frac{1}{\sqrt{2\pi}}\int_0^u e^{-t^2/2}dt, \tag{10}$$

$$F=\frac{\sigma^2(\lambda,\mu)}{\rho(\lambda)}=\frac{\varepsilon}{u\rho(\lambda)}. \tag{11}$$

u value can easily be found by giving the probability of $\rho^{\bullet}(\lambda)$ values falling into intervals $|\rho^{\bullet}(\lambda)-\rho(\lambda)|\le\varepsilon$.

Ratio (11) allows, with known i and ε at $\sigma^2(\lambda,\mu)$ value, to determine required implementation length μ. However, it would be more convenient to obtain μ using F value.

By jointly solving relations (6), (7), and (11), it is possible to obtain

$$\mu F^2=\frac{2}{(ae^{-\lambda}-e^{-a\lambda})^2}\left\{\left[\frac{a^2(2\lambda+1)}{2}+\frac{2a^2}{1-a^2}\right]e^{-2\lambda}+\right.$$
$$\left.+\left[\frac{2a\lambda+1}{2a}-\frac{2a}{1-a^2}\right]e^{-2a\lambda}+\frac{a^2}{2}+\frac{1}{2a}-\frac{2a}{1+a}\right\}\qquad \text{if}\qquad a>1, \tag{12}$$

$$\mu F^2=\frac{2}{(1+\lambda)^2e^{-2\lambda}}\left\{\left[\frac{5}{4}+\frac{5}{2}\lambda+2\lambda^2+\lambda^3\right]e^{-2\lambda}+\frac{5}{4}\right\}\qquad \text{if}\qquad a=1. \tag{13}$$

Since the assumption of the standard distribution law is used for small $\rho(\lambda)$, then the required implementation length μ should be determined from the variability coefficient value f at the expected point of correlation function truncation (λ_y). By choosing the truncation ordinate and specifying the value of the variability coefficient, one can find the required implementation length.

From the viewpoint of preliminary estimation of parameters γ a, the foregoing calculations and conclusions assume the presence of a priori information about the investigated random process. The task is reduced to the determination of the correlation function's two parameters: γ and a.

For a preliminary rough estimation of values γ and a, the required information may be obtained by measuring the average number of zeros $n_0$and the average number of maxima $m_0$per time unit. The average number of zeros and maxima of standard stationary differentiable random processes can be found by the following formulas

$$n_0 = \left[\int_0^\infty \omega^2 S(\omega) d\omega \Big/ \int_0^\infty S(\omega) d\omega \right]^{1/2}, \tag{14}$$

$$m_0 = \left[\int_0^\infty \omega^4 S(\omega) d\omega \Big/ \int_0^\infty \omega^2 S(\omega) d\omega \right]^{1/2}, \tag{15}$$

where $S(\omega)$ is the spectral density.

According to (3)

$$S(\omega) = D \frac{2\gamma^3 a(1+a)}{(\gamma^2 a^2 + \omega^2)(\gamma^2 + \omega^2)}, \quad a \geq 1. \tag{16}$$

By substituting (16) into (14), it can be shown as follows:

$$n_0 = \gamma \sqrt{a}, \quad a \geq 1. \tag{17}$$

When using (15), difficulties arise due to the fact that the calculated average number of maxima for processes with spectral density (16) turns out to be infinitely large. It should be noted that real processes in manufacturing systems represent random functions with a finite number of maxima on any finite interval of time. In order to obtain, within the selected class of correlation functions (3), the process that would be closest to the real one, the method of studying the emissions of non-smooth processes was used for calculation. As a result, the following semi-empirical formula was obtained

$$m_0 = \gamma \sqrt{a^2 + 3a + 1}, \quad a \geq 1, \tag{18}$$

Analysis of expressions (17), (18) shows that $m_0 > n_0$ and both roots of (18) (a_1 and a_2) are positive. Possible cases: when $a_1 > 1$, $a_2 < 1$ or $a_1 = a_2 = 1$. According to the conditions of formula (3), it would be advisable to assume $a > 1$ or $a = 1$.

2.2. Selection of the Test Sequence's Discreteness Step in Time Terms When Calculating the Correlation Function of Random Processes

Proposed was the method of choosing the discreteness step in time terms for experimental determination of standard correlation function of stationary differentiated random processes.

The step algorithm is most often used to calculate the correlation functions' estimates. the characteristic feature of the step algorithm is that the correlation function's estimate is obtained at discrete points with constant steps Δt. At the same time, the output implementations can be presented in the form of either continuous or sample functions of time with discrete steps Δt. In the first case, the algorithm is called a continuous-step one, and in the second case – a selective-step one. In the selective-step algorithm, $\Delta\tau = \Delta t$ [8] is used in most cases.

Real processes have an unlimited spectrum, therefore it is assumed that there is a priori information for choosing the frequency, above which the harmonic components of the process do not have a significant impact on the nature of the change in the correlation function. It should be noted that such information is unavailable in practice [8–10].

The discreteness step $\Delta\tau$can be found based on the specified accuracy of the correlation function's description in the interpolation interval between reference points.

Let us solve the given task for the correlation function of standard stationary differential random percentage with a zero mean value.

Let the correlation function's given values be at the argument's discrete points with step $\Delta\tau$. Based on these function values, we will construct the interpolation Lagrange polynomial for equidistant nodes. The interpolation polynomial will match the given function at interpolation nodes $\tau_0, \tau_1, \dots, \tau_i$and differ therefrom at other points. The intermediate values' accuracy is characterized by the interpolation error, which can be divided into two parts: the error that depends on the accuracy of the correlation function's calculated values at the interpolation nodes and the error that depends on the interpolation method.

The error of calculated values $R(\tau)$ depends on the implementation length, and in the selective-step algorithm – also on the step of calculation discreteness $\Delta\tau$ of the original random process. In the future, the error only arising from the interpolation method and step $\Delta\tau$ will be called the main error, with other errors to be called the additional interpolation error

Let us consider the case of the continuous-step algorithm. If we limit ourselves to the first two terms of the Lagrange formula, then the additional error, which in this case only depends on the implementation length, will remain unchanged at any discreteness step $\Delta\tau$. Error $\delta(\tau)$ is determined by the following ratio

$$\delta(\tau) = R(\tau) - \Psi(\tau) = \frac{R''(\vartheta)}{2!}(\tau - \tau_{i+1})(\tau - \tau_i), \tag{19}$$

where $\Psi(\tau)$ is an interpolating correlation function ϑ that belongs to the interval between two values τ_{i+1} of the argument τ_i.

The right-hand side of expression (19) takes the largest modulus value at $\tau = (\tau_{i+1} + \tau_i)/2$. Hence,

$$|\delta(\tau)| = \frac{\sup\limits_{\vartheta\in[\tau_i,\tau_{i+1}]}|R''(\vartheta)|}{8}\Delta\tau^2 \tag{20}$$

or, passing to standardized correlation function $\rho(\tau)$:

$$|\eta(\tau)| \le \frac{\sup\limits_{\vartheta\in[\tau_i,\tau_{i+1}]}|\rho''(\vartheta)|}{8}\Delta\tau^2 \cdot \tag{21}$$

where $\eta(\tau)$ is the interpolation error of intermediate values of the standardized correlation function. In its turn

$$-\rho''(\vartheta) = \frac{\int\limits_0^\infty \omega^2 S(\omega) e^{j\vartheta\omega} d\omega}{\int\limits_0^\infty S(\omega) d\omega}, \tag{22}$$

where $S\,(\omega)$ is the spectral density of the random process.

Using the property of defined integral, we can write as follows

$$|\rho''(\vartheta)| \le \frac{\int\limits_0^\infty \omega^2 \left|S(\omega) e^{j\vartheta\omega}\right| d\omega}{\int\limits_0^\infty S(\omega) d\omega}, \tag{23}$$

Inequality (23) is the generalization for the case of the integral of the sum's known property: the sum's absolute value is less than or equal to the sum of the terms' absolute values.

But

$$\left|S(\omega)e^{j\vartheta\omega}\right| = \left|S(\omega)\right| = S(\omega). \qquad (24)$$

Then

$$\left|\rho''(\vartheta)\right| \le \frac{\int_0^\infty \omega^2 S(\omega)d\omega}{\int_0^\infty S(\omega)d\omega} = -\rho''(0), \qquad (25)$$

which is equivalent to the following condition

$$\sup_{\vartheta\in[\tau_i,\tau_{i+1}]}\left|\rho''(\vartheta)\right| = \sup_{\vartheta\in[0,\Delta\tau]}\left|\rho''(\vartheta)\right| = -\rho''(0),$$

that is, maximum $|\rho''(\vartheta)|$ belongs to the interval [0, $\Delta\tau$].

The right-hand side of inequality (25) can be expressed in terms of the average number of crossings n_0 by a random process of zero level per time unit. For a stationary standard differentiated random process with a zero mean value, the mean number n_0 is determined by the following ratio:

$$n_0 = \sqrt{\frac{\int_0^\infty \omega^2 S(\omega)d\omega}{\int_0^\infty S(\omega)d\omega}}. \qquad (26)$$

Taking into account (25) and (26), expression (21) for the intrinsic error of the standardized correlation function may be written as the following inequality:

$$\sup_{\tau\in[\tau_i,\tau_{i+1}]}\left|\eta(\tau)\right| = \left|\eta(\Delta\tau/2)\right| \le \frac{n_0^2\pi^2}{8}\Delta\tau^2. \qquad (27)$$

Thus, for the interpolation error not to exceed in absolute value $\left|\eta(\Delta\frac{\tau}{2})\right|$, it is necessary to choose $\Delta\tau$ subject to the following condition

$$\Delta\tau \le \frac{2}{\pi n_0}\sqrt{2\left|\eta(\Delta\tau/2)\right|}. \qquad (28)$$

It would be advisable to proceed to the assessment of discreteness step $\Delta\tau$ when calculating the correlation function based on sampled data. Such being the case, an additional interpolation error $\tilde{\rho}(\tau)$ calculated on finite time interval *T* also depends on the discreteness step $\Delta\tau$. Random process discretization leads to a partial loss of information, therefore the additional error will be slightly greater than in the case of implementation of the continuous-step algorithm. It would be advisable to assess the relative increase of MSD $\tilde{\sigma}$when calculating $\rho(\tau)$ from sample data in comparison with MSD σ when calculating using continuous data. MSDs of estimates of correlation functions of centered random processes with standard distribution are determined using the following formulas:

$$\sigma^2 = \sigma^2(\tau,T) = \frac{2}{T}\int_0^T \left(1-\frac{\theta}{T}\right)\left[\rho^2(\theta)+\rho(\tau+\theta)\rho(\theta-\tau)\right]d\theta, \tag{29}$$

$$\tilde{\sigma}^2 = \tilde{\sigma}^2(\Delta\tau l, N) = \frac{2}{N}\sum_{k=1}^{N}\left(1-\frac{k}{N}\right)\times$$

$$\times\left[\rho^2(k\Delta\tau)+\rho(k\Delta\tau+l\Delta\tau)\rho(k\Delta\tau-l\Delta\tau)\right]+\frac{1}{N}\left[\rho^2(0)+\rho^2(l\Delta\tau)\right], \tag{30}$$

where $T = N\Delta\tau$; $k = 1,\ldots,l,\ldots,N-1$.

However, in the case of $\tau = 0$ the formula independent of the upper MSD limit would be more convenient for $\tau, k\Delta\tau$ calculation:

$$\sigma^2 = \sigma^2(0,T) \le \frac{4}{T}\int_0^\infty \rho^2(\theta)d\theta, \tag{31}$$

$$\tilde{\sigma}^2 = \tilde{\sigma}^2(\Delta\tau, N) \le \frac{4}{N}\sum_{k=1}^{\infty}\rho^2(k\Delta\tau)+\frac{2}{N}. \tag{32}$$

Studying the relative increase in MSD for all classes of differentiated random processes is quite a difficult task. In this case, it is necessary to limit ourselves to the class of random processes, the correlation function of which monotonously decreases as the argument increases. Since MSD depends on $T, \Delta\tau$ and the properties of the correlation function itself, to compare the increase of MSD in the selected class, the parameter is required that would reflect characteristic properties $\rho(\tau)$ and steps $\Delta\tau$. As such a parameter, it is necessary to assume number of points *m* placed on the correlation function for conditional decay time $\tau_з$. Value $\tau_з$ is determined from the following equality

$$\rho(\tau_з) = 0{,}05, \tag{33}$$

and number of points *m* using the formula:

$$m = \tau_з / \Delta\tau . \quad (34)$$

Then the relative increase in MSDε may be estimated using the formula:

$$\varepsilon(m) = (\tilde{\sigma} - \sigma)/\sigma . \quad (35)$$

With $\rho(\tau)$ arranged in the specified class by growth $\tau_з$, then the first element will be as follows:

$$\rho(\tau) = \frac{1}{a-1}\left(ae^{-\gamma|\tau|} - e^{-a\gamma|\tau|}\right) \quad if \quad a \to \infty , \quad (36)$$

and the last one is as follows:

$$\rho(\tau) = e^{-\frac{\gamma^2\tau^2}{4}} , \quad (37)$$

where γ and a are the constants.

By substituting (37) into (31) and (32) and introducing dimensionless parameters $\mu = \gamma T = \Delta\tau\gamma N,$ $\lambda_з = \gamma\tau_з,$ after integration and reduction:

$$\sigma^2(0,\mu) = \frac{2(a^4 + a^3 - 4a^2 + a + 1)}{\mu(a-1)^2(a+1)a} , \quad (38)$$

$$\tilde{\sigma}^2\left(\frac{\lambda_з}{m}, \mu\right) = \frac{\lambda_з}{\mu m}\left\{\frac{4}{(a-1)^2}\left[\frac{a^2 e^{-\frac{2\lambda_з}{m}}}{1-e^{-\frac{2\lambda_з}{m}}} - \frac{2ae^{-\frac{(1+a)\lambda_з}{m}}}{1-e^{-\frac{(1+a)\lambda_з}{m}}} + \frac{e^{-\frac{2a\lambda_з}{m}}}{1-e^{-\frac{2a\lambda_з}{m}}}\right] + 2\right\} . \quad (39)$$

Solution of (35) taking into account (38), and (39) in general form is impossible. Therefore, according to the ratio (33) and using the trial-and-error procedure, $\lambda_з$ were calculated for (36) and (37), and after that dependence values $\varepsilon(m)$ were determined using numerical methods. Dependence curves$\varepsilon(m)$ are shown in fig. 3.

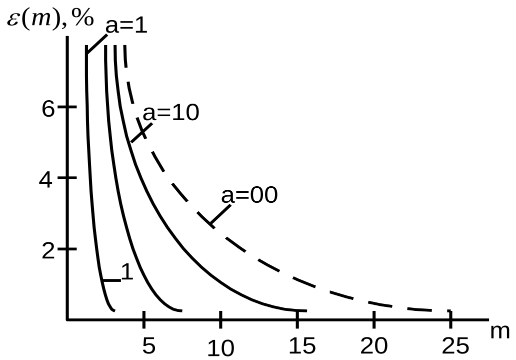

Figure 3. Dependence between relative growth of MSD and the number of points

Source: developed by the author

Curve 1 corresponds to correlation function (37) with other curves corresponding to function (36) at different a. The case $a = \infty$ $(\rho(\tau) = e^{-\gamma|\tau|})$ refers to the limit one and corresponds to an undifferentiated random process. The curves in Fig. 3 show that for m > 10, the increase in MSD due to the discreteness step for differentiated random processes of specified class is less than 1 %, that is, it is small compared to the error from the implementation length.

Let the absolute value of MSD accretion be equal to the basic error at the same t values for the mean random process from the specified class. In this case, we determine value $\tau_з$ using the formula:

$$\tau_з = 2 / n_0 . \tag{40}$$

Solving (40) together with (28), we can obtain

$$\left|\eta(\Delta\tau / 2)\right| = \pi^2 / 2m^2 . \tag{41}$$

The dependence curve (41) is shown in Fig. 4.

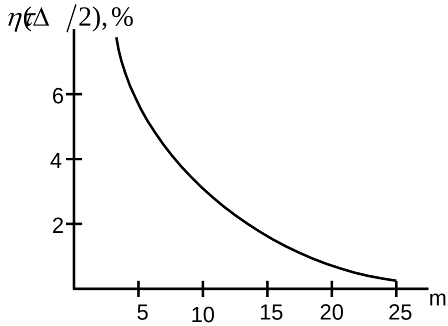

Figure 4. Dependence between the absolute error's standardized value and the number of points

Source: developed by the author

It is necessary to compare it with the absolute value of MSD growth. Because $\sigma < 1$, therefore, according to (35)

$$\bar{\sigma} - \sigma < \varepsilon(m).$$

Curves *1* and *2* show that

$$\bar{\sigma} - \sigma << \eta(\Delta\tau / 2). \qquad (42)$$

For example, if $\eta = T\gamma = 10, a = 10, m = 10$, a = 10, t = 10, then

$$\bar{\sigma} - \sigma \approx\sim 0{,}00126, \qquad |\eta(\Delta\tau / 2)| \approx 0{,}05.$$

The foregoing analysis shows that the discreteness step's influence on the error of calculated values $\rho(\tau)$ is small compared to the error of the implementation length if the discreteness step $\Delta\tau$is chosen so that each conditional decay interval $\tau_з$ comprises no less than ten points. The last condition is easy to satisfy if the value $|\eta(\Delta\tau/2)| \leq 0{,}05$ is assumed.

Consequently, when choosing the discreteness step both for continuous and for sample data, one can use formula (28). Having set maximum permissible error $\eta(\Delta\tau/2)$ and knowing the value of n_0, $\Delta\tau$ can easily be determined.

For example, with $\eta(\Delta\tau/2) = 0{,}05$ we have $\Delta\tau \leq 0{,}2 / n_0$.

2.3. Assessment of the Discreteness Step of the Test Sequence in Time Terms When Calculating Spectral Densities of Random Processes

Proposed is the practical method for selecting the time step of discreteness in the experimental determination of random processes' spectral densities, such method being based on the connection between the average number of zeros of a standard stationary random process and the mean square frequency of the spectral density.

When transforming a continuous implementation into the digital form, there occur difficulties associated with the choice of time discreteness step. Too small a discreteness step leads to an unjustified increase in the volume of digital data and labor intensity of all calculations, while too large a step can lead to a complete distortion of the spectral density estimate. For a rational choice of the discreteness step, it is necessary to possess some particular information about the nature of the spectral density of the investigated random process. In this connection, the following two questions arise [8, 11]:

1) what information about the nature of spectral density should be available to enable a rational choice of the discrete-time step,

2) how can one practically obtain this information before calculating the spectral density estimate?

The first question arises due to the fact that spectral densities of real random processes tend to zero when $\omega \to \infty$ having no exact value of cutoff frequency. Such being the case, the choice of required discreteness step depends on the following factors at the least:

a) on the permissible value of the error arising due to time quantization;

b) on some parameter characterizing the «width» of the spectral density;

c) on the parameter defining the spectral density's behavior at $\omega \to \infty$.

The conditional cutoff frequency ω_c can be found on the following condition

$$S(\omega_c)/S(0) = \Delta, \tag{43}$$

where Δ is a small value, for example, 0.05.

It can not provide complete information for the selection of the discreteness step, because, in a certain sense, it only characterizes the «width» of the spectral density.

The second question is very important. Required information about the nature of the spectral density should be easily determined directly by the implementation type before calculating the spectral density estimate.

Known recommendations for determining the discreteness step in time terms either assume the presence of a priori information, which is absent in practice [10–12], or lead to rather an arbitrary choice of value Δt.

In order to obtain information about the nature of the spectral density of the investigated random process, it is necessary to use the average number of zero levels crossing thereof. For a standard stationary differentiated random process with a zero mean, the average number of zeros is related to the rms frequency of the spectral density as follows:

$$n_{cp} = \frac{1}{\pi}\sqrt{-r''(0)}\,, \tag{44}$$

where n_{cp} is the average number of zeros per time unit,

$r''(0)$ is the second derivative of the standardized correlation function with the displacement value equaling zero

In its turn

$$-r''(0) = \omega_{II}{}^2 = \int_0^\infty \omega^2 S(\omega)d\omega \Big/ \int_0^\infty S(\omega)d\omega\,, \tag{45}$$

where $\omega_{II}{}^2$ is the mean square frequency of spectral density $S(\omega)$.

From (44) and (45):

$$n_{cp} = \omega_{II}/\pi\,. \tag{46}$$

One should obtain the formula that would relate the required discreteness step in time terms to the average number of zeros of the random process for some class of random processes with monotonous small-rational spectral densities being satisfactorily approximated by expressions of the following type

$$S(\omega) = a\prod_{i=1}^{\infty}\frac{1}{T_i^2\omega^2+1}, \tag{47}$$

where a and T_i are constant coefficients.

As is known, the relationship between the spectral density of discrete series and the spectral density of implementation of a continuous random process, from which this discrete series is obtained, has the following form:

$$S^*(\omega) = \sum_{\kappa=-\infty}^{\infty} S(\omega - 2\kappa\omega_{mp}), \tag{48}$$

where $S^*(\omega)$ is the spectral density of a discrete random process,

$S(\omega)$ is the spectral density of the respective continuous random process,

$\omega_{mp} = \frac{\pi}{\Delta t}$ is the transposition frequency.

Hence, absolute error $Q(\omega)$, which arises due to discreteness, can be obtained $|\omega| \leq \omega_{mp}$ in the following way:

$$\begin{aligned} Q(\omega) &= S^*(\omega) - S(\omega) = \left[\sum_{\kappa=-\infty} S(\omega - 2\kappa\omega_{mp}) \right] - S(\omega) = \\ &= \sum_{\kappa=1}^{\infty} \left[S(2\kappa\omega_{mp} - \omega) + S(2\kappa\omega_{mp} + \omega) \right]. \end{aligned} \tag{49}$$

Relative error $\delta(\omega)$ equals to:

$$\delta(\omega) = \frac{Q(\omega)}{S(\omega)} = \frac{\sum_{\kappa=1}^{\infty} \left[S(2\kappa\omega_{mp} - \omega) + S(2\kappa\omega_{mp} + \omega) \right]}{S(\omega)}, \quad |\,\omega\,| \leq \omega_{mp}. \tag{50}$$

For random processes with monotonous frequency-unlimited spectral densities, the relative error at frequency ω_{mp} will exceed 100 % and descend with decreasing frequency. The relative error of spectral density estimation in the operating frequency range [0, ω_{mp}], which arises due to time quantization, should not exceed a few percent. Hence it is clear that the condition $\omega_p < \omega_{mp}$ must be fulfilled.

In order to obtain a connection between Δt and n_{cp} it is necessary to perform the following operations.

1. Assume the operating frequency range [0, ω_{mp}], in which the spectral density estimate is supposed to be calculated. Should there be no special reasoning, one can assume that the operating frequency range is limited by conventional cutoff frequency ω_c.
2. Assume the value of maximum permissible relative error δ_{max}.
3. Determine ω_{mp} in such a way that the condition is fulfilled $\delta(\omega) \leq \delta_{max}$ in the operating frequency range.
4. Establish the connection between ω_{mp} and ω_{II}.
5. Obtain required formula $\Delta t = f(n_{cp})$.

It is clear that, in order to perform the above-mentioned operations, one should know the spectral density's form. In addition, for various spectral densities, different expressions will be generated, because one parameter ω_{II} or n_{cp} fails to completely defines the discreteness step. Value Δt is also affected by other, more subtle properties of spectral density and primarily by the rate of decrease of spectral density's tail part. Provided that for each spectral density from the class of monotonous small-rational spectral densities under the above-mentioned technique, the final dependence is obtained. Thus, a set of functions would be defined

$$\Delta t_i = f_i(n_{cp}). \tag{51}$$

If, in addition, it would be possible in any way to introduce a probabilistic measure, i.e. to assign a certain probability of occurrence to each element of the set under consideration (51), then for the purposes of experiment planning it would be possible to recommend, in a certain sense, the best formula from the set (51). Provided that, during an experimental study with equal probability, the data may be described by any random process from the class under consideration, that is, set (51) is characterized by a uniform distribution and probability law. It is necessary to harmonize the set of spectral densities, and therefore, the set of functions (51) in accordance with the rate of decrease of spectral densities' tail branches, placing first the element with the lowest reduction rate. This first element will be the spectral density of a random process obtained by white noise filtering with a single-capacitance link:

$$S_1(\omega) = A\big/(T^2\omega^2 + 1), \qquad \Delta t_1 = f_1(n_{cp}), \tag{52}$$

where T is the shaping filter's time constant,

A is a constant coefficient.

Hence, the more serially connected links the forming filter contains and the closer these links' time constants lie to each other, the faster the spectral density's tail part will decrease. It can be shown that if the number of serially connected single-capacitance elements of the shaping filter with the same time constants tends to infinity, the spectral density of the random process at the output of the filter would tend to

$$S_\infty(\omega) = B\exp\left\{-T_s^2\omega^2\right\}, \qquad \Delta t_\infty(n_{cp}), \tag{53}$$

where B is a constant coefficient,

T_S is the dispersion time of the shaping filter's impulse function, that is, the radius of inertia of the impulse function area relative to the center axis weight.

At one and the same size n_{cp} for case (52) it is necessary to obtain the smallest discreteness step, and for case (53) – the largest step. For the purposes of experiment planning, under the assumption of equal probability of occurrence of random processes from the class under consideration, it would be natural to use the following average value

$$\Delta t = \left[f_1(n_{cp}) + f_\infty(n_{cp}) \right] / 2 . \qquad (54)$$

The final formula that connects the average number of zeros in the studied random process with the discreteness step, which is advisable to assume when quantizing the implementation by time, has the following form

$$\Delta t \approx 0{,}2 / n_{cp} . \qquad (55)$$

The relationship between the average number of zeros and the time discreteness step was obtained for a narrow class of stationary ergodic differentiated random processes with standard distribution law, a zero mean value, and a monotonous small-rational character of spectral densities. These assumptions limit the possibility of using this technique in the experimental determination of spectral densities of random processes taking place in industrial automatic control systems.

The factors limiting the use of this technique are as follows:

– Presence of non-zero average value. The average value of the implementation of the random process with the accuracy sufficient for this case can be estimated by the type of implementation, after which this average value should be assumed as zero-level one.

– Standard law of distribution. The dynamics of industrial facilities with small deviations from the steady state may, as a rule, be described by a mathematical model close to a linear one. Therefore, there is a reason to assume that random industrial processes generated as a result of multiple linear filtering by the objects representing low-frequency filters have a distribution law close to a standard one.

– Non-stationarity of random industrial processes. Normally, random processes occurring in industrial automatic management systems are non-stationary. In case of change in time of mathematical expectation *M(t),* its estimate should be taken as a zero-level one, after which the entire subsequent method of choosing the discreteness step Δt remains unchanged.

– Differentiation of random processes. Industrial stochastic processes are almost always differentiated, except for the cases when broad-band noise is superimposed on studied stochastic processes. The presence of such noise leads to implementation line smearing. At the point of zero-level intersection by smeared implementation, there are actually several merging intersections. Therefore, in such cases, one should either pre-filter the implementation or reduce the obtained value Δt by 5-10 times.

– Small-rational nature of spectral density. From a practical point of view, this limitation is insignificant, since spectral densities of industrial random processes are mostly satisfactorily approximated by small-rational expressions.

– Monotonous nature of spectral density. If spectral density is non-monotonous, that is, if there are maxima at frequencies other than zero, maximum relative error δ_{max} can shift insideward the operating frequency range. However, when choosing $\omega_p = \omega_c$, as it was done in the derivation of formula (55), a similar phenomenon may occur in those rare cases when the spectral density's secondary maxima occur at frequencies close to ω_c.

When calculating ω_{II}^2 for case (52), difficulties arise due to the fact that integral $\int_0^\infty \frac{\omega^2}{T^2\omega^2+1} d\omega$ does not exist. Therefore, the spectral density's mean square frequency for this case is determined using the formula:

$$\omega_{II}^2 = \frac{\int_0^\infty | f\omega W(j\omega) - \left[j\omega W(j\omega) \right]_{\omega=\infty} |^2 \, d\omega}{\int_0^\infty |W(j\omega)|^2 \, d\omega}, \tag{56}$$

where $W(j\omega)$ is the shaping filter's transfer function,

Frequency's root mean square coincides with the standard one because

$$\left[j\omega W(j\omega) \right]_{\omega=\infty} = 0 .$$

Thus, using formula (56), one can obtain

$$\omega_{II}^2 = \frac{\int_0^\infty \left| j\omega \frac{K}{Tj\omega+1} - \left[j\omega \frac{K}{Tj\omega+1} \right]_{\omega=\infty} \right|^2 d\omega}{\int_0^\infty \frac{K^2}{T^2\omega^2+1} d\omega} = \frac{1}{T^2}, \tag{57}$$

$$\omega_{II}^2 = \frac{1}{T}. \quad (58)$$

Conditional cut-off frequency, if $\Delta = 0.05$:

$$\frac{1}{T^2\omega^2 + 1} = 0{,}05, \qquad \omega_c = \frac{4{,}38}{T}. \quad (59)$$

Let the relative maximum permissible error be in the operating frequency range $\delta_{\max}$ and equal to 0.02. Then, accordingly

$$\delta(\omega_c) = \delta_{\max} = \frac{\sum_{k=1}^{\infty}\left[\frac{A}{T^2(2k\omega_{mp} - \omega_c)^2 + 1} + \frac{A}{T^2(2k\omega_{mp} + \omega_c)^2 + 1}\right]}{\frac{A}{T^2\omega_c^2 + 1}} = 0{,}02. \quad (60)$$

Starting from frequency $\omega_{s,}$ the effect of the unit in spectral density's denominator may be neglected:

$$S_1(\omega) = A/(T^2\omega^2 + 1) \approx A/T^2\omega^2, \qquad \omega \geq \omega_c. \quad (61)$$

This allows simplifying expression (60)

$$0{,}02 \approx a^2 \sum_{k=1}^{\infty}\left(\frac{1}{(2k - a)^2} + \frac{1}{(2k + a)^2}\right), \quad (62)$$

where a indicates the following relation:

$$a = \omega_c / \omega_{mp}. \quad (63)$$

If expression (62) is reduced to the common denominator, it is possible to obtain

$$2a^2 \sum_{k=1}^{\infty}\left\{\frac{(2k)^2}{\left[(2k)^2 - a^2\right]^2} + \frac{a^2}{\left[(2k)^2 - a^2\right]^2}\right\} \approx 0{,}02. \quad (64)$$

To find the relative error's expression in the general form, one should use the formulas of sums of infinite trigonometric series, from which, the case quotient will be

$$\sum_{k=1}^{\infty}\frac{(2k)^2}{\left[(2k)^2-a^2\right]^2}=\frac{\pi}{8}ctg\frac{a\pi}{2}\left(\frac{\pi}{\sin a\pi}-\frac{1}{a}\right), \tag{65}$$

$$\sum_{k=1}^{\infty}\frac{(2k)^2}{\left[(2k)^2-a^2\right]^2}=\frac{\pi}{8a^2}ctg\frac{a\pi}{2}\left(\frac{\pi}{\sin a\pi}+\frac{1}{a}\right)-\frac{1}{2a^4}. \tag{66}$$

By substituting (65) and (66) into (64), after transformations

$$\frac{\pi^2a^2}{4}\frac{1}{\sin^2\frac{\pi a}{2}}-1\approx 0,02, \tag{67}$$

from which

$$a=0,153, \tag{68}$$

$$\omega_{mp}=6,53,\quad \omega_c=30,5/T. \tag{69}$$

Thus, taking into account (46), (60), and (69)

$$\Delta t_1=0,103/\omega_{II}\approx 0,032/n_{cp}. \tag{70}$$

Similar calculations for case (53):

$$\omega_{II}^2=\frac{\int_0^{\infty}B\exp\left\{-T_s^2\omega^2\right\}d\omega}{2T_s^2\int_0^{\infty}B\exp\left\{-T_s^2\omega^2\right\}d\omega}=\frac{1}{2}\frac{1}{T_s^2}, \tag{71}$$

$$\omega_{II}=\frac{1}{\sqrt{2}}\frac{1}{T_s}=\frac{0,707}{T_s}. \tag{72}$$

The conditional cutoff frequency equals to

$$\exp\left\{-T_s^2\omega_c^2\right\}=0,05,\qquad \omega_c=1,73/T_s. \tag{73}$$

The relative error is equal to

$$\delta(\omega_c)=\frac{\sum_{k=1}^{\infty}\left[B\exp\left\{-(2k\omega_{mp}-\omega_c)^2T_s^2\right\}+B\exp\left\{-(2k\omega_{mp}+\omega_c)^2T_s^2\right\}\right]}{B\exp\left\{-\omega_c^2T_s^2\right\}}. \quad (74)$$

The series in the numerator of expression (74) converges quickly, so to assess value $\delta(\omega_c)$ only the first term of the series shall be taken into account:

$$\delta(\omega_c)\approx\frac{\exp\left\{-(2k\omega_{mp}-\omega_c)^2T_s^2\right\}}{\exp\left\{-\omega_c^2T_s^2\right\}}=\exp\left\{4\omega_c^2T_s^2\left(\frac{1}{a}-\frac{1}{a^2}\right)\right\}. \quad (75)$$

If $\delta(\omega_c)=0{,}02$, then

$$a=0{,}786, \quad (76)$$

$$\omega_{mp}=1{,}27 \qquad \omega_c=2{,}2/T_s\,. \quad (77)$$

Taking into account (46), (72) and (77)

$$\Delta t_\infty=1{,}02/\omega_{II}=0{,}325/n_{cp}\,. \quad (78)$$

According to (53) and taking into account (70) and (78), the final expression has the following form

$$\Delta t=0{,}56/\omega_{II}\approx0{,}2/n_{cp}\,. \quad (79)$$

3. Method of Adaptation by Arbitration in the Course of Transmission

The problem of adaptation by arbitration during transmission is solved by the fact that the level of interference in the communication channel is first measured on the transmitting side, after which the number of times the transmission must be repeated is determined, and then information is transmitted with repetition and arbitration in the accumulation mode.

If during the transmission time, the signal level is constant and equal to U_c, and the signal is affected by additive interference U_ξ, the sequence of calculations may be presented in the following form:

$$\begin{cases} U_1 = U_c + U_{\xi 1} \\ U_2 = U_c + U_{\xi 2} \\ \dots\dots\dots\dots \\ U_m = U_c + U_{\xi m} \end{cases}, \quad (80)$$

where $U_{\xi m}$ is the voltage value at the moment of the *mth* counting.

The following signal will pass through the communication channel:

$$U = \sum_{i=1}^{m} (U_c + U_{\xi i}) = m \cdot U_c + \sum_{i=1}^{m} U_{\xi i}. \quad (81)$$

The ratio of signal and interference powers will be determined by the ratio [7, 12]:

$$\left(\frac{P_c}{P_\xi}\right) = \frac{(m \cdot U_c)^2}{D\left(\sum_{i=1}^{m} U_{\xi i}\right)}, \quad (82)$$

where $D\left(\sum_{i=1}^{m} U_{\xi i}\right)$is the interference dispersion in the communication channel.

Taking into account the fact that the interference level values are uncorrelated, the variance of the sum of deductions $U_{\xi i}$ equals the sum of deductions variances:

$$D\left(\sum_{i=1}^{m} U_{\xi i}\right) = \sum_{i=1}^{m} D(U_{\xi i}). \quad (83)$$

Assuming that disturbance is a stationary random process, one can obtain:

$$D\left(\sum_{i=1}^{m} U_{\xi i}\right) = m \cdot D(\xi_i). \quad (84)$$

Then the ratio of signal power and interference within the communication channel can be expressed as:

$$\left(\frac{P_c}{P_\xi}\right)_2 = \frac{(m \cdot U_c)^2}{m \cdot D(U_\xi)} = m \cdot \frac{U_c^2}{D(U_\xi)} = m \cdot \left(\frac{P_c}{P_\xi}\right)_1 \quad (85)$$

That is, under the conditions listed above, repeated transmission of the same information *m* times may be considered the increase in the signal-to-noise ratio by *m* times.

The volume of signal V may be written as:

$$V = 3{,}5 \cdot log_2\left(\frac{P_c}{P_\xi}\right) = 3{,}5 \cdot N \cdot log_2\left(\frac{P_c}{P_\xi} \cdot \frac{1}{m} \cdot m\right)$$
$$= 3{,}5 \cdot N \cdot log_2\left(\frac{P_c}{m \cdot P_\xi} \cdot m\right) =$$
$$= 3{,}5 \cdot N \cdot \left(log_2 m + log_2\left(\frac{P_c}{P_\xi}\right)\right) = 3{,}5 \cdot N \cdot log_2 m$$
$$+3{,}5 \cdot N \cdot log_2\left(\frac{P_c}{P_\xi}\right) \qquad (86)$$

Or, if we succeed from power to amplitude:

$$V = 3{,}5 \cdot N \cdot \log_2\left(\frac{U_c}{U_\xi}\right)^2 = 7 \cdot N \cdot \log_2\left(\frac{U_c}{U_\xi} \cdot \frac{1}{m} \cdot m\right) = 7 \cdot N \cdot \log_2\left(\frac{U_c}{m \cdot U_\xi} \cdot m\right) =$$
$$= 7 \cdot N \cdot \left(\log_2 m + \log_2\left(\frac{U_c}{U_\xi}\right)\right) = 7 \cdot N \cdot \log_2 m + 7 \cdot N \cdot \log_2\left(\frac{U_c}{U_\xi}\right) \qquad .(87)$$

In practical terms, expressions (86) and (87) may be interpreted as follows: should the interference level have increased by m times, the information transmitted to the communication channel must be repeated $log_2 m$ times or transmitted ($log_2 m+1$) times. At the same time, random interference's influence decreases by $log_2 m$ times, that is, the probability of signal distortion decreases, and, accordingly, the probability of information transmission through the communication channel increases by $\log_2 m$ times.

In the case of m-fold transmission, in order to raise the efficiency, it is advisable to implement the arbitration mode, when the information is transmitted an odd number of times and the correct one is determined based on the majority of repetitions.

Voltage values should be recorded in conditions close to the real transmission mode (with due regard to the speed) to avoid a dynamic error. The interference voltage measurement period must be determined from the following ratio:

$$T_{вим} = \tau_{інф} = \frac{1}{k \cdot \nu}, \qquad (88)$$

where τ_{inf} is the duration of one information pulse's transmission.

The proposed method may be implemented using the structure, the generalized form of which is shown in Fig. 5. The algorithms of the system's transmitting and receiving parts are shown in Fig. 6 and Fig. 7.

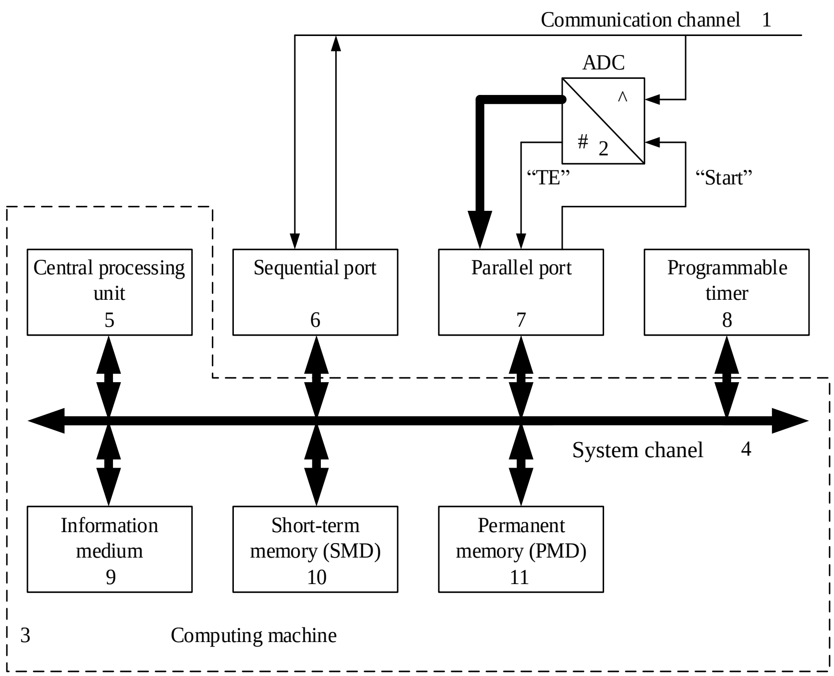

Figure 5. Flow Diagram for Implementation of the Information Transmission Method with Adaptation by Arbitration

Source: developed by the author

4. Assessment of Probability of Information Transmission for the Adaptation Method Developed

The task of detecting a signal on the receiving side lies in determining whether it contains an informative signal or not as a result of received signal processing. The two types of errors may occur during the solution of signal identification problems:

– in the absence of an informative signal, the vector of the received signal is in region v_1 and, in accordance therewith, hypothesis H_1 is accepted: «informative signal is present»;

– in the presence of an informative signal, the vector of the received signal is in region v_0, and in accordance therewith, hypothesis H_0 is accepted: «no informative signal».

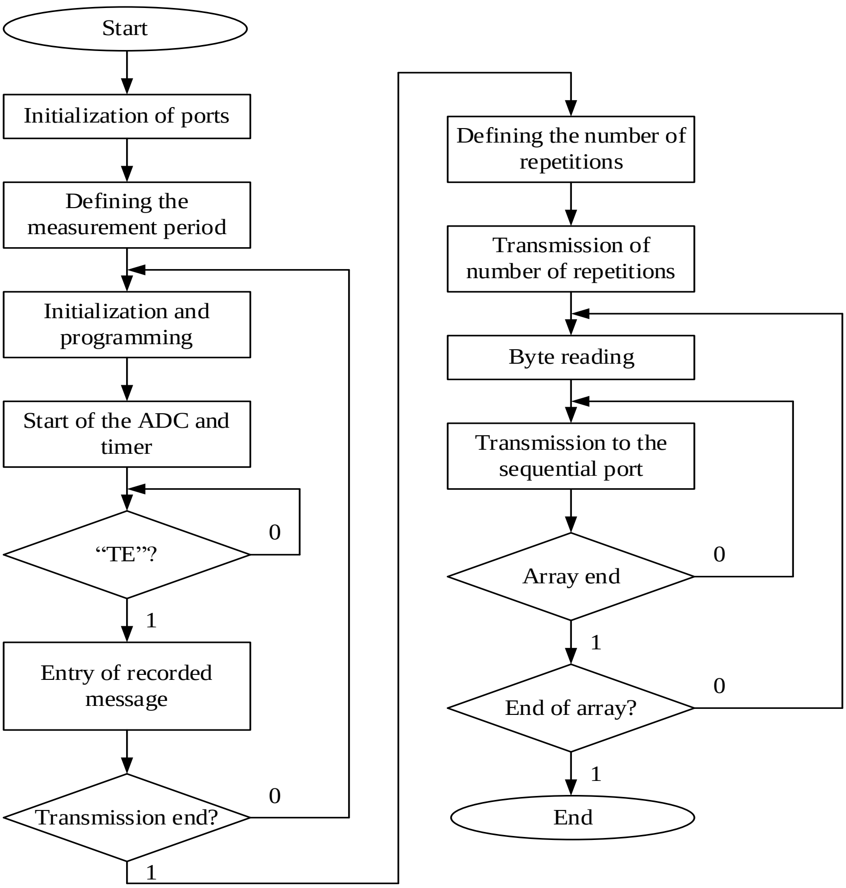

Figure 6. Operating Algorithm
for the Device Featuring Adaptation
by Arbitration on the Transmitting Side

Source: developed by the author

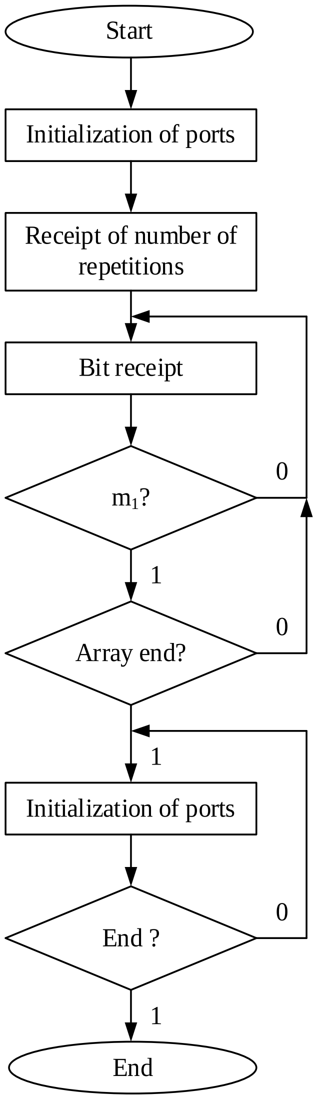

Figure 7. Operating Algorithm for the Device Featuring Adaptation by Arbitration on the Receiving Side

Source: developed by the author

The first of them is called the first kind error or «false alarm», the other being called the second kind error or «signal loss». Numerically, errors of the first and second kind are estimated by probabilities α and β of erroneous decisions about the presence of the signal, when it is actually absent and about the absence of the signal, when it is actually present

$$\alpha = p\left(Y \in v_1 / x_0\right) = \int_{v_1} w\left(Y / x_0\right) dY, \tag{89}$$

$$\beta = p\left(Y \in v_0 / x_1\right) = \int_{v_0} w\left(Y / x_1\right) dY. \tag{90}$$

Joint unconditional probability of a wrong decision is determined by the expression:

$$p_{пом} = p(x_0) \cdot \alpha + p(x_1) \cdot \beta. \tag{91}$$

The ideal observer criterion (Kotelnikov criterion) allows for minimizing the error:

$$P_{пом} = min. \tag{92}$$

The likelihood ratio for the case of two alternative situation and continuous acceptance during time t_{pr} has the following form:

$$\lambda = \exp\left(\frac{\int_0^{t_{пр}} \left(y(t)\right)^2 dt - \int_0^{t_{пр}} \left(y(t) - x(t)\right)^2 dt}{p_0} \right) =$$

$$= \exp\left(\frac{2\int_0^{t_{пр}} y(t)x(t)dt - \int_0^{t_{пр}} \left(x(t)\right)^2 dt}{p_0} \right) = \exp\left(\frac{2\int_0^{t_{пр}} y(t)x(t)dt - E_x}{p_0} \right), \tag{93}$$

where E_x is the informative signal's energy;

$p_0 = \frac{\sigma_\xi^2}{\Delta f_{nep}}$ is the specific power of additive interference of white Gaussian noise type with a zero mean.

The decision about the presence of the signal shall be made if its amplitude exceeds the threshold level:

$$\lambda > \lambda_0 = \frac{p(0)}{p(A)}, \tag{94}$$

or

$$\frac{2}{p_0}\int_0^{t_{np}} y(t)x(t)dt > \frac{p_0}{2A}\ln\frac{p_0}{p(A)} + \frac{E_x}{p_0} = \lambda_0', \tag{95}$$

where *p* (*A)* is a priori probability of signal presence;

A is the informative signal's amplitude.

The signal's threshold level may be determined according to the algorithm proposed.

The conditional probability of the first kind of error is the probability that in the absence of an informative signal, the receiving device will record it, i.e. $y(t) = \xi$(t) provided that ξ(t) is the interference.

Integral $\int_0^{t_{np}} \xi(t)x(t)dt$ is obtained from the sum, in which all terms obey the normal law of distribution with a zero mean. Then the sum and, accordingly, value $\eta_1 = \frac{2}{p_0}\int_0^{t_{np}} \xi(t)x(t)dt$ are subject to the normal law of distribution with a zero mean.

Thus, the expression for the conditional probability of the first kind of error may be represented as:

$$\alpha = \int_{\lambda_0}^{\infty} \frac{1}{\sqrt{2\pi\sigma_{\eta_1}^2}} \cdot e^{-\frac{\eta_1^2}{2\sigma_{\eta_1}^2}} d\eta_1. \tag{96}$$

The conditional probability of the second kind of error is the probability that, in the presence of a useful signal, the following inequality holds true:

$$\frac{2}{p_0}\int_0^{t_{np}} y(t)x(t)dt \le \ln\frac{p_0}{p(A)} + \frac{E_x}{p_0} = \lambda_0^{'}, \tag{97}$$

where $y(t) = x(t) + \xi(t)$.

A random variable characterizing the second kind of error is described by the following expression:

$$\eta_2 = \frac{2}{p_0}\int_0^{t_{np}} \left(x(t)+\xi(t)\right)x(t)dt = \frac{2}{p_0}\int_0^{t_{np}} \left(x(t)\right)^2 dt + \frac{2}{p_0}\int_0^{t_{np}} \xi(t)x(t)dt =$$
$$= \frac{2E_x}{p_0} + \int_0^{t_{np}} \xi(t)x(t)dt = \frac{2E_x}{p_0} + \eta_1 \tag{98}$$

Hence, the random variable η_2 contains a constant component equal to $\frac{2E_x}{p_0}$ and a variable component distributed according to the normal (probability) law with variance $\frac{2E_x}{p_0}$. Based thereon, one can state that η_2 is a random variable distributed according to the normal law with mathematical expectation $\frac{2E_x}{p_0}$ and variance:

$$\sigma_{\eta_2}^2 = \frac{2E_x}{p_0}. \tag{99}$$

Then conditional probability of the second kind of error may be represented as:

$$\beta = \int_{-\infty}^{\lambda_0^{'}} \frac{1}{\sqrt{2\pi\sigma_{\eta_2}^2}} \cdot e^{-\frac{\left(\eta_2 - \frac{2E_x}{p_0}\right)}{2\pi\sigma_{\eta_2}^2}} d\eta_2. \tag{100}$$

By replacing variables $z_1 = \frac{\eta_1}{\sigma_{\eta_1}}$ and $z_2 = \frac{\eta_2 - \frac{2E_x}{p_0}}{\sigma_{\eta_2}}$, one can obtain expressions for the first- and second-kind errors:

$$\alpha = \frac{1}{\sqrt{2\pi}}\int_{\frac{\lambda_0^{'}}{\sigma_{\eta_1}}}^{\infty} e^{-\frac{z_1^2}{2}} dz_1 = \frac{1}{2} - \Phi\left(\frac{\ln\frac{p(0)}{p(A)} + \frac{E_x}{p_0}}{\sqrt{\frac{2E_x}{p_0}}}\right), \tag{101}$$

$$\beta = \frac{1}{\sqrt{2\pi}} \int_{\infty}^{\frac{\lambda_0' - \frac{2E_x}{p_0}}{\sigma_{\eta 2}}} e^{-\frac{z_2^2}{2}} dz_2 = \frac{1}{2} + \Phi\left(\frac{\ln \frac{p(0)}{p(A)} + \frac{E_x}{p_0}}{\sqrt{\frac{2E_x}{p_0}}} \right). \qquad (102)$$

The Laplace functions making part of expressions (101) and (102) are determined according to respective tables [13].

Taking into account real parameters of information transmission at the speed of 10... 40 Kbit/s with the signal amplitude of 5... 12 V, it is possible to calculate the first- and second-kind errors for devices that do/do not employ the developed adaptation algorithms. Calculation results are summarized in Table 2.

Table 2

RESULTS OF CALCULATION OF THE FIRST- AND SECOND KIND ERRORS

Adaptation algorithm used	α	β	$p_{пом}$
With no adaptation algorithms used	$2 \cdot 10^{-2}$	$8.4 \cdot 10^{-1}$	$1.84 \cdot 10^{-1}$
Adaptation method with arbitration	$2.5 \cdot 10^{-2}$	$1.5 \cdot 10^{-1}$	$5 \cdot 10^{-2}$
Adaptation method for secure coding conditions	$3.75 \cdot 10^{-4}$	$6 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
Adaptation method taking into account boundary disturbances	$1.25 \cdot 10^{-3}$	$4.5 \cdot 10^{-2}$	$1 \cdot 10^{-2}$

Source: developed by the author

The foregoing data show the effectiveness of the developed device. At the same time, for the information transmission system, it would be advisable to perform calculations that would show the probabilities of converting one to zero and zero to one in the course of transmission due to the influence of interference. In this case, the Kotelnikov technique is normally used [9, 14].

$$p_{1-0} = V\left(\alpha_0 \sqrt{2} - \beta\right), \qquad (103)$$

$$p_{0-1} = V\left(\beta\right), \qquad (104)$$

where $\beta = \dfrac{U_{пор}}{U_{\xi.ск}}$;

$U_{пор}$ is the signal's threshold value;

$U_{\xi.sk}$ is the root mean square value of the interference voltage;

α is potential interference protection;

V is the symbol of the Kotelnikov integral, the values of which are calculated by numerical methods and summarized in tables [9, 14].

Conclusions

Universal principles of information transmission with adaptation to communication channel parameters have been developed, which provide the ability to justify the optimal length of implementing a test sequence when calculating the correlation function of random noise processes and the sampling interval of the test sequence.

A method of adapting devices to communication channel parameters by arbitration has been proposed, which allows for optimizing the number of necessary duplications of information during its transmission by preliminary measuring the level of disturbances in the communication channel from the transmitter side. This, in turn, significantly increases the throughput of the data transmission channel without altering its physical properties.

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METHODS AND BASIC PRINCIPLES OF COLLECTIVE INTELLIGENCE / IN IN INFORMATION MANAGEMENT SYSTEMS

Collective intelligence refers to the ability of a group of people or robotic agents to work together to solve problems, make decisions, or achieve common goals. The basic principles of collective intelligence include [1–4]:

- Diversity: Having a balanced group of members with different knowledge, skills, backgrounds, and approaches can lead to better problem solving and creative thinking;
- Collective Alignment: The group must have a clear common goal or objective so that everyone understands how their contribution contributes to that goal;
- Interaction and Communication: Effective interaction and open communication among group members facilitates the exchange of ideas, clarifies understanding, and improves the overall solution;
- Synergy: Interaction in a group should lead to the creation of entirely new ideas, solutions, or opportunities that go beyond the individual contributions of each participant;
- Equality and Mutual Assistance: Ensuring equality of participation and mutual assistance can improve the exchange of ideas and knowledge, leading to better problem solving;
- Adaptability: The group must be ready to adapt to new circumstances, respond quickly to changes and adjust its strategies accordingly;
- Trust and Understanding: Developing mutual understanding and trust among participants can improve collaboration and increase the effectiveness of the group process.

These principles of interaction can be used in a variety of contexts, such as business, science, technology, education, etc., to achieve common goals and solve complex problems.

Collective intelligence methods are used to study and understand the phenomena related to how groups and teams can effectively solve problems and make decisions based on internal interactions and information sharing. Here are some models of collective intelligence:

- Ant Colony Optimization (ACO) method: This method is inspired by the way ants find the shortest path from place to place using pheromones. Ant colonies are used in logistic combinatorial optimization problems such as the traveling salesman problem;
- The Bee Algorithm method: This method is based on the way bees find the most efficient food sources and return to the hive with them. It uses the ideas of competition and cooperation to solve optimization problems;
- Particle Swarm Optimization (PSO): This method simulates the movement of particles in space (drones) based on their individual and group dynamics. The particles work together to find an optimal solution in the parameter space;
- The Swarm Intelligence with Narrow Agents optimization method: This method uses the idea of narrow agents that specialize in solving specific problems and exchange information to provide an optimal solution;
- The method of immune response (Artificial Immune System, AIS): This method is inspired by the functioning of the immune system in the body. It applies the ideas of self-defense and cellular interaction to solve optimization problems;
- The Diversity in Swarm method: This method considers the importance of diversity in collective systems. Maintaining diversity can help avoid downtime and resource depletion;

These methods are used in various fields, including optimization, robotics, transportation systems, and others, to solve complex problems and improve decision-making in collective systems.

1. Bee Algorithm method of bee colonies

The development and creation of new generation information management systems, including toolkits for information and cognitive support of the processes of synthesis, integration and updating of knowledge, is one of the key areas of basic research in the field of applied artificial intelligence systems. These systems are characterized by innovation and have the potential to be used in various sectors of the economy and technology.

One of the new directions in the development of artificial intelligence methods is the use of multi-agent intelligent optimization methods that model the collective intelligence of social animals, insects, and other living beings – Swarm Intelligence methods. This area is young and little researched, but multi-agent methods are already showing good results in solving various optimization problems. The main feature of multiagent collective intelligence methods is their bionic nature, which is based on the analysis of methods of colonies of social animals, insects and other living beings, such as evolutionary optimization, metasequoia of ants and bees. These methods model the behavior of groups of social animals and allow them to effectively solve complex problems in nature, which indicates the prospects of their application. An important aspect is the use of the agent-based programming paradigm to implement these methods, which is based on modeling social intelligence. Multi-agent distributed artificial intelligence systems include collective intelligence methods, such as the ant colony method, the bee colony method, particle swarm optimization, and others. These methods have been successfully used to solve various optimization tasks, from salesman to scheduling.

Multi-agent systems can be represented as a set of agents, an environment, and their interactions (Fig. 1). Each agent has its own state, input, output, and process. The environment includes a state and a process, and can interact with agents. This model can be used not only in software systems but also in natural systems. Thus, the study and development of multi-agent intelligent optimization methods is an urgent task that requires further research and development of new mathematical models based on the behavior of collective animals.

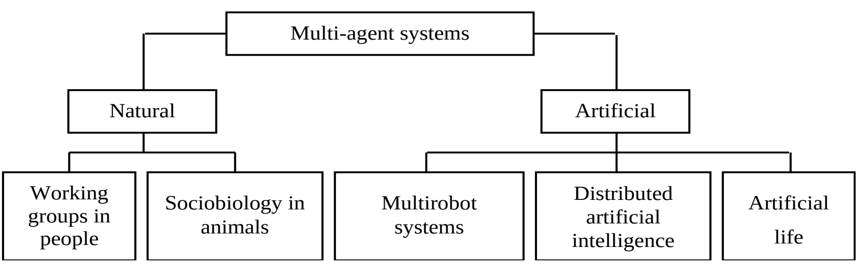

Figure 1. Classification of multi-agent systems

Source: developed by the authors based on [5].

To understand collective intelligence, it is necessary to identify the different functions that social insects perform during task solving. The four main functions include coordination, cooperation, collective decision-making, and specialization, which interact to achieve colony goals.

Coordination, for example, is about organizing the tasks of individuals in space and time to solve collective problems. This can be seen in organizing the movement of bee nests or locust swarms. Cooperation, on the other hand, occurs when individuals work together to solve problems that are beyond the capabilities of individuals. Collective decision-making involves mechanisms that are activated when a colony is faced with a choice, leading to a joint selection of one of the possible solutions. For example, honey bees can choose more productive areas to collect nectar through the forager dance. Specialization is manifested in the distribution of different actions among specialized groups of individuals, such as foraging or caring for offspring. This can be achieved through behavioral differentiation or depending on the age of the individual. By coordinating spatial, temporal, and social connections, and by interacting through cooperation and collective decision-making, social insects form a collective intelligence to achieve common goals.

2. The method of ant colonies

Ants belong to the group of social insects, i.e. those that form collective families or colonies. About 2 % of all insects on Earth are «social» and half of them are ants. The behavior of ants in carrying food, overcoming obstacles, and building an ant hill demonstrates a theoretically optimal approach. The basis of their «social» behavior is self-organization – the interaction of elements at a low level that achieves a global goal without centralized control.

Social behavior of ants is based on four components: chance, positive and negative feedback, and repeated interaction. Ants use biochemical channels to transmit information, including pheromones, which regulate colony life and influence individual behavior.

Ants use two ways of transmitting information: direct (food exchange, mandibular, visual, and chemical contact) and indirect (using stigmata). Stigmata include pheromones that remain as ants move and show the way to others. Ant self-organization is a system of dynamic mechanisms that are regulated at the global level through the interaction of their components at the lower level. Positive and negative feedback, instability of positive feedback, and multiple interactions play a key role in this process. Dynamism, emergence, nonlinear interactions, and multistability are also important. For an insect colony, a certain type of communication is important for effective cooperation in solving problems. This connection can be different in the form of direct or indirect interaction, depending on the specific circumstances.

Direct communication between colony individuals can take many forms. For example, when a bee discovers a nectar source, it alerts the others by performing a characteristic dance that indicates the direction and distance to the find. This is an example of direct communication, which involves other bees perceiving the dance to determine the location of the nectar source. Other forms of direct communication include physical contact or sharing food or fluids.

Indirect communication between individuals in a colony is more subtle and requires one individual to change the environment in a way that changes the behavior of others in the future. An example of indirect communication is the use of pheromones by species of ants that leave traces to influence others.

The term «self-organization» is used to describe complex behavior that results from the interaction of simple agents. Thanks to self-organization, ants can successfully solve complex problems. The principle of changing the environment to influence behavior is called stigmergy and is key to ant colonies, where there is no centralized leadership and self-organization plays an important role (Fig. 2).

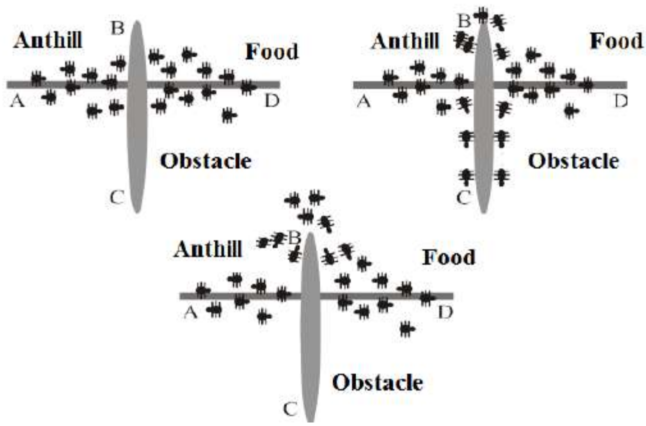

Figure 2. Double asymmetric bridge experiment

Source: developed by the authors based on [5].

The collective behavior of biological ants ensures finding the shortest path to food, as exemplified by experiments on an asymmetrical bridge. The asymmetrical bridge (Fig. 2) connects the ant nest to the food source with two branches of different lengths. The experiments were conducted according to the following scheme:

1) The A-B-C-D bridge was being built;

2) The door was opened at point A;

3) The number of ants that chose the long (A-C-D) and short (A-B-D) paths was recorded. At the beginning of the experiments, ants chose both branches with equal probability because there were no pheromones on the bridge. After a while, almost all ants moved along the shortest route A-B-D, which is explained as follows. The ants that chose the short route A-B-D-B-A were more likely to return with food to the nest, leaving pheromone trails on the short branch of the bridge. When choosing the next route, the ants preferred the short bridge branch because it had a higher concentration of pheromones. Consequently, the pheromone accumulates faster on the A-B-D branch, which pushes the ants to choose the shortest route.

Ants in the longer stretch between intersections A and B, untouched by other ants they encountered earlier in the straight stretch, reach intersection B and will also split; However, because the intensity of the pheromone trail placed on the way back to the nest is approximately twice that of the pheromone trail reaching the food area, most ants will return to the nest, arriving at the same time as the other ants that chose the long route.

The behavior of the ants on the second bridge in the intersections between *C* and *D is* virtually identical to the behavior shown earlier on the first bridge between intersections *A* and *B*. Eventually, most ants will reach the food and collect some of it, to bring back to the nest.

It should be noted that the pheromone used by the ants gradually leaks out over a period of time, which removes any doubts related to the explanation of the double bridge experiment. In fact, the paths that have not been chosen for a certain time remain consistently longer, and these routes are almost free of pheromones due to its gradual evaporation. This factor greatly increases the likelihood that ants will choose shorter paths. It is important to note that the shortest route has the maximum value because of the high concentration of pheromones left behind by the ants.

The ant colony method is based on simulating the interaction of several artificial analogs of ants, which are programmatically represented as intelligent agents that are part of a united colony. By moving along the decision graph, the simulated agents jointly solve the problem and contribute to the optimization of other agents' decisions. Thus, the optimization task is solved through the interaction of agents that are in indirect communication with each other. In the ant colony method, this connection is achieved by simulating the release of pheromones by agents as they move. A generalized scheme of the ant colony method can be found in Fig. 3.

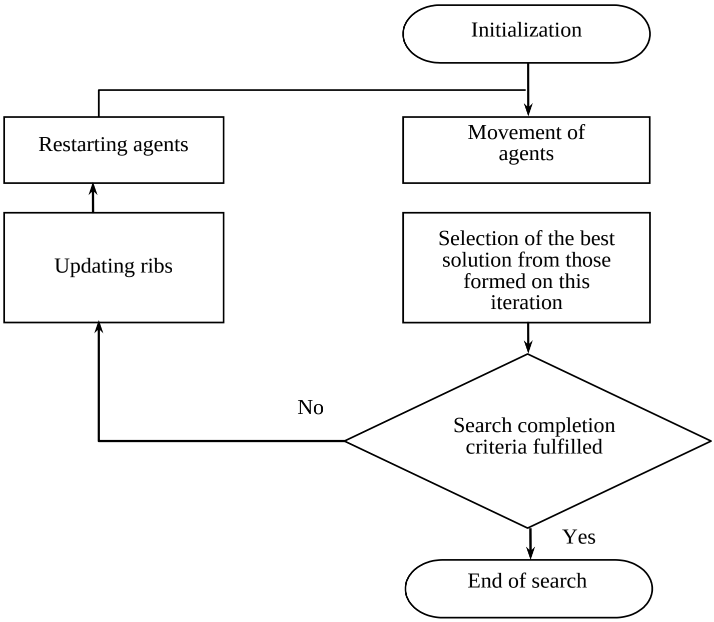

Figure 3. Generalized scheme of the ant colony method

Source: developed by the authors based on [5].

The initial problem to which the ant colony method was applied was the Traveling Salesman Problem (TSP). This problem was chosen because of its requirement to find the shortest path, which is easily adaptable to the principles of the ant colony method.

To solve this problem, several methods based on ant colony optimization have been developed. The first such method was the Ant System (AS) method, which served as the basis for numerous subsequent methods based on the principles of ant colonies.

In the ant system method, the agent forms its decision as it moves along the decision graph. The method works for a fixed number of iterations (tmax). At each iteration, agents form their decisions in n steps, each of which applies a rule for selecting the next node. Three methods of ant systems are proposed: ant-density, ant-quantity, and ant-cycle. In the density and quantitative methods, agents leave pheromones in the process of forming a decision, while in the cyclic method, pheromones are left after the movement is completed.

Experiments on solving test problems confirmed that the cyclic method showed significantly better results than the others.

Consequently, the other two methods were rejected, and the cyclic method of ant colonies is hereinafter referred to as the cyclic method of ant systems.

The amount of pheromones left by an agent (τru(t)) corresponds to the weight of an edge (r, u), reflecting the preference for choosing this edge when moving. The information about pheromones on the edges changes in the process of decision formation, where the amount of pheromones left by agents is proportional to the quality of the formed decision.

The memory of the nodes that have been visited by the agent is provided by the taboo list tList, which determines which nodes have already been visited. Thus, the agent passes through each node only once, and the nodes in the «current journey» list Path are arranged in the order of their visit. This list is used to determine the length of the path between nodes.

The ant colony method includes the following basic steps:

Step 1. Set the method parameters: α is a coefficient that determines the relative importance of the path; β is a parameter that shows the importance of distance; ρ is a coefficient of the amount of pheromone left by the agent on the path, where (1 – ρ) shows the coefficient of pheromone evaporation on the path after its completion; *Q is a* constant related to the amount of pheromone left on the path; *startPheromone is the* initial value of pheromone on the paths before the start of the simulation.

Step 2. Initializing the method. Creating a population of agents. After the population is created, agents are distributed evenly across the network nodes. It is necessary to distribute agents evenly among the nodes so that all nodes have an equal chance of becoming a starting point. If all agents start from the same point, it would mean that this point is considered to be the optimal starting point, but in fact it may not be. At the same time, if the number of agents is not a multiple of the number of nodes, then the number of agents in the nodes will be different, but this difference should not exceed 1.

Step 3. Movement of agents. If the agent has not yet completed the path, i.e., has not visited all network nodes, the probability of moving to the *u-th* node when the agent is in the *r-th* node is calculated to determine the next path edge using the following formula:

$$P_{ru} = \frac{\tau_{ru}(t)^{\alpha} \cdot \eta_{ru}(t)^{\beta}}{\sum_{k \in J} \tau_{rk}(t)^{\alpha} \cdot \eta_{rk}(t)^{\beta}} > rand(1), \quad (1)$$

where P_{ru} is the probability that the agent will move to the *u-th node* from the *r-th node*; $rand(1)$is a random number in the interval (0; 1);

J is the set of nodes not yet visited by the agent; $\tau_{ru}(t)$ is the pheromone intensity on the edge between nodes *r* and *u* at time *t*; $\eta_{ru}(t)$ is a function representing the inverse distance measurement for the edge.

The agent moves only along those nodes that have not yet been visited (marked with the taboo list *tList*). Therefore, the probability is calculated only for edges that lead to nodes that have not yet been visited.

Step 3 is repeated until each agent completes the path. Loops are not allowed because the method includes a taboo list *tList*.

Step 4. After the agents have completed their movements, the path length can be calculated. It is equal to the sum of all edges along which the agent traveled. The amount of pheromone left on each edge of the path of the *i-th* agent is determined by the formula:

$$\Delta\tau^{i}\ (t) = \frac{Q}{L^{i}(t)}, \tag{2}$$

where $\Delta\tau^{i}\ (t)$ is the amount of pheromone left by the *i-th* agent; $L^{i}(t)$ is the path length of the *i-th* agent. The variable Q is constant.

The result is a means of measuring the path: a short path is characterized by a high pheromone concentration, and a longer path by a lower concentration. The result is then used to increase the amount of pheromone along each edge traveled by the *i-th* agent of the path using the formula:

$$\tau_{ru}(t) = \tau_{ru}(t-1) + \rho \cdot \sum_{i=1}^{N_{ru}} \Delta\tau^{i}\ (t), \tag{3}$$

where r, u are the nodes that form the edges visited by the *i-th* agent; N_{ru} is the total number of agents that visited the edge ru.

This formula is applied to the entire path, with each edge marked with a pheromone in proportion to the length of the path. Therefore, it is worth waiting until the agent finishes moving and only then updating the pheromone levels, otherwise the true path length will remain unknown. The constant ρ takes on a value between 0 and 1.

At the beginning of the path, each edge has a chance to be selected. To gradually remove edges that are part of the worst paths in the network, a pheromone evaporation procedure is applied to all edges. Using the constant ρ from the previous expression, the following formula can be derived:

$$\tau_{ru}(t) = \tau_{ru}(t) \cdot (1-\rho), \tag{4}$$

Step 5. Checking for the optimal result. The check can be performed in accordance with the limit on the maximum number of iterations, or the check can be considered successful when no changes in the choice of the best path have been noted for several iterations. If the test is successful, the method is terminated (go to step 7), otherwise, go to step 6.

Step 6. Restart. After the agents' paths are completed, the edges are updated according to the path lengths, and the pheromone has evaporated on all edges, the method is run again. The taboo list is cleared and the path lengths are reset to zero. Go to step 3.

Step 7. Stopping. The best path is determined, which is the solution.

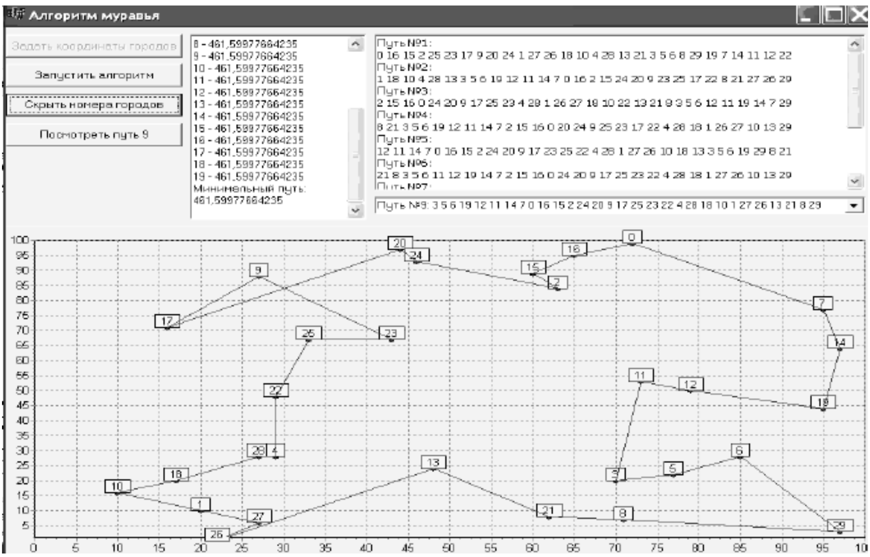

Figure 4. The result of the ant colony method program

3. Varieties of the ant colony method

Due to the possibility of different mathematical descriptions of ant behavior, extensions of the ant systems method have been developed. These include: 1) the ant systems method based on elite strategy; 2) the ant systems method based on ranking (AS_{rank}); 3) the ant colony system method; 4) the maxi-min ant systems method (MAX-MIN AS – MMAS).

The first extension of the ant system method was the *elite strategy*. This approach is based on an additional increase in the number of pheromones for the best global path at time *t*. Thus, the procedure of adding pheromone for the edges that are part of the best path at this time is repeated, with the amount of pheromone added calculated according to the length of the best path.

The second method proposed was the *ranking-based ant* system method (AS_{rank}). This method is essentially an extension of the elite strategy and consists in the following: agents are sorted by the length of the paths they make, after which pheromones are increased with weight *w on the* globally best path, and pheromone increase is performed only for edges that are included in the path of (w – 1) best agents; the *k-th* best agent will add pheromone with weight (w – k):

$$\tau_{ru}(t+1) = \rho \cdot \tau_{ru}(t) + w \cdot \Delta\tau_{ru}^{gb}(t) + \sum_{k=1}^{w-1}(w-k) \cdot \Delta\tau_{ru}^{k}(t), \quad (5)$$

where $\Delta\tau_{ru}^{gb}(t) = 1/L^{gb}(t)$, $L^{gb}(t)$, is the length of the best global path.

The third method, the Ant Colony System (ACS), improves on the ant system method by using information obtained by previous agents to explore the search space. This is achieved through two mechanisms. First, a strict elite strategy is used when recovering pheromones on edges. Second, agents choose the next node to move to using the so-called pseudo-random proportional rule: with probability q_0 , the agent moves to the point u for which the product of the number of pheromones and heuristic information is maximized: $u = arg\,max_{u \in J^r}\{\tau_{ru} \cdot \eta_{ru}(t)^{\beta}\}$, while with probability $1 - q_0$, the basic approach to determining the next point to move to described in the ant system method will be applied. The value of q is a constant. If q_0 is close to 1, then only the pseudo-random proportional rule is used, while if $q_0 = 0$, then the ant colony system method works according to the principle of the ant system method.

When updating paths, as already mentioned, a strict elite strategy is applied, according to which only the agent that has made the best decision releases pheromone along the path of its movement. Then the number of pheromones on the edges changes according to the formula:

$$\tau_{ru}(t+1) = \rho \cdot \tau_{ru}(t) + (1-\rho) \cdot \Delta\tau_{ru}^{best}(t). \quad (6)$$

The best agent can be the agent that obtained the best solution in a given iteration or the globally best agent that obtained the best solution in all iterations since the beginning of the method.

The last difference between the ant colony system method and the slit method is that agents update the amount of pheromones as they make their decisions (similar to the slit and quantitative ant system methods). This approach reduces the likelihood of all agents choosing the same paths. This reduces the likelihood of looping in a local optimum.

The fourth maximum-minimum ant system method (MAX-MIN AS – MMAS) introduces lower and upper bounds for possible pheromone values on an edge, and this method also differs in the approach to determining their values during initialization. In practice, MMAS uses a range of pheromone values limited by : $\forall \tau_{ru} \tau_{min}$ andτ_{max} $\forall$ $\tau_{ru}\tau_{min}$ and τ_{max}, i.e. $\tau_{min} \leq \tau_{ru} \leq \tau_{max}$. The number of pheromones of the edges during initialization is set equal to the lower bound of the interval, which provides a better exploration of the solution space. In MMAS, as well as in ACS, only the best agent (globally best or locally best) performs the addition of pheromones after each iteration of the method. Computational results have proven that the best results are obtained when pheromone updates are performed using the globally best solution. Local search is also often used in MMAS to improve its performance.

Later, the described models of the ant colony method were used to solve other optimization problems. The Quadratic Assignment Problem (QAP) was solved using the ant colony method and MMAS. The application of these methods was to use the relevant heuristic information of the problem. The following problems were also solved: Job-shop Scheduling Problem (JSP), Vehicle Routing Problem (VRP), Shortest Common Super sequence Problem (SCSP), graph coloring problem, sequential ordering problem, etc. When solving the test problems, ant colony methods showed good results compared to traditional optimization methods designed to solve these problems.

In general, the differences between the varieties of the ant colony method are shown in Table 1. In general, the ant colony method can be applied to any combinatorial problem that can be consistent with the following requirements:

− appropriate task representation – the task should be described as a graph with a set of nodes and edges between nodes;

− heuristic suitability of edges – the ability to apply a heuristic measure of the adequacy of paths from one node to each neighboring node in the graph;

− drawing up alternative solutions, which can be used to rationally determine acceptable solutions;

− next node selection rule – a rule that determines the probability of moving an agent from one node of the graph to another.

The task of feature selection is to find a reduced set of the most informative features from the full set of features with the number of *outCF* elements specified. In this case, the conclusion about the informativeness is made on the basis of a model built in a certain way based on the analyzed set of features. Thus, the task of modifying the ant colony method is to find such a set of features H_o , which will achieve the specified error of the model built on the basis of the obtained set.

Table 1

DIFFERENCES BETWEEN THE VARIETIES OF THE ANT COLONY METHOD

Criterion.	Method.			
	AS	ASrank	ACS	MMAS
Adding Pheromone	After receiving the decision	After receiving the decision	In the process of obtaining a decision	In the process of obtaining a decision
The rule for selecting the next item	Traditional approach	Pseudo-random proportional rule	Traditional approach	Traditional approach
Applying an elite strategy	All agents are involved in the restoration of paths	Recovery is performed by (w – 1) locally best agents and the globally best agent	Only the best agent (globally or locally) performs recovery	
Using constraints for different parameters	Absent	Limitations on the number of agents involved in path restoration	Absent	The pheromone value interval is used
Application of local optimization	None	None	Traditional methods of local optimization are used	None
Tasks to be solved	TSP, QAP, JSP, VRP, SCSP	TSP	TSP, JSP	TSP, QAP
On finding The effect of the number of result agents	Strong	Medium	Weak	Weak

Source: developed by the authors

The problem of selecting informative features can be represented in a form that corresponds to the ant colony method. The ant colony method requires that the problem be represented in the form of a graph, the nodes of which characterize the features, and the edges between them are the choice of the next feature. This is the appropriate modification of the ant colony method to solve the problem of selecting informative features.

To solve the problem of selecting informative features, it is proposed to use the following modifications of the ant colony method: modification based on the representation of destinations by features and in the form of feature informativeness; using operations on clear sets; using operations on fuzzy sets.

Based on the basic principles of the ant colony method, its variants and applications, the advantages and disadvantages of this method can be identified.

The advantages of the ant colony method include:

- Can be used in dynamic applications: the method easily adapts to changes in the environment.
- Utilization of colony memory: provided by modeling the release of pheromones, which improves the exchange of information between agents.
- Guaranteed convergence to the optimal solution: ensures accuracy in finding the optimal solution.
- Stochasticity: random search prevents getting stuck in local optima.
- Multi-agency: using a group of agents to solve problems.
- Higher speed of finding the optimal solution: faster than traditional methods.
- Application to various optimization problems: versatility in applying to various optimization problems.

The disadvantages of the ant colony method include:

- Complexity of theoretical analysis: the final decision is formed through a sequence of random choices, which makes theoretical analysis difficult.
- Uncertainty of convergence time: convergence is guaranteed, but the time is not always predictable.
- High iterativity of the method: requires a large number of iterations to find the optimal solution.
- Dependence on initial parameters: results can vary greatly depending on the choice of initial parameters.

From the analysis of applications, it follows that the method has an advantage in solving discrete optimization problems and in dynamic environments. It should be noted that the efficiency of the method increases in conditions of high dimensionality, when traditional methods may be less effective. In contrast, the basic ant colony method is not recommended for solving continuous optimization problems, but its flexibility allows for the creation of hybrid systems to solve a wider range of problems.

4. Bionic bases of the bee colony method

The bee colony method is an iterative heuristic approach to solving various optimization problems that include both discrete and continuous optimization. The *main features of* this method include:

Classification of agents by type: All agents are categorized into types according to their actions in solving tasks.

1.1. Foragers: Occupied foragers ensure that already known nectar sources are utilized without significantly altering previously found solutions.

1.2. Unoccupied foragers: Divided into two subtypes:

1.2.1. Observers: Wait for other agents and do not perform actions intended to find solutions.

1.2.2. Scouts: Search for new nectar sources by randomly selecting possible solutions in the search space.

Communication between agents: The interaction between agents is modeled through a zigzag dance performed by bees. This creates positive and negative feedback. Positive feedback: Agents can start to learn from the solutions obtained by other agents. Negative feedback: Agents may decide to stop learning their solution because it performs worse than others.

The process of finding solutions: Two procedures are used to ensure that solutions are found:

2.1. Searching for new nectar sources: Scouts randomly explore the search space, providing an overview of the entire potential region.

2.2. Deeper utilization of plots: Busy foragers use solutions located close to already known nectar sources.

This method allows you to effectively solve optimization problems through interaction between agents and iterative search for solutions in the search space, Fig. 5.

Thus, the division of functions between busy bees and scouting bees is performed to improve the study of the found places with nectar and to find new places. Due to this division of duties, the efficient work of the entire swarm of bees is achieved.

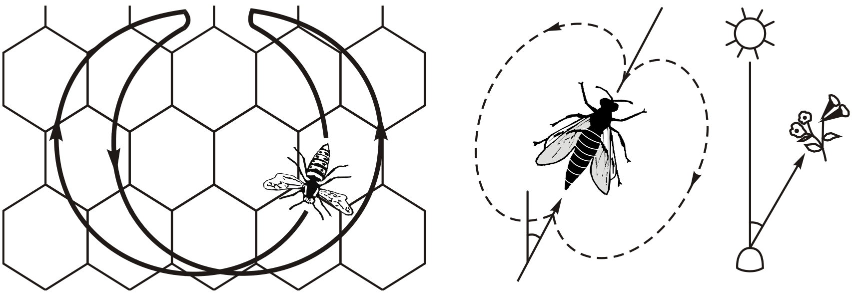

Figure 5. Diagram of the circular
and whirling dance of bees

Source: developed by the authors

The main features of bee behavior can be explained with the help of Fig. 6, which depicts the case when two nectar sources *A* and *B have* already been found, and also shows a bee – a potential forager. In the beginning, this bee can make one of two decisions:

− become a scout («R») and then go in search of nectar in any direction;

− go to the hive and continue to participate in recruitment («B»).

In this case, if a bee goes to the hive to perform a dance, it can either become a busy forager («BF1») or, if it has not been recruited, also become a scout.

When a bee becomes a busy forager, it can be directed to either source *A* or source *B*. This depends on the waggle dance performed. After the bee, being a busy forager, has collected nectar from the source, it returns to the hive and leaves the collected nectar there. When the forager bee returns, it can either remain a busy forager if the nectar is still in the source or become an unoccupied forager («UOF»). After the bee has left the nectar, it can go to the dance floor or immediately return to the nectar source («FF2»). After that, this cycle can be repeated until the nectar source under study is finally used.

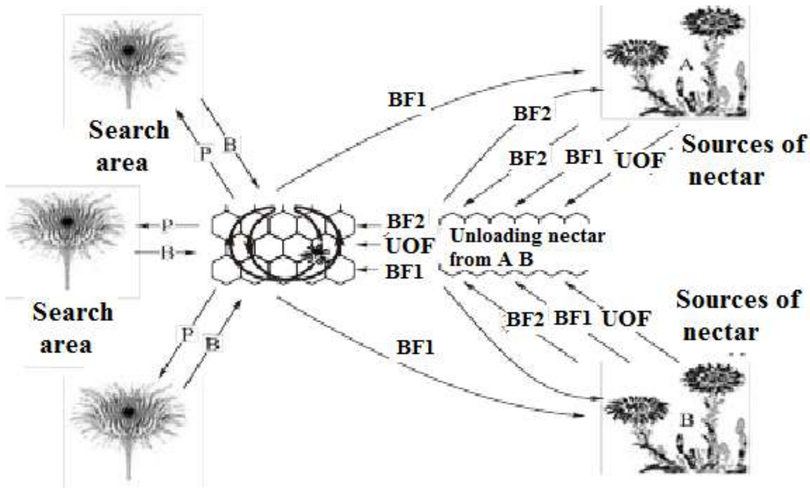

Figure 6. Main features of bee behavior

Source: developed by the authors

5. Formalization of bee behavior in the process of foraging

This behavioral model of the self-organization of a colony of bees can be redefined in terms of CCS (Calculus of Communicating Systems), a formal language for describing parallel processes. Let us introduce some CCS elements to describe the interaction of bees in a hive:

CCS Agents:

We will have two main agents: Foragers and Hive.

Each forager will have a unique name and behavior.

CCS events:

Events will determine the actions performed by agents.

Events may include: Returning to the hive, Performing a wagging dance, Watching a dance, Foraging.

CCS operators:

The operator will be used to define a sequence of events, for example, Forager.Return to Hive.

The + operator will be used to select alternative actions, for example, WiggleDance + Observe.

Agent behavior:

The behavior of each agent will be determined by the set of events it can perform.

For example, Forager = {WigglingDance, Observation, Foraging, ReturningToHive}.

Feedback:

Feedback will ensure interaction between agents based on the usefulness of the nectar source.

A threshold mechanism can be used to activate the recruitment signal, which can be represented, for example, as if Utility > Threshold then WaggingTango. A more detailed description of each agent and their interaction will require specification in the context of CCS.

CCS deals with agents, which describe the state of a bee or the state of a group of bees, and with actions, which represent the ability to move from one state to another. Thus, a colony can be represented as a connected graph with vertices being agents and edges being actions. For example, an agent can be represented as follows:

$$\text{Scout } b_l = \text{good}(b_j ,1...n)(s). \text{ Search}(b_j ,1...n)(s) + \\ + \text{ bad}(b_j ,1...n). \text{ Unoccupied}(b_j ,1...n).$$

If the scout searches *poorly for* nectar, it will become *an unemployed forager, but* if it searches *well, it will* continue to search (b_j ,1...n)(s) *for* some source S. In this description: b_l is a unique identifier of one agent, *S is a* source of nectar.

Then the modeling of bee behavior in terms of CCS can be depicted as shown in Fig. 7.

The foraging process can be formalized using CCS as follows:

Successful (b_i ,1...n) (s) = Employed (b_i ,1...n) (s). Recruitment (b_i ,1...n) (s),

Failed (b_i ,1...n)(s) = Nothing (b_i ,1...n). Unoccupied (b_i ,1...n) (s),

Recruitment (b_i ,1...n)(s) = Dance (b_i ,1...n). Recruitment$_b$ (s) + + Leave (b_i ,1...n). Use (b_i ,1...n)(s),

Unoccupied (b_i ,1...n) = dance (b_i ,1...n)(s). Use (b_i ,1...n)(s) + + Research (b_i ,1...n). Scout (b_i ,1...n),

Scout (b_i ,1...n) = Good (b_j ,1...n)(s). Search (b_j ,1...n) (s) + Bad (b_j , 1...n). Unoccupied (b_j ,1...n).

Use (b_j ,1...n)(s) = Go to (b_i ,1...n)(s). Search (b_i ,1...n)(s),

Search (b_i ,1...n)(s) = Nectar (b_i ,1...n)(s). Successful (b_i ,1...n)(s) + + Nothing (b_i ,1...n). Failed (b_i ,1...n)(s),

Thus, the proposed formalization models the behavior of bees.

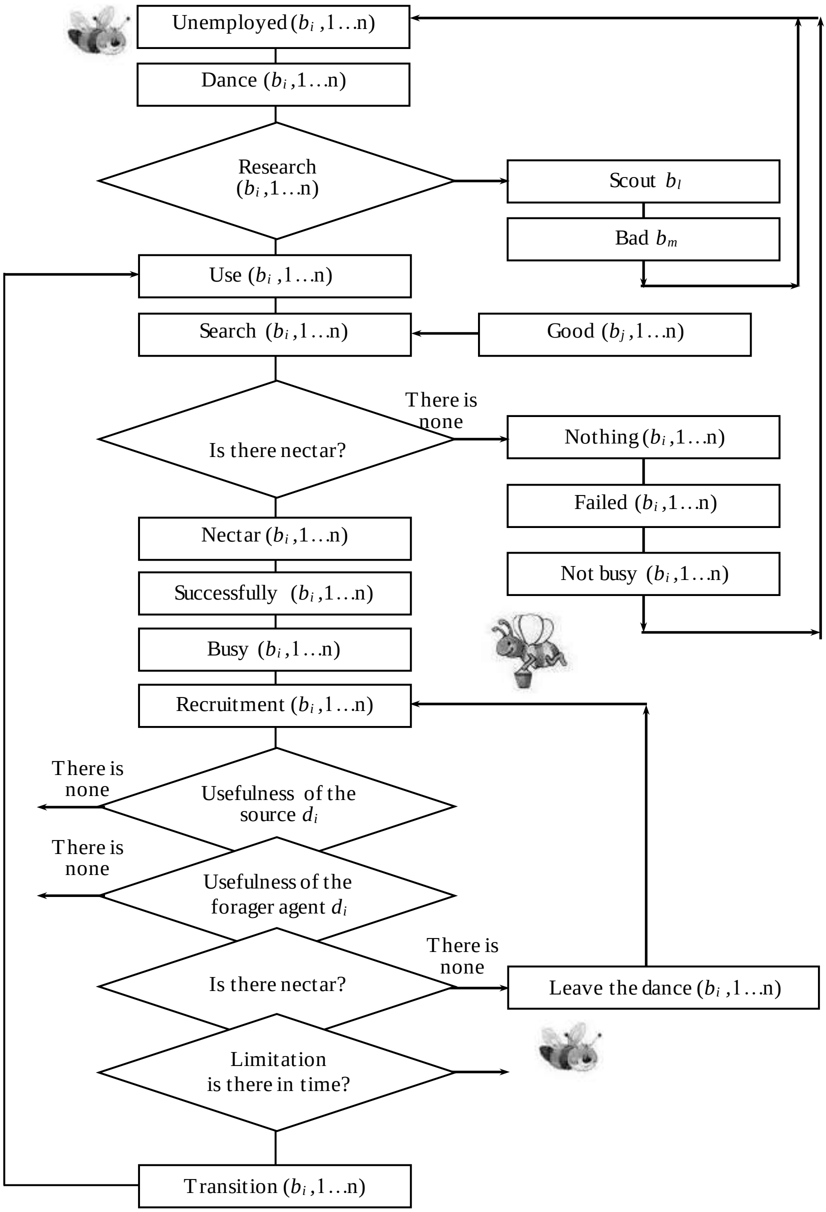

Figure 7. Algorithm for modeling bee behavior using CCS

Source: developed by the authors based on [5].

6. Example of modifications of the BCO-FPV bee colony methods

Based on the proposed approach, a method of attacking the artificial multi-agent system of the GEPRC MARK4 FPV drone colony was developed to solve the attack problem (Bee Colony Optimization FPV, BCO- FPV).

The BCO-FPV attack planning task can be characterized by a set of jobs, each of which consists of one or more operations. Operations are performed on a specific sequence of special machines. The goal of planning is to schedule the operations that minimize (maximize) the execution time.

The attack problem is NP-hard. The performance measure includes: equipment utilization (equipment utilization rate), cycle time, productivity (flow rate, throughput), and inventory level.

In general, an attack problem is represented by a disjunctive graph. The graph consists of nodes that represent operations. There are also two additional nodes that represent resources and costs. A set of oriented arcs is used to describe the benefits of each operation. Since the main features of the bee colony method are the meandering dance and the foraging process, the proposed modification to solve the attack problem differs in these stages of the bee colony method compared to the previously proposed method. The analogy of the nectar source in this modification is a path that can be considered as a solution to the scheduling problem.

After returning to the hive, the agent performs a meandering dance with probability *p*. The duration D_i of the meandering dance of the *i-th* agent is calculated by the formula:

$$D_i \;=\; d_i \cdot A, \tag{7}$$

where A is the scaling factor, d_i is the relative utility of the found nectar source of the *i-th* agent.

The absolute usefulness of the nectar source of the *i-th* agent Pf_i for the attack task is calculated by the formula:

$$Pf_i = \frac{1}{C_i}, \tag{8}$$

where C_i is the objective function for the path of the *i-th* agent. In this case, it represents the duration of all operations of all jobs for the path.

Then, by calculating the absolute utility of each agent, we can get the average utility of the entire Pf_{colony}:

$$Pf_{colony} = \frac{1}{n}\sum_{j=1}^{n} Pf_j, \qquad (10)$$

where *n is the* number of twisting dances performed at time *t*.

Thus, we can calculate the relative utility d_i *of the i-th* forager:

$$d_i = \frac{Pf_i}{Pf_{colony}}. \qquad (11)$$

The probability p_i that the *i-th* agent will be followed by other unoccupied foragers after performing the dance is determined by the formula:

$$p_i = \begin{cases} 0{,}60, \text{if} Pf_i < 0{,}9 \cdot Pf_{colony}; \\ 0{,}20, \text{if} 0{,}9P \cdot f_{colony} \le Pf_i < 0{,}95 \cdot Pf_{colony}; \\ 0{,}02, \text{if} 0{,}95 \cdot Pf_{colony} \le Pf_i < 1{,}15 \cdot Pf_{colony}; \\ 0{,}00, \text{if} 1{,}15 \le Pf_i. \end{cases} \qquad (12)$$

Since in the process of foraging, agents form decisions by moving from node to node on the graph describing possible operations, it is necessary to calculate the probability of adding a given node to the agent's path.

The probability P_{ij} that the agent will choose the next *j-th node while* in the *i-th* node is calculated by the formula:

$$P_{ij} = \frac{{\rho_{ij}}^{\alpha} \cdot {d_{ij}}^{-\beta}}{\sum_{j \in J^k} {\rho_{ij}}^{\alpha} \cdot {d_{ij}}^{-\beta}}, \qquad (13)$$

where ρ_{ij} is the cost of the arc between the *j-th* and *i-th* nodes; d_{ij} is the heuristic distance between the *j-th* and *i-th* nodes; $\alpha\beta \in [0;\ 1]$ are coefficients chosen experimentally; J^k is the set of nodes to which one can move from the *i-th* node.

ρ_{ij} estimate is determined using the formula below:

$$\rho_{ij} = \frac{1 - m\alpha}{k - m}, \qquad (14)$$

where *k* is the number of nodes to which you can move from the *i-th* node; *m* is the number of path preferences, which can be equal to 1 or 0. The best path is the one that was considered suitable for performing the dance at some iteration. At the same time, the number of so-called elite paths is limited. So, at the initial iteration, all edges have the number *m* = 0, which equals the chances of choosing any edge.

This method was compared with the ant colony method and with the search created by Glover in 1986. Experiments have shown that the results obtained using the bee colony method are almost indistinguishable from the results obtained using the ant colony method and are no worse than the results obtained using tabu search.

Lucic and Teodorovic were the first to use the basic principles of collective intelligence of bees to solve combinatorial optimization problems. They developed the so-called Bee System (BS) method and tested it by solving the traveling salesman problem. Based on the BS, the Bee Colony Optimization Metaheuristic (BCO) and Fuzzy Bee System (FBS) methods were proposed.

In the BCO method, all agents are in the hive at the beginning of the search process. During the search process, agents communicate with each other indirectly. Each agent performs a series of local movements, and thus gradually forms a solution to the problem. The search process consists of iterations. The first iteration is considered complete when the agents create at least one acceptable solution. The best solution is saved, and then the next iteration is started. Then the process of compiling solutions is repeated. The total number of iterations is limited based on the optimization problem.

When moving in the search space, agents can move in the forward or backward direction. When moving in the forward direction, agents form different partial solutions, which is achieved through individual exploration of the search space and through the collective experience gained in previous iterations.

After creating a partial solution, the agents move in the opposite direction, i.e., they return to the hive, where they can participate in the recruitment process by performing a dance, thus exchanging information about the different partial solutions they have created. After visiting the hive, agents move back in the forward direction and continue to create partial solutions. The iteration ends when at least one feasible solution is created. Thus, BCO, like dynamic programming methods, solves combinatorial optimization problems in stages.

Based on the above, it can be noted that in BCO, unlike the previously described bee colony method, there is no separation in the roles of agents (busy foragers, unoccupied foragers, and scouts), and the solution is compiled in stages, as partial solutions are found, until a complete acceptable solution is obtained.

The FBS method is designed to solve problems characterized by uncertainty; agents use fuzzy logic rules to organize the connection between agents and their actions.

According to the FBS, when adding a solution component to its own solution, an agent may consider it as: «less useful», «useful», or «more useful». Agents are also able to distinguish between additional properties: «short», «medium», or «long», «nonvaluable», «medium», or «valuable».

The features of the considered modifications of the bee colony method and the differences between them are shown in Table 2.

Table 2

DIFFERENCES AND FEATURES OF MODIFICATIONS OF THE BEE COLONY METHOD

Comparison criterion	**Method.**		
	BCO-JSSP	**BCO**	**FBS**
The procedure for performing a winding dance	The duration of the dance is modeled	Depending on the quality of the solution	There is no circle dance procedure as such. It is modeled by performing recruitment
Selection of reconnaissance agents	The initial number of scout agents is equal to the total number of agents. After recruitment, the number of scouts decreases	Scouts are all unoccupied fodder	All unoccupied foragers are scouts
Peculiarities of the scout's choice of solutions	Scouts find solutions randomly	Scouts create random solutions	Information left by previous agents is used
Researching solutions at the expense of other agents	This is achieved due to the fact that recruitment is carried out in virtually every node	Recruited agents simply navigate through the chosen solution	Not happening. Occupied feeders are moved to the selected solution
Class of tasks to be solved	The task of calendar planning	Problems of combinatorial optimization	The problem of pairing
Recruitment	It is carried out when the agent selects the next item in the decision column	It is carried out after creating your own solution	Recruitment is based on the usefulness of the solution

Source: developed by the authors

7. Particle swarm optimization (PSO method)

Particle Swarm Optimization (PSO) is a search method that uses the concept of population to model the behavior of birds in flocks or schools of fish. Initially, the concept was aimed at graphically simulating the beautiful and unpredictable movement of birds or fish in a flock to study the principles of their synchronized flying (smooth) movement and the ability to change direction for optimal regrouping.

In the PSO method, particles representing individuals move in a multidimensional decision space. Changes in the coordinates of the particles in this space are caused by the natural social and psychological tendency of particles to compete with each other. Thus, changes in the state of a particle depend on the experience and information received from its neighbors.

The simplified behavior of particles in a swarm is that they strive to surpass the achievements of neighboring particles and improve their own. This leads to the emergent property of the system – exploring optimal parts of the multidimensional search space.

The PSO method manages a swarm of particles, where each particle represents a potential solution. Similarly to evolutionary strategies, the swarm can be viewed as a population, and a share as an individual (chromosome). Thus, a particle «flies» in a multidimensional decision space, and its position is determined by its own experience and the experience of its neighbors.

The $x_i(t)$ denotes the position of particle i in the search space at time t (t denotes discrete time values). The position of the particle is changed by adding the velocity $v_i(t)$ to the current position:

$$x_i(t+1) = x_i(t) + v_i(t+1). \qquad (15)$$

The initial state is defined as follows: $x_i(0) = U(x_{min}, x_{max})$, where $U(a, b)$ is a function of generating random numbers from the range $[a, b]$. This formula is a velocity vector and defines the optimization process itself, as well as reflects the use of both the particle’s knowledge and the exchange of information with neighboring particles. The particle’s own knowledge, also called *the cognitive component of the velocity* formula, is directly proportional to the particle’s current distance from its best position, which was found from the start of its life cycle. And the exchange of information by this individual with others is the *social component of the velocity* formula.

Historically, two approaches have been developed, which are actually variants of the basic PSO method: *gbest* and *lbest*; they differ in the degree of connectedness of particles in the search space.

8. Analysis of PSO method types

We will compare the variants of the basic PSO method. We will also include in the analysis a modified method that flexibly adjusts the velocities of particles in the search space. The comparative analysis will be conducted on the basis of the most important and significant differences identified during the study, as well as on the basis of the proposed criteria. The analysis is presented in Table 3.

Table 3

COMPARATIVE ANALYSIS OF PSO-METHOD TYPES

Criteria.	**Methods.**			
	The gbest PSO method	**The lbest PSO method**	**PSO method with particle velocity control**	**Multi-criteria PSO method**
Adaptability	High	High	High	Low
Scalability	Medium	Medium	Medium	Medium
Flexibility of the model	Medium	High	High	Low
Convergence rate	High	Low	Medium	It depends on the task at hand
Quality of optimization	Medium	High	High	Low
Error tolerance	High	High	High	Low
Number of fitness function calculations	Medium	Low	Medium	High

Source: developed by the authors

The lbest and *gbest* variants of the basic PSO method are similar in that in both cases they move towards the global optimum when updating the velocity components.

But there are two important differences between these approaches that affect convergence:

− due to the greater degree of connectivity between the particles (star topology), the *gbest* PSO method converges faster; however, fast convergence leads to a less thorough exploration of the solution space;

− the *lbest* PSO method has a lower chance of hitting the local optimum and thus finding only a suboptimal solution; on the other hand, this method is slower than *gbest*.

Let's take a closer look at the components of speed.

1. The *previous velocity* $v_i(t)$ acts as the particle's memory, i.e., it contains information about its movements in the past. This memory can be defined as an impulse that prevents abrupt changes in the direction of the particle's movement. This velocity is also an inertial component.

2. The *cognitive component* $c_1 r_1 \, (y_i \, - \, x_i \,)$ determines the performance of the i-th share relative to past results and acts as an individual memory of the most optimal positions of this share. Using it, a particle can return to the states that were best for it in the past. This is one of the emergent properties of the system as a whole.

3. The *social component* $c_2 r_2 (y *_i - x_i)$ in *gbest* PSO or $c_2 r_2 (y *_i - x_i)$ in *lbest* PSO determines the performance of a share relative to its neighbors or those connected to it. Thanks to it, a share is able to move to the optimal positions found by neighboring shares. The degree of contribution of the cognitive and social components is determined by the random variables $c_1 r_1$ and $c_2 r_2$, respectively.

9. Areas of application of the PSO method

The first application of the PSO method was to train feed-forward neural networks (FNNs). Since then, a number of studies have shown that the PSO method can also be used as a method for training NNs of any architecture. In such developments, it is necessary to determine the desired form of the fitness function, which can be represented as a function of the error to be minimized. Each particle in the PSO method represents a separate solution to the optimization problem, in this case, it is a whole neural network. And each coordinate of the particle in the search space is the value of the corresponding weighting coefficient.

C. Zhang and H. Shao proposed using the PSO method to continuously optimize the weights of the NM and its architecture. To do this, two swarms of particles should be used: the first one searches for the optimal architecture, and the second one optimizes the weights. The particles in the first swarm move in only two dimensions: the first coordinate is the number of hidden layers, and the second is the density of connections. At the first iteration of the algorithm, the particles are initialized randomly in the specified intervals. The particles of the second swarm search for the optimal set of NM weights. This PSO method creates a group of particles in the second swarm for each particle from the first swarm. After the method finishes its work, the desired architecture and the corresponding optimal set of NM weights are selected.

Let $d_{attract}$ be the depth of the cell's attractant (nutrients) and $w_{attract}$ be a measure of the width of the attractant. Cells exclude each other through local consumption and by not being food for each other. Let $h_{repellent} = d_{attract}$ *be the* height of the harmful substance (repellent), and $w_{repellent}$ be the measure of the width of the repellent. Thus, we can use the function $J_{cc}^{i}(X), i = 1, 2, \dots, S$ to model cell-to-cell signaling by bacteria releasing attractant and repellent:

$$J_{cc}(X) = \sum_{i=1}^{S} J_{cc}^{i} = \sum_{i=1}^{S}\left[-d_{attract}\, exp\left(-w_{attract} \sum_{j=1}^{p}(X_j - X_j^i)^2\right)\right] + \\ + \sum_{i=1}^{S}\left[h_{repellent}\, exp\left(-w_{repellent} \sum_{j=1}^{p}(X_j - X_j^i)^2\right)\right], \quad (16)$$

where $X = [x_1, \dots, x\ ]p^T$is a point in the optimization space.

Important features of this approach to calculating $J_{cc}(X)$ are:

− the value of $J_{cc}(X)$ does not depend on the value of the objective function at point θ;

− by varying the $w_{attract}$ and $w_{repellent}$ coefficients, one can influence the behavior of the drone population in the search process: with small values of $w_{attract}$ and larger values of $w_{repellent}$, the population is prone to large dispersion in the search space, and vice versa, i.e., with small values of $w_{attract}$ and larger values of $w_{repellent}$, the population is prone to grouping in small search areas.

Obviously, the strength of chemical release by bacteria depends on the environment, i.e., a bacterium in an environment with a high concentration of nutrients will release a stronger attractant than the same bacterium in an area with a low concentration of nutrients. Therefore, this method uses the function $J_{ar}(\theta)$ to model the interaction between areas, taking into account environmental features: $J_{ar}(X) = exp(M - J(X))J_{cc}(X)$, where M is a parameter whose value is chosen experimentally. So, to find the optimum, it is necessary to minimize the expression $(J(i, j, k, l) + J_{ar}\ (X^i\ (j, k, l)))$, which allows bacteria to search for useful substances, avoiding areas with harmful substances, while approaching other areas, but not too close to them.

Thus, the optimization method based on modeling the movement of drones with grouping due to the connection between regions differs from the basic method in that it minimizes not just the function $J(i, j, k, l)$, but minimizes the sum: $J(i, j, k, l) + J_{ar}(X^i\ (j, k, l)))$

which allows taking into account the position of all drones in the population.

The function $J_{ar}\ (X^{i}\ (j,k,l)))$provides the following relationship: the smaller $J(X)$, the larger $J_{ar}\ (X)$, and then the greater the attractiveness, which depends on $J_{cc}(X)$. The control parameter *M is* typically chosen based on the reasoning that if *M is* large enough, then $J_{cc}(X)$ is much larger than $J(X)$, and, therefore, the dominant direction in the search space is the chemical attractant released by the bacterium. On the other hand, if *M* is very small, then $J_{ar}\ (X)$ is much smaller than $J(X)$ and hence the environmental nutrients dominate. An exponential relationship was chosen for $J_{ar}\ (X)$, but it is not the only possible choice. Any other function that monotonically decreases and asymptotically approaches zero is a possible candidate, although some additional restrictions may be necessary.

10. An optimization method based on modeling the movement of drones with grouping by using the PSO operator a

One of the most studied drones is an analog of the bacterium E. Coli. Under appropriate conditions, the latter can self-replicate (split) in 20 minutes. The ability of the E. Coli bacterium to move is ensured by six or more flagella that rotate at a frequency of 100–200 revolutions per second, each of which is controlled by its own biological motor (engine).

The general scheme of the bacterium's movement is as follows: when the motor runs in one direction, all the flagella in the bacterium fold and rotate together, and the bacterium moves in a straight line. At the end of the run, the bacterium stops, the motor switches over and starts running in the other direction. The flagella separate and «dangle» independently of each other. The bacterium reorients itself randomly in space. After that, the motor switches again and starts working in the direction in which the flagella work together, and the next segment of straight-line movement occurs.

Chemotaxis is a motor response of a bacterium in response to the presence of an attractant (a substance that attracts drones) or a repellent (a substance that repels drones) in the environment.

If there is a spatial variation in the concentration of attractants or repellents, the frequency of rollovers and thus the free running length of the bacteria change. The free running length of a bacterium moving in the direction of increasing attractant concentration increases, and decreases when moving in the direction of increasing repellent concentration.

Thus, we can distinguish the following chemotactic actions of E. Coli:

– If the bacterium is in a neutral environment, it alternates between rotation and movement, which is how the search is performed;

– If the bacterium moves along the attractant gradient, it continues to move in the same direction. Thus, the search for a more favorable environment is ensured;

– if the movement is in the opposite direction to the repellent gradient, then the prevention of unfavorable environmental conditions is ensured.

Thus, the bacterium (drone) can move through useful substances while avoiding hazardous substances. The sensors used by E. Coli are protein receptors that are very sensitive (a slight change in the concentration of nutrients can cause significant changes in the behavior of the bacterium). The signals from the receptors are sent to methylation proteins, which collect all the signals from the receptors, and the resulting signal is sent to the flagellum motor, which controls the movement of the bacterium depending on the ratio of nutrients and hazardous substances in the environment.

The PSO method is based on the grouping of particles, so it is logical to apply the approaches used in PSO to the optimization method based on modeling the movement of drones. It is known that in the PSO method, the connection between particles is achieved due to the fact that the speed of movement of a particle depends on the solutions obtained by other particles in the population. Therefore, it is proposed to change the position of the bacterium in the search space according to the PSO operator. Such a change is performed within the chemotaxis cycle, after modeling the bacteria's sliding.

Let $V^i = (v_1^i, v_2^i, \dots, v_p^i)$ be the velocity vector of the *i-th* bacterium in dimensions 1, 2, ... *p*, and $X^i = (x_1^i, x_2^i, \dots, x_p^i)$ be the position of the *i-th* bacterium in the search space. Then, according to the PSO method, the speed and position of the *i-th* bacterium at the *j-th* chemotactic step, the *k-th* reproduction step, and the *l-th* exclusion-dispersal event changes as follows:

$$V^i(j+1,k,l) = \omega \cdot V^i(j,k,l) + C_1 \cdot \phi_1 \cdot (X^i_{l\_best} - X^i(j,k,l)) + \\ + C_2 \cdot \phi_2 \cdot (X_{g\_best} - X^i(j,k,l)), \\ X^i(j+1,k,l) = X^i(j,k,l) + V^i(j+1,k,l), \tag{17}$$

whereω is the coefficient of inertia, C_1, C_2 are positive acceleration constants used to vary the weights of the cognitive and social components of the bacterium's speed, respectively; $\phi_1, \phi_2 = rand(0,1)$ are random values in the range [0, 1]; X_{g_best} is the globally best position selected from all agent decisions starting from the first search iteration;$X^i_{l\_best}$ is the best position of the *i-th* bacterium from the beginning of the search.

The optimization method based on modeling the movement of grouped drones using the PSO operator can be described as a sequence of the following steps.

Step 1. Initialization. Set the parameters that affect the operation of the method: $S, N_{re}, N_s, N_c, N_{ed}, P, ed^{\omega}, C_1, C_2$. Randomly distribute the initial values X^i, $i = 1, 2, ..., S$, in the search space, set zero initial drone speeds: $v^i_j = 0, i = 1, 2, \ldots, S, j = 1, 2, \ldots, p$. The initial values of the objective function for each bacterium J^i are calculated. For each bacterium, $X^i_{l\_best} = X^i$ $J^i_{l\_best} = J^i$, and J_{g_best} and X_{g_best} are selected.

Step 2. Set: $l = l + 1$.

Step 3. Set: $k = k + 1$.

Step 4. Set: $j = j + 1$.

Step 5. Chemotaxis modeling.

Step 5.1. Set: $i = i + 1$.

Step 5.2. Rotation and movement. The new position of the *i-th* bacterium is calculated using the formula:

$$X_i(j+1,k,l) = X_i(j,k,l) + C(i)\frac{\Delta}{\sqrt{\Delta^T\Delta}}. \tag{18}$$

Calculate the value of the objective function $J(i,j+1,k,l)$. If $J(i,j+1,k,l) < J^i_{l_{best}}$, then set: $J^i_{l_{best}} = J(i,j+1,k,l), X^i_{l_{best}} =$ $= Xi(j+1,k,l)$.

Step 5.3. Sliding. As long as the condition: $J(i,j+1,k,l) <$ $< J(i,j,k,l)$ is met, step 5.2 is repeated. This repetition can occur N_s times. If the condition is not met, then proceed to step 5.4.

Step 5.4. If $i < S$, then go to step 5.1, otherwise go to step 6.

Step 6. Application of the PSO operator. The speed and new position are calculated for each bacterium:

$$\forall i = \overline{1,S}: \rightleftarrows V^i(j+1,k,l) = \omega \cdot V^i(j,k,l) + C_1 \cdot \phi_1 \cdot (X^i_{l_{best}} - X^i(j,k,l)) +$$
$$+C_2 \cdot \phi_2 \cdot (X_{g\_best} - X^i(j,k,l)), \tag{19}$$
$$X^i(j+1,k,l) = X^i(j,k,l) + V^i(j+1,k,l).$$

Step If $j < N_c$, then go to step 4, otherwise go to step 8.

Step 8. Reproduction. All agents are sorted according to the obtained values of the objective function, after which the worst half is discarded and the best half is duplicated.

Step 9. If $k < N_{re}$, then proceed to step 3, otherwise proceed to step 10.

Step 10. Exclusion and dispersion. The condition is checked: $U^i < P_{ed}$, where U^i is a random number in the interval [0; 1] for the *i-th* bacterium. If this condition is met, then the bacterium is placed in the position $X^i(j,k,l)$, obtained randomly.

Step 11: If $l < N_{ed}$, then proceed to step 2, otherwise proceed to step 12.

Step 12. The best solution J_{g_best} and the corresponding position X_{g_best} are selected and saved.

Step 13. Checking for the end of the search. If all the cycles for all agents have been completed, then the search proceeds to step 15, otherwise, a restart is performed, and the search proceeds to step 14.

Step 14. Restarting agents: new random positions are selected for each agent $X^i, i = 1,2,...,S$, the velocity vector V^i is zeroed, the corresponding values of the objective function $J^i, i = 1,2,...,S$ are calculated.

Step 15. Stopping.

The considered optimization method based on modeling the movement of drones and its variants with grouping based on different approaches were used to find the global optimum of multidimensional functions.

Experiments have shown that the results of the method without grouping and its variants with grouping are identical in terms of the value of the optimal values of the objective function, but the speed of convergence to the optimal solution is better in the variants that use grouping. The general scheme of the optimization method based on modeling the movement of drones is shown in Fig. 9.

11. Advantages and disadvantages of BFO

One of the most studied bacteria is E. Coli, which has shown impressive self-replication abilities under conditions where it can break down within 20 minutes. The movement of the bacterium E. Coli bacterium is caused by the presence of six or more rotating flagella, which are controlled by its own biological motor. The general movement pattern of the bacterium includes a straight-line movement where all the flagella rotate together, which is achieved by the motor working in one direction. After that, the bacterium stops, the motor switches over, and a new segment of straight-line movement begins. The process of reorientation of the bacterium in space occurs randomly.

Chemotaxis, or the response to movement according to the presence of an attractant or repellent in the environment, affects the frequency of directional changes and the free running length of the bacterium. Under more favorable attractant conditions, the free run length increases, while in the presence of a repellent it decreases.

The considered method of optimization based on modeling the movement of drones did not take into account one of the important features of drone behavior: the bacteria E. Coli bacteria, as already mentioned, are able to create spatial and temporal structures by grouping. In this regard, several approaches have been proposed to take into account the movement of drones and this feature of their behavior in the modeling process, the main ones being: modeling signals between cells and the use of the PSO operator (Particle Swarm Optimization, PSO).

The chemotactic effects of E. Coli can be described as follows:

In a neutral environment, rotation and movement occur, enabling search. When moving along an attractant gradient, movement occurs in the same direction, facilitating the search for a favorable environment. In the case of movement in the opposite direction to the repellent gradient, an undesirable environment is avoided.

Thus, the bacterium E. Coli can move along beneficial substances and avoid hazardous substances by using sensitive protein receptors and methylation proteins that control the movement of the bacterium depending on the conditions in the environment.

12. Applications and relevant modifications of the optimization method based on modeling the movement of drones

Since the optimization method based on modeling drone movement has proven itself in solving problems of optimizing multidimensional functions, it has been applied to various optimization problems, developing appropriate modifications to take into account the specifics of particular tasks.

Finding the optimal energy flow: For this purpose, a modification of the optimization method based on modeling the movement of drones with grouping through the interconnection between regions is applied. This helps to speed up convergence. Features of the modification include sorting drones based on the minimum values of the objective function obtained at each step of chemotaxis. This approach allows bacteria with better solutions to move to the next generation more efficiently, accelerating convergence to the globally better solution.

The grouping is calculated by the distance of each bacterium to the current best solution, taking into account the relationship since the beginning of the method. Experiments confirm that this modification provides higher accuracy than the traditional IPSLP method.

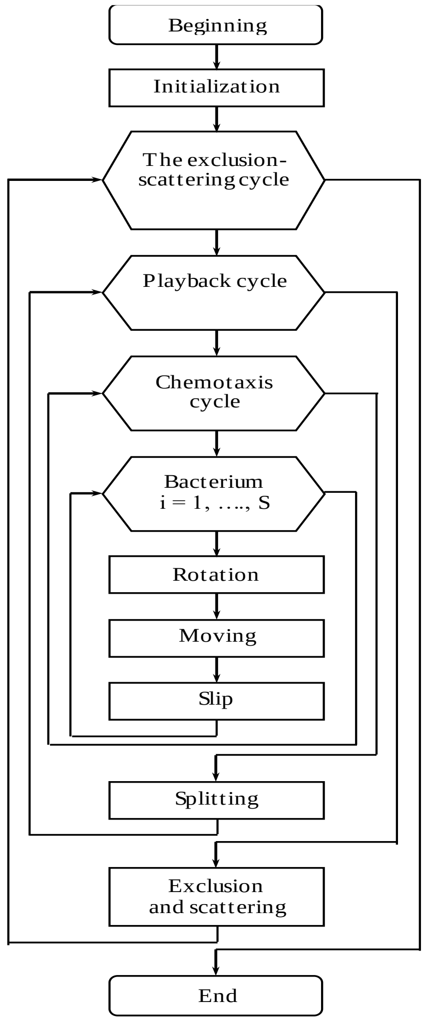

Figure 9. General scheme of the method based on modeling the movement of drones

Source: developed by the authors

Independent Component Analysis (ICA): The optimization method based on drone motion modeling is applied to independent component analysis in the context of Independent Component Analysis (ICA). ICA is a statistical method for linearly representing data distributed according to a non-Gaussian law. Due to the fact that existing ICA methods can get stuck in local optima, the optimization method based on drone motion simulation is used as an efficient random search method to find global optima in the case of ICA.

It is proposed to use the kurtosis as a function of the difference, which should be maximized, and thus, according to the BFO method, the nutrient concentration function is minimized:

$$J = \frac{1}{ContrastFunction}, \tag{20}$$

where $ContrastFunction$ is a contrast function.

To find the minimum of this function, we used a basic optimization method based on modeling the movement of drones. The results of the experiments proved that the results obtained using the BFO were more accurate than the previously developed fast ICA and CGAICA (constrained genetic algorithm based ICA) approaches.

Tuning a proportional-integral-differential (PID) controller: Despite new advances in control theory, proportional-integral-differential (PID) controllers continue to be widely used in many industrial processes. Most of the approaches to PID tuning developed over the past years use traditional methods, such as the frequency response method. Such methods require a large number of technical experiments, which is a time-consuming and expensive task. Therefore, it is proposed to use an optimization method based on modeling the movement of drones to tune the parameters of the PID controller.

As an inverse measure of efficiency, it is proposed to use the integral of the time-weighted square of the error:

$$PI = \int_0^\infty t(E(t))^2 dt, \tag{21}$$

where $E(t)$ is the controller error. $E(t)$ depends on the controller's operation parameters (*p)*. Then, for the best tuning of the controller's PID, it is necessary to find such values of the controller's parameters *p* that will achieve the minimum $PI\colon \min_p PI(p)$. The search for the minimum PI was carried out by optimization based on modeling the movement of drones with grouping due to communication between regions.

The results obtained were compared with those obtained by applying other methods based on a random approach: genetic algorithms and the method of modeling immune systems. The results of all methods were sufficiently accurate and did not differ greatly from each other, thus confirming the effectiveness of the optimization method by simulating the movement of drones to tune the PID controller.

Dynamic attack object recognition problem: The basic BFO method was used to solve the dynamic attack object distribution problem and was tested using an experimental platform characterized by different temperatures in different parts of the platform. The experimental platform consisted of two parts: a board (consisting of various design elements) and a data acquisition layer that collects data on the temperature in different parts of the attacked objects, using the example of the artificial multi-agent system of the GEPRC MARK4 FPV drone colony.

Thus, the movement of the drones on the experimental platform was modeled, and the areas with the lowest temperature were searched for. The performance of the BFO method was compared with traditional methods, as well as with the ant colony method. The results showed that the BFO method finds optimal solutions faster than other methods.

The field of application of the BFO method is not limited to the tasks described above. We have described only the main and already well-known areas in which this method is used. However, it is also used to solve other optimization problems.

Conclusions. The development and creation of new generation information management systems, in particular, toolkits for information and cognitive support of the processes of synthesis, integration and updating of knowledge, is an important area of basic research in the field of applied artificial intelligence systems. These areas are characterized by innovation and can be applied in various sectors of the economy and technology. A new and promising direction in the development of artificial intelligence methods is the use of multi-agent methods of intellectual optimization that model the collective intelligence of social animals using Swarm Intelligence methods. This young and poorly researched area already shows good results in solving various optimization problems, which indicates its prospects based on the bionic approach. Multi-agent distributed artificial intelligence systems, in particular, Swarm Intelligence methods, use bionic principles and model the collective intelligence of natural systems. These methods are promising for solving various optimization problems, especially in the context of combinatorial optimization.

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MODELLING AND USE OF GRAPH DATABASES IN INFORMATION CONTROL SYSTEMS

One of the goals of the digital transformation initiative by the Ministry of Education and Science of Ukraine is to optimize and automate management processes within the education sector and higher education institutions (HEIs), specifically concerning the accreditation of educational programs [1, 2].

The development of educational programs for HEIs is crucial, as these programs lay the foundations for the formation of future competences and program learning outcomes in the specialty for which they are developed. Under the Law of Ukraine «On Higher Education», an educational program consists of educational components logically sequenced for study, assigned ECTS credits, and designed to achieve specific learning outcomes, which a student must master to earn a qualification [3].

The analysis of domestic and foreign works on the subject of the study showed that there are a significant number of publications and scientific reviews on improving the quality of education in the higher education system, including through the introduction of a competence-based approach [4]. However, most of these studies are generally recommendatory and lack practical guidance on the tools, methods, and ways to compare the nomenclature of competencies and learning outcomes listed in educational programs against the actual competencies developed in future specialists.

Paper [5] examines the impact of higher education standardisation on the quality of the educational process, in particular, the «contradictions of quality control», among which the author highlights the practice of assessing learning outcomes not in the workplace, but in the classroom (i.e. at the theoretical level), which can lead to a lack of correlation between declarative competencies and real learning outcomes. The publication attempts to reflect the relationship between the regulatory documents in the field of higher education standardisation and the quality of the education system through the educational qualification characteristics of a future specialist and his/her educational training.

The monographic study [6] is devoted to the problem of improving the quality of vocational education in Ukraine, and it is proposed to use «passports of professions» for each speciality, which will contain a list of competences desired by the employer. In the development of such a portrait, considerable attention is paid to the modelling method, which can provide optimal prerequisites for the formation of competitive specialists with a high level of knowledge and skills required by employers.

Publication [7] is devoted to the issue of identifying a set of professional competences of future specialists in the speciality 122 «Computer Science». The authors note that the current educational standard for first (bachelor's) level applicants in this speciality has an important drawback – it was developed by specialists of the Ministry of Education and Science of Ukraine without the involvement of employers. In order to address the issue of improving the quality of education in the higher education system, the authors propose to improve the existing standards of training by involving representatives of the IT sector and employers in the development of professional standards. The paper also emphasises the need for annual review of curricula and discipline materials to bring them as close as possible to the needs of the IT industry and the labour market, as noted in other sources [8]. This raises the problem of the need to revise and update educational programs and, in particular, a set of competences and learning outcomes to bring them in line with market needs, employers' demands, innovative technologies, etc. For example, in the EU countries, a special classification of skills, competences, qualifications and occupations (European Skills, Competences, Qualifications and Occupations or ESCO) is developed and annually updated, which contains, among other things, a list of qualification requirements that a specialist of a certain speciality in the EU countries must meet [9]. Implementation of this classification in Ukraine, according to the authors of the publication, will require not only appropriate changes to the standards and educational programs for training highly qualified specialists, but also their constant updating and revision. The review shows that the publications under consideration prove the relevance and timeliness of the research topic, but, on the other hand, only partially characterise this issue.

Today, the majority of educational programs in HEIs are developed manually by specialists who are members of expert groups, which, according to the authors of the study, emphasises the need to digitalise the processes of preparing it using modern information technologies.

One of the priority tasks of digitalisation is to create information control systems that simplify and optimise the process of creating educational programs. An important step in this direction is information modelling, which is the initial stage of designing automated solutions and involves studying the subject area, defining and designing data structures in accordance with the rules for building the selected data model. This modelling not only allows for efficient data organization but also deepens understanding of the subject area, identifying needs and opportunities for optimization. It helps to identify the key elements of educational programs, their interrelationships and the dynamics of change, which allows for the development of more efficient automated solutions. When modelling the formation of HEI educational program, it is important to take into account the following special characteristics of the process: the presence of textual and poorly structured data, a large number of links between educational components that need to be modified and/or rethought at the stage of formation. Given these features, the modelling issue covers the choice of a data representation model and an appropriate database management system (DBMS) to create a database of an information control system with educational programs development functions, which, among other things, will create an effective tool for analysing possible scenarios for optimising or developing educational programs and will support their rapid adaptation to changes in the requirements of the labour market and the technological environment.

This **study aims** to explore opportunities to optimize and enhance the development of educational and professional programs (EPPs) by automating the process, identifying its main informational components and characteristics, and establishing rules for information modeling within a graph DBMS environment to generally improve the efficiency and quality of EPPs.

Theoretical foundations of the study

The basis for the development of educational programs in HEIs is the current regulatory framework in this area. Based on the legislation and the Higher Education Standard (Standard) [10], each HEI develops its own EPPs and corresponding to them curricula to prepare professionals in the required field.

The standard structure of the EPP at Kyiv National Economic University named after Vadym Hetman includes the following sections:

1) profile of the educational program, for example in the speciality 122 «Computer Science»;

2) a list of the EPP components and their logical sequence (includes: a list of educational components, EPP structure, EPP structural and logical diagram);

3) form of certification of higher education students;

4) matrixes: compliance of the competences defined by the educational program with the compulsory components, ensuring the learning outcomes with the compulsory components of the educational program, compliance of the competences/learning outcomes defined by the Standard with the descriptors of the National Qualifications Framework, compliance of the learning outcomes and competences defined by the Standard;

5) additions.

Based on the EPP, a curriculum is developed that contains a schedule of the educational process, a list and scope of educational components, including[1]:

– a block of compulsory (normative) academic disciplines divided into cycles:

  - general training;
  - professional training;

– a block of elective courses;

– practical training block (internship, computer training, preparation of a qualifying master's thesis).

On the basis of the developed EPP and curricula, the academic staff of the departments prepare work programs and methodological materials for academic disciplines and courseworks, other methodological documentation. The work programs demonstrate how the applicant for the relevant degree of higher education will achieve the learning outcomes declared in the EPP.

As a result of educational activities, competences are formed, which, according to the legislation, are usually divided into: integral, general and special (professional). The list of these competences for the specialty 122 «Computer Science» is also defined by the Standard [10] and may be supplemented by the decision of the project team involved in the development of the EPP.

Modelling of the described process requires, first of all, the reflection of the interrelationships of the EPP, the list of educational

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[1] *It is considered on the example of the EPP «Information Control Systems and Technologies« of Kyiv National Economic University named after Vadym Hetman. Department of Information Systems in Economics, 2023.*

components and the competences formed by these components. Among the most significant problems is the complexity and non-triviality of the comparison process in matters related to the presentation of unstructured and/or poorly structured data. Thus, there are issues of determining an adequate data model that can be used to work with the information contained in the EPP and selecting an acceptable DBMS.

Until recently, the development of information systems was dominated by the use of relational databases or RDBMS. Over time, the focus has shifted to the use of non-relational databases (NoSQL) [11]. A study of the subject area shows that when designing an information control system with educational programs development functions, the use of RDBMS has significant limitations:

– they are not well suited for storing poorly structured and unstructured data. A significant amount of data describing the processes described above has a many-to-many («M:N») relationship. From the point of view of design methodology and normalisation theory [12], to implement this kind of relationship, additional tables need to be created that will not have a semantic interpretation in the real terms and concepts of the process of forming the EPP;

– support a static diagram (scheme), which is not desirable to change after its design, while the content of the EPP and the links between educational components can change quite often;

– do not have visualisation tools that would allow them to view and analyse data and the links between them;

– are difficult to scale horizontally.

Based on the above considerations, a study was conducted of non-relational databases, which were created as opposed to RDBMS to provide the ability to support unstructured or poorly structured data, horizontal scaling and work with distributed clusters in the web space. As we know, the main data models used in NoSQL include: key-value, document-oriented, column-oriented and graph-oriented [11, 13, 14].

Comparative characteristics of relational, graph, and other NoSQL models are shown in Table 1. It should be noted that graph data representation models are highlighted in a separate column in the table because they have their own specifics and features relative to other NoSQLs, and some of their characteristics are similar to RDBMS.

A comparative analysis of existing data models has led to the conclusion that the graph model is the most suitable for the subject area under study, since they allow modelling numerous relationships between entities, which is typical for the EPP, and storing, viewing and analysing both structured and unstructured data.

The conclusions obtained are confirmed by the results of studies by other researchers. For example, study [15] substantiates the idea of the expediency of working with graph models of data representation when identifying qualification frameworks in the assessment of various EPPs for their compliance with existing standards and desired sets of competencies. The authors prove that the use of a graph data model allows to improve the quality of perception of a large array of poorly structured data by means of visualisation, perform in-depth analysis of EPPs and form the basis for their further improvement.

According to modern approaches to the classification of graph databases, they are divided into the main types: property graphs and triples (RDF graphs) [16]. On the one hand, these two main types of graphs help to explore and graphically represent related data, on the other hand, the ways of displaying the relationships between data in these types are completely different. For example, triples are used to represent knowledge in the form of triples with the structure <subject, predicate, object>. Each triplet is a form of declarative knowledge representation in which links are built between subjects and objects, which are the nodes of the graph, and predicates are its edges [17]. They are overwhelmingly used on the Semantic Web. The RDF model is well suited for representing ontologies and knowledge bases, so it is very common in artificial intelligence systems and is often used to process the results of scientific research.

Table 1

COMPARATIVE CHARACTERISTICS OF RELATIONAL AND NON-RELATIONAL DATABASES

#	**Features**	**Models of modern databases**		
		Relational models	**NoSQL models**	
			Key/value, column-oriented, document-oriented	**Graph**
1	*2*	*3*	*4*	*5*
1	Theoretical basis	Normalisation theory, relational algebra	CAP theorem	CAP theorem
2	Claims and transaction support	Support for transactions and ACID requirements	Support for BASE requirements	Support for transactions and ACID requirements

End of the table 1

1	*2*	*3*	*4*	*5*
3	Support for the SQL query language	Supports	Does not support	Declarative languages similar to SQL, for example, the Cyrher language in Neo4j DBMS and SPARQL in RDF graphs
4	Support for scaling	Vertical scaling	Horizontal scaling	Horizontal scaling
5	Support for a static data chart (diagram)	Supports	Does not support	Interconnections in the form of a graph, the structure of which is adaptive, i.e. it can change as needed
6	Processing of atomic and aggregated data	Atomic data (aggregate-ignore)	Aggregated data of any structure	Atomic data (aggregate-ignore)
7	Built-in visualisation tools	Absent	Absent	Available (in the absence of built-in tools, can use Gephi)[2]
8	Data normalisation	Structured normalised data with guaranteed consistency	Unstructured, denormalised, poorly consistent data	Normalisation is optional, the database can be normalised or denormalised under certain conditions

Source: developed by the authors

Graphs with properties allow to describe any entities in the subject area and the relationships that exist between them [18]. In a generalised form, a graph model with properties can be represented as follows:

$$G = (N, E), \tag{1}$$

where N – is a finite set of nodes (or vertices, nodes), $N = \{v_1, v_2, \dots, v_m\}$; E – is a set of orientated arcs (or edges),

[2] *Gephi is a graph visualisation software [19].*

$E = \{e_1, e_2, \dots, e_n\}$ each of which represents a connection between different pairs of nodes (v_i, v_j) [20].

Each node of the property graph is described as:

$$N = \{(id, [L_1, \dots, L_h\ ], [(k_1 v_1), \dots, (\ k_m v_m)])\} \tag{2}$$

where id – is the unique identifier of the node, L_i – node label, $(k_j v_j)$ – key-value pairs that characterise the properties of node, while k_j – key identifying the name of the attribute property, v_j – value of the property [16].

Each edge belongs to a certain type (TypeEdges), which characterises the semantics of the connection and necessarily contains the initial (ParentNode) and final (ChildNode) nodes. The structured representation of a node is as follows:

$$E = \{(ParentNode) - \left[s{:}\,TypeEdges\left(\begin{matrix}[k_1 v_1],\\ \dots, [k_m v_m]\end{matrix}\right)\right] \rightarrow (ChildNode)\} \tag{3}$$

where s – is an edge variable, $(k_j v_j)$ – key-value pairs that characterise the properties of the edge and are optional components; the arrow symbol (→) indicates the orientation of the connection. Arrows between two nodes can be forward (→) or backwards (←) direction. If necessary, two edges of different orientations can be drawn between two entities. When the direction of the connection is difficult to determine or is not important, then the construction $(Node1) - [edges] - (Node2)$.

The limitation of using graph databases based on the RDF format is the difficulty of building N-ary relationships between graph nodes. Therefore, as a rule, property graphs are best suited for heterogeneous data with a large number of attributes and complex graph operations, while triplets are best suited for homogeneous data with a small number of attributes and simple semantic analysis. Therefore, triplets are not suitable for modelling data that characterise the EPP, as it is difficult and impossible to describe all entities and relationships between them in the form of RDF graphs.

The search and analysis of the option for creating and storing data describing the EPP is narrowed down to the choice of a graph DBMS that supports a graph with properties. The authors have identified the following criteria for such a choice:

– DBMS rating, which characterises its current popularity and use in practice;

– availability of graph visualisation tools that will allow viewing and analysing the graph;

– horizontal scaling;

– availability of a query language;

– support for ACID requirements (atomicity, consistency, isolation, reliability) and transactions;

– support for GRUD operations (Great, Read, Update, Delete);

– availability of a library that implements typical operations with graphs;

– the ability to work offline or in the cloud;

– support for the most common programming languages;

– availability of an open source version that does not require a licence, which will reduce additional costs.

As noted in [8], most HEIs, due to a number of objective factors, are unable to fully provide a high level of material and technical base of computer classes and research laboratories. Additional costs for proprietary software are highly undesirable.

Among the graph databases, the number of which is currently 41, the most fully meets the above requirements DBMS Neo4j, which, according to DB-Engines [21], ranks first in the ranking in terms of the level of prevalence of use (see Fig. 1).

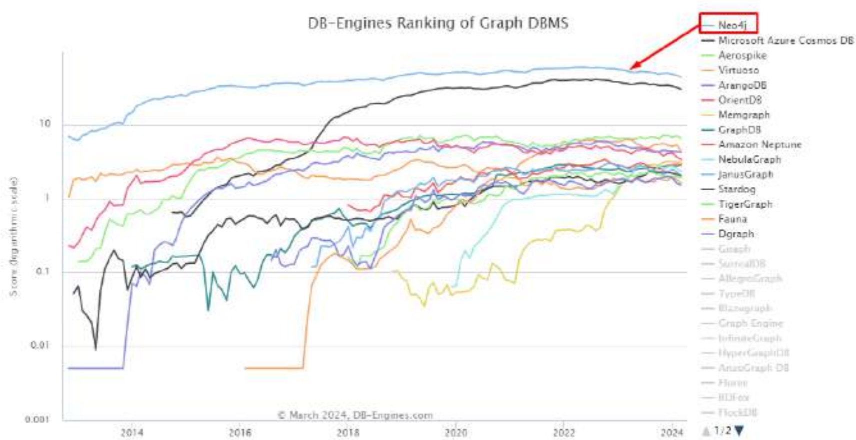

Figure 1. Graph DBMS rating (data as of January 2024)

Source: [21]

A review of the literature shows that a significant number of scientists are inclined to believe that in modelling complex processes of activity, it is worth focusing on the Neo4j DBMS [22–24]. In particular, work [25] substantiates the feasibility of using Neo4j as an accessible and convenient tool for visualising data generated as a result of developing a set of competencies required for healthcare professionals. In [26], it is proposed to use Neo4j to solve complex management problems based on the need for a deep understanding of the semantic meaning of textual information.

The Neo4j DBMS is:

– open source software;

– focused on working with graphs with properties;

– compatible with operating systems: Linux, OS X, Solaris and Windows;

– supports programming languages such as .Net, Clojure, Elixir, Go, Groovy, Haskell, Java, JavaScript, Perl, PHP, Python, Ruby, Scala;

– can run on a standalone basis or in the cloud under the Neo4j AuraDB cloud service;

– has a SQL-like query language Cypher Query Language (Cypher);

– has web browser-based visualisation tools [27].

The Neo4j database model is an oriented graph containing a set:

– nodes, which represent the vertices of the graph and characterise certain objects (entities) of the subject area;

– node labels that characterise the node type and semantics;

– relations or edges that reflect the connections between the nodes of the graph;

– properties – specific data described by key-value pairs and characterising the nodes and edges of the graph.

The key advantage of graph databases is the speed of traversing a large number of nodes and finding the necessary information. The Neo4j performs fast navigation through the graph nodes and has indexing tools that speed up the search for nodes and edges by certain properties or determining the starting node for traversing the graph.

Building a graph and designing a graph database that will be used in the operation of an information control system with the functions of forming educational programs involves identifying entities, their attributes, and the relationships between them, which is what information modelling is actually for.

The modelling process includes:

– defining the types of nodes that represent the entities of a given subject area;

– defining properties of nodes that describe their characteristics;

– defining the edges that describe the connections between nodes;

– defining link rules that limit the permissible connections between nodes.

The importance of information modelling in the development of a graph database is to ensure a clear understanding of the data structure, its consistency and integrity, reduce duplication, and facilitate the effective use of graphs for analytics and visualisation. Thus, modelling data using a graph model is the process of creating an abstract representation of this data in a graph.

The general issues of organising the modelling of graph data models are studied in the scientific and practical literature [11, 16, 28], which demonstrates a significant interest in the development and implementation of graph technologies in information control systems. For example, paper [29] discusses methods and approaches to modelling in graph databases, identifies the advantages and disadvantages of working with graph models. Another paper [17] presents a methodology for modelling one-dimensional and multidimensional data using graphs with properties, which includes approaches to modelling events, behaviour, relationships, aggregation of events and behaviour. The proposed methodology is focused on representing and analysing events in the form of graphs, which will help to increase the efficiency of processing and analysing complex interactions. Work [30] deals with the normalisation of graphs with properties as one of the stages of the modelling process aimed at optimising and improving the performance of software products that use graph models to process large data sets. Papers [31, 32] contain recommendations for representing the data structure, methods of their optimisation, and representation in graph models, in particular, in the Neo4j DBMS environment. The authors note that a deep understanding of the data structure represented in graphs contributes to the effective solution of data analysis tasks. The basic principles of data modelling, recommendations and examples of creating effective graph models are provided in the official Neo4j documentation [33].

Thus, the problem of data modelling in graph databases is relevant and has a wide range of applications in information control systems. The presented research describes the general rules and principles of data modelling, identifies possible problems and potential of using graph databases. In particular, it is established that:

– data modelling in graph databases should be carried out in stages (analysis of the subject area, identification of entities and relationships, selection of a graph data model, model development and implementation);

– for modelling complex data structures with multiple relationships, it is advisable to use graphs with properties, and for application implementation – the Neo4j;

– data presented in graph models can and should be normalised.

Thus, the process of data modelling using graph models involves creating an abstract representation of information objects in the form of a graph. In this context, it is important to present a unified approach to data modelling in graph databases, illustrate the process with examples, provide recommendations and tips on the peculiarities of modelling graphs with properties in the Neo4j environment.

Based on the **results of research**, the authors propose their own approach to information modelling of the EPP data using graphs with properties. The modelling process should include the following steps:

1) studying the subject area, research of data specifics, their structure and semantics;

2) defining the type of data representation model, selecting the type of graph model;

3) modelling of information objects:

3.1) selection of a given subject area entities, modelling of properties, labels;

3.2) data normalisation;

3.3) determining the orientation and building relationships (edges) between entities.

Above, an example of the analysis of the subject area – the process of forming the EPP for HEIs and the justification of the feasibility of choosing a graph data model on the example of a graph with properties for modelling the data of such a subject area was given. Now let's consider the process of modelling information objects on the example of developing a graph database for the EPP «Information Control Systems and Technologies» of the second (master's) level of higher education.

To identify the entities or nodes of a graph, it is recommended to describe the subject area under study in simple narrative sentences that characterise it [34]. The authors recommend following the following rule: each such sentence should contain nouns and verbs (nouns will be comparable to entities, and verbs – to relations between them). Thus, for the chosen subject area, such basic sentences would be the following:

– The specialty provides the acquisition of Competencies;
– Competencies form the Specialty;
– Competencies are revealed by the Discipline;
– The discipline provides Learning Outcomes.

Thus, the main entities of the selected subject area are: *Specialty*, *Competencies*, *Discipline* and *Learning_outcomes*.

Having determined the list of the main objects of the graph, proceed to modelling the properties and labels of the entities. Properties are specific data values that are represented in the key-value format and characterise each individual entity, labels are named elements of a graph node that are used when grouping them into sets.

The generalised structure of the syntax for creating an entity in the Neo4j is as follows:

$$\text{CREATE (Node variables: } label_1, \ldots, \\ label_n \{Key_1 : Value_1, \ldots, Key_m : Value_m\}), \quad (4)$$

where *Node variables* – an entity variable. It can be entered when creating an entity or later, through queries when accessing nodes. Variables can be designated with separate letters, as it is done in programming, or they can be named with names that reflect their semantics;

label – label of the entity (node). Since a node in a graph can participate in various relationships, for semantic identification, each node is assigned labels that will allow us to group and select certain sets of entities depending on their semantics and purpose. Labels can be used to group nodes by their purpose;

Key:Value – properties of an entity represented as key-value pairs. In the Neo4j, keys are represented as a textual data type – string, values can be represented by an arbitrary data type or an array.

When creating labels, the authors of the study recommend following the following rules:

1) an entity can have one, several, or no labels. Since labels help to distinguish entities, it is better that each node has at least one label, since a node without a label makes it difficult to search and read, which can reduce database performance. But a large number of labels is also not desirable, as it complicates the work with entities and affects the performance of queries. The recommended number of labels for one entity is from 1 to 4. In Neo4j, when creating a node, 4 slots are reserved for labels by default;

2) labels can be orthogonal, i.e. mutually opposite;

3) when modelling labels, we need to take into account the semantics of the subject area and possible queries to the graph. That is, before creating a label, it is advisable to pre-model the queries in which this label will participate;

4) accessing labels in the Neo4j is case-sensitive, while the Cypher language does not generate an error if the name is specified in the wrong case. This aspect requires attention from developers and future users of the graph database.

Let us consider an example of modelling the essence of «speciality». According to the authors of the study, it is important to distinguish for which level of higher education it is intended when developing the EPP for a particular speciality, since the same speciality, for example, 122 «Computer Science», has different requirements, goals and objectives for the first (bachelor's), second (master's) and third (educational and scientific) levels of higher education. Thus, we propose to supplement the «speciality» entity with the labels *Bachelor* (to characterise the first (bachelor's) level) and *Master* (for the second (master's) level).

Thus, the structure of the modelling operator of the «speciality» entity for the second (master's) level of higher education in Cypher will be as follows:

CREATE(s: Master {name: «122_Computer_science», educational_qualification: «Master of Science in Computer Science», branch_knowledge: «12_Information _technologies»})

When modelling entities, it should be borne in mind that all educational components (disciplines) are divided into two groups: compulsory and elective. In turn, compulsory educational components are represented by two groups: general and professional training. That is, labels should be used when modelling the «discipline» entity: *Compulsory*, *Selective* to group them into compulsory and elective educational components. The disciplines of the general training cycle will be identified by the *General* label, and those of the professional training cycle by the *Professional* label.

The structure of the entity to be represented in the column of compulsory disciplines:

– of the general training cycle:

CREATE (d: Compulsory: General {name: «code_discipline_name»,hours: hours, credits: credits, semester: semester number, final control: offset/exam))

– of the professional training cycle:

CREATE (d: Compulsory: Professional {name: «code_discipline_name»,hours: hours, credits: credits, semester: semester number, final control: offset/ exam, swork))

The following is an example of creating a node to represent the data of the compulsory discipline of the professional training cycle «Information Control Systems»:

CREATE (ok1210: Compulsory: Professional {name: «OK1.2.10-Information Control systems», hours: 120, credits: 4, semester: 3, exam: «1 kur_r» })

The structure of the entity for elective subjects will be similar to the entity structures for compulsory subjects, but will contain only one

Selective label for filtering and selecting educational components of the student's choice.

When creating competence essences, one should take into account that there are different types of competences:

– general (universal) – do not depend on the professional orientation of the EPP;

– special or professional (subject) – aimed at gaining knowledge in a particular professional field.

The entities for displaying competences and learning outcomes will be similar in structure to the «speciality» entity and only labels will differ: *general_competencies* – general (universal) competences, *professional_competencies* – special or subject competences, *learning_outcomes* – learning outcomes.

The following are examples of creating a node for general competence (GC1):

CREATE (zk1: general_competencies {name: «GC1 Ability to think abstractly, analyse and synthesise»})

Fig. 2 shows the result of the creation of nodes of the EPP «Information Control Systems and Technologies».

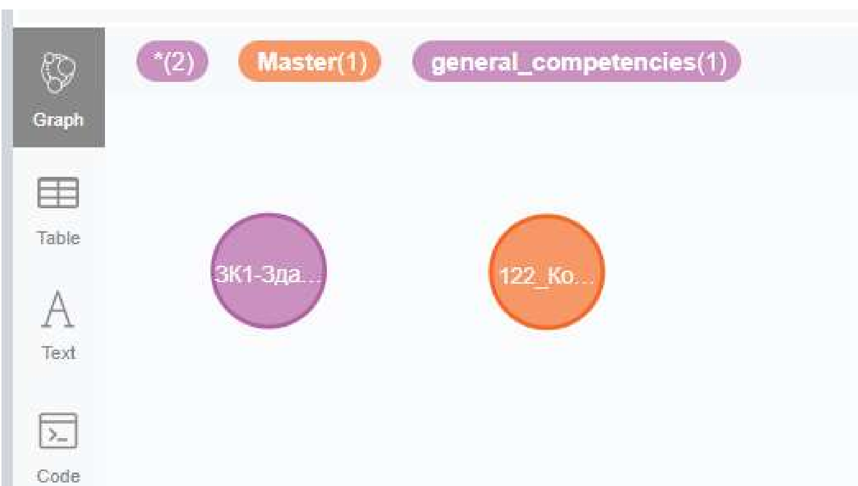

Figure 2. The result of creating the node in the Neo4j

Source: built by the authors

Having modelled the entities that will be represented by the nodes of the graph database, we should pay attention to the issue of their normalisation. It is generally accepted that only the relational data model should be normalised to reduce redundancy and eliminate anomalies when making changes to databases. That is, NoSQL databases can be stored in a denormalised form. However, this statement does not apply to graph databases. Always, after modelling the entity structures, it is necessary to check the fulfilment of the requirements of the normalisation theory, at least for the compliance of the entity representation with the third normal form (3NF) [30]. Given that graph databases, unlike other NoSQL models, are aggregate-ignore, solving the normalisation problem reduces duplication, facilitates and speeds up data modification, and ensures data consistency.

The final step in information modelling is to build relationships between entities, which will be represented by the edges of a graph database.

When modelling relationships, remember that there can be no incomplete relationships in the graph, i.e. each edge must connect two nodes, respectively:

– each created edge can be a directed edge if it leaves the initial (parent) node and enters the final (child) node, thus indicating its orientation;

– the created edge can be undirected, such a relationship can go in any direction (between nodes). Undirected relationships between entities are created in cases where there is no complete certainty about the direction of the relationship, but there is a need to implement certain queries that should reflect the interaction of entities regardless of the physical connection between them. The Neo4j supports the creation of such relationships between entities.

The literature review above suggests that there is currently no clear theory of relationship modelling. Relationships can describe any connections between entities [35]. Therefore, for our part, we believe it is necessary to distinguish the following rules for modelling relationships:

– creating relationships should be done strictly after modelling entities and normalising them;

– the semantics of the subject area should be taken into account and the information needs of end users should be analysed, which will ensure clarity and comprehensibility of structural relationships and help to avoid data inconsistency. Taking into account semantic aspects and subject area analysis when modelling relationships also allows us to optimise database query processes, reducing data processing and increasing the speed of responses to user requests;

– when defining relationships, we should focus on the key connections that are most important for analytics and decision-making. This will allow us to focus on the most critical relationships and optimise analysis and visualisation processes;

– relationship modelling should be limited to those necessary to meet specific information needs, avoiding excessive complexity that could make data management and analysis difficult;

– the formed relationships between entities are basic, but may not always reflect all the needs of users when implementing queries to a graph database. Therefore, an important aspect of relationship modelling is the research and modelling of possible queries to the graph database under design;

– given that oriented edges reduce the number of relationships when implementing queries, when modelling a graph, should avoid using undirected edges whenever possible.

Each relationship in a graph database can include variables, properties, and information about its type, which will reflect the semantics of the relationship.

Since the graphical data model is easily modified and extended, when modelling relationships, first of all, basic ones are created (those highlighted by verbs in the narrative description of the subject area). Other types of relationships, which will require modelling when implementing queries on a research graph model, were not considered in this study.

It should be noted that the current requirements for the formation of the EPP do not require the reflection of the links of elective educational components with other entities of the subject area. On the other hand, elective subjects may have links with the compulsory subjects of the professional training cycle, as they provide an opportunity for in-depth specialised study of certain topics or sections of the compulsory educational components. Given that each compulsory discipline of the professional training cycle has links to the relevant competencies, we can assume that elective courses may also have an indirect (transitory) link to these competencies. In addition, elective educational components that do not have any semantic links with the Compulsory educational components affect learning outcomes by specifying them or expanding them with additional knowledge and skills.

Based on the above, the authors propose to divide the elective courses into two conditional categories:

– Group A – elective courses that complement and expand the study of compulsory educational components;

– Group B courses courses that specify and expand the learning outcomes with additional knowledge and skills.

Therefore, the regulatory framework governing the development of EPPs needs to be modified in terms of taking into account the links between elective disciplines and the competencies and learning outcomes they form. If the legislative framework is so refined, elective educational components can be taken into account in the information modelling of the EPP.

After identifying the relationship and determining its type, it is advisable to proceed to describing its characteristics in a key-value format. These characteristics, for the most part, can be quantified (e.g., reflect distance, price, weight, absolute or percentage shares, certain rating coefficients, time intervals, etc.). As part of the construction of a graph database for this subject area, the authors concluded that there are no properties with quantitative characteristics. Therefore, only names and variables will have relations in the graph modelled by the EPP.

Below is an example of creating a relationship between a speciality (parent entity) and a general competence GC1 (child entity).

MATCH (s: Master {name: «122_Computer_science», educational_qualification: «Master of Science in Computer Science», branch_knowledge: «12_Information _technologies»}),

(zk1: general_competencies {name: «ZK1 – Ability to think abstractly, analyse and synthesise»}) CREATE(s)-[r:S_3K1]->(zk1) RETURN s, zk1

As a result of executing the command, a symmetrical directional connection was created, as shown in Fig. 3.

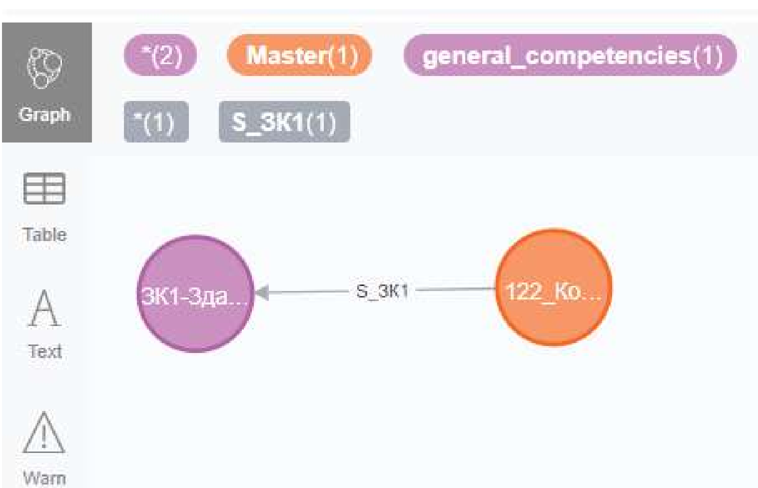

Figure 3. The result of creating the relationship in the Neo4j

Source: compiled by the authors

Other relations between the entities «speciality» and «competence» are created in a similar way, the result is shown in Fig. 4.

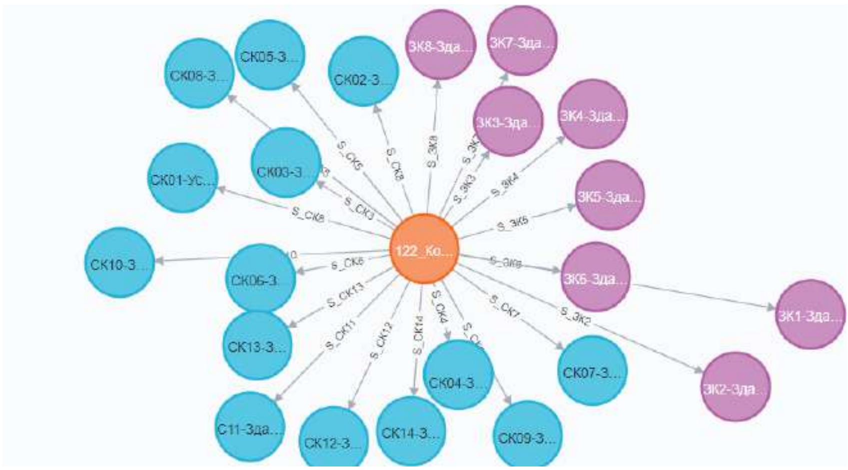

Figure 4. The result of modelling the relationship between the nodes of the EPP «Information Control Systems and Technologies» and general and professional competences in the Neo4j

Source: compiled by the authors

Further, the relations of the graph database are modelled on the basis that each specific general and special (professional) competence is formed by the compulsory educational components of the general and professional training cycles. That is, the parent node of this type of edge is a certain competence, and the final node is the corresponding academic discipline, which should take into account this competence and ensure its formation in students based on the results of training.

Next, it is necessary to build edges that reflect the relationship (links) of compulsory educational components with the corresponding learning outcomes. This group of edges reflects the final essence of students' learning and indicates the results that will be obtained by them in the form of theoretical knowledge and practical skills and abilities. The parent node of such edges should be the academic disciplines, and the child node should be the learning outcomes provided by the study of the relevant disciplines [14].

Based on the results of information modelling, a graph of the subject area is formed, which demonstrates the relationships between entities. Thus, in Fig. 5 shows a fragment of the result of graph database modelling for the EPP «Information Control Systems and Technologies».

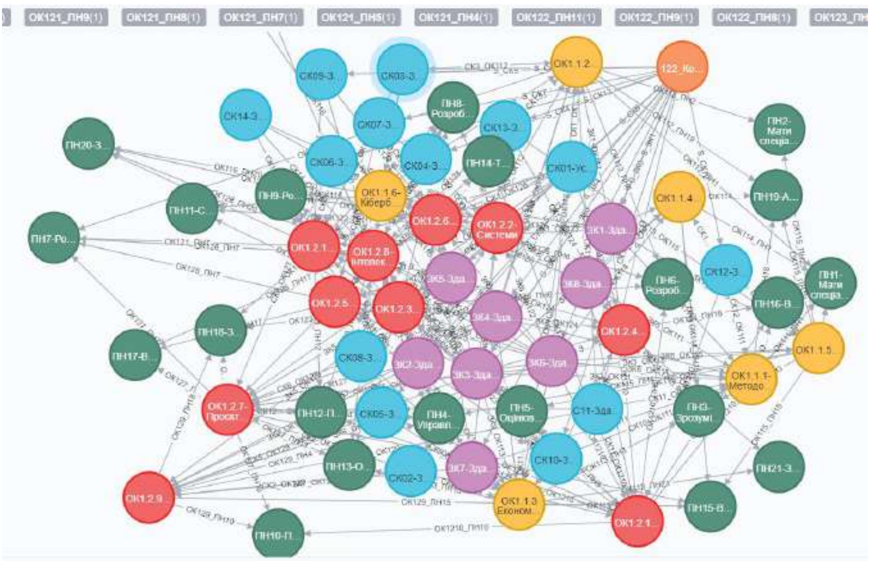

Figure 5. The result (fragment) of information modelling
of the EPP «Information Control Systems and Technologies» in the Neo4j

Source: built by the authors

The created graph allows to efficiently perform various queries for detailed research, analysis and evaluation of the EPP for balance and quality.

Below, as an example, is a request for a sample of competences covered in the discipline of the professional cycle «Information Control Systems»:

MATCH (ok1210: Compulsory: Professional {name: «OK1.2.10-Information control systems», hours: 120, credits: 4, semester: 3, exam: «1 kur_r» })<-[]-(zk) RETURN ok1210

The visualisation of the results of this query in the form of a graph is shown in Fig. 6.

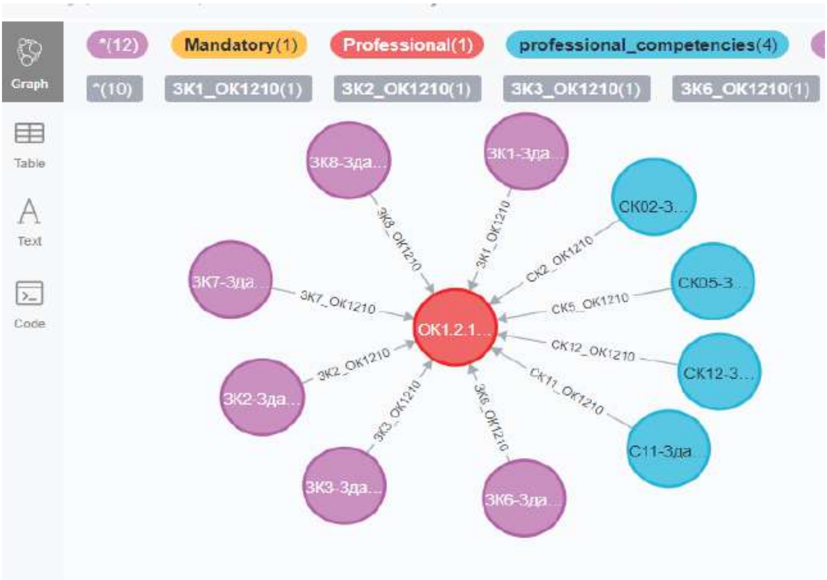

Figure 6. Graph of correspondence between general and professional competences and the discipline «Information Control Systems» in the Neo4j

Source: built by the authors

Conclusions and prospects for further research

The study proves the expediency of using graph databases to optimise the operational processes of HEIs in matters related to the development, analysis and improvement of educational programs.

The considered theoretical, methodological and practical aspects of creating and modelling information objects in graph models of data representation allowed the authors to propose a unified methodology of information modelling and demonstrate its key ideas on the example of creating a graph of the EPP «Information control systems and technologies» of the second (master's) level of higher education, which was introduced at the Kyiv National Economic University named after Vadym Hetman. It has been determined that graph databases provide flexible management of unstructured data, improving data visualisation and analysis, which is critical for modern HEIs. Applied aspects of information modelling are performed using the Neo4j DBMS, the main advantage of which is the ability to effectively store, visualise and analyse complex relationships between numerous entities of the subject area.

The data modelling algorithm proposed by the authors focuses on creating a graph structure that reflects complex interdependencies and interactions between objects of the subject area, while ensuring the flexibility and scalability of the model. Data modelling in graph models should be carried out in stages, including: studying the subject area; determining the type of data representation model; identifying entities, their properties, labels; normalising data in the identified entities; identifying relationships between entities, determining their type and building relationships. The process of data modelling and building graph databases requires developers to study the subject area in detail, to have a deep understanding of user needs, and to take into account the specifics of various types of relationships between entities, without which it is impossible to achieve an accurate and efficient representation of data in graph models.

Information modelling of data using Neo4j allows solving a number of important organisational and methodological tasks: to demonstrate the links between competences and learning outcomes within the EPP; to present the contribution of each educational component to the formation of competences and learning outcomes; to identify and reveal competences and programme learning outcomes that are not formed by the disciplines of the current curriculum; to determine the ratio of the level of competence formation by the disciplines of general and professional training blocks;

The proposed methodology and modelling algorithm not only form the basis for further research, but also open up new opportunities for improving the quality and efficiency of the EPP, providing a basis for innovative approaches to managing the quality of education.

Prospects for further research are to continue the work of the author's team on the implementation of the developed graph database into an information control system with the functions of forming educational programs to promote digitalisation and automation of management processes in the field of education and activities of HEIs. Also, in future works of the authors, it is planned to expand the created graph by supplementing it with new nodes with appropriate relationships that characterise the subject matter of each educational component by highlighting the topics included in the work program of the discipline. Such filling of the graph with new nodes and edges will allow clustering nodes and combining them by similarity of topics and identifying elements of duplication in the work programs of different educational components. This will allow for an in-depth analysis of the EPPs and informed decisions on their improvement, which will ultimately contribute to improving the quality of university education in general.

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METHODS AND MEANS FOR ASSESSING THE ELECTROMAGNETIC COMPATIBILITY OF MATERIALS IN CONTACT WITH HUMAN TISSUES

1. Modern concepts of compatibility of materials in contact with human tissue

Throughout his or her life, a person is in constant contact with the environment, materials, and substances of natural and artificial origin, as well as products made from them. The physical and mechanical characteristics of substances and materials have a significant impact on the human condition and sensations. For example, everyone has experienced the impact of uncomfortable or seasonally inappropriate clothing on the physical, moral, and psychological state of a person. In this case, we are talking about only one of the many parameters that can cause discomfort, namely the temperature in the underwear space. In fact, there are many such parameters, and assessing their compliance with certain indicators is an important task. In most cases, the parameters that affect the interaction of materials with human skin or tissue can be estimated numerically, i.e. they have certain numerical values. Taking into account the values of the parameters allows us to conclude that each material is compliant or not compliant under certain conditions of human use. To assess the conformity of substances and materials, it is advisable to use the term «compatibility».

Evaluating the compatibility of substances and materials with human tissues is an important step in the development, production, and use of various medical devices, clothing, household products, and other goods that have direct contact with skin or tissues.

To conduct a compatibility assessment, it is advisable to perform some preliminary procedures, including material composition analysis, toxicity assessment, study of the reaction of body tissues, determination of the impact on physiological processes, compliance with standards, etc.

When analyzing the composition of materials, it is advisable to analyze the documentation from manufacturers or analyze the chemical composition, including chemical compounds, impurities, and other components.

The procedure for analyzing the composition of materials allows you to assess its toxicity due to the presence of substances that can cause irritation, allergic reactions, or other negative effects on human skin or tissue.

The data obtained on the composition and toxicity allow us to assess the compliance of the material or substance with the established standards and regulations regarding safety and compatibility with human tissues.

In case of a positive result of the above procedures, it is advisable to study the reaction of body tissues to the interaction with the material. This stage is experimental and involves conducting experiments or testing on volunteers to assess the skin's reaction to contact with the material or substance. Even if the composition is appropriate and there are no toxic substances, contact with certain materials can cause irritation, redness, itching, skin rashes, and other symptoms.

Determining the impact on physiological processes is a rather complicated and lengthy procedure. First of all, it is advisable to determine the effect of the material on such processes as skin respiration, heat transfer, moisture removal, etc.

Taking into account the results of the above studies, it is possible to preliminarily assess the compatibility of substances and materials with human tissue and minimize risks to the health of users. However, the final conclusion about compatibility can only be made when numerical indicators of the parameters that determine the compatibility of materials with human tissue are obtained.

For example, for clothing materials, such parameters are usually divided into four groups: hygienic, technological, aesthetic, and economic [1].

Hygienic parameters include the ability to absorb and permeate moisture and air, and thermophysical, optical, and acoustic properties. In particular, they determine the ability of clothing to protect the human body from environmental influences, remove moisture and carbon dioxide from the undergarment space, and maintain the microclimate necessary for the body's vital activity in the undergarment space, i.e., they determine the hygiene of clothing.

Technological parameters can only partially be attributed to the determinants of compatibility with the human body. These include material strength, resistance to friction and bending, elongation due to stretching, stiffness, and others.

Aesthetic and economic parameters can also only conditionally be attributed to the determinants of compatibility, mostly characterizing the appearance and consumer's ability to use certain materials.

These are currently the generally accepted ideas about the compatibility of materials in contact with the human body.

Unfortunately, they do not take into account an essential component of the interaction of materials with human tissue. This component is the electromagnetic interaction of materials used both in everyday life and for medical purposes. The peculiarities of this interaction and the mechanisms of electromagnetic radiation generation are discussed below.

2. General information on intrinsic electromagnetic fields and their interaction

The electromagnetic radiation (EMR) surrounding a person throughout life can be divided into two components by origin: natural and man-made.

The Sun and outer space irradiate the Earth with broad-spectrum electromagnetic waves. It includes signals in the optical (ultraviolet (UV) to visible spectrum), microwave, radio, and low-frequency ranges. Most of the ultraviolet radiation is absorbed by the Earth's atmosphere. Radiation with longer wavelengths passes freely through the Earth's atmosphere. The peculiarity of the UV component of radiation (wavelength 180...400 nm) is a significant quantum energy (3.1...6.2 eV) and ionizing ability. UV radiation can have both a positive effect (bactericidal effect, increased immunity, stimulation of photochemical synthesis of vitamin D, and other effects) and a negative effect (burns, stimulation of gene mutation processes, and skin cancer) [2]. The visible part of the spectrum covers optical electromagnetic radiation in the range of 400...750 nm, and infrared (thermal) radiation with a wavelength of more than 750 nm. The energy of the quanta of these radiation components is lower (1.24...2.95 eV), but the depth of penetration into human tissue is greater. If the protective reaction of the human body against UV radiation is manifested in the form of a tan on the skin surface, then the radiation of the visible and infrared ranges is better absorbed and has a greater effect on the inner layers of human tissues. This is also true for the microwave range of EMR.

This effect is widely used in various spheres of human activity, in particular for diagnostics and treatment of humans [3].

Of particular interest is the EMR of cosmic origin in the millimeter wavelength range (frequency 30...300 GHz). It includes microwave relict radiation with a maximum intensity at a frequency of 160 GHz [4]. The energy of the millimeter-wave signals is much lower than that of the 1.24 optical band (10^{-5}...10^{-4} eV), so their effect on the human body at equivalent power will be more «mild».

The Earth's atmosphere absorbs microwave signals of different frequencies in different ways. The radiation of most of the spectrum is attenuated, and for some frequencies, in the so-called «transparency windows», it is transmitted almost without loss. One of the reasons for the attenuation of radiation is the resonant absorption by water and oxygen molecules. Microwave radiation of cosmic origin is considered to be primary.

At the same time, solar radiation in the infrared range, having passed through the atmosphere, heats up living and non-living objects located on the earth's surface (water, sand, stones, etc., including those in contact with human tissue). It is known that when heated, any dielectric materials emit electromagnetic waves in a wide range of frequencies. This radiation is commonly referred to as radio-thermal radiation. It has a noise-like spectrum, and the distribution of its energy density over frequency is described by Planck's law. The maximum heating temperature of objects on the Earth's surface by solar radiation can reach 100 degrees Celsius or more. As a result, this leads to the formation of low-intensity broadband microwave radiation, which, by analogy with radiation of cosmic origin, is considered secondary.

The source of the intrinsic EMR of materials is thermal fluctuations, or the so-called thermal noise, which is characteristic of dielectric materials. Thermal noise is a consequence of the chaotic movement of electric charge carriers, which can be electrons and ions in dielectrics or holes in semiconductors. In a system that is in a balanced state, where there are no reverse processes associated with dissipation phenomena, charge carriers are in thermal equilibrium with the molecules of the substance. At the same time, the Brownian motion of charge carriers causes fluctuations in their uniform distribution in the volume of the material and causes the appearance of unbalanced charges. Unbalanced charges cause the creation of a potential difference and a corresponding current, the flow of which equalizes the potential difference. In dielectric materials that have a small number of free electrons (textile materials, materials for implantation and prosthetics, etc.), thermal noise is largely generated by fluctuating dipoles.

The man-made component of EMR includes fields and signals generated by artificially created technical means. This category includes a huge set of mobile communication equipment, special radio systems for civilian and military purposes, generators for microwave therapy, and many other technical devices. They create an uneven electromagnetic background in the environment with a power level of (10^{-9}...10^{-8}) W [5]. The result is the so-called electromagnetic pollution of the environment, which will continue to increase due to the use of

4G, 5G, and satellite systems. The level of man-made radiation power can significantly exceed the natural microwave background and, accordingly, have a significant impact on biological objects. Studies conducted by some authors have noted the harmful effects of a constant man-made electromagnetic background in the environment on the biosphere and living beings [6].

At the same time, low-intensity signals in the millimeter range can have a stimulating and therapeutic effect on living beings and the human body in the short term, which is the basis of microwave therapy.

Primary and secondary microwave radiation of natural origin is weak compared to the man-made component. Nevertheless, it constantly affects living organisms that are in the zone of their influence. The power of such radiation can be determined using special radiometric receivers [7]. The radiation level is estimated using the Rayleigh-Jeans formula:

$$P = 2\pi\beta(f,T)\frac{f^2}{c^2}kT_oS_0\Delta f, \tag{1}$$

where $\beta(f,T)$ – is the emissivity coefficient; T – is the thermodynamic temperature of the radiation source; f – is the radiation frequency; $k = 1{,}38 \cdot 10^{-23}$ – is the Boltzmann constant; S_0 – is the surface area of the object under study, which is limited by the aperture of the receiving antenna; Δf – is the radiation frequency band to which the receiver is tuned.

The human body, which has an average temperature of 36.6°C, is also a source of EMR. The main part of it falls on the infrared part of the spectrum, but there is also microwave radiation.

Physiological processes occurring in the human body at the cellular level are regulated. In this case, the regulator is the EMR of millimeter and submillimeter wavelengths (frequency 3...3000 GHz). Radiation in this range is formed as a result of oscillations of cell membranes electrically charged due to ionic intracellular transfer. The natural frequency of oscillations of different tissues and cellular structures is different and, for example, for DNA macromolecules lies within 2...9 GHz, the frequency of oscillations of chromosomes is 0.75...15 THz, and the frequency of the human genome is about 25 THz.

In the case of the coincidence of natural frequencies of oscillations of individual cells or cellular structures with the frequency of irradiating waves of these ranges, resonance phenomena are caused, which transform weak effects of external EMR into significant bioinformational and structural changes for the body. A characteristic property of human body tissues is the ability to selectively interact only with certain frequencies of noise-like broadband radio-thermal secondary radiation.

The integral power of the microwave signal of the human body and its individual parts is in the range of $10^{-14}...10^{-13}$ W and depends on the state of the body. As shown by experimental studies [8], the average value of the radiation level of the palm of most respondents is in the range of $(3...6)10^{-13}$ W.

Radiometric systems used to measure intrinsic EMR have their own temperature, different from the temperature of the objects under study. Therefore, the output signal level of the meter is determined by the temperature difference between the object under study and the measuring system:

$$\Delta P = 2\pi K_1(f)\beta(f,T)k(T_o - T_R)\Delta f, \tag{2}$$

where $K_1(f)$ – is the conversion coefficient of the antenna receiving electromagnetic radiation; T_o – is the temperature of the object; T_R – is the temperature of the radiometric system.

Based on the above equation, it can be concluded that in order to measure low-intensity electromagnetic fields and radiation, it is necessary to ensure the sensitivity of the measuring system, which is an order of magnitude higher than the level of the measuring signals.

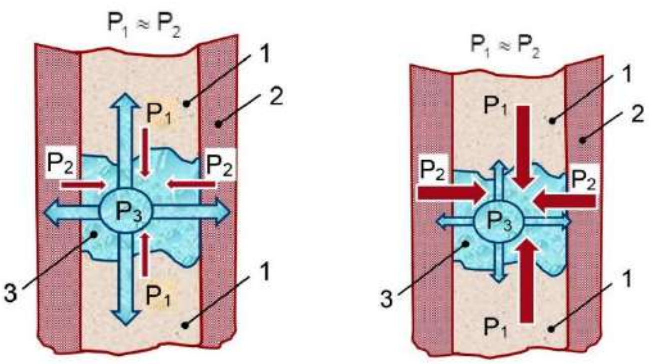
Ensuring such sensitivity of measurement systems is a complex technical task that requires fundamentally new approaches to the structural design of measurement systems and the creation of new algorithms for processing measurement information.

It was noted above that millimeter-wave signals are actively absorbed by water and oxygen molecules, which are integral components of living organisms. The phenomenon of absorption of low levels of EMR is the basis of microwave resonance therapy [9]. The power level of microwave signal generators, which are used to produce therapeutic effects, is in the range of $10^{-12}...10^{-6}$ W. It is the effect of signals of such a low level that provides positive changes in the indicators of the patient’s body during treatment, which are recorded by laboratory tests. Taking into account the therapeutic effect of exposure to signals of this level, a number of scientists have introduced new terms for this area, such as «quantum medicine» and «bioinformation signals» [10]. In this case, the targets of microwave signals are biologically active zones that are stimulated at the cellular level with subsequent transfer of information to the level of organs and systems of the human body.

Taking into account the above mechanism of secondary microwave radiation generation and the assessment of its power level, an interesting conclusion can be drawn. It is that conventional dielectric materials in contact with human tissues at certain temperature values can generate EMR comparable in level to signals from microwave therapeutic generators. That is, materials of clothing, footwear, implants, reconstructive surgery parts and everything else that has contact with human tissue will inevitably interact by transmitting electromagnetic radiation.

Analyzing the interaction of EMR with human tissues, it is advisable to return to expression (2). In fact, the interaction process is determined by the temperature gradient between the tissue and the object with which it interacts. If the temperature of the radiation object exceeds the temperature of the human body tissue $T_O > T_T$, a positive irradiating flux of microwave radiation is formed. In the opposite case, when the temperature of the radiation object is lower than the temperature of the human body tissue $T_O < T_T$, a negative EMR flux is formed.

In Fig. 1 shows a diagram of the formation and interaction of electromagnetic fluxes between the installed bone implant 3 and the adjacent tissues of the human body – bone 1 and soft 2. If the level of intrinsic electromagnetic radiation of these tissues differs, positive (Fig. 1a) or negative (Fig. 1b) electromagnetic radiation fluxes are formed.



a *b*

Figure 1. Formation of positive
and negative electromagnetic radiation fluxes

Source: developed by the authors

Notation in the figure: P_1, P_2 – radiation power per unit surface of bone and soft tissue, respectively, P_3 – radiation power per unit surface of the implant.

The EMR powers of the bone P_1 and soft adjacent tissues P_2 are naturally physiologically consistent with each other, and the implant radiation level P_3 in the variant shown in Fig. 1a is increased, so the surrounding tissues receive constant additional radiation. In the variant shown in Fig. 1b, on the contrary, the implant absorbs the EMR of the surrounding tissues, since its radiation level is lower.

This transfer of energy in the form of microwave EMR from an object with a higher value of emissivity β_1 to an object with a lower value of β_2, subject to prolonged exposure, can both improve and worsen the course of reparative processes in the body. Such a process thereby determines the clinical effectiveness of the use of the materials under study. An increase in microwave EMR is equivalent to the onset of an inflammatory process due to excess energy at the implant site. Therefore, such studies help to select materials for implantation more efficiently.

Positive EMR fluxes increase the energy of the area they affect, while negative ones decrease it accordingly. Absorption of electromagnetic field energy by cells of a living organism in the case of a positive flow stimulates biochemical processes in cells and intercellular space. Negative fluxes, on the contrary, inhibit the course of biochemical processes at the interaction site. This is evidenced by laboratory studies conducted at the Kyiv Oncology Institute of the Ministry of Health of Ukraine on mice with irradiated sarcoma tumors [11].

This clearly demonstrates the importance of assessing both the level of intrinsic radiation of human tissues and materials in contact with tissues and their electromagnetic compatibility. An important condition for this is the availability of measuring devices that, against the background of electromagnetic pollution, allow measuring lower power radiation of a radio thermal nature.

3. Methods of measuring intrinsic electromagnetic radiation

The main problem of creating and using radiometric measuring devices capable of measuring ultra-weak EMR levels is that the measured signals have a power less than or comparable to the radiation of man-made origin and the intrinsic thermal noise of the high-frequency paths of the measuring devices. Thus, the spectral power density of the EMI of a dielectric having a temperature of 25...30 °C is in the range of $10^{-21}...10^{-19}$ at a channel bandwidth of 1 MHz. This corresponds to the power of the radiation source at the level of $10^{-13}...10^{-12}$ W. This value is much less than the background power from man-made sources received by the radiometric meter antenna and is commensurate with the intrinsic noise of the receiving antenna. Therefore, special methods of converting a useful informative signal are used to build radiometric meters. One such method is the switching-modulation conversion of the signal from the object under study.

Let's consider variants of modulation radiometric systems, which provide the ability to increase the measurement accuracy by minimizing the influence of the measuring equipment's own noise and external radiation. The functional diagram of the switching-modulation radiometric meter is shown in Fig. 2.

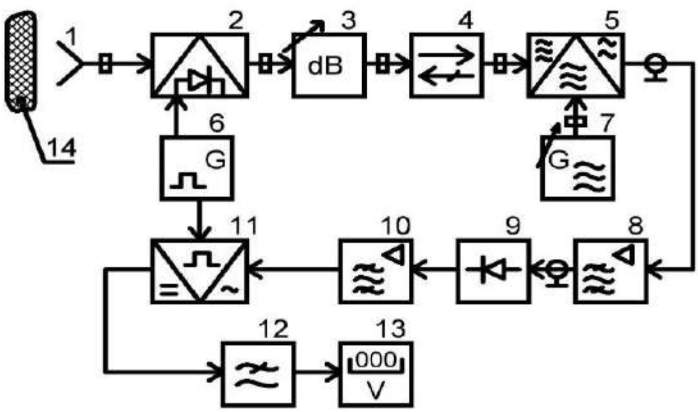


Figure 2. Functional diagram of a switching-modulation radiometer

Source: developed by the authors

The diagram shows: 1 – horn receiving antenna; 2 – microwave controlled modulator; 3 – controlled attenuator; 4 – valve; 5 – signal mixer (multiplier); 6 – clock; 7 – microwave radiation generator; 8 – band-pass high-frequency amplifier; 9 – high-frequency detector; 10 – selective amplifier; 11 – synchronous detector; 12 – low-pass filter; 13 – voltage meter; 14 – source of electromagnetic radiation.

The principle of operation of the above scheme is as follows. The material to be tested is preheated to a temperature close to the surface temperature of the human body (approximately 37°C). This generates broadband noise-like radio-thermal radiation, the level of which depends on both the temperature and the structural features of the material under investigation. The radiation from the material is received by antenna 1 and through the microwave-controlled modulator 2 is fed to the input of the controlled attenuator 3. The modulator 2 is controlled by a clock 6. The signal modulation operation consists in the fact that in one half-period of the clock (in the absence of a positive voltage) the modulator passes the signal from the antenna to the attenuator, and in the second half-period (in the presence of a positive voltage) the modulator blocks the signal passage to the attenuator. This ensures the creation of a variable component of the useful signal (as you know, it is much easier to convert signals of variable frequency than constant signals). The attenuator allows you to set the level of the modulated signal to ensure the operation of the following circuit elements. From the attenuator, the modulated signal is sent through the ferrite valve 4 to the balance mixer 5. The task of the valve is to block the passage of the signal reflected from the mixer 5, which may occur due to load unbalance. The second input of the balanced mixer receives a signal from the microwave radiation generator 7 (heterodyne). When the signals from the antenna and the heterodyne are mixed, a difference signal of an intermediate frequency is formed, which is amplified by a bandpass amplifier 8. The balanced mixing procedure is designed to transfer the signal processing from the microwave range to the high-frequency region. The amplified signal is fed to the detector 9, from the output of which it is sent to the selective amplifier 10. The selective amplifier is tuned to the frequency of the clock, which allows at its output to obtain an amplified signal whose frequency coincides with the modulation frequency of the antenna input signal. From the output of the amplifier 10, the low-frequency signal is sent to one of the inputs of the synchronous detector 11. The output of the clock generator 6 is connected to the second input of the synchronous detector. As a result of synchronous detection, a signal with a constant component is formed, the value of which is proportional to the power of microwave radiation received by the antenna. The low-pass filter 12 separates the DC component of the useful signal from the low-frequency noise and is measured by a voltmeter 14.

One of the problems with using the described radiometric system is the cooling of the test sample during the measurement process. Cooling results in a constant change in readings and the resulting measurement error. It should be noted that in this case, the greatest interest is in the EMI level of the material for the temperature corresponding to the human body temperature.

To avoid this disadvantage, it is advisable to use a thermostat with the ability to adjust the temperature within the range near the average human body temperature. Due to this, the material placed on the surface of the heating element will always have a constant temperature. Fig. 3 shows the structural implementation of the measuring system with a thermostat.

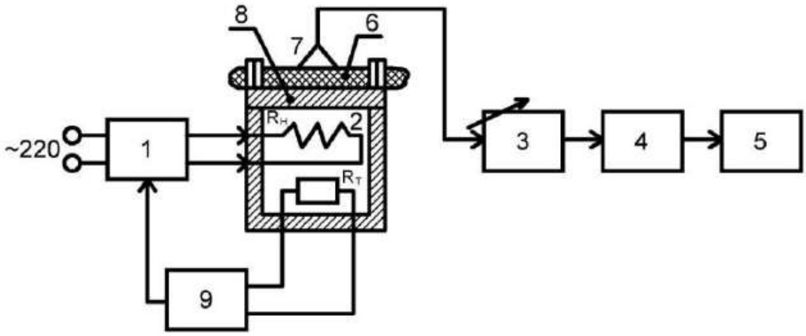


Figure 3. Radiometric system with a thermostat

Source: developed by the authors

The following notations are used in the diagram: 1 – regulated power supply; 2 – thermostat; 3 – input signal attenuator; 4 – radiometric converter; 5 – measuring device; 6 – test material; 7 – receiving antenna of the radiometer; 8 – metal plate on which the test material is placed; 9 – temperature controller; R_H – heating element; R_T – temperature sensor.

Since the thermostat maintains a constant temperature of the upper metal plate on which the test material is placed, the methodological component of the error caused by the cooling of the material is excluded. At the same time, when using a single-channel radiometer construction scheme, the radiation generated by the heated thermostat plate is added to the intrinsic EMR of the material under test. This leads to an additional error. It can be reduced by measuring the radiation of the plate without material on it and then finding the difference between the two radiation levels. However this approach does not fully compensate for the level of additional radiation. This is due to the fact that part of the heater's EMR is dissipated in the material as it passes through it. As a result, the level of radiation from the heater in the absence and presence of material is different. In addition, time-separated measurements of low EMR levels can lead to random errors due to the influence of environmental conditions.

To avoid these drawbacks, it is advisable to use a two-channel scheme for constructing a switching-modulation radiometric system shown in Fig. 4.

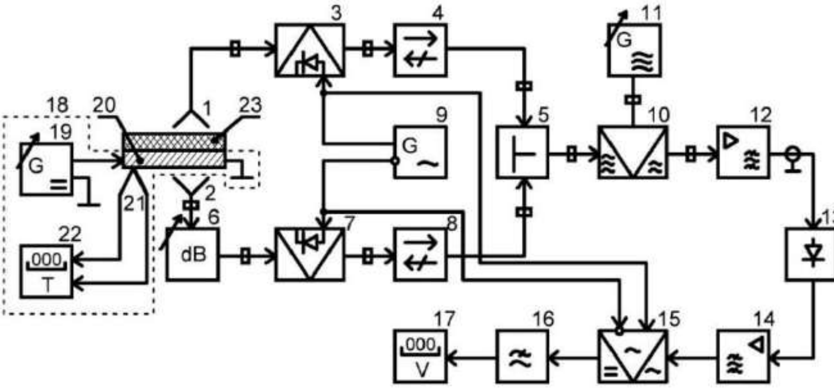


Figure 4. Two-channel diagram of the radiometric system

Source: developed by the authors

The diagram shows 1, 2 – measuring antennas; 3, 7 – microwave controlled modulators; 4, 8 – valves; 5 – waveguide tee; 6 – controlled attenuator; 9 – clock pulse generator; 10 – signal mixer (multiplier); 11 – microwave radiation generator; 12 – high-frequency bandpass amplifier; 13 – high-frequency detector; 14 – selective amplifier; 15 – synchronous detector; 16 – low-pass filter; 17 – voltmeter; 18 – heating element; 19 – heating element current setter; 20 – metal plate; 21 – temperature sensor; 22 – temperature meter; 23 – material under test.

The principle of operation of the above scheme is as follows.

Antenna 1 receives the EMR from the material under test. The radiation from the heating element also partially reaches it. Antenna 2 receives the radiation generated only by the heating element. The radiation power received by antennas 1 and 2 is described by the following expressions:

$$P_1 = S_1(P_x + P_0 - \Delta P) + P_{n1}, \tag{3}$$

$$P_2 = S_2 q P_0 + P_{n2}, \tag{4}$$

where S_1 and S_2 – are the conversion coefficients of the receiving antennas 1 and 2; P_x – is the intrinsic EMR power of the material sample under test; P_0 – is the EMR power of the heating element; ΔP – is the

EMR power loss of the heating element in the material under test; q – is the attenuation level generated by the controlled attenuator; P_{n1} and P_{n2} – are the intrinsic noise power levels of the measuring antennas.

The signals (3) and (4) received by the antennas are transmitted to the microwave-controlled modulators 3 and 7, where they are periodically interrupted. The frequency of interruption (modulation) is determined by the frequency of the clock generator 9. The modulated signals pass through gates 4 and 8, after which they are sent to the inputs of the waveguide tee 5.

Microwave switches 3 and 7 are controlled by out-of-phase voltages from the clock generator 9. Due to this, a sequence of radio pulse packets received from antennas 1 and 2 is formed at the output of the waveguide tee. The frequency of this sequence corresponds to the switching frequency of the controlled modulators (modulation frequency). From the output of the tee, the packets of radio pulses are sent to one of the inputs of the mixer 10. A microwave radiation generator 11 is connected to its second input. The mixer alternately mixes the radio pulse packets with the monochromatic oscillations of the microwave generator. At the output of the mixer, signals of differential frequency are emitted, which are amplified by a bandpass high-frequency amplifier 12 tuned to a differential (intermediate) frequency. It is known that the radio-thermal radiation received by antennas is noise-like in nature and has a wide spectrum. Accordingly, the radio pulses that arrive at the first input of the mixer are broadband. After mixing them with a monochromatic signal and amplifying them with a bandpass amplifier, narrowband noise-like pulses are generated at its output, which falls into the amplifier’s bandwidth. They are sent to the high-frequency detector 13, where they are detected and averaged. As a result, the output of detector 13 generates video pulses with two amplitudes corresponding to the radiation level received by antennas 1 and 2:

$$U_1 = S_3 K_1 S_4 (P_1 + P_3), \tag{5}$$

$$U_2 = S_3 K_1 S_4 (P_2 + P_3), \tag{6}$$

where S_3 – is the steepness of the heterodyne conversion of the radio pulse frequency; K_1 – is the gain of the bandpass amplifier 12; S_4 – is the conversion steepness of the high-frequency detector; P_3 – is the power of the heterodyne conversion’s own noise.

Since the amplitudes of signals U_1 and U_2 are different, the sequence of video pulses (5) and (6) contains a variable voltage component whose frequency corresponds to the modulation frequency:

$$U_3 = \frac{U_1 - U_2}{2} = \frac{1}{2} S_3 K_1 S_4 (P_1 - P_2). \quad (7)$$

The alternating voltage U_3 is sent to the selective amplifier 9, tuned to the frequency of the clock 9 (modulation frequency). After amplification by the synchronous detector 15, the DC component of the voltage is isolated, which is smoothed by the low-pass filter 16. The output of the filter is a constant voltage:

$$U_4 = \frac{1}{2} S_3 K_1 S_4 K_2 S_5 K_3 (P_1 - P_2), \quad (8)$$

where K_2 – is the gain of the amplifier 14; S_5 – is the conversion slope of the synchronous detector; K_3 – is the transmission coefficient of the low-pass filter 16.

Taking into account the expressions describing the radiation power perceived by the antennas, we obtain:

$$U_5 = \frac{1}{2} S_3 K_1 S_4 K_2 S_5 K_3 [S_1 (P_x + P_0 + \Delta P) - S_2 q P_0 + P_{n1} - P_{n2}]. \quad (9)$$

The antennas used in radiometric systems usually have the same design and, accordingly, the same parameters. Therefore, the following relations are valid:

$$S_1 = S_2; P_{n1} = P_{n2} \quad (10)$$

Taking this into account, the voltage supplied to the voltmeter can be estimated:

$$U_6 = \frac{1}{2} S_1 S_3 K_1 S_4 K_2 S_5 K_3 (P_x + P_0 - \Delta P - q P_0). \quad (11)$$

During the measurement, the attenuator 6 sets the attenuation of the signal coming from the antenna 2. The attenuation value is chosen proportional to the thickness of the material under study. This fulfills the conditions:

$$P_0 - \Delta P = q P_0. \quad (12)$$

If the above condition (12) is fulfilled, the value of the voltage measured by the voltmeter 17 is determined by the equation:

$$U_7 = \frac{1}{2} S_1 S_3 K_1 S_4 K_2 S_5 K_3 P_x = S_0 P_x, \quad (13)$$

where $S_0 = \frac{1}{2} S_1 S_3 K_1 S_4 K_2 S_5 K_3$ – is the resulting conversion factor of the radiation power of the material under study into a constant voltage.

The analysis of the conversion equation (13) shows that the value of the output voltage of the two-channel radiometric system is proportional to the power of the intrinsic radiative heat radiation P_x of the material under study. It should be noted that the measurement result is not affected by the power of the EMR P_0 generated by the heater plate 20. The equation also shows that the proposed signal conversion algorithm eliminates the influence of the intrinsic noise of antennas 1 and 2, as well as the intrinsic noise of the heterodyne conversion. In addition, the use of a selective amplifier 14, a synchronous detector 15, and a low-pass filter 16 eliminate the low-frequency noise of quadratic detection.

Thus, the use of the proposed two-channel radiometric system with switching-modulation signal conversion provides the ability to measure ultra-weak levels of the intrinsic EMR of the materials under study and eliminates the influence of the intrinsic noise of the elements of the high-frequency signal conversion path on the measurement result.

4. Results of experimental studies

4.1. Investigation of electromagnetic radiation of materials for dental filling

Materials from various companies are used in dentistry for root canal filling and tooth surface formation. As a rule, specialists pay attention to the strength of the final material and its aesthetic properties. At the same time, as noted above, if there is a difference in the EMR levels of the filling material and bone tissue, positive or negative EMR fluxes may occur.

Therefore, it is advisable to use such materials whose electromagnetic properties coincided or were close to the bone tissue of the tooth.

Samples of 10 materials were used for the study [12]. They are conventionally numbered from 1 to 10. The labeling of the materials used for the experiments and their manufacturers are listed below.

1 – Foredent (SPOFA, Slovenia);
2 – Endion (VOCO, Germany);
3 – Endomethazone (Septodont, France);
4 – AN Plus (Dentsply, USA);
5 – Spectrum (Dentsply, USA);
6 – Compolux (Septodont, France);
7 – Cavitan plus (SPOFA, Slovenia);
8 – tooth enamel;
9 – dentin;
10 – porous bone material.

From the above list, materials 1 to 4 are intended for filling root canals, and materials 5 to 7 are intended for restoration of the tooth surface. Samples 8 to 10 represent natural tooth material. Therefore, to evaluate the compatibility, samples 1 through 4 were compared with sample 9, and samples 5 through 7 with tooth enamel sample 8.

The experimental samples were studied using a two-channel radiometric system at a frequency of 52 GHz. The results of measuring the intrinsic electromagnetic radiation power of the studied dental materials are concentrated in the range (1,8...3,1)10^{-13} W/cm^2.

The compatibility of the filling materials and natural tissues was determined by comparing the coefficients of their emissivity $\boldsymbol{\beta_M}$, which was calculated by the formula

$$\beta_M = \frac{P_M}{P_{\mathrm{ABB}}}, \tag{14}$$

where P_M – is the radiation power of the material, recorded by the radiometric system; P_{ABB} – is the radiation power of an absolutely black body. This value is calculated by the formula:

$$P_{\mathrm{ABB}} = R(f)kT, \tag{15}$$

where $R(f)$ – is the frequency coefficient of radiation; T – is the temperature of the test sample.

The calculated values of the emissivity coefficients of materials are given in Table 1.

Table 1

EMISSIVITY OF SOME DENTAL MATERIALS

No. of sample	1	2	3	4	5	6	7	8	9	10
Emissivity coefficient β	0,71	0,6	0,46	0,41	0,46	0,51	0,48	0,46	0,67	0.58

Source: developed by the authors

A comparison of the emissivity coefficients of the filling materials and tooth tissues revealed the largest deviation in samples 4 and 9, which is about 38 %. For materials numbered 6 and 8, the difference is 10.8 %, 1 and 9 – 7.8 %. For materials numbered 5 and 8, the emissivity coefficient is the same.

These results allow a reasonable approach to the choice of materials for filling in each case, based on a quantitative assessment. When using materials, materials with similar emissivity deserve preference, since in this case, positive and negative fluxes of electromagnetic radiation are minimal. Such a test methodology deserves to be used in the development of new dental materials.

4.2. Investigation of electromagnetic radiation of medical materials implanted in the human body

Modern surgical practice widely uses implants to replace individual elements of the bone, vascular, visual system, and even entire artificial organs. In this case, materials of both natural and artificial origin are used. These can be metals, synthetic polymers, bio ceramics, and various powdered preparations for filling bone defects and soft tissue regeneration of individual injuries. Tissue extracts of animal origin, hybrid, and combined materials are widely used, for example, a metal base is covered with a material with dielectric properties that are close to human tissue in terms of characteristics [13]. Recently, studies have been conducted using promising nanomaterials [14].

The use of materials for implantation involves extensive research and testing for compatibility with human tissue. The main indicators that are paid attention to include biological tolerance, resistance to biocorrosion, chemical stability, and antimicrobial resistance. This fully applies to all types of implant materials, the classification of which is shown in Fig. 5.

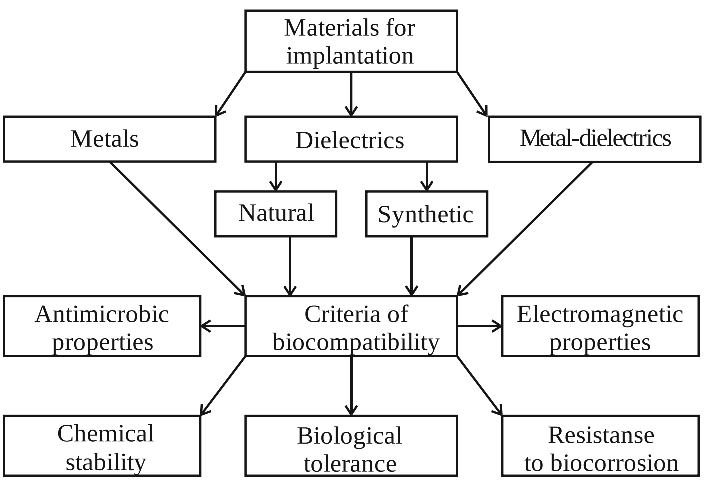


Figure 5. Classification of materials for implantation and requirements for them

Source: developed by the authors

When implants made of foreign materials are inserted into the body, an interaction occurs between them and the body tissue, in particular through electromagnetic radiation. The electromagnetic properties of materials for implantation have not been studied to date, although they can significantly affect the processes of their interaction with living organisms. The study of dielectric and composite materials has revealed another important criterion that should be considered: the electromagnetic compatibility of materials for implantation with human body tissues.

Paper [13] investigated the EMC of materials for implantation used to replace bone defects, in dental implantation, etc. In the course of the study, the EMR level of materials with a temperature close to the human temperature was determined. The results were compared with the level of intrinsic radiation of human tissues.

In metal implants, due to the presence of a skin layer, intrinsic microwave radiation is practically absent. At the same time, dielectric materials generate their own EMR when heated to human body temperature. As mentioned above, the electromagnetic energy fluxes generated by implants in relation to human body tissues can be neutral, positive, or negative. This is especially important for human cells that are able to respond to low-intensity EMF. The radiation (electromagnetic) characteristics of implants may differ significantly from those of living tissues. When the fluxes of the implant and the body tissue are equal, full electromagnetic compatibility occurs. Significant deviation from it, in one direction or another for a long time, can cause a violation of the electromagnetic state of nearby cells and the appearance of complications in the tissues near the implanted material.

Samples of 10 implant materials were used for the study. They are conventionally numbered from 2 to 11. The labeling of the materials used for the experiments is indicated below:

1 – H – the average value of a person’s own electromagnetic radiation (H – human);

2 – Osteoplast K;

3 – Bone powder. Bone powder (ground tubular bone of animal origin);

4 – Osteoplast T;

5 – Polihemostat (powder);

6 – Calcium salt of orthophosphoric acid $Ca_3(PO_4)_2$;

7 – Calcium salt with the addition of silver ions $Ca_3(PO_4)_2$+Ag;

8 – Bioactive glass (500 microns)

9 – Bioactive glass (1000 microns);

10 – Biomin GT-700;

11 – Biomin GT-500.

Before each experiment, the respondents' own EMR was measured under the same conditions.

According to the determined levels of electromagnetic radiation of materials, the relative emissivity coefficient K was calculated by the formula:

$$K = \frac{P_M}{P_H}, \tag{16}$$

where P_M – is the radiation power of the material under study; P_H – is the average human EMF power level. The research results are presented in Table 2.

Table 2

EMISSIVITY OF SOME MATERIALS FOR IMPLANTATION

Sample No	1	2	3	4	5	6	7	8,9	10	11
Emissivity, *K*	1,0	0,98	0,95	0,92	0,90	0,14	0,13	0,13	<0,01	<0,01

Source: developed by the authors

In the process of researching these materials for implantation, a number of features related to the human body and the properties of some materials were identified. A number of materials have approximately the same emissivity (difference within 10 %) as the human body. This probably results in a very small transfer of energy in the form of microwave radiation from a body with a higher level (healthy tissues) to a body with a lower level. Thus, materials that have a relative emissivity coefficient slightly lower than the level of human emissivity (Osteoplast K, Osteoplast M, Osteoplast T, Polyhemostat) are likely to be more compatible with human tissues in terms of electromagnetic compatibility. Implants based on such materials create virtually coincident positive EMR fluxes from implants to body tissues, and their use can lead to increased treatment efficiency.

On the contrary, known materials (calcium salt of orthophosphoric acid with the addition of silver in various amounts, Biomin GT-500, Biomin GT-700, bioactive glass) have a low relative emissivity coefficient (difference from the human body by one or two orders of magnitude), which can cause the formation of a negative microwave flux.

In turn, the presence of a negative microwave flux from living tissues to the implanted material can cause chronic inflammation and pain.

Thus, in order to improve the prediction of engraftment and long-term successful use of implants, as well as to increase the effectiveness of treatment, it is necessary to take into account the level of electromagnetic radiation of the materials used and their electromagnetic compatibility with human tissue.

4.3. Investigation of electromagnetic radiation of clothing materials

Clothing materials, like the implantable materials discussed above, are in contact with human skin for a long time. Depending on the purpose, style and other features, such materials can be fabrics, leather, film materials, etc. Since these materials are dielectrics and heat up when in contact with the surface of the human body, they also generate their own electromagnetic radiation. Therefore, in addition to the generally accepted methods [1] for assessing the properties of clothing materials, it is important to assess the electromagnetic compatibility of clothing materials with the surface tissues of the human body.

It is advisable to assess the level of EMR of clothing materials having a temperature close to the average human temperature by the level of spectral power density of radio-thermal radiation in the millimeter wavelength range. The middle of the millimeter range corresponds to the oscillation frequency of 52 GHz. The two-channel switching-modulation radiometric system discussed above was used for the measurements.

The spectral power density is determined by the formula:

$$G_M(f,T) = \frac{P_M}{\Delta f}, \tag{17}$$

where Δf – is the frequency band in which the measurements are made.

For the radiometric system described above, the frequency range is determined by the bandwidth of the intermediate frequency amplifier and is 100 MHz.

In the course of experimental studies, 14 types of textile materials made of natural, chemical, and mixed fibers were used. Designation of research objects:

1 – H is the average value of the human electromagnetic radiation level (H – human);

2 – cloth made of wool fibers (100 %);

3 – cloth made of flax fibers (100 %);

4 – cloth made of wool and silk fibers (70 % + 30 %);

5 – cloth made of wool and silk fibers (45 % + 55 %);

6 – cloth made of cotton fibers (100 %);
7 – cloth made of silk fibers (100 %);
8 – cloth made of viscose fibers (100 %);
9 – cloth made of cotton and polyester fibers (65 % + 35 %);
10 – cloth made of cotton and polyester fibers (60 % + 40 %);
11 – cloth made of cotton and polyester fibers (55 % + 45 %);
12 – cloth made of cotton and polyester fibers (47 % + 53 %);
13 – cloth made of viscose and polyester fibers (55 % + 45 %);
14 – cloth made of polyester fibers (100 %);
15 – cloth made of polyamide fibers (100 %).

The results of measuring the power spectral density of the tested materials are shown in Table 3.

Table 3

SPECTRAL POWER DENSITY OF TEXTILE MATERIALS

Sample No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Power spectral density, G_M	5,2	4,3	4,1	4,0	3,9	3,8	3,6	2,8	2,4	2,2	2,1	1,9	1,7	1,5	1,3

Source: developed by the authors

The analysis of the data in Table 3 shows that materials made from natural fibers, such as wool, linen, cotton, and silk, generate an EMR level close to the radiation level of the surface tissues of the human body. Therefore, in terms of electromagnetic compatibility, these materials are compatible with human tissue. It should also be noted that these materials do not interfere with the electromagnetic interaction of human surface tissues with the environment. This is due to the electromagnetic coherence of the materials with human tissue. From a physical point of view, this is explained by the fact that the emission coefficients, and, accordingly, reflection and absorption, are close in value to the corresponding coefficients of the surface tissues of the human body.

The data in Table 3 also show that an increase in the percentage of chemical fibers in the composition of the materials under study causes a significant decrease in the level of intrinsic EMR. This leads to a deterioration in the electromagnetic interaction of the human body with the environment and the occurrence of negative reactions of the body in case of prolonged contact with such materials.

The presented results of studies of the radiating ability of clothing materials made of natural and artificial fibers generally confirm the subjective assessment of people using products made of materials of different origins accumulated over the years. The advantage of the proposed method is the availability of a numerical estimate of the compatibility index, which makes it possible to obtain an objective assessment of the material. This does not take into account the influence of factors that change the psychological state of a person and affect the results of subjective assessment.

4.4. Study of the emissivity of minerals and semiprecious stones

Minerals are used in such a highly specialized heat treatment technology as lithotherapy. In addition, minerals and semi-precious stones are often used as jewelry that is placed on the surface of the body. Heating of minerals, like other dielectric materials, leads to the formation of low-intensity microwave electromagnetic radiation. Paper [7] presents the results of a study of the emissivity of a number of minerals. The electromagnetic radiation level was measured at a frequency of 60 GHz at a temperature of objects close to the average human body temperature. Fig. 6 shows the distribution of radiation intensity of the studied materials in comparison with the radiation level of humans and water.

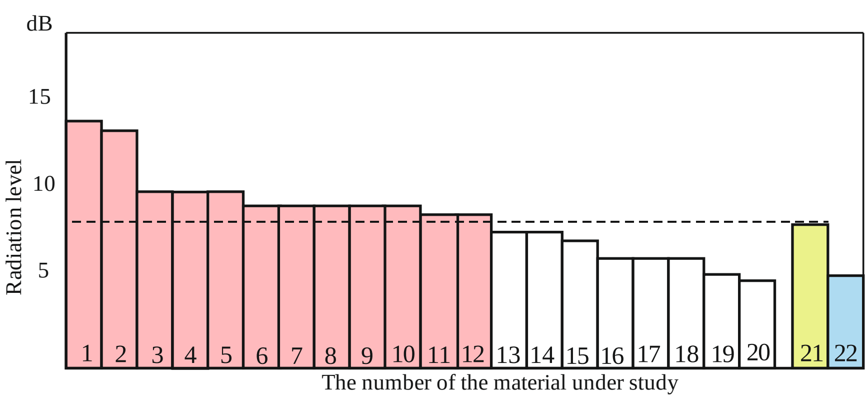


Figure 6. Intrinsic radiation level of minerals, human surface tissues and water

Source: developed by the authors

The studied materials have the following digital indexing: 1 – jade; 2 – onyx; 3 – agate; 4 – shell rock; 5 – large fragment of bone tissue; 6 – amethyst; 7 – amber; 8 – red jasper; 9 – pyrite; 10 – small fragments of bone tissue; 11 – quartz (single crystal); 12 – chalk; 13 – sulfur; 14 – fluorite; 15 – flint; 16 – amazonite; 17 – rock crystal; 18 – calcite (feldspar); 19 – topaz; 20 – morion (quartz). Number 21 indicates the level of intrinsic radiation of the human palm, 22 – the level of electromagnetic radiation of water at a temperature close to the temperature of the human body.

The results of measurements of the intrinsic EMR level presented in Fig. 6 show that the studied materials can be divided into two groups. The radiation level of the first group (above the dotted line) is higher than the radiation level of the human palm. These minerals include jade, onyx, agate, amethyst, amber, and jasper. When in contact with the human body and at a temperature equilibrium, they are able to generate microwave radiation that is excessive for the surface tissues of the human body. This creates a positive flow of EMR. Thus, these minerals provide energy support to the body during lithotherapy sessions or when worn by a person. The second group of materials under study has an EMR level lower than the radiation level of the human palm (below the dotted line). The materials in this group include sulfur, fluorite, silicon, amazonite, rock crystal, calcite, topaz, and morion. At the same temperature as the human body, they form a negative flux of electromagnetic radiation. Water has the same property. There is a hypothesis that such materials should be used in the treatment of inflammatory processes, but it requires additional research.

4.5. Investigation of electromagnetic radiation of physiotherapeutic materials

In physiotherapy, heat treatment is one of the most common procedures that use a variety of dielectric materials, including minerals, peat, sand, therapeutic mud, and some oil field materials such as naphthalene, ozocerite, and paraffin. Among the group of materials for physiotherapy, ozocerite, and paraffin should be singled out, which, alone or in a mixture, are most often used in physiotherapy procedures. The high heat capacity, heat retention capacity, and lowest thermal conductivity of ozokerite determine the high efficiency of its use in physiotherapy procedures. The factors that influence the treatment area are considered to be thermal, mechanical, and chemical [13]. The therapeutic effects that arise in this case, first of all, include anti-inflammatory and vasodilating effects, as well as acetylcholine-like, estrogen-like, and chemical effects of ozokerite.

Heat therapy technologies involve preheating the material (applicator), applying it to the patient's skin surface, and keeping it cool for a period of time to the patient's body temperature. Usually, the temperature of the applicator does not exceed 50°C. At the same time, as follows from expressions (1,2), an increase in the temperature of the material leads to the appearance of low-intensity microwave electromagnetic radiation, which, along with other factors, has an effect on the human body and needs to be studied.

Work [13] investigated the electromagnetic radiation of an ozokerite applicator, the process of its formation, and changes in the microwave field during a physiotherapy procedure.

From the point of view of physics, the process of heat treatment should be considered as a violation of thermodynamic equilibrium in a system that includes a section of each human surface and the applied applicator. The exchange of energy in any system whose parts have different temperatures is known to be carried out through the processes of heat conduction, convection, and radiation. In our case, convection can be ignored, and the energy exchange between the applicator surfaces and the patient's skin is mainly due to the phenomena of thermal conductivity and electromagnetic radiation.

In Fig. 7 shows two arbitrary objects, or the applicator and the patient's body, which are in thermal contact. In the state when thermodynamic equilibrium is disturbed ( ), and the power of the heat fluxes , are not balanced, the direction of energy transfer depends on the temperature ratio. For example, in the case when the patient's temperature is higher than the applicator's temperature (the applicator is cooling), the heat flux will be directed away from the patient's skin, and it can be considered negative in relation to the person (Fig. 3b)

$$\varDelta P = P_A - P_H < 0. \tag{18}$$

If, on the contrary, the applicator is heating, as in the case of heat therapy, the flux will be directed towards the patient and can be considered positive (Fig. 3c).

$$\varDelta P = P_A - P_H > 0. \tag{19}$$

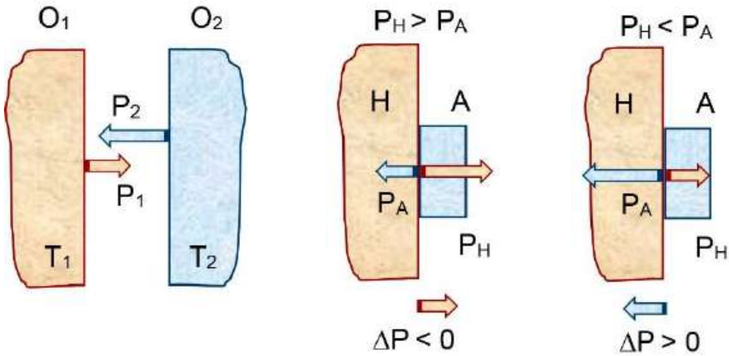


Figure 7. Distribution of energy fluxes between an arbitrary tangential object, option (a) and the applicator and the patient's body:
(b) with negative electromagnetic radiation flux;
(c) with positive electromagnetic radiation flux

Source: developed by the authors

The figure shows: P – patient's body; A – applicator; P_H – patient's electromagnetic radiation flux; P_A – applicator's electromagnetic radiation flux

Measurements of electromagnetic radiation power were performed at a frequency of 52 GHz with an analysis bandwidth of 100 MHz. For comparison, the average value of the intrinsic radiation power density of the human palm of the three respondents was determined, which was $2{,}25 \cdot 10^{-14}$ W/cm^2.

The absolute values of the electromagnetic radiation level were determined using a certified reference noise generator, which is part of the radiometric system. According to the results of measurements at the maximum therapeutic temperature of 50°C (Fig. 8), it is clear that the radiation level of pure ozokerite is slightly higher than that of the human palm. At the same time, the radiation level of pure paraffin at the same temperature does not exceed 20 % relative to the radiation level of human skin. This can cause the formation of a negative flux of electromagnetic radiation, the intensity of which increases with an increase in the percentage of paraffin in the mixture with ozokerite.

From the graph of the temperature dependence of the intrinsic radiation power of pure ozokerite during its cooling, shown in Fig. 8, it can be seen that a change in temperature can lead to a change in the redistribution of electromagnetic energy between the applicator and the skin. Thus, in the temperature range from 50 to 46°C, a positive flux ($\Delta P > 0$) is formed on the graph, and in the temperature range from 45°C to 36°C, a negative flux of microwave radiation is formed, at which ($\Delta P < 0$).

Experimental studies have shown that ozokerite, paraffin and their mixtures generate low-intensity electromagnetic radiation in the millimeter range. This factor, in combination with thermal effects, enhances the therapeutic effect.

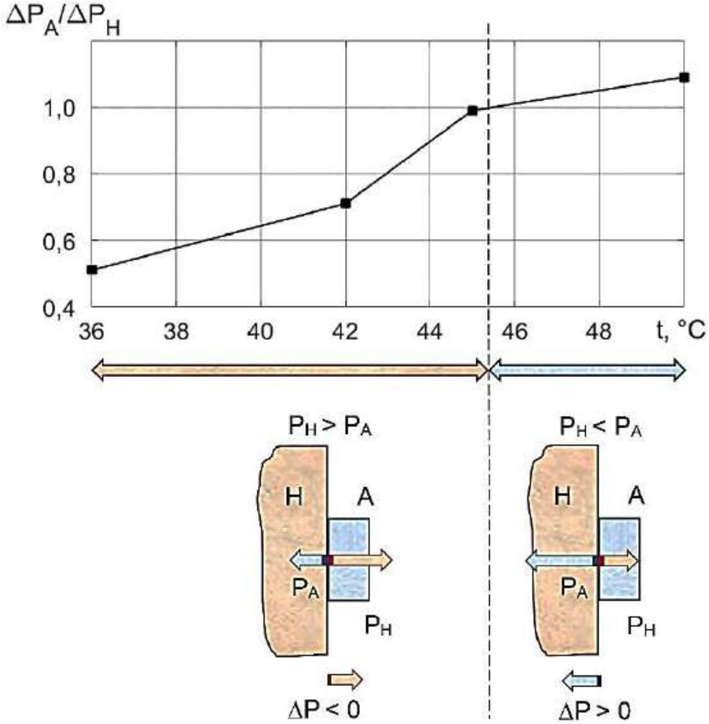


Figure 8. Dependence of relative power on temperature and distribution of electromagnetic energy flux for an ozokerite applicator during cooling

Source: developed by the authors

Conclusions

The results of theoretical and experimental research presented in the work allow us to state that when in contact with the tissues of the human body, the materials generate electromagnetic radiation, in particular, in the microwave range. This radiation is radio thermal in nature. Its level depends on the temperature of the material and its internal structure. At the same time, there is an interaction of the electromagnetic radiation of the tissues of the human body with the radiation of the material in contact with the tissue. Since the levels of radiation are different, their long-term interaction can cause both positive and negative effects on the human body. Taking this into account, when developing materials in contact with human tissues, it is necessary to study their electromagnetic properties. When using contact materials, it is also necessary to take into account their electromagnetic compatibility with the human body.

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SECTION 4
USING OF MODERN ARTIFICIAL INTELLIGENCE MODELS IN INFORMATION CONTROL SYSTEMS

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4.1. Basic concepts of Artificial Intelligence

Artificial Intelligence (AI) has become one of the most important and discussed fields in modern science and technology. The concept of AI arouses admiration and indignation, creates hopes and fears, because it involves the creation of systems capable of self-education, self-learning and self-improvement.

AI is a branch of computer science that seeks to create intelligent agents that can reason, learn, and act autonomously. These agents can be software systems, robots, or other types of machines that possess a certain level of intelligence.

There are many different concepts that underlie AI. Some of the most important of these include [1–4]:

– *Machine Learning* (ML) – explores methods by which computer systems can learn from data without explicit programming;

– *Deep Learning* (DL) is a subfield of ML that uses ANNs with many layers to automatically perform learning tasks;

– *Artificial Neural Networks* (ANNs) – this type of models imitates the work of the human brain and is used in many applications of AI, in particular in Machine Learning;

– *Natural Language Processing* (NLP) – studies the interaction between computers and humans through natural language, it includes language recognition, language understanding, language generation and other aspects;

– *Computer Vision* (CV) – explores methods by which computers can interpret visual information;

– *Expert Systems* – software systems that use a knowledge base, rules and information to solve problems in a specific fields, providing recommendations or solutions based on input data;

– *Autonomous Systems* – systems that can act independently of external influence, making their own decisions and interacting with the environment;

– *Distributed Systems* – systems that combine various AI components to work together and achieve common goals;

– *Search* – focuses on the development of algorithms that can find optimal solutions for the different complex tasks.

Let's look at the main differences between the main components of AI as a scientific and applied field (Fig. 4.1).

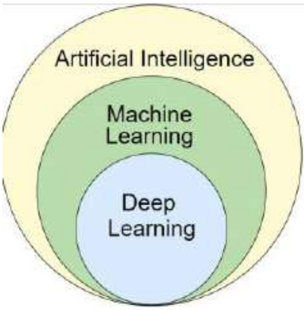

Figure 4.1. Relations between AI, ML and DL

Source: designed by the authors based on [1–4]

Artificial Intelligence: AI is a broad field that aims to create intelligent machines or systems that can perform tasks that typically require human intelligence, such as perception, reasoning, learning, problem-solving, and decision-making. AI encompasses various techniques and approaches, including machine learning, deep learning, expert systems, natural language processing, and robotics.

The main concept behind AI is to develop algorithms and computational models that can mimic human-like intelligence and behaviour. AI systems can be rule-based, where they follow a set of predefined rules and logic, or they can be based on machine learning and deep learning techniques, where they can learn from data and adapt their behaviours accordingly.

ML is a subset of AI that focuses on developing algorithms and statistical models that enable systems to learn from data and make predictions or decisions without being explicitly programmed. The main concept behind ML is to identify patterns and relationships within data and use these insights to make accurate predictions or decisions on new, unseen data.

ML algorithms can be broadly categorized into Supervised Learning (where the data is labelled, and the algorithm learns to map inputs to outputs), Unsupervised Learning (where the data is unlabelled, and the algorithm tries to find inherent patterns and structures), and Reinforcement Learning (where an agent learns to make decisions by interacting with an environment and receiving rewards or penalties).

DL is a subset of ML that is inspired by the structure and function of the human brain. It involves the use ANNs with multiple layers, allowing the model to learn and represent complex patterns and features from data automatically.

The main concept behind DL is to create hierarchical representations of data by stacking multiple layers of non-linear transformations. Each layer in a deep neural network learns to extract increasingly abstract and complex features from the input data. These learned features are then used to make predictions or decisions.

DL algorithms, such as Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), Autoencoders and Transformers have been particularly successful in areas like CV, NLP, speech recognition, and time series forecasting, where they can effectively capture and model complex patterns and relationships within the data.

Distinguishing between AI, ML, and DL:

– AI is the broadest field, encompassing various techniques and approaches for creating intelligent systems, including ML and DL.

– ML is a subset of AI that focuses on developing algorithms and models that can learn from data and make predictions or decisions without being explicitly programmed.

– DL is a subset of ML that uses deep neural networks with multiple layers to automatically learn hierarchical representations and complex patterns from data.

So, AI is the overarching field, ML is a specific approach within AI that enables systems to learn from data, and DL is a powerful technique within ML that uses deep neural networks to automatically learn hierarchical representations and patterns from data.

The main tasks of ML can be defined as follows [1-5]:

– *Classification*: Classification is a supervised learning task where the goal is to assign a class label or category to a given input instance based on its features. Examples include image classification (recognizing objects in images), spam detection (classifying emails as spam or not spam), and sentiment analysis (classifying text as positive, negative, or neutral).

– *Clustering* (Clusterization): Clustering is an unsupervised learning task that aims to group similar instances or data points together based on their features or characteristics. The goal is to identify inherent patterns or structures within the data without any predefined labels. Examples include customer segmentation (grouping customers based on their behaviours or preferences) and image segmentation (identifying distinct regions or objects in an image).

– *Regression*: Regression is a supervised learning task that involves predicting a continuous numerical value based on input features. It is commonly used for tasks like stock price prediction, sales forecasting, and estimating real estate prices based on various factors.

– *Anomaly Detection*: Anomaly detection, also known as outlier detection, is the task of identifying rare or unusual instances or patterns within a dataset that deviate significantly from the norm. It has applications in fraud detection, intrusion detection systems, and predictive maintenance, where identifying anomalies can help prevent failures or detect malicious activities.

– *Dimensionality Reduction:* Dimensionality reduction is the process of reducing the number of features or variables in a dataset while retaining most of the relevant information. It is useful for visualizing high-dimensional data, reducing computational complexity, and improving the performance of machine learning models by removing redundant or irrelevant features.

– *Reinforcement Learning*: Reinforcement learning is a type of machine learning where an agent learns to make decisions by interacting with an environment and receiving rewards or penalties for its actions. It is used in applications like game playing (e.g., chess, Go), robotics, and autonomous systems (e.g., self-driving cars).

– *Time Series Forecasting*: Time series forecasting is the task of predicting future values of a sequence of data points based on historical observations. It is used in various domains, such as finance (stock market prediction), weather forecasting, sales forecasting, and energy demand prediction.

To solve these problems, a large number of effective models and algorithms have been developed within the ML paradigm:

Linear Regression: Linear regression is a supervised learning algorithm used for regression tasks. It models the relationship between a dependent variable and one or more independent variables using a linear equation. It is commonly used for predicting continuous values, such as house prices or stock prices.

Logistic Regression: Logistic regression is a supervised learning algorithm used for classification tasks. It models the probability of an instance belonging to a binary class (0 or 1) based on its features. It is widely used in areas like spam detection, credit scoring, and medical diagnosis.

Decision Trees: Decision trees are a type of supervised learning algorithm that can be used for both classification and regression tasks. They work by recursively splitting the data based on the feature values, creating a tree-like structure of decisions. Decision trees are easy to interpret and can handle both numerical and categorical data.

Random Forests: Random Forests are an ensemble learning method that combines multiple decision trees. Each tree is trained on a random subset of the data and features, introducing randomness and reducing overfitting. Random Forests are highly accurate and can handle high-dimensional data and complex relationships.

Support Vector Machines (SVMs): SVMs are supervised learning algorithms used for both classification and regression tasks. They work by finding the optimal hyperplane that maximizes the margin between classes or data points. SVMs are effective for high-dimensional data and can handle non-linear problems using kernel tricks.

Naive Bayes: Naive Bayes is a family of probabilistic classifiers based on Bayes' theorem. It assumes independence between features and calculates the probability of an instance belonging to each class given its feature values. Naive Bayes classifiers are simple and computationally efficient, making them suitable for large datasets and real-time applications.

K-Nearest Neighbors (KNN): KNN is a non-parametric algorithm used for both classification and regression tasks. It works by finding the k nearest neighbors of a new instance in the feature space and predicting the class or value based on the majority vote or average of the neighbors.

K-Means Clustering: K-Means is a popular unsupervised learning algorithm used for clustering tasks. It partitions the data into k clusters by iteratively minimizing the sum of squared distances between data points and their assigned cluster centroids.

Principal Component Analysis (PCA): PCA is a dimensionality reduction technique used for feature extraction and data visualization. It transforms the high-dimensional data into a lower-dimensional space while preserving the maximum variance in the data.

ANNs: ANNs are a class of algorithms inspired by the structure and function of the human brain. They consist of interconnected nodes (neurons) that can learn complex patterns and relationships from data. ANNs are widely used for tasks like image recognition, natural language processing, and time series forecasting.

Stages of an AI models design and development

The development of an AI model is a complex process that involves multiple stages and requires careful consideration of various factors (Table 4.1).

Table 4.1

STAGES OF AN AI MODELS DEVELOPMENT

Stage	Description
Task Definition	• Formulate the problem the AI model should solve • Define success/performance metrics and expected results • Collect data for training and testing models
Algorithm Selection	• Select an AI algorithm based on the task type and available data • Algorithms can include ANNs, Decision Trees, SVMs, Genetic Algorithms, etc.
Data Preparation	• Clean and format data for the AI model to understand • Divide data into training, validation, and test datasets
Model Training	• Train the AI model on the training dataset Optimize model parameters to minimize error on the validation dataset
Model Testing	• Test the AI model on the test dataset to evaluate generalization ability identify strengths and weaknesses of the model
Model Improvement	• Improve the AI model based on test results Modify model parameters, algorithm, or data as needed
Model Deployment	• Deploy the improved AI model in a real environment • Use the model for decision-making, prediction, or task automation
Monitoring and Maintenance	• Continuously monitor the AI model's effectiveness • Update or retrain the model as new data or conditions emerge

Source: designed by the authors

The process of developing an AI model begins with a clear understanding of the problem or task at hand. This involves defining the objectives, success criteria, and performance metrics that the model should achieve. Additionally, it is crucial to determine the type and quality of data required for training and evaluating the model.

Once the task is well-defined, the next step is to select the appropriate AI algorithm or model architecture. This choice depends on the nature of the problem, the available data, and the desired performance characteristics. There are numerous algorithms and architectures to choose from, such as deep neural networks, decision trees, support vector machines, and ensemble methods, each with its own strengths and weaknesses.

Data preparation is a critical stage in the AI model development process. It involves collecting, cleaning, and formatting the data to ensure that it is suitable for training the chosen model. This may involve handling missing values, removing outliers, and transforming the data into a format that the model can understand. Additionally, the data is typically divided into training, validation, and testing sets to evaluate the model's performance and generalization ability.

The model training stage is where the AI algorithm learns from the prepared training data. This process involves iteratively adjusting the model's parameters to minimize the error or loss function between the model's predictions and the true labels or values in the training data. Techniques like regularization, early stopping, and learning rate scheduling are often employed to prevent overfitting and improve the model's generalization performance.

Once the training process is complete, the model is evaluated on the *validation and testing* datasets to assess its performance and generalization ability. This evaluation may reveal areas for improvement, such as the need for additional data, adjustments to the model architecture, or the selection of a different algorithm altogether.

The development process is iterative, and the model may go through multiple cycles of refinement and improvement before it is ready for deployment. This may involve exploring different model architectures, tuning hyperparameters, or incorporating additional data sources.

Finally, once the model meets the desired performance criteria, it can be *deployed* in a production environment for real-world use. However, even after deployment, the model may require on-going monitoring and maintenance to ensure that it continues to perform well as new data becomes available or as the underlying conditions change over time.

Overall, the development of an AI model is a complex and iterative process that requires careful planning, domain expertise, and a deep understanding of the underlying algorithms and techniques.

It is important to note that AI model development is an iterative process. At each stage, problems may arise that need to be solved. With careful planning, the right choice of algorithms and careful testing, you can create AI models that will help solve complex problems.

The 20th century witnessed the rapid development of AI. Starting with theoretical considerations about the possibility of creating artificial people, AI has turned into a powerful scientific discipline with many practical applications.

It should be noted that the development of AI has not been linear. There have been periods of rapid progress and periods of stagnation. However, the general trend is that AI is becoming more powerful and sophisticated, and has many potential applications to improve our lives.

Despite significant progress, AI still faces a number of challenges:

– Ethical issues – AI can have negative consequences for society, such as job losses, bias and abuse;

– Black box problem – some AI algorithms are unclear, making it difficult to understand their solutions;

– Security issues – AI can be used to create autonomous weapons or other dangerous systems.

4.2. The role of time series forecasting in the development and use of AI models for ICS

AI has a wide range of applications in many industries, such as:

– Medicine – for diagnosis of diseases, development of new drugs and personalization of treatment;

– Production – for optimization of production processes, demand forecasting and supply chain management;

– Transport – for the development of self-driving cars, optimization of routes and management of transport networks;

– Finance – to detect fraud, predict market trends and automate trade.

It should be noted that time series forecasting is an important task in various fields and industries due to its ability to predict future values or patterns based on historical data. Accurate forecasting can provide valuable insights and support decision-making processes, leading to improved planning, resource allocation, and risk management. Here are some key points highlighting the importance of time series forecasting and its applied fields:

1. Business and finance:

– Sales and revenue forecasting: Predicting future sales figures and revenue streams is crucial for budgeting, inventory management, and resource planning.

– Stock market forecasting: Forecasting stock prices, indices, and trends can aid in investment decisions and portfolio management.

– Demand forecasting: Predicting customer demand for products or services helps optimize production, logistics, and supply chain management.

2. Economics and government:

– Economic forecasting: Predicting macroeconomic indicators like GDP, inflation, unemployment rates, and interest rates supports policymaking and economic planning.

– Population forecasting: Estimating future population growth or decline aids in urban planning, resource allocation, and social program development.

3. Energy and utilities:

– Energy demand forecasting: Predicting energy consumption patterns helps utility companies plan generation, distribution, and pricing strategies.

– Renewable energy forecasting: Forecasting wind, solar, and other renewable energy sources supports integration into the grid and optimizes energy storage systems.

4. Transportation and logistics:

– Traffic flow forecasting: Predicting traffic patterns and congestion helps optimize route planning, transportation scheduling, and infrastructure development.

– Demand forecasting for transportation services: Forecasting demand for services like ride-sharing, public transportation, and freight can improve resource allocation and pricing strategies.

5. Healthcare:

– Epidemic and disease forecasting: Predicting the spread and progression of diseases or epidemics aids in preparedness, resource allocation, and targeted interventions.

– Patient demand forecasting: Forecasting patient volumes and admissions supports staff scheduling, bed management, and resource planning in hospitals.

6. Meteorology and environmental sciences:

– Weather forecasting: Predicting weather patterns, temperature, precipitation, and extreme events is crucial for various industries, agriculture, and public safety.

– Climate change forecasting: Forecasting long-term climate trends and patterns supports mitigation strategies, adaptation planning, and policy development.

7. Manufacturing and production:

– Predictive maintenance: Forecasting equipment failures or degradation allows for timely maintenance, reducing downtime and increasing operational efficiency.

– Inventory management: Predicting demand for raw materials and finished goods optimizes inventory levels and reduces costs associated with overstocking or stockouts.

These are just a few examples of the applied fields where time series forecasting plays a vital role. As data collection and analysis capabilities continue to advance, the importance of accurate forecasting will only increase, enabling better planning, decision-making, and resource allocation across various sectors.

For the purposes of analysis and forecasting of time series (both for regression and classification tasks), an extensive arsenal of ML methods is currently used. Therefore, let's look at the main ML approaches to the problem of modelling and forecasting time series.

To identify and evaluate nonlinear dependencies, ML models are widely used. The most widespread are ANNs, models based on support vectors (Support Vector Machines, SVM), Classification and Regression Trees (C&RT), in particular, Random Forest (RF) and Gradient Boosting (Gradient Boosting Machine, GBM) and so on [6-11].

It should be noted that the regression problem (predicting a continuous variable) can be reduced to the classification problem (predicting changes in direction of movement target variable).

Feed Forward ANNs. The main advantages of ANNs are their ability to take into account any nonlinear dependencies in the data without requiring prior knowledge of clear dependencies or logical connections between variables, while ANN models have the ability to generalize the found properties or patterns in the data.

The most popular is feed forward architecture which is named the Multilayer Perceptron, (MLP) (Fig. 4.2).

Numerous empirical studies tested the effectiveness of the application of ANNs to the forecasting time series, in particular, in the financial field. Results of papers [8, 10] showed that MLP-type ANNs have better predictive properties than time series models and other ML algorithms for the time series forecasting task.

SVM. The main idea behind using SVMs for time series forecasting is to treat the forecasting problem as a regression task. SVMs are typically used for classification problems, but they can be adapted for regression tasks, such as time series forecasting, by introducing an alternative cost function known as the epsilon-insensitive loss function.

The SVM model attempts to find the optimal hyperplane that maximizes the margin between the data points and the hyperplane, allowing for some error (determined by the epsilon parameter). The kernel function, which maps the input data into a higher-dimensional space, plays a crucial role in capturing non-linear relationships in the data.

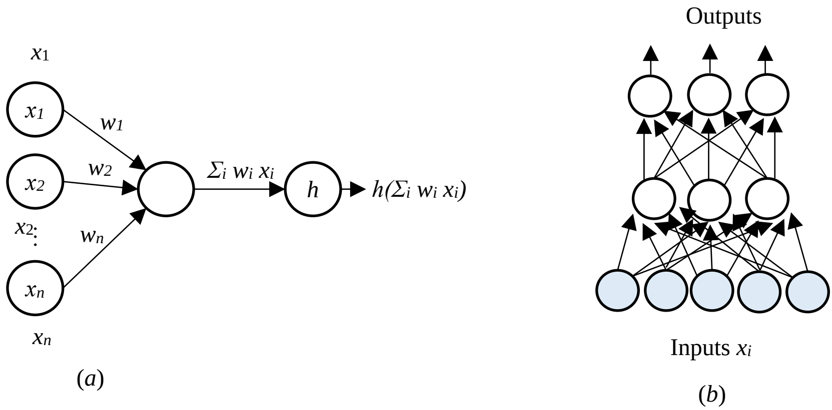

Figure 4.2. The main idea of the architecture of a multi-ball perceptron
(a) Computational graph of single neuron;
(b) Fully connected ANN with one hidden layer
and one output layer

Source: designed by the authors based on [11]

Once the SVM regression model is trained, it can be used to make predictions on new, unseen data. The model takes the input features (including lagged values and engineered features) and predicts the future value(s) of the time series.

One advantage of using SVMs for time series forecasting is their ability to handle non-linear relationships and high-dimensional data. Additionally, SVMs are less prone to overfitting than some other regression techniques, thanks to their regularization mechanisms.

However, SVMs can be computationally expensive, especially for large datasets, and their performance can be sensitive to the choice of kernel function and hyperparameters (such as the regularization parameter and epsilon). Furthermore, SVMs may struggle with certain types of time series patterns, such as long-range dependencies or complex seasonality.

In practice, SVMs are often used in combination with other techniques, such as feature selection or ensemble methods, to improve their forecasting performance for time series data.

By the way, SVM models are widely used for the financial time series forecasting, in particular, to predict the price movement of assets on financial markets [12]. At the same time, they often give better results than other algorithms [13].

C&RTs and ensembles. Another powerful class of machine learning models are C&RT and their ensembles. In the C&RT algorithm, each tree node has two splits. At each step, the given rule divides the training sample into two parts – the part in which the rule is fulfilled (right branch) and the part in which the rule is not fulfilled (left branch) (Fig. 4.3). Splitting occurs up to a certain depth or number of training examples in the leaves on which the prediction is directly performed.

However, in their pure form, models of this type are not very effective due to low accuracy. Ensembles of models built on the basis of C&RT trees are used in practice, in particular, the Random Forest (RF) and Gradient Boosting (Gradient Boosting Machine, GBM) models.

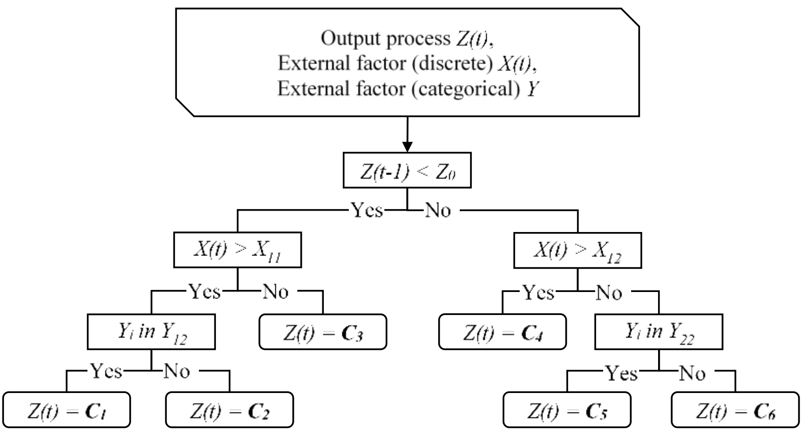

Figure 4.3. Schematic representation of C&RT model

Source: designed by the authors based on [11]

The RF algorithm is based on the construction of an ensemble of classification (regression) trees, each of which is built from subsamples of the original training sample using bagging.

In the RF algorithm, bagging is combined with the method of random subspaces: that is, each tree is built based on different randomly selected subsets of features (features). This process is called subspace sampling.

The main idea behind using GBM for time series forecasting is to leverage the power of ensemble learning and boosting algorithms to capture complex patterns and trends in the data.

GBMs are a type of ensemble learning technique that combines multiple weak learners, typically decision trees, into a strong predictive model. In the context of time series forecasting, GBMs work by iteratively fitting weak learners (decision trees) to the residuals of the previous iteration, with the goal of minimizing the overall prediction error.

The GBM algorithm is initialized with a set of hyperparameters, such as the number of trees, the maximum depth of the trees, the learning rate, and the loss function (e.g., squared error for regression tasks). The algorithm then iteratively fits decision trees to the residuals of the previous iteration, with each new tree focusing on the instances that were poorly predicted by the previous ensemble.

The main advantages of using GBM for time series forecasting include:

– Ability to capture non-linear relationships and complex patterns in the data.

– Robustness to outliers and noise due to the ensemble nature of the algorithm.

– Automatic feature selection and handling of feature interactions through the decision tree structure.

– Regularization techniques, such as shrinkage and subsampling, help prevent overfitting.

However, GBMs can be prone to overfitting if not properly tuned, and they may struggle with long-range dependencies or highly non-stationary time series. Additionally, GBM models can be relatively complex and computationally expensive, especially for large datasets or deep trees.

In practice, GBMs also are often used in combination with other techniques, such as feature engineering, rolling-window validation, and ensemble methods, to improve their forecasting performance for time series data.

4.3. Deep Neural Networks (DNNs)

Recently, more powerful computing platforms and cloud services have appeared thanks to the development of hardware and software tools that enable the implementation of more complex forecasting algorithms – DNNs with dozens and hundreds of layers, the theoretical foundations of which were laid in the work [10].

DNNs have proven to be quite effective for the tasks of image recognition and segmentation, streaming video processing, machine translation and many other applications. During the last ten years, there has been an increased attention of researchers in the application of DNNs to the problems of time series research.

The base concept behind Recurrent Neural Networks (RNNs) for time series forecasting is their ability to model sequential data and capture long-term dependencies within the data.

In traditional Feed Forward ANNs, the inputs and outputs are independent of each other, making them unsuitable for modelling sequential data like time series. RNNs, on the other hand, introduce a form of memory that allows them to process inputs sequentially, using information from previous time steps to inform the current output.

The key idea behind RNNs is the use of recurrent connections, which allow the network to maintain an internal state or memory that captures information from previous time steps (Fig. 4.4). This internal state is updated at each time step based on the current input and the previous state, creating a dynamic system that can model temporal dependencies.

At each moment of time t, the network receives not only the input values (vector $x(t)$), but also the values of the parameters characterizing the internal state of the network at the previous moment of time $h(t-1)$. This allows you to process a series of events over time.

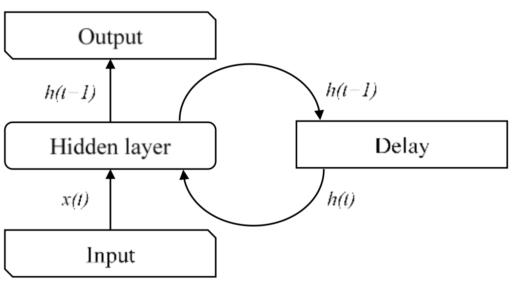

Figure 4.4. Simplified structure of a RNN

Source: designed by the authors based on [16]

So, the main advantage of RNNs over Feed Forward ANNs is their ability to use internal memory to process sequences of arbitrary length. Therefore, networks of this architecture are more suitable for processing sequences (text, time series data) than Feed Forward networks, in particular MLP.

Other common used architecture of DNNs is Convolutional Neural Networks (ConvNets, CNN), which is the main tool in processing with data which has a spatial structure. Such networks are successfully used to extract spatial properties of graphic images, streaming video or audio.

Recurrent Neural Networks (RNNs)

Let's give a formalized description of the RNN using the apparatus of differential equations. Let $\vec{s}$(t) be the value of the *d*-dimensional state signal vector. Then the general nonlinear inhomogeneous differential equation of the first order, which describes the evolution of the state signal as a function of time, *t*, can be written as:

$$\frac{d\vec{s}(t)}{dt} = \vec{f}(t) + \vec{\phi}, \tag{4.1}$$

where $\vec{f}(t)$ – *d*-dimensional function of time, $t \in R^{+}$, and $\vec{\phi}$ – constant *d*-dimensional vector [12].

The canonical form of $\vec{f}$(t) is:

$$\vec{f}(t) = \vec{h}(\vec{s}(t), \vec{x}(t)), \tag{4.2}$$

where $\vec{x}$(t) – is *d*-measurement vector of the input signal, a $\vec{h}(\vec{s}(\mathrm{t}), \vec{x}(\mathrm{t}))$ – vector-valued function of vector-valued arguments [17].

In certain cases, it is possible to consider *s* and *x* as «analog» quantities (that is, functions not only of time *t*, but also of another independent continuous variable ξ, which determines coordinates in multidimensional space). Using these notations, the input intensity displayed on a flat two-dimensional scale will be represented as x($\vec{\xi}$,t) з $\xi \in$R^2.

Sampling $x(\vec{\xi}$,t) on a uniform two-dimensional scale transforms this data set into the representation $x(\vec{\imath}$,t), where $\vec{\imath}$ is a discrete two-dimensional index. Finally, adding the values $x(\vec{\imath}$,t) or all permutations of the components of index $\vec{\imath}$ into the column vector gives $\vec{x}(t)$, as represented by Eq. (4.3)

$$\frac{d\vec{s}(t)}{dt} = \vec{h}(\vec{s}(\mathrm{t}), \vec{x}(\mathrm{t})) + \vec{\phi}. \tag{4.3}$$

A special case of $\vec{f}$(t) y of Eq. (4.2) is:

$$\vec{f}(t) = \vec{a}(t) + \vec{b}(t) + \vec{c}(t), \tag{4.4}$$

The component equations (4.4) $\vec{a}(t), \vec{b}(t), \vec{c}(t)$, *d*-dimensional values vector of functions of time *t*. Equation (4.4) is called an «additive model» in the brain dynamics research literature because it adds terms, possibly nonlinear, that determine the rate of change of neuronal activity or potentials $\vec{s}(t)$.

As a cornerstone of neural network research, the abstract form of the additive model in equation (4.4) has been elaborated in many ways, including the inclusion of delay effects, the imposition of «maneuvering» (or «saturating») system state limits, and other factors.

Biologically motivated uses of the additive model include computational vision analysis, decision-making, reinforcement learning, sensory-motor control, short- and long-term memory, and the study of temporal order in language [17]. It has also been pointed out that the additive model generalizes the Hopfield model [18], which, being rooted in biological plausibility, has had an impact on physics and engineering [17].

In fact, a simplified and discretized form of the additive model played a key role in relating the nonlinear dynamical systems governing morphogenesis, one of the fundamental aspects of developmental biology, to a generalized version of the Hopfield network and its application to an engineering problem in image processing.

Consider the saturating additive model in equation (4.4) with three components, $\vec{a}(\mathrm{t}), \vec{b}(\mathrm{t}), \vec{c}(\mathrm{t})$, which defined as follows:

$$\vec{a}(\mathrm{t}) = \sum_{k=0}^{K_s-1} \vec{a}_k \left(\vec{s}\big(t-\tau_s(k)\big)\right) \tag{4.5}$$

$$\vec{b}(\mathrm{t}) = \sum_{k=0}^{K_r-1} \vec{b}_k \left(\vec{r}\big(t-\tau_r(k)\big)\right) \tag{4.6}$$

$$\vec{c}(\mathrm{t}) = \sum_{k=0}^{K_x-1} \vec{c}_k \left(\vec{x}\big(t-\tau_x(k)\big)\right) \tag{4.7}$$

$$\vec{r}\big(t-\tau_r(k)\big) = G\left(\vec{s}\big(t-\tau_s(k)\big)\right) \tag{4.8}$$

where $\vec{r}(\mathrm{t})$, the input signal vector, which is a warped version of the state signal vector, $\vec{s}(t)$. For an elementary non-linear, saturating and rotating «strain» (or «activation») function $G(z)$ is an optionally scaled and/or shifted hyperbolic tangent form.

Then the resulting system, obtained by substituting equations 4.5–4.8 into Eq. (4.4) and inserting into (4.1):

$$\frac{d\vec{s}(t)}{dt} = \sum_{k=0}^{K_s-1} \vec{a}_k \left(\vec{s}\big(t-\tau_s(k)\big)\right) + \sum_{k=0}^{K_r-1} \vec{b}_k \left(\vec{r}\big(t-\tau_r(k)\big)\right) + \\ + \sum_{k=0}^{K_x-1} \vec{c}_k \left(\vec{x}\big(t-\tau_x(k)\big)\right) \tag{4.9}$$

Eq. 4.9 is a nonlinear ordinary delay differential equation with discrete delays. Delay is a common feature of many processes in biology, chemistry, mechanics, physics, ecology, and economics, among others, so that the nature of the processes dictates the use of delay equations as the only appropriate modeling tool.

The definition of the three weight matrices and the displacement vector transforms Eq. 4.9 and 4.8. into the canonical form of a recurrent neural network (RNN):

$$\vec{s}[n] = W_s\vec{s}[n-1] + W_r\vec{r}[n-1] + W_x\vec{x}[n] + \vec{\theta}_s \quad (4.10)$$

$$\vec{r}[n] = G(\vec{s}[n]) \quad (4.11)$$

A visualization of the principle of operation of the RNN from the Eq. 4.4 is shown in the Figure 4.5.

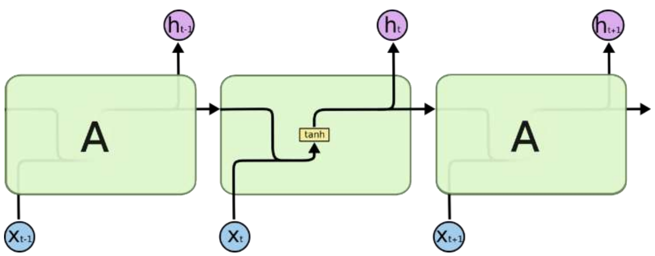

Figure 4.5. The recurrent layer in a standard RNN consists of one layer

Source: designed by the authors based on [19]

In the RNN guarding system, the cell reading signal is a twisted version of the cell signal itself. It is important that a copy of this distorted signal is transmitted back from one cycle to the next as part of the update signal to the coming stage.

This close connection between the signal read on one step and the signal on the next step immediately flows onto the gradient of the goal function of the signal. This influx will occur at the stage of training, which will end with a significant gradient.

Long-Short Term Memory (LSTM)

One of the different types of RNN architectures that are designed to accommodate hourly durations is a measure of «long short-term memory» (LSTM, from the English Long Short-Term Memory). Instead of traditional RNNs, LSTMs are more effective in forecasting hourly series during periods of time when the important parts are separated by hourly lags from unidentified fluctuations or intervals. The LSTM measure was found to solve the problem of missing gradients.

The key insight of the LSTM model was the inclusion of nonlinear, latent data elements in the RNN package, which can be ensured in such a way that the gradient of the target function is consistent with the signal (a value that is directly proportional to the updated parameters is calculated per hour of training using the Gradient Descent help), without knowing [15].

The LSTM cell can be extracted from the canonical RNN package, as before (4.10) by introducing various additional elements. To avoid the problem of the existing gradient, a cell can be created by modifying the cell design. As the exit point, it is necessary to divide the right part of the level 4.10 (the update signal will become a mark on the index, *n*) into two parts:

$$\vec{s}[n] = \vec{F}_s(\vec{s}[n-1]) + \vec{F}_u(\vec{r}[n-1], \vec{x}[n]), \tag{4.12}$$

$$\vec{r}[n] = G_d(\vec{s}[n]). \tag{4.13}$$

Where $G_d(\vec{s}[n])$ is hyperbolic tangent.

$$\vec{F}_s(\vec{s}[n-1]) = W_s\vec{s}[n-1], \tag{4.14}$$

$$\vec{F}_u(\vec{r}[n-1], \vec{x}[n]) = W_r\vec{r}[n-1] + W_x\vec{x}[n] + \vec{\theta}_s \,. \tag{4.15}$$

The first part, $\vec{F}_s(\vec{s}[n-1])$, represents the input from the signal at the front edge. The other part, $\vec{F}_u(\vec{r}[n-1], \vec{x}[n])$, represents the update information that results from the combination of the signal read from the forward timeline and the input signal (external destructive force) on exact time (plus displacement vector $\overrightarrow{\theta_s}$).

In discrete systems, time has less historical significance. It would be more correct to use the term «smart» if we were to talk about the meaning of the signal at the stages. Here the terms «front», «stream» and «offensive» are used more for clarity.

RNN systems can be easily activated in a reversal direction, in which case all indices are reversed, and the values of «forward» and «advance» change. Improved performance was achieved through bidirectional processing in various applications.

As the input data is prepared in advance and supplied to the system as a whole, then the causality bias can be completely weakened.

This can be done in additions, where before the start of processing the entire set of initial data or a collection of independent segments of initial data is collected. Gratuitous processing (a technique characterized by the use of historical input data) can be useful for identifying the presence of «context» among data expressions.

Corresponding to the same (4.11), the signal will be absorbed by the information source in the same proportions on the skin. These proportions can be adjusted by multiplying two values by special «shutter» signals $\vec{g}\mathrm{cs}[n]$ («control state») and $\vec{g}\mathrm{cu}[n]$ («updated control»), as follows:

$$\vec{s}[n] = \vec{g}_{cs}[\mathrm{n}] \odot \vec{F}_s(\vec{s}[n-1]) + \vec{g}_{cu}[\mathrm{n}] \odot \vec{F}_u(\vec{r}[n-1], \vec{x}[n]), \quad (4.16)$$

$$\vec{0} \le \vec{g}_{cs}[\mathrm{n}], \vec{g}_{cu}[\mathrm{n}] \le \vec{1}. \quad (4.17)$$

The elements of the gate signals are positive fractions. Abbreviated designation, $\vec{g}[\mathrm{n}] \in [\vec{0}, \vec{1}]$, means that the value of all elements of the gate vector signal, ~ $\vec{g}[n]$, at the step with index n lie on a closed segment between 0 and 1.

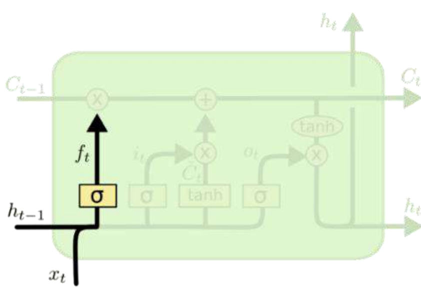

Figure 4.6. Adding a state control gate to control the magnitude of the state signal

Source: designed by the authors based on [19]

Gate signals $\vec{g}_{\mathrm{cs}}[n]$ and $\vec{g}_{\mathrm{cu}}[n]$ in the equations (4.16), (4.17) provide a mechanism for fine-grained control of two types of contributions to the state signal at each step. In particular $\vec{g}\mathrm{cs}[n]$ allows you to control the value of the state signal, which is retained from the previous step, and $\vec{g}\mathrm{cu}[n]$ controls the amount of update signal that should be injected into the state signal at the current step.

In Eq. (4.18) W_s is a diagonal matrix with positive shares $\frac{1}{|a_{ij}|}$ on the main diagonal. So, since the elements $\vec{g}\mathrm{cs}[n]$ are also fractions. Let's define:

$$W_s = I \tag{4.18}$$

$\vec{g}_{cs}[\mathrm{n}]\odot W_s$ is acceptable if the gate functions can be parameterized and their parameters are learned during training. Under these conditions, equation (4.14) can be simplified to:

$$\vec{F}_s(\vec{s}[n-1]) = \vec{s}[n-1] \tag{4.19}$$

Thus, equation (4.15) can be reduced to the following form:

$$\vec{s}[n] = \vec{g}_{cs}[\mathrm{n}]\odot\vec{s}[n-1] + \vec{g}_{cu}[\mathrm{n}]\odot\vec{F}_u(\vec{r}[n-1],\vec{x}[n]) \tag{4.20}$$

The contribution from the state signal in the previous step remains fractional, ensuring the stability of the overall system. Schematically, the insertion of advanced control elements from equation (4.20) into the canonical RNN system of equation (4.1) is shown in Fig. 4.7.

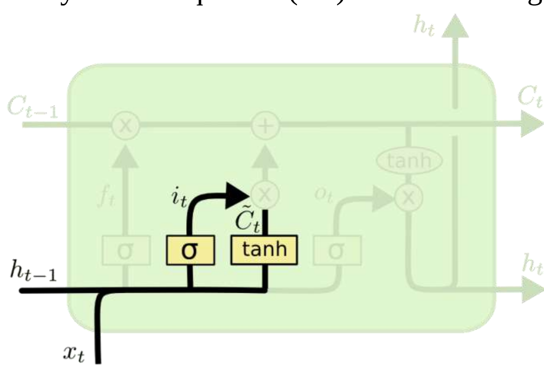

Figure 4.7. State control gate

Source: designed by the authors based on [19]

Although the update time$\vec{F}_u(\vec{r}[n-1],\vec{x}[n])$, is generally controlled by $\vec{g}_{cu}[n]$, the internal state of $\vec{F}_u(\vec{r}[n-1],\vec{x}[n])$ needs to investigate.

According to equation (4.20), the readout signal from the previous step and the input signal at the current step constitute the update candidate signal at each step with index n, and both terms contribute in equal proportion.

The problem is to always use $W_r\vec{r}[n-1]$ in its entirety, is that when $\vec{g}_{cu}[\mathrm{n}]\rightarrow 1$, $\vec{s}[n-1]$ та $\vec{s}[n]$ are connected through W_r and the strain function. This limits the gradient of the objective function with respect to the state signal, thereby subjecting the system to the vanishing/exploding gradients problem.

To cancel this feedback path, the readout signal, $\vec{r}[n]$ distributed using another gate signal, $\vec{g}_{cr}[n]$ («input control»), as follows:

$$\vec{v}[n] = \vec{g}_{cr}[n] \odot \vec{r}[n] \tag{4.21}$$

$$\vec{0} \le \vec{g}_{cr}[n] \le \vec{1} \tag{4.22}$$

The control element $\vec{g}_{cr}[n]$, determines the partial magnitude of the readout signal, which becomes the signal of the observed value of the cell at the stage with the index *n*.

Thus, using $\vec{v}[n-1]$ instead of $\vec{r}[n-1]$ in Eq. (4.20) turns it into:

$$\vec{F}_u(\vec{v}[n-1], \vec{x}[n]) = W_r \vec{v}[n-1] + W_x \vec{x}[n] + \vec{\theta}_s \tag{4.23}$$

The schematic diagram, an extension to accommodate the control reading, is shown in equation (4.20), and the modified repetition ratio used in equation (4.21) is shown in Fig. 4.8.

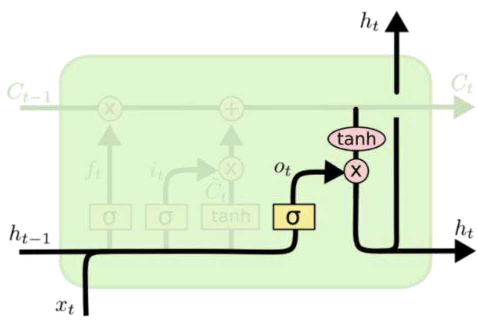

Figure 4.8. Gate «control reading»

Source: designed by the authors based on [19].

The external input does not affect the stability of the system and does not affect its tendency to vanishing / exploding gradients, the combination of the input data with its own «control input» input makes the system more flexible. By multiplying the external input signal, $\vec{x}[n]$, in equation 4.16 on the selected gate signal, $\vec{g}_{cx}[n]$, transforms equation (4.21) into:

$$\vec{F}_u(\vec{v}[n-1], \vec{x}[n]) = W_r \vec{v}[n-1] + \vec{g}_{cx}[n] \odot W_x \vec{x}[n] + \vec{\theta}_s \tag{4.24}$$

According to equation (4.21) and equation (4.23), using as a control read gate, $\vec{g}_{cr}[n]$, and the input control gate, $\vec{g}_{cx}[n]$, allows you to enter the update period, $\vec{F}_u(\vec{v}[n-1], \vec{x}[n])$, to contain any combination of read signal and external input.

The dynamic range of the cell value $\vec{v}[n]$, is determined by the readout signal $\vec{r}[n]$, which is limited by the deformation nonlinearity G_d(z). In order to maintain the same dynamic range while absorbing contributions from the input signal, $\vec{x}[n]$ (or $\vec{g}_{\text{cx}}[\text{n}] \odot \vec{x}[n]$, if the control input is part of the system architecture), the aggregate signal $\vec{F}_u(\vec{v}[n-1], \vec{x}[n])$, is hardened by a saturating nonlinearity deformation G_d(z), *n* order to obtain a candidate signal for updating $\vec{u}[n]$:

$$\vec{u}[n] = G_d\left(\vec{F}_u(\vec{v}[n-1], \vec{x}[n])\right). \tag{4.25}$$

Thus, replacing the update period in equation (4.19) with $\vec{u}[n]$, given by equation (4.25):

$$\vec{s}[n] = \vec{g}_{cs}[\text{n}] \odot \vec{s}[n-1] + \vec{g}_{cu}[\text{n}] \odot \vec{u}[n]. \tag{4.26}$$

Equation (4.26) is the main component of the set of formulas defining the cell of the LSTM network. According to Equation (4.26), the cell state signal at the current stage is a weighted combination of the cell state signal at the previous stage and the aggregation of historical and new update information available at this stage.

The complete data path of an LSTM cell, completed by strengthening the canonical RNN system with controls and signal suppression, is illustrated in Fig. 4.9.

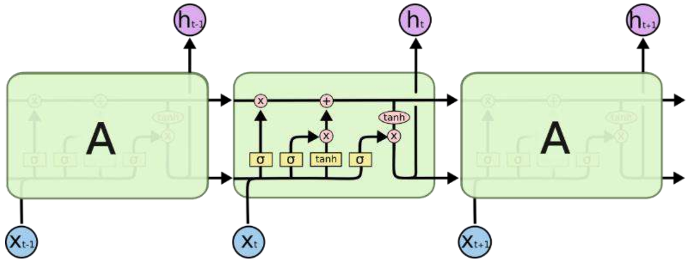

Figure 4.9. The recurrent LSTM network model consists of four interacting layers

Source: designed by the authors based on [19]

Similar to a standard RNN, an LSTM network is trained using Gradient Descent. LSTM can also learn short-range dependencies among subsequence samples comprising the training data.

Gated Recurrent Unit (GRU)

A more modern version of the DNN architecture is the Gated Recurrent Unit Neural Networks (GRU) model, which is a modification of the LSTM model (Fig. 4.10).

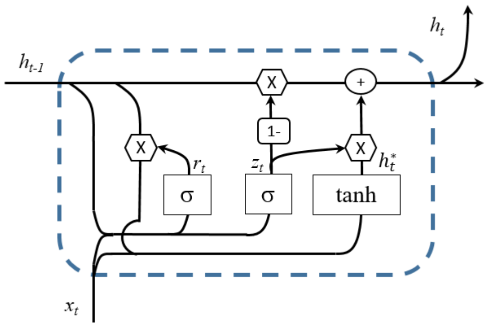

Figure 4.10. Architecture of a neural network cell with a Gate Recurrent Unit (GRU)

Source: designed by the authors based on [21]

Here through h_{t-1} is marked the initial information from the cell at the previous moment in time. This information, together with the input of the current moment of time x_t, is fed to the input gate (filter), which determines kind of information to save and pass on to the next step, and which should be «forget». In parallel with this, the update vector $z_t$is calculated.

Mathematically, this is written as:

$$r_t = \sigma\big(W_r \cdot (x_t, h_{t-1})\big), r_t \in [0,1], \tag{4.27}$$

$$z_t = \sigma\big(W_z \cdot (x_t, h_{t-1})\big), z \in [0,1], \tag{4.28}$$

where $\sigma(\cdot)$ – Sigmoid activation function, a W_r, W_z – weight matrices of forgetting and updating gates.

Then a new initial state vector h_t is calculated, which is a weighted linear combination of the previous output state h_{t-1} and «candidate» for saving in a new state ${h_t}^*$:

$${h_t}^* = tanh\big(W_h \cdot (x_t, r_t \cdot h_{t-1})\big), \tag{4.29}$$

$$h_t = (1 - z_t) \cdot h_{t-1} + z_t \cdot h_t^*, \tag{4.30}$$

where $tanh(\cdot)$ – is a Hyperbolic Tangent activation function, and W_h is weight matrices of the output gate.

The performance of GRU-based models for many problems is comparable to that of LSTMs, but they have fewer parameters and therefore train faster, while requiring less data to train and tune.

RNNs and their modifications (LSTM, GRU) are a type of ANNs particularly well-suited for processing sequential data, such as text, speech, or time series data. Unlike traditional FNNs, RNNs have an internal state or memory that allows them to capture and incorporate information from previous inputs when processing the current input. This capability makes RNNs valuable for modelling and analysing sequences, enabling them to uncover patterns and dependencies within the data over time.

In the context of information control systems, RNNs can play a crucial role in various applications, such as Natural Language Processing (NLP), sentiment analysis, and online content moderation. For example, RNNs can be employed to analyze text data from social media platforms, news articles, or online forums to identify potentially harmful or misleading content, hate speech, or misinformation. By processing the text sequentially, RNNs can capture contextual information and understand the underlying meaning and intent, making them more effective than traditional bag-of-words models.

Moreover, RNNs can be integrated into larger ICS that monitor and analyse data streams in real-time. These systems can leverage the sequential processing capabilities of RNNs to detect patterns, trends, and potential threats or risks as they emerge. For instance, RNNs could be used to monitor online discussions and identify coordinated disinformation campaigns or the spread of harmful narratives, allowing for timely intervention or counter-messaging efforts.

In addition to content analysis, RNNs can also be employed in information control systems for user profiling and personalization. By analysing a user’s historical interactions, browsing behaviour, and content consumption patterns, RNNs can learn to model individual preferences and interests over time. This information can then be used to tailor content recommendations, targeted advertising, or personalized information feeds, enhancing user engagement and serving relevant information to the right audiences.

Convolutional Neural Networks (CNNs)

CNNs are considered the best tool for identifying graphic images, finding patterns for recognizing and segmenting objects, persons, and scenes in deep machine learning [21]. They learn directly from images, using patterns for classification, eliminating the need for manual «extraction» or feature construction.

CNNs are effectively used for image and streaming video classification and segmentation tasks. They are capable of finding hidden regularities and patterns in data, extracting features from local input patterns, and can also be used for time series analysis and forecasting tasks. The use of CNNs for deep learning has become more popular due to three important factors:

– CNNs eliminate the need for manual feature extraction, the network itself extracts or constructs features;

– CNNs have the best recognition results among neural networks of various architectures;

– they can be reconfigured to perform new recognition tasks, allowing the use and retraining of existing networks.

CNNs provide an optimal architecture for pattern detection. Combined with advances in GPUs and parallel computing, such networks are an effective technology that can be used to detect patterns in time series dynamics. A convolutional neural network can have dozens or hundreds of layers, each of which learns to detect different features of an image.

Filters are applied to each training image with different resolution, and the output of each collapsed image is used as input to the next layer. Filters start processing from the simplest «surface» characteristics of the image (at the initial convolutional layers of the network) to the characteristics that uniquely define the object (depth characteristics). Like other neural networks, CNN consists of an input layer, an output layer, and a set of hidden layers between them (Fig. 4.11).

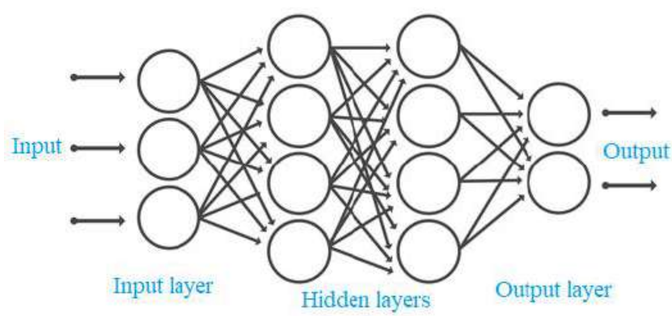

Figure 4.11. Structure of CNN

Source: designed by the authors based on [16]

These layers perform operations that modify data to learn characteristics specific to that data. The most common types of layers include:

– *Convolution* passes input images presented as numerical matrices through a set of filters, each of which activates certain features;

– *Rectified Linear Unit* (ReLU) provides faster and more efficient training, displaying negative values to zero and saving positive values. This is sometimes called activation because only activated characteristics carry over to the next level;

– *Pooling* simplifies inference by performing non-linear degradation of image quality, reducing the number of parameters the network needs to learn.

These operations are repeated on tens or hundreds of layers, while each layer learns to define different characteristics (Fig. 4.12).

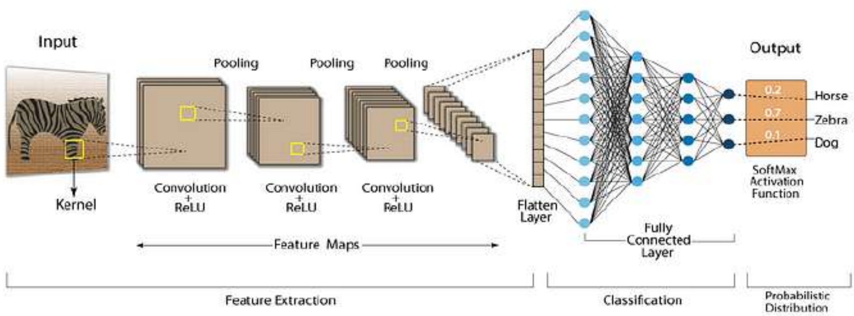

Figure 4.12. Scheme of learning process of CNN

Source: designed by the authors based on [16]

Filters are applied to each training example with different resolution, and the output of each collapsed image is used as input to the next layer.

The penultimate layer is a fully connected layer that outputs a vector of size K, where K is the number of classes the network will be able to predict. This vector contains the probabilities for each class of any image under study.

After learning the features at many levels, the CNN architecture proceeds to classification: the last layer of the CNN architecture directly performs the classification using the Softmax activation function.

The mathematical formalization of the convolution operation is given in equation (4.31), where *t* is time, *s* denotes a map of objects, *w* is a kernel, *x* is feature map of previous layer.

$$s(t) = (x * w)(t) = \sum_{a=-\infty}^{\infty} x(a)w(t-a) \quad (4.31)$$

Equation (4.32) shows the convolution operation for a two-dimensional image, where *l* denotes the input image, *K* is a kernel, (*m*, *n*) – image size, and *i, j* are the indexes of variables.

$$S(i,j) = (l * K)(i,j) = \sum_m \sum_n l(m,n)K(i-m, j-n) \quad (4.32)$$

Thus, a sequence of convolution layers, unification and fully connected layers form a deep convolutional network [16].

Equation (4.33) describes the operation of the fully connected layer of the convolutional neural network, where *W* denotes the weights, *x* denotes the input, *b* – biases, and z – output of neurons.

$$z_i = \sum_j W_{i,j}x_j + b_i. \quad (4.33)$$

At the last layer of the network, the Softmax function is used to obtain the classification result (4.34):

$$softmax(z_i) = \frac{\exp(z_i)}{\sum_j \exp(z_j)}. \quad (4.34)$$

Applying a CNN to time series can be thought of as applying and shifting a time series filter. Unlike images, scalar time series filters have only one dimension (time) instead of two dimensions (width and height).

A filter can also be considered as a general nonlinear transformation of a time series. So, if we apply a filter of length 3 of the form $\begin{bmatrix}\frac{1}{3} & \frac{1}{3} & \frac{1}{3}\end{bmatrix}$ to a one-dimensional (1D) time series, the convolution will result in a moving average with a sliding window of length 3.

The general form for applying convolution for a centrifugal time stamp *t* can be defined as follows:

$$C_t = f\left(\omega * X_{\frac{t-l/2}{t+l/2}} + b\right) \; \forall \; t \in [1, T], \quad (4.35)$$

where *C* – is the result of a convolution (element-wise product and addition, «*») applied to a 1D time series *X* of length *T* with a filter *ω* of length l, a bias parameter *b*, and a nonlinear activation function *f* (for example, ReLU).

The result of the convolution (of one filter) on the input time series *X* can be viewed as another one-dimensional time series *C* that has undergone the filtering process.

Thus, the application of several filters to a time series will lead to a multidimensional time series, the dimension of which is equal to the number of used filters [21]. The same convolution (the same filter values ω and b) will be used to find the result for all timings $t \in [1, T]$.

This property of CNNs, called weight distribution, allows them to self-tune (train) filters that are time-invariant. Considering the multidimensional time series as input to the convolutional layer, the filter also has a dimension consistent with the dimension of the input multidimensional time series.

In addition to pooling layers, some deep learning architectures include normalization layers to reduce sensitivity to the initial initialization of the weights. For time series data, the batch normalization operation is performed on each channel, thus preventing the covariance shift of the internal weights during one mini-packet of data.

Another type of normalization is to normalize each instance, rather than the entire mini-batch, by determining the mean and standard deviation of each training instance for each layer using gradient descent. The last approach is called instance normalization and simulates the determination of z-normalization parameters for training time series data [16].

The last fully connected layer takes a representation of the input time series (the results of convolutions and joins) and gives a probability distribution of belonging to a certain class. Typically, this layer uses a Softmax activation function, similar to a multilayer perceptron. In general, the learning process of a deep CNN network is identical to the learning of a multilayer perceptron: as a rule, the method of error backpropagation is used.

Thus, CNNs have emerged as a powerful tool in the field of artificial intelligence, particularly for tasks involving image and video processing. These neural networks are designed to effectively capture spatial and temporal dependencies in data by applying learnable filters or kernels across the input data. The ability of CNNs to automatically learn and extract relevant features from raw data has led to their widespread adoption in various applications, including computer vision, natural language processing, and information control systems.

In the realm of ICS, CNNs can play a crucial role in various stages, such as data preprocessing, feature extraction, and decision-making. For instance, in content moderation systems, CNNs can be employed to analyse images and videos, identify potentially harmful or inappropriate content, and assist in content filtering or removal processes. By learning patterns and features from vast datasets of labelled images and videos, CNNs can achieve high accuracy in detecting and classifying different types of content, such as explicit or violent material, hate speech, or misinformation.

Moreover, CNNs can be integrated into larger ICS that monitor and analyse data streams from various sources, including social media platforms, news outlets, and online forums. These systems can leverage the feature extraction capabilities of CNNs to identify patterns, trends, and potential threats or risks within the data. This information can then be used to inform decision-making processes, such as content moderation, risk assessment, or targeted interventions.

In addition to content analysis, CNNs can also contribute to information control systems by improving user experience and personalization. For example, recommender systems that suggest relevant content to users can employ CNNs to analyse user behaviour, preferences, and interactions with the system. By learning patterns from historical data, CNNs can help these systems provide more accurate and tailored recommendations, ultimately enhancing user engagement and satisfaction.

While CNNs have demonstrated remarkable performance in various applications, it is essential to consider ethical implications and potential biases that may arise from their use in information control systems. These systems can have significant impacts on freedom of expression, privacy, and the spread of information. Therefore, it is crucial to ensure transparency, accountability, and the incorporation of human oversight mechanisms to mitigate potential risks and biases associated with the use of CNNs and other AI models in these sensitive domains.

Similar to RNNs, the use of CNNs in ICS raises important ethical considerations. These systems can have significant impacts on freedom of expression, privacy, and the spread of information. It is crucial to ensure transparency, accountability, and the incorporation of human oversight mechanisms to mitigate potential biases and unintended consequences associated with the use of RNNs and other AI models in these sensitive domains.

Transformers

Transformers are a type of neural network architecture that has gained significant popularity in recent years, particularly in the field of natural language processing (NLP). Unlike traditional recurrent neural networks (RNNs) or convolutional neural networks (CNNs), transformers rely solely on attention mechanisms to capture the relationships between different parts of the input sequence, without relying on recurrence or convolution operations [22–24].

At the core of the transformer architecture is the attention mechanism, which allows the model to weigh the importance of different parts of the input sequence when processing a specific part of the sequence (Fig. 4.13). This mechanism enables the model to selectively focus on relevant information and capture long-range dependencies within the data, a task that was particularly challenging for traditional RNNs.

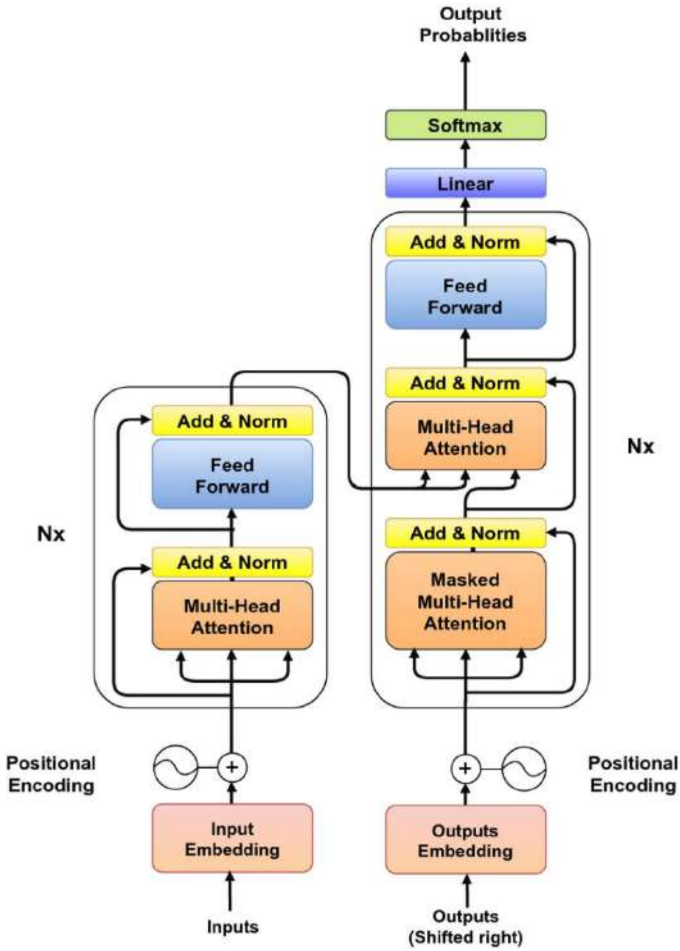

Figure 4.13. Structure of Transformer

Source: designed by the authors based on [22–24]

The transformer architecture is composed of two main components: the encoder and the decoder. Both components are based on the multi-head attention mechanism, which is the core building block of the transformer model.

Encoder: The encoder is responsible for processing the input sequence and generating a set of vector representations that capture the context and relationships within the input data. It consists of several identical layers, each containing two sub-layers: a multi-head attention layer and a position-wise fully connected feed-forward network.

– *Multi-Head Attention Layer*: This layer applies the multi-head attention mechanism to the input sequence, allowing the model to attend to different positions of the input simultaneously. The attention weights are computed based on the similarity between the query, key, and value vectors derived from the input. The outputs of the attention heads are then concatenated and linearly transformed to produce the final attention output.

– *Position-wise Feed-Forward Network:* This sub-layer consists of two fully connected layers with a ReLU activation function in between. It applies a position-wise transformation to the output of the multi-head attention layer, allowing the model to capture non-linear relationships and further refine the representations.

The encoder layers are stacked on top of each other, and the output of each layer is fed as input to the next layer, enabling the model to capture increasingly complex representations of the input sequence.

Decoder: The decoder is responsible for generating the output sequence, one token at a time. Similar to the encoder, it consists of several identical layers, each containing three sub-layers: a multi-head attention layer over the output sequence, a multi-head attention layer over the encoder output, and a position-wise fully connected feed-forward network.

– *Masked Multi-Head Attention Layer* (over output sequence): This layer applies the multi-head attention mechanism to the previously generated output tokens, allowing the model to attend to the past context when generating the next token. However, to prevent the model from attending to future tokens, a masking technique is applied to the attention weights, ensuring that the model only attends to the tokens it has already generated.

– *Multi-Head Attention Layer* (over encoder output): This layer allows the decoder to attend to the output of the encoder, enabling it to incorporate relevant information from the input sequence when generating the output.

– *Position-wise Feed-Forward Network*: Similar to the encoder, this sub-layer applies a non-linear transformation to the output of the multi-head attention layers, refining the representations further.

The decoder layers are also stacked on top of each other, with the output of each layer serving as input to the next layer. Additionally, residual connections and layer normalization are employed throughout the encoder and decoder to improve the training stability and convergence of the model.

The transformer architecture's innovative use of self-attention mechanisms and parallelization capabilities have made it a powerful and versatile model for various sequence-to-sequence tasks, such as machine translation, text summarization, and language generation.

One of the key advantages of transformers is their ability to parallelize computations, making them more efficient and scalable compared to RNNs, which process sequences sequentially. This parallelization is achieved by the attention mechanism, which operates on the entire input sequence simultaneously, rather than processing it one element at a time.

Transformers have revolutionized various NLP tasks, such as machine translation, text summarization, question answering, and language modelling. They have also found applications in other domains, such as computer vision and speech processing, where they can effectively capture long-range dependencies and leverage self-attention mechanisms.

Despite their success, transformers are computationally expensive and require large amounts of training data to achieve optimal performance. Additionally, the attention mechanism can be susceptible to certain biases and limitations, such as the inability to capture hierarchical or nested structures effectively. On-going research efforts aim to address these challenges and further improve the efficiency, interpretability, and robustness of transformer models.

Application of transformers:

– machine translation: Transformers significantly improved the quality of machine translation;

– text summarization: they can generate short descriptions of texts, preserving their main content;

– answer to questions: they can give clear and informative answers to questions posed in natural language;

– detection and correction of errors: they can detect grammatical and spelling errors in texts;

– writing texts: they can generate texts of various styles and formats, for example, articles, poems, code, etc.

Disadvantages of transformers:

– complexity: transformers can be difficult to understand and debug;

– amount of data: transformers need large amounts of data for training;

– computing resources: learning and using transformers can require significant computing resources.

Examples of successful use of transformers:

– GPT-4 model from OpenAI or Gemini from Google, which process and generate texts based on prompts;

– the Google Translate machine translation system, which uses transformers to translate texts between 135 languages.

Transformers have already significantly improved the quality of machine translation, text summarization, question answering and other NLP tasks. In the future, transformers will probably play an even bigger role in our lives, because they give us the opportunity to better understand complex processes and use natural language for this.

Transformers have emerged as a powerful architecture for artificial intelligence models, particularly in the field of NLP. Their ability to effectively capture long-range dependencies and model complex relationships within sequential data has made them invaluable in various applications, including information control systems.

In the context of ICS, transformers can play a crucial role in content moderation, misinformation detection, and sentiment analysis. By processing textual data, such as social media posts, news articles, or online forums, transformers can identify potentially harmful or misleading content, hate speech, or coordinated disinformation campaigns. Their self-attention mechanism allows them to understand the context and nuances within the text, making them more effective at identifying subtle forms of misinformation or malicious intent.

In addition to content analysis, transformers can also be employed in ICS for user profiling and personalization. By analysing a user's historical interactions, browsing behaviour, and content consumption patterns, transformers can learn to model individual preferences and interests over time. This information can then be used to tailor content recommendations, targeted advertising, or personalized information feeds, enhancing user engagement and serving relevant information to the right audiences.

Furthermore, transformers can be applied to tasks such as text summarization and question-answering, which can be valuable in ICS. For example, transformers could be used to generate concise summaries of lengthy documents or online discussions, allowing human moderators or analysts to quickly identify key points and potential issues. Similarly, they can be employed in question-answering systems, enabling users to quickly access relevant information from large datasets or knowledge bases.

While transformers have demonstrated remarkable performance in various applications, their use in ICS raises important ethical considerations. These systems can have significant impacts on freedom of expression, privacy, and the spread of information. It is crucial to ensure transparency, accountability, and the incorporation of human oversight mechanisms to mitigate potential biases and unintended consequences associated with the use of transformers and other AI models in these sensitive domains.

4.4. Application of DNNs to multimodal data processing tasks (images, video, audio, text)

DNNs are becoming an increasingly powerful tool for solving multimodal data processing problems. Their ability to handle complex nonlinear dependencies makes them ideal for tasks where data is presented in multiple formats, such as text, images, audio, and video.

DNNs can handle complex nonlinear dependencies and can be used for training on large volumes of data. This is important for multimodal data processing problems, where the data are often very complex and multidimensional, and solving these problems is difficult or impossible for traditional methods.

We will give several examples of the application of deep neural networks to the problems of multimodal data processing.

Intelligent agents in the context of NLP are advanced software or algorithmic entities that possess the remarkable ability to interact with users through natural language. These agents are designed to comprehend and process human speech, enabling them to provide insightful answers, solve complex problems, or perform a wide range of intricate tasks tailored to the user’s needs.

One prominent application of intelligent agents in NLP is the development of conversational agents, commonly known as chatbots. These agents are specifically designed to engage in natural language conversations with humans, leveraging cutting-edge language understanding and generation techniques. Chatbots can be employed in various domains, including customer service, marketing, and education, offering users a seamless and intuitive interface for accessing information, resolving inquiries, or seeking guidance.

Beyond conversational interactions, intelligent agents in NLP can also excel at text analysis tasks, such as information extraction, emotion detection, and theme identification. By analysing and comprehending the nuances of written language, these agents can uncover valuable insights, sentiments, and contextual information embedded within textual data. This capability has far-reaching applications in areas such as marketing research, social media analysis, and content cu-ration, enabling organizations to gain deeper understanding of customer preferences, market trends, and public discourse.

The versatility of intelligent agents in NLP extends even further, enabling them to contribute to a diverse range of tasks and domains. In the realm of education, for instance, these agents can facilitate personalized learning experiences by adapting to individual learning styles, providing tailored feedback, and offering customized educational resources. Furthermore, intelligent agents can play a vital role in knowledge management, assisting in the organization, retrieval, and dissemination of information across various platforms and repositories.

As the field of NLP continues to evolve, intelligent agents are poised to become increasingly sophisticated and capable, driven by advancements in machine learning, natural language understanding, and language generation techniques. These agents hold the potential to revolutionize the way we interact with technology, bridging the gap between human communication and machine intelligence.

However, it is crucial to recognize the ethical considerations surrounding the development and deployment of intelligent agents, particularly in sensitive domains such as healthcare, finance, and decision-making processes. Ensuring transparency, accountability, and the mitigation of potential biases or unintended consequences will be paramount as we continue to integrate these powerful agents into our daily lives and critical systems.

Machine translation is a ground-breaking technology that enables computers to automatically translate text from one language to another, leveraging not only textual data but also integrating information from diverse media sources such as images, video, and audio. Its primary objective is to transcend language barriers and facilitate seamless communication among individuals who speak different languages, fostering greater understanding and connections across cultures.

While several approaches to machine translation have been explored, the most prevalent and promising method currently employed is neural machine translation (NMT). NMT systems harness the power of artificial neural networks, which are trained on vast volumes of parallel translated texts. These intricate neural networks analyze and uncover intricate patterns and relationships between languages, learning to reproduce and generalize these patterns to accurately translate new texts.

One of the key strengths of NMT lies in its ability to capture contextual nuances and produce more natural-sounding translations compared to earlier rule-based or statistical approaches. By learning from extensive language data, these neural networks can better comprehend the complexities of language, including idioms, colloquialisms, and cultural references, thereby enhancing the quality and fluency of the translations produced.

Machine translation technology is a rapidly evolving field, driven by continuous advancements in deep learning algorithms, computational power, and the availability of larger and more diverse training datasets. As the amount and diversity of training data increase, and the algorithms become more sophisticated and fine-tuned, we can anticipate further improvements in the accuracy, naturalness, and overall quality of machine-translated content across a wide range of languages and domains.

However, it is crucial to acknowledge that machine translation is not a perfect solution, and there are still challenges and limitations to overcome. Certain linguistic complexities, such as ambiguity, context-dependent expressions, and cultural nuances, can pose difficulties for these systems. Additionally, the quality of translations can vary depending on the language pair, the domain, and the availability of high-quality training data. Continuous research and development efforts are necessary to address these challenges and further refine machine translation capabilities.

Despite these challenges, the potential of machine translation technology to facilitate global communication and break down language barriers is immense. As this technology continues to advance, it holds the promise of enabling more inclusive and seamless interactions among diverse communities, fostering greater understanding, collaboration, and cultural exchange on a global scale.

Recognition of emotions is a fascinating field that involves the process of determining and interpreting human emotions through computational methods. This technology leverages advanced algorithms and techniques to analyse various data sources, including text, body language, facial expressions, and other relevant information, to gain insights into an individual’s emotional state.

One of the primary approaches to emotion recognition involves analysing textual data, such as the words, grammar, and punctuation used by a person. By examining the linguistic patterns and sentiment expressed in written communication, these systems can infer the underlying emotions behind the text. Furthermore, video analysis plays a crucial role in emotion recognition, enabling the detection of subtle non-verbal cues, such as gestures, facial expressions, and the activation of specific facial muscles associated with certain emotions.

Additionally, audio data, including voice pitch, tonality, speech rate, and potential speech disorders, can provide valuable insights into an individual's emotional state. By combining these various modalities – text, video, and audio – emotion recognition systems can achieve a more comprehensive and accurate understanding of human emotions.

The ability to recognize and comprehend emotions has numerous practical applications and can significantly enhance human-computer interactions. In the field of medicine, for instance, emotion recognition can aid in the diagnosis and treatment of psychological disorders, enabling healthcare professionals to better understand and address the emotional needs of their patients. Similarly, in the realm of education, recognizing the emotions of learners can help tailor and adapt the educational process to their specific needs, fostering a more personalized and effective learning experience.

In the realm of marketing and customer service, emotion recognition can play a pivotal role in creating more emotionally appealing advertising campaigns and providing personalized services tailored to the emotional states of customers. By identifying and responding to customer emotions, businesses can enhance customer satisfaction, loyalty, and overall engagement.

Moreover, emotion recognition has applications in the financial sector, where analysing market sentiment – whether bullish, bearish, or neutral – can provide valuable insights for investment decisions and risk management strategies. By leveraging emotion recognition techniques, financial institutions can gain a deeper understanding of market dynamics and make more informed choices.

As emotion recognition technology continues to advance, it holds the potential to revolutionize the way we interact with machines and each other. By enabling systems to comprehend and respond to human emotions effectively, we can foster more empathetic, intuitive, and meaningful interactions, ultimately enhancing our ability to communicate, understand, and connect with one another on a deeper emotional level.

Medical diagnosis. Artificial intelligence is revolutionizing the field of medical diagnostics, helping doctors make more accurate and faster diagnoses. Here are some examples of how AI is being used in this industry:

– *Analysis of medical images*. AI can help doctors interpret X-rays, MRIs, CT scans and other medical images, detecting abnormalities that may be missed by the human eye, aiding in the early detection of cancer, stroke and other serious diseases.

– *Analysis of patient's data*. AI can analyse patients' electronic health records to identify risk factors and predict the likelihood of developing certain diseases, helping doctors better personalize treatment and preventive measures for each patient.

– *Development of new medicines*. AI can be used to virtually screen millions of chemical compounds to find new drugs and therapies, greatly speeding up the process of developing new drugs.

– *Robotic surgery*. AI is being used to develop robotic surgical systems that give surgeons greater precision and control during operations, resulting in better patient outcomes, fewer complications, and faster recoveries.

The main benefits of using AI in medical diagnostics include early detection of diseases, when these diseases are easier to treat, and lower healthcare costs due to more accurate diagnosis and better treatment outcomes.

However, there are ethical issues related to the use of AI in medicine, such as the privacy of patient data and liability for errors made by intelligent systems.

AI has significant potential to revolutionize medical diagnostics. Thanks to the continuous development of AI technologies, we can expect even greater advances in this field in the coming years.

Robotics. DNNs can be used to control robots that can perceive and interact with the surrounding world using various sensors based on Computer Vision (CV).

CV is a technology that enables computers to «see» and «understand» the world around them. This is achieved through cameras (capture images or videos of the environment), sensors (used to measure various characteristics of light such as intensity, colour and depth) and image processing algorithms (extract useful information) that allow computers to analyse and interpret visual information as the human brain does.

Application of CV:

– industry – used for product quality control, automation of production processes and equipment inspection;

– security – used for face recognition, motion tracking and security monitoring;

– transport – used for autonomous driving, traffic monitoring and transport management;

– robotics – used for robot navigation, object manipulation and interaction with the environment.

The use of CV in robotics also includes solving military tasks:

– reconnaissance – analysis of images and video taken from satellites, aircraft and drones to identify enemy forces, equipment and infrastructure;

– surveillance – monitoring of the battlefield and detection of enemy movements of manpower, equipment, etc.;

– targeting – accurate targeting of missiles, bombs and other munitions, including capturing the target by a drone in the terminal area in conditions of dense countermeasures by enemy means of radio-electronic warfare;

– facial recognition – recognition of people on the battlefield, including enemy combatants and civilians;

– autonomous systems – the development of autonomous weapons systems that can operate without human intervention.

Analysis of financial data. Financial data is distinguished by its diversity – digital (financial indicators, prices), text (news, reports), images (diagrams, graphs).

DNNs are a powerful tool that can be used to improve decision-making accuracy in the financial market and can help traders, investors and other market participants in:

– forecasting prices for shares, bonds, currencies, goods and other assets;

– forecasting economic indicators, such as GDP, inflation, interest rates, unemployment, etc.;

– predicting risks such as defaults, bankruptcies and financial crises; detection of fraudulent transactions such as money laundering and identity theft;

– assessment of borrowers' creditworthiness;

– detection of abnormal data, such as sudden changes in prices or trading volumes;

– analysis of news articles to determine how they may affect the market;

– recognizing technical patterns on price charts to help traders make better trading decisions.

It is crucial to acknowledge that DNNs, despite their remarkable capabilities, do not guarantee success in the financial market or any other applied domain. These powerful models are merely tools, and their effectiveness heavily relies on their proper application and integration within larger systems.

DNNs are often employed as components within more extensive models, particularly in information control systems (ICS). In such contexts, they serve specific functions, such as data processing, uncovering hidden patterns or features, and contributing to decision-making processes or controlling the impact of ICS. However, their performance is contingent upon the overall system design, the quality of the data they are trained on, and the careful consideration of potential biases or limitations.

While DNNs have demonstrated impressive results in various tasks, their effectiveness should not be overstated or treated as a panacea. They are tools that require thoughtful implementation, continuous monitoring, and a deep understanding of their strengths and weaknesses. Overreliance on DNNs or a failure to incorporate human oversight and domain expertise can lead to unintended consequences, particularly in sensitive domains like finance or information control.

It is essential to approach the deployment of DNNs with caution and a holistic perspective. Their integration into larger systems should be accompanied by rigorous testing, evaluation, and the implementation of appropriate safeguards. This includes establishing clear accountability mechanisms, ensuring transparency in decision-making processes, and fostering a culture of ethical and responsible use of these powerful technologies.

Furthermore, it is crucial to recognize that DNNs are not infallible and can be susceptible to biases present in the training data or the algorithms themselves. Continuous efforts should be made to identify and mitigate such biases, as they can perpetuate or amplify existing societal inequalities or lead to unfair outcomes. Regular audits, diverse and representative data sources, and the involvement of interdisciplinary teams can help address these challenges.

In summary, while DNNs have revolutionized various domains and hold immense potential, it is essential to approach their application with a nuanced understanding of their limitations and the broader context in which they operate. Their effectiveness relies not only on their architectural design but also on the thoughtful integration into larger systems, the quality of data, and the incorporation of human oversight and ethical considerations.

4.5. Construction of an Information Control System based on DNNs for the forecasting financial market

The ICS for the financial market should include a system for predicting the value of the price (or the direction of its change – up, down) and a function that opens a trade agreement according to the forecast (automatically or with confirmation by the trader).

To identify hidden regularities in the data and automatically generate predictors, the use of CNN allows finding technical patterns in price quotations submitted as input in the form of candlestick patterns [16] (Fig. 4.14).

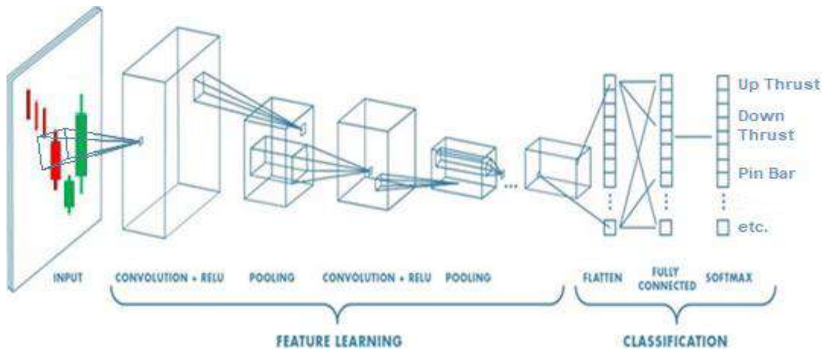

Figure 4.14. Schematic framework of a CNN for graphical pattern recognition of currency quotes

Source: designed by the authors

At the same time, the input to the network is not a two- or three-dimensional graphic image, but a scalar or vector time series. This network is the main block of the built system of models, since after the selection of features (used as predictors) based on kernels or convolution filters (weight matrix) when moving from local trends to longer-term trends, it can make predictions directly and transmit selected signs for the input of another model for forecasting.

The input of the CNN is a two-dimensional tensor, in which the first dimension is the length of the sliding window of the input time series, which in the model is equal to 28 observations (four weeks for daily observations).

The second dimension (which is analogous to the application of three-channel convolutions for colour images) contains 9 channels for the following time series: opening (Open), closing (Close), maximum (High) and minimum price (Low) prices, as well as values of 5 technical indicators – Exponential Moving Averages with periods of 5 (EMA(5)) and 32 (EMA(32)), Relative Market Strength Index (RSI), Average Range (ATR), and probable change in trend direction (Candlestick Indicator).

This set of predictors is based on the fact that exponential moving averages characterize short-term (EMA(5)) and medium-term (EMA(32)) trends, the RSI index characterizes the probability of a trend change, and the ATR index characterizes the degree of volatility of the time series.

The CNN architecture includes an Input Layer (InputLayer), Convolutional Layer (Conv1D), Pooling (MaxPoolling1D), Flattening layer (Flatten) and Fully Connected layers (Dense) (Fig. 4.15).

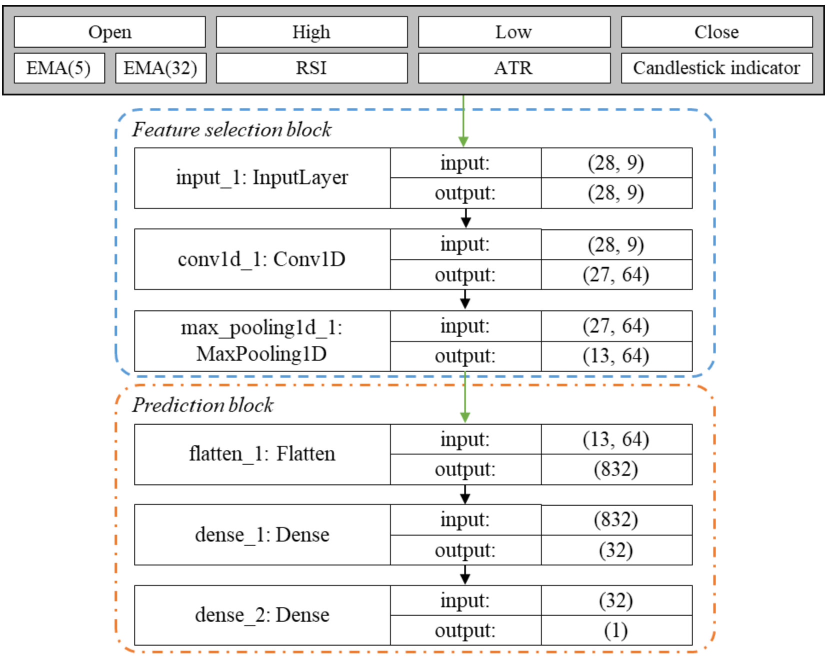

Figure 4.15. The architecture of a CNN for forecasting currency quotes

Source: designed by the authors

At the input layer, an input data set is formed: 9 time series with a window length of 28 observations, which are passed to the convolution layer.

The convolutional layer is the main block of CNN, which is designed to extract features from the signal (time series) and transform them. It contains for each channel its own kernel (filter), which processes fragments of the time series from the previous layer and forms sets (maps) of features – one map for each filter.

Mathematically, this can be described by a formula:

$$x_j^l = f\left(\sum_{i=1}^{n} x_i^{l-1} * k_j^l + b_j^l\right), \tag{4.35}$$

where x_j^l – a set of initial values from layer *l* which forming a feature map *j*; $f(\cdot)$ – activation function; b_j^l – *j*-th bias coefficient of the *l*-th layer; k_j^l – the convolution kernel of the *j*-th feature map for the *l*-th layer; «*» – convolution operation with kernel k, which consists in element-by-element product and summation of the input *x* (the output values of the previous layer) and the matrix of kernel weights.

A set of 64 filters is applied to each time series on the convolutional layer. At the same time, the matrix of connection weights during network design is not known because the convolution kernels are adjusted during the learning process. The scalar result of each convolution is pass to the activation function.

Semi-linear ReLU function was used, which has the form ReLU $= max(0, x)$. The advantage of this function over others (in particular, sigmoid or hyperbolic tangent) is that its use allows solving the problem of the vanishing gradient, since with a positive value of the signal, it does not change. In addition, the application of ReLU allows to reduce the training time of the model.

The Pooling layer performs the function of local averaging of the feature map in order to cut off secondary details in the found patterns, while its use helps to prevent overtraining of the neural network. So, the main purpose of this layer is to reduce the dimensionality of feature maps from the previous layer.

Formally, it can be described as follows:

$$x^l = f(a^l subsample(x^{l-1}) + b^l), \tag{4.36}$$

where x^l – is the output from the *l*-th layer; a^l, b^l – are the bias factors for the *l*-th layer; $subsample(\cdot)$ – operation of sampling local maximum values.

After several iterations of convolution and pooling of the time series the model is retuned (by adjusting the weights) from the specific data set to the more abstract feature maps which are used as predictors. Thus, after passing the convolution and MaxPooling layers, the feature maps increase (depending on the number of filters) and the length of the sliding window decreases (depending on the size of the kernel).

Since the output of the MaxPooling layer is an array (tensor), and the input to the fully connected layer (Dense) must be a one-dimensional array, an alignment layer (Flatten) is used to transform the data, which decomposes the array into a vector. The output of this layer contains 832 neurons, which, in particular, is shown in Fig. 4.14.

The obtained feature vector is passed to fully connected layers. The output of the first layer contains 32 neurons (dense_1), the values of which are fed to the second fully connected layer (with one output neuron) to form the final prediction. Their functioning can be described by the formula:

$$x_j^l = f\left(\sum_{i=1}^{n} x_i^{l-1} * w_{ij}^{l-1} + b_j^{l-1}\right), \quad (4.37)$$

where x_j^l – is a set of initial values from layer l forming a feature map j; $f(\cdot)$ – activation function; b_j^{l-1} – j-th bias coefficient of the (l-1)-th layer; w_{ij}^{l-1} – weights $(l-1)$-th layer; n – number of neurons on the Fully connected layer.

Depending on the architecture of the network, the Fully connected layer can directly forecast (or classify) the time series of currency quotes, or can transfer the generated features (predictors) to the next block of the model.

Unlike GRU, CNN is non-recurrent, which means that this network does not retain memory of previous time series patterns. Instead, it can only train based on data that is input by the model at a given point in time.

For this reason, GRU and CNN layers are often combined in time series forecasting. This allows the GRU layer to account for consistent dependencies in the time series, while the CNN layer further informs this process with advanced convolutions.

The CNN block and the GRU block take the same time series input in two different representations. CNN treats a time series as a one-dimensional time series with many time steps. If there is a time series of length L, the CNN block will receive data in L time steps. In contrast, the GRU block receives the input time series as multivariate time series with one time step. This is achieved by a dimensional blending layer that transposes the time dimension of the time series.

The use of GRU is reduced to processing one parameter of time data of currency quotes at a time. Each currency quote data is separated and processed independently, and then the processed data from each currency quote is combined and processed to estimate the final forecast.

Such an approach allows you to develop models that can independently extract useful information from various data of currency quotes and subsequently process this information to achieve accurate and reliable forecasts [16].

The information control system is built on the architecture of deep neural networks CNN+GRU (Fig. 4.16).

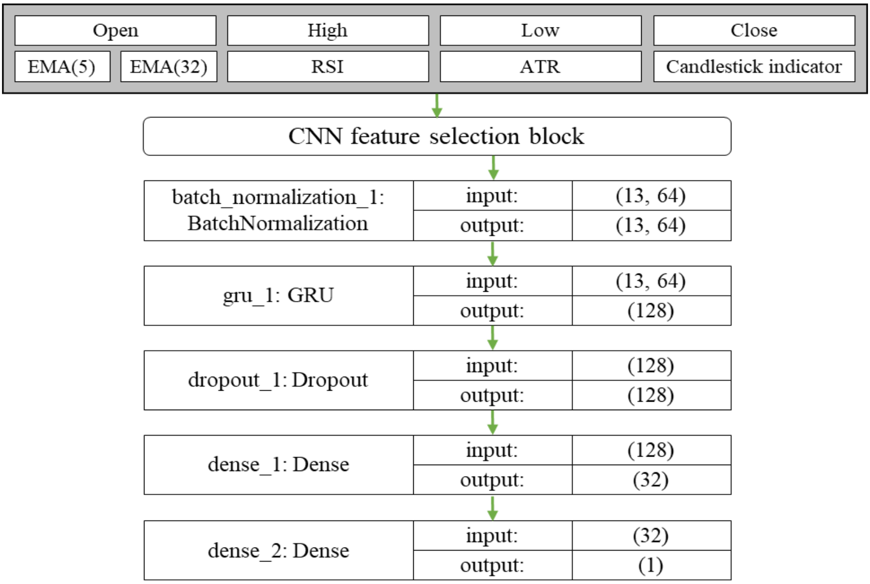

Figure 4.16. Architecture of a DNN for forecasting currency quotes based on a Convolutional and Recurrent model

Source: designed by the authors

In this architecture, a block of convolutional layers is used to detect features and construct predictors, while the detected features are transmitted to the input of the recurrent block, which makes the prediction.

According to the ML methodology, the development of an ICS should be carried out according to a conceptual scheme based on decomposition into a number of such tasks (Fig. 4.17):

1. Determination of the input set of factors (predictors) that must be taken into account when forecasting currency quotes. The criteria or requirements for the selection of significant factors are the achievement of the required accuracy of the forecast on the test or validation sample, provided that this set of predictors is minimized.

2. Data preparation (pre-processing), which consists in removing noise, for example, using the Fourier transform and the wavelet transform.

3. Determination of the necessary size of training, test and validation samples (datasets). When solving this task, there are also conflicting requirements related to the ability of ANNs to overfitting or underfitting.

4. Selection of the type and architecture ANNs, training methods (optimizers), etc.

5. Optimization of the basic architecture by conducting a series of computer experiments using different datasets.

6. Testing and validation of developed models for regression and classification tasks using various accuracy metrics, setting hyperparameters.

7. Application of developed models for forecasting.

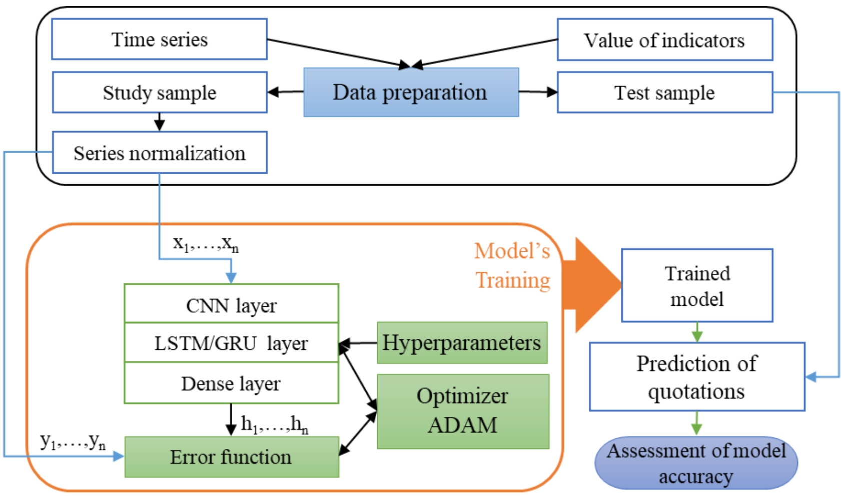

Figure 4.17. Conceptual diagram of the ICS
for forecasting currency quotes using a system of DNN models

Source: designed by the authors

All models were trained for 25 epochs using a modified gradient descent method (implemented by the Adam function in the Keras library for Python) [16]. When training the models, the input data were supplied in packets (mini batches) of 32 data blocks each (two-dimensional tensors: 9 time series of 28 observations), the weights are adjusted during the passage of each packet.

At the same time, computer simulations showed that further building up of layers and increasing the number of neurons does not lead to a noticeable increase in the efficiency of the model, but significantly increases the duration of optimization and causes the problem of retraining.

Conclusions

The integration of AI models, particularly DL architectures, into ICS holds immense potential for enhancing decision-making processes, optimizing operations, and driving innovation across various industries. The capabilities of these models, including transformers, language processing models, and computer vision, can revolutionize the way organizations process, analyse, and leverage data for strategic advantage.

DL models, with their ability to learn from vast amounts of data and uncover intricate patterns, offer promising avenues for improving decision support systems within ICS. CNNs and RNNs have already demonstrated remarkable performance in computer vision and NLP tasks, respectively. These models can be employed to analyse vast repositories of structured and unstructured data, such as images, videos, and text, enabling organizations to extract valuable insights and make informed decisions based on comprehensive data analysis.

Transformers, a recent breakthrough in deep learning architecture, have garnered significant attention due to their superior performance in various natural language processing tasks, including machine translation, text summarization, and question-answering. By leveraging transformers, ICS can integrate advanced language models capable of comprehending and generating human-like text, facilitating seamless communication and information exchange between systems and users. This can revolutionize areas such as customer service, knowledge management, and content generation, enabling organizations to deliver personalized and contextually relevant information to stakeholders.

Additionally, the integration of computer vision models within ICS can unlock new possibilities for visual data analysis and automation. CNNs can be employed to process and interpret visual data from various sources, such as surveillance footage, product images, or medical scans, enabling real-time monitoring, quality control, and predictive maintenance, among other applications. This can significantly enhance operational efficiency, reduce human error, and provide valuable insights for decision-making processes.

Furthermore, the combination of these AI models with traditional ICS can lead to the development of intelligent decision support systems. By leveraging the predictive capabilities of DL models, organizations can anticipate future trends, identify potential risks, and devise proactive strategies to mitigate challenges and capitalize on emerging opportunities.

However, it is crucial to address the ethical considerations and potential biases associated with the deployment of AI models in sensitive domains. Ensuring transparency, accountability, and the incorporation of robust governance frameworks is essential to mitigate risks and foster trust in these systems. Additionally, the need for interdisciplinary collaboration between AI experts, domain specialists, and decision-makers cannot be overstated, as it is vital for the responsible and effective integration of AI models into management information systems.

In summary, the prospects of leveraging DL models, transformers, language processing models, and computer vision within management information systems are vast and promising. These AI models possess the potential to revolutionize decision-making processes, enhance operational efficiency, and drive innovation across various industries. However, their successful integration requires a careful consideration of ethical implications, bias mitigation strategies, and a collaborative approach involving diverse stakeholders.

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SECTION 5
DEVELOPMENT OF APPLIED INFORMATION CONTROL SYSTEMS, THEIR COMPONENTS AND TECHNOLOGIES

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INFORMATION SYSTEM FOR MANAGEMENT OF LOGISTICS PROCESSES AT SPECIAL PURPOSE ENTERPRISES

A special-purpose enterprise, in the military context, is an enterprise engaged in the development, production, or use of special technologies, equipment, or systems for military or intelligence purposes. Such enterprises may be involved in the production of communications equipment, military equipment, aerospace systems, cryptographic devices, etc.

Thus, in most cases, for special-purpose enterprises, especially in the military-industrial complex, customers are state or business entities, representatives of the military-industrial complex, and military authorities. These organizations can finance and set targets for the development and production of military technologies, weapons, electronics, software, and other specialized products and services.

The state usually acts as the main customer for such enterprises, as their products and services are oriented to address military or defense needs. The task, creation, and maintenance of high technological and military capabilities are often national security priorities for states.

In today's globalized world, efficient logistics operations are the backbone of any organization. They ensure that a business can source from suppliers, and produce and deliver its products or services to the end customer in a timely and cost-effective manner.

Logistics is a «service» part of the business that covers all processes from the moment of purchasing raw materials for its production to the moment of selling finished products (including delivery of products to the buyer) [1].

We can provide the following understanding of the essence of logistics – logistics is a scientific and practical direction of management and optimization of logistics flows to achieve operational, tactical, and strategic goals in a particular logistics system.

The modern idea of logistics can be formulated as follows: logistics is a management concept for the development, organization, management, and implementation of efficient and cost-effective movement of objects (goods, information, money, and personnel) in value-creation systems within one or more enterprises. A more detailed definition of logistics objects as the flow of goods, information, money, and personnel shows that logistics is a common important topic for all industries and belongs to the general service sector and the field of public administration. This is also reflected in the names: industrial logistics, trade logistics, service logistics, and banking logistics [2].

Information systems in logistics management can be created to manage material flows at the level of an individual enterprise, or they can facilitate the organization of logistics processes in regions, countries, and even a group of countries.

At the level of an individual enterprise, information systems, in turn, are divided into three groups (Fig. 1):

– strategic;
– management;
– operational.

Logistics information systems belonging to different groups differ both in their functional subsystems and in their supporting subsystems. Functional subsystems differ in the composition of the tasks they solve. Supporting subsystems may differ in all their elements, i.e., technical, information, and mathematical support. Let’s take a closer look at the specifics of certain information systems.

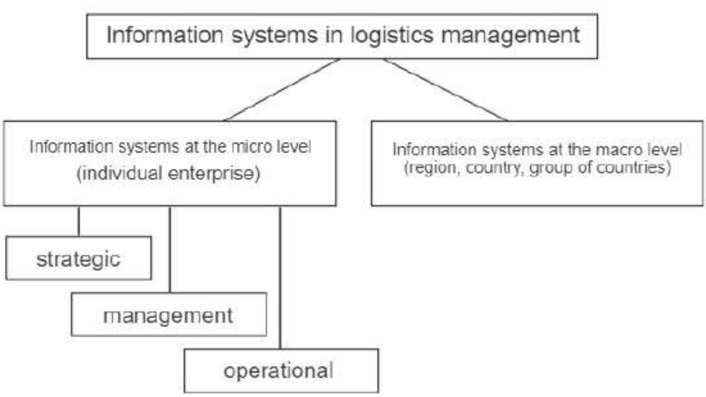

Figure 1. Types of information systems in logistics

Source: [3]

Logistics information systems

LIS is the basis of modern logistics operations. In comparison with traditional logistics, the management and functioning of modern logistics differ in intelligence, systematization, automation, and other aspects. LIS is a human-computer interaction system consisting of employees, computer hardware and software, network equipment, and other office equipment. Its mission is to provide the administrative staff of the logistics department and other administrators with support for strategic, tactical, and operational decisions by collecting, storing, transporting, processing, maintaining, and outputting information about logistics, thus giving full opportunity to use the strategic advantages of the organization and increasing efficiency and profits of enterprises from logistics operation. Information plays a vital role in modern logistics, the central nervous system which is built by the information system. By tracking the information dynamics in the logistics system quickly, accurately, and in real-time, enterprises can respond promptly to the market and achieve an efficient cycle between business flow, information flow, and capital flow.

The logistics information system is the placement of information and the means of processing information flows among themselves and in relation to other logistics subjects in order to perform the tasks of planning, management, and control at enterprises.

Information flows are ensured by the technique of collection, transmission, issuance of data processing and decoding. A feature of the information flow in logistics can also be defined as an accompanying material flow, as it contains information about material flows, which is necessary for managing the movement of material flows.

In addition, part of the information flows in logistics is necessary for the maintenance of formation processes, storage of resources in the warehouse, and processes of intra-production and intra-warehouse movement of material resources.

When designing information flows, the effectiveness of their functioning is ensured on the basis of the choice of a rational path and mode of service by means of communication to ensure the reliability of material and technical support of information flows.

The main information systems are designed to perform the main functions of logistics and the formation and improvement of information flows based on their rational organization and the intensity of transmission and processing of information coming from its source to the consumer. Efficiency is achieved by taking into account all the chains in the data processing system, the scheme of information connections of the units of the economic object between itself and the external environment.

Information Systems in Manufacturing and Logistics

Logistics information systems are specially designed to support all elements of logistics processes, including coordination of logistics activities, material flow and replenishment of stocks. Where necessary, this involves the integration of hardware and software in addition to the support of data exchange and data capture technologies supported at the interrelated phases of production and logistics between different companies by specialized production and logistics information systems (MLIS). It is recognized that overall supply chain performance can be improved through information technology (IT), and although many firms have incorporated transactional processing, they still require improvements so that IT supports improved planning and decision-making programs. These are provided by both specific firms and are also a major contributor to the many third-party logistics firms that companies outsource their logistics needs to.

Before continuing with MLIS/LIS, it should be clarified that the terms «MLIS» and «LIS» can be used interchangeably, but LIS can also be defined as a subsystem or component of MLIS that focuses on the logistics aspects of a business. While MLIS can cover a wider range of functions, including both production and logistics, for comprehensive management of the entire business process.

First of all, the individual elements of MLIS (related to identification, warehouse management systems, systems. Transport management, quality management, information exchange, and enterprise resource planning (ERP)) and their key use for both the collection and processing of transactions and support for improved decision-making. This is facilitated by the emergence of interest in radio frequency identification (RFID) technologies to support the identification and tracking of commodity stocks.

MLISs can be configured to work in a variety of scenarios and often support warehousing and transportation management by streamlining processes and tracking inventory locations and movements. MLIS acts as a transactional system that attempts to record all information changes and material movements in such a way that it is available to all stakeholders at all times. In fig. 2 presents an overview of MLIS components.

Information systems of logistics are increasingly integrated into enterprise resource planning systems. The approach is based on the ability to accurately record information about the location and movement of materials, people and equipment. This is supported by the use of bar coding, RFID technology, warehouse management systems, transport management systems, quality management, information exchange between enterprises and inclusion in ERP packages.

Together, these systems capture transaction-level information and support decision-making in logistics, transportation, and materials management using specialized optimization and planning tools. Efforts are still underway to connect and integrate MLIS and ERP for multiple enterprises to support the visibility and management of logistics and quality activities in the supply chain. This is supported by new software approaches using service-oriented architecture (SOA) and software as a service (SaaS) architecture, and the increasing adoption of RFID combined with the ability to collect, transmit, and use RFID-related information for logistics efficiency to improve supply chain productivity.

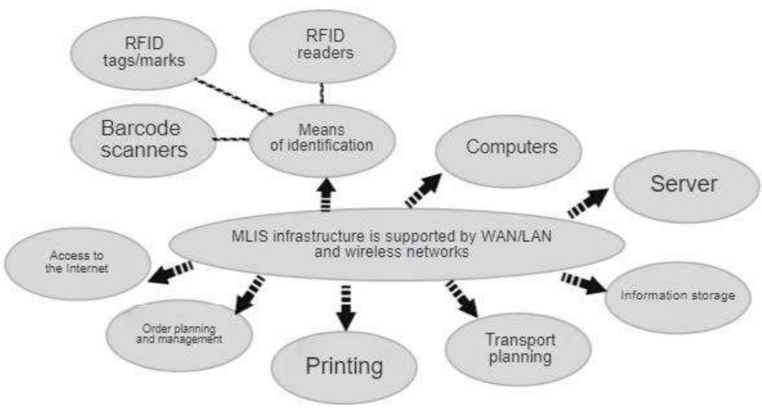

Figure 2. Components of MLIS

Source: [5]

Logistics Information Systems in Ukraine

A significant number of factors that are formed both in the internal and external environment affect the performance of any economic object. The formation of the necessary level of management decisions is possible on the effective management of information logistics flows based on the optimization of the activity processes of the structural subdivisions of the economic object. This is due to the need to manage the movement of all resources based on the logistics of information and its flows, which ensures the objectivity of management decisions. The analysis of such processes showed that both the management of information logistics flows at the appropriate level and the evaluation of the effectiveness of its functioning are time-consuming. In this context, it is necessary to pay attention to the fact that logistics costs in the EU and the USA make up 8–10 % of the total, and in Ukraine such costs are much higher and account for 35 %. Therefore, the analysis of information flows of logistics and the effectiveness of management of logistics flows of economic objects remains relevant, and the named factors are determinants of the formation of logistics costs.

Unsolved parts of the problem in the field of formation of logistics information systems at domestic enterprises are the lack of a systemic vision in building a logistics strategy. This has a significant impact on the competitive positions of domestic enterprises in various industries, since international companies that use a well-developed logistics strategy operate on the territory of Ukraine. Such strategies became the basis for the formation of integrated logistics information systems of a global scale, in which the main component is modern information support. In this regard, the researchers formulated the problems that arise in the way of implementing LIS at domestic trade enterprises and developed methodical approaches to the organization of such systems. Formulation of problems with the implementation of LIS was done based on the study of the state and conditions of the functioning of information flows at domestic trade enterprises. Based on this, a description of the main principles of building a logistics information system and recommendations for removing obstacles to their implementation in modern business conditions were defined and formed.

The use of information technologies in the logistics systems of Ukrainian enterprises is constantly growing (Fig. 3).

It should also be noted that a characteristic feature and, as a result, a problem of statistical research of the logistics services market is the existence of a significant number of methods that are difficult to implement in practice, are incomplete or not interconnected, which leads to heterogeneous and inaccurate results, which in the complex do not allow qualitatively solve the problem of evaluating the logistics services market.

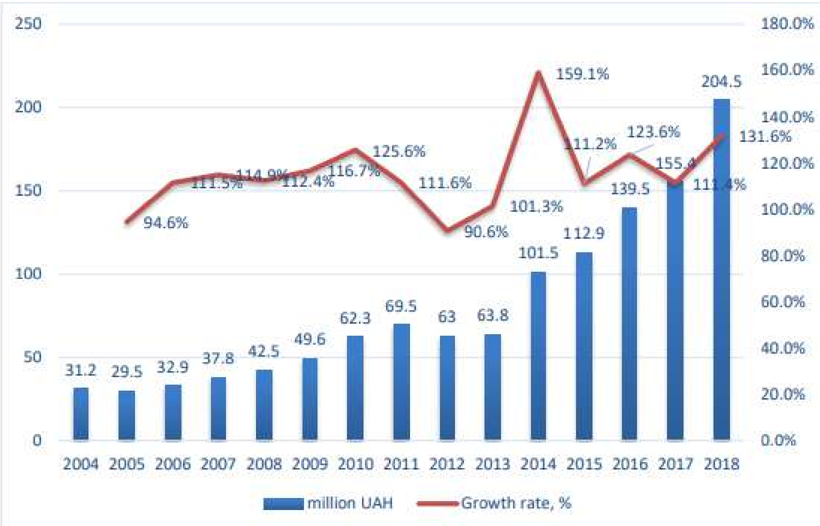

Figure 3. Use of information technologies in logistics systems

Source: [5]

Selection of approaches and technologies for system development

The development of a quality product begins with defining its life cycle. This is a clear plan of action that allows developers to understand what should be achieved, how to achieve the result and what methods to use for this.

The Software Development Life Cycle, or SDLC in short, is a well-defined, structured sequence of software development stages for the development of an intended software product. The SDLC defines the complete development cycle, that is, all the tasks related to the collection of requirements for the maintenance of the product. The SDLC provides a series of steps that must be followed to effectively design and develop a software product. The SDLC framework includes software stages: communication, requirements gathering, feasibility study, system analysis, software design, coding, testing, integration, implementation, operation and maintenance, and disposition.

The choice of a life cycle model for the development of IS for the management of logistics processes at special-purpose enterprises depends on the specific needs and requirements of the project, as well as on the characteristics of the enterprise itself. The following models can be considered for this project:

1. The cascade model is a traditional model with a linear workflow where development proceeds through sequential stages such as analysis, design, implementation, testing, and implementation. It is suitable if the requirements can be clearly defined from the very beginning and are not subject to change (Fig. 4).

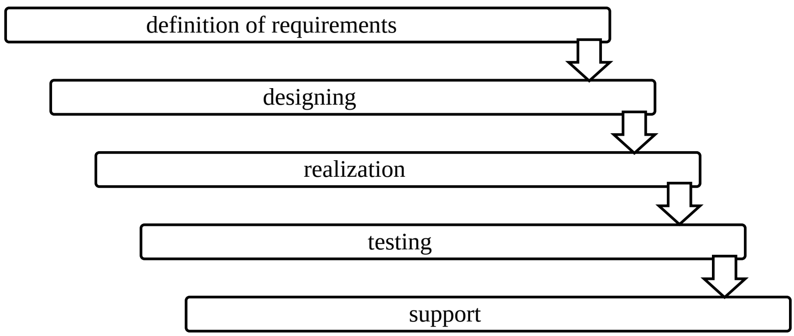

Figure 4. Cascade model of IS development

Source: designed by the authors

2. The Iterative Development model is a model where development occurs partly through iterations, and requirements may change during the process. It is useful if the requirements are not clearly defined or may change during the project (Fig. 5).

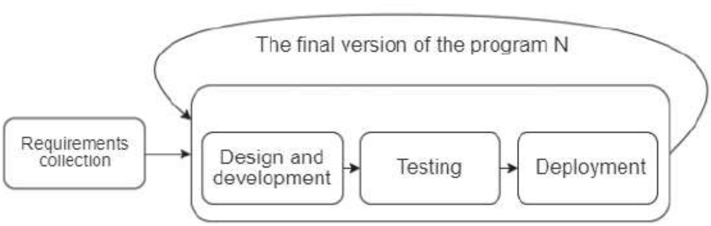

Figure 5. Iterative model of IS development

Source: [6]

3. The joint application development model is a model where there is intensive interaction with project participants during the definition of

requirements and development. It is well suited for projects where the active participation of end users is important.

4. The spiral model is a model that provides flexibility and adaptability, allowing the team to quickly respond to changing requirements. It is suitable for projects with significant changes in requirements or the need to quickly implement some functionality. In Fig. 6 presents the work of the spiral development model.

5. The evolutionary prototyping (layout) model is a model that provides system prototyping for requirements clarification and feedback. It is suitable for projects where it is important to understand and clarify requirements through an iterative process.

To decide which lifecycle model is appropriate, we need to consider the requirements for our system. To develop an information system for managing logistics processes at special purpos enterprises (military enterprises), we can highlight the following characteristics of requirements:

1. A large number of changing requirements are due to rapid changes in military needs.

2. High level of data security and privacy.

3. Requirements for the speed and efficiency of logistics management due to the possibility of emergencies.

4. The need for great adaptability and the ability to quickly change the functionality of the system.

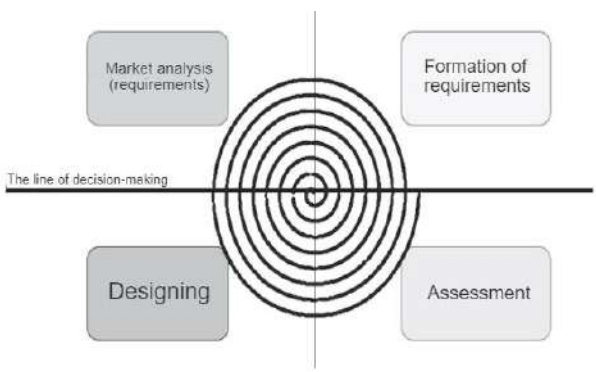

Figure 6. Spiral model of IS development

Source: [7]

In this case, the evolutionary prototyping model or the spiral model may be most effective. These models provide the ability to flexibly respond to changing requirements, quickly iterating and implementing functional changes as needed. Increased adaptability and the possibility of implementing prototypes will contribute to the effective implementation of the system in conditions of great dynamics and uncertainty.

The choice of programming language depends on several factors, in particular, on the specific requirements of the program, the level of skill of the development team and the hardware on which the program will work [8]. Here are a few programming languages that can be important when developing a system for military logistics management:

1. Java:

– Advantages: Code portability, large community support, high security.

– Usage: Java is well-suited for developing distributed systems, which can be important for logistics systems with many different components.

2. C# (with the use of the .NET platform):

– Advantages: Integration with Windows, large public support, developed infrastructure for creating corporate applications.

– Usage: C# is well suited for developing desktop and web applications that may be important for logistics management systems.

3. Python:

– Advantages: Simplicity, code readability, a large number of libraries.

– Usage: Python can be effective for prototyping, data processing, and implementing some logistics algorithms.

4. C++:

– Advantages: High execution speed, and control over resources.

– Usage: C++ can be important for systems that require high efficiency and large amounts of data processing, such as logistics systems in military enterprises.

In terms of performance, C++ is generally considered the fastest of the three languages, followed by C#, Java, and Python. However, the performance difference between these four languages may vary depending on the specific application and the hardware it is running on. In terms of maintainability, Python is often considered the easiest to maintain due to its simple and straightforward syntax, followed by Java and C++. However, the ease of support may also depend on the complexity of the application and the skill level of the development team. In terms of flexibility, Python is often considered the most flexible due to its dynamic typing and ability to support both functional and object-oriented programming styles. C# is a powerful programming language that offers a number of advantages for OOP. It is efficient, easy to learn, and integrates well with the .NET platform.

The software development environment chosen was Visual Studio Community 2022[9], a free integrated software development environment (IDE) provided by Microsoft. It is a powerful tool for building different types of software, including desktop apps, web apps, mobile apps, and more.

Visual Studio Community 2022 is built on the .NET platform, allowing developers to use programming languages such as C#, VB.NET, F#, and more. The integrated environment contains many useful tools, including a code editor, Git support, a debugger, a profiler, and more.

One of the main advantages of Visual Studio Community 2022 is that it is free. This means that developers can access a powerful development environment without the need for large licensing costs. Moreover, Visual Studio Community 2022 gives users the ability to create and edit projects on any platform, which greatly simplifies the development process. For example, it has a built-in debugging system that allows you to find and fix errors in your code. The environment also includes code testing and profiling tools that allow you to identify and correct application performance issues.

In addition, Visual Studio Community 2022 provides users with a wide range of plugins and extensions that extend its capabilities. For example, you can install extensions for mobile app development, web extensions, and more. This allows developers to create software that meets their needs and the needs of their customers.

Visual Studio Community 2022 also has built-in support for Git, which allows developers to work with code and control its version. This is especially useful for teamwork when multiple developers are working on the same project.

One of the new features of Visual Studio Community 2022 is improved support for .NET 6 assemblies, which enables faster and more efficient development of NET-based software. Also, Visual Studio Community 2022 has support for the new version of C# 10, which allows developers to use new features of the programming language and improved tools for working with code. Another important feature of Visual Studio Community 2022 is its ability to integrate with other development tools such as Azure DevOps and Visual Studio Code. This allows developers to easily switch between different tools, which makes the development process easier and provides a more efficient use of time.

Structure and characteristics of IS

The effective development of production logistics is closely related to the introduction of logistics information systems (LIS) in enterprises. Timely provision of information to the production and supply units of the enterprise is one of the determining factors in increasing the efficiency of its functioning. Therefore, in the general system of tasks aimed at improving the operation of the enterprise and, in particular, logistics, the development and installation of appropriate logistics information systems is an urgent task.

LIS are information networks, the creation of which begins from the moment of determining the requirements of customers in a given market segment and distributing the received information through distribution channels and production directly to the suppliers of the necessary material resources of the enterprise.

Within the production system of the enterprise, LIS performs an auxiliary function for the implementation of the process of managing the movement of material flows (MP) by «delivering» the necessary information to specific consumer units with minimal time expenditure. LIS of a manufacturing enterprise is created according to the standard information processing procedure: collection → synthesis → analysis → transfer to the manager. With this in mind, the LIS structure should consist of the following main subsystems: information collection, information systematization, and logistics analysis [10].

The first subsystem accumulates information about the purchase of material resources; implementation of the production plan for the production of products, generation of waste and their disposal; distribution and sale of products, return of damaged products to consumers (if necessary), and destruction of waste (if necessary). Further, all information is sent to the «Systematization of information» subsystem, from where it is sent in a condensed form to the information and analytical division of the enterprise's logistics service (the third subsystem). At the same time, it should be noted that an important component of the functioning of the LIS of the enterprise is a thorough analysis and evaluation of the received information about the movement of vehicles within the production system of the enterprise and the external environment surrounding it.

Processed and systematized information about logistics flows and the external environment is transferred to the head of the logistics service, who, after analysis, correction, and appropriate documentation, sends it to the deputy director of logistics. In turn, the deputy director of logistics coordinates the obtained results with the production plan.

After the agreement, plans for the implementation of specific logistics operations and processes of production sites and workshops are adjusted. The deputy director of logistics transforms the received information into relevant orders, instructions, and orders, which are delivered in real-time to the logistics service, and through it to its divisions, thus ensuring the efficiency and flexibility of the company's logistics management [10].

An information system for managing logistics processes at special-purpose enterprises can provide a variety of benefits for various stakeholders.

1. Special purpose enterprise:

– Automation and optimization of logistics processes, which allows the enterprise to effectively manage stocks, supply, and distribution of materials and equipment.

– Reduction of costs related to logistics management due to automation and optimization of processes.

– Increasing the productivity and speed of logistics operations.

– Improvement of control and management of logistics processes, which helps to reduce risks and increase reliability.

2. Management of the enterprise:

– Providing access to key information about logistics processes for making strategic decisions.

– Monitoring the efficiency and productivity of logistics operations to identify opportunities for optimization and efficiency improvement.

3. Employees:

– Providing access to the necessary information and tools to fulfill their responsibilities for managing logistics processes.

– Providing a convenient and efficient interface for using the system and performing work tasks.

4. Customers and partners:

– Ensuring fast and efficient service through optimized logistics processes.

– Increasing the level of service due to accurate and timely deliveries of goods and services.

The main stages of logistics processes at special-purpose enterprises include:

- Planning and forecasting;
- order and supply of raw materials;
- production;
- warehousing and inventory management;
- transportation;
- order management and service;

– information technology;
– risk and security management.

Logistics processes at special-purpose enterprises are aimed at ensuring efficient production, reducing costs, and meeting customer needs for timely and high-quality products.

Formulation of the problem

The development of business requirements, functional requirements and non-functional requirements is a key stage in the process of creating an information system for managing logistics processes at special-purpose enterprises. We have formulated the following requirements for our IS:

1. Business requirements:

– Ensuring the accuracy and reliability of accounting information about stocks and deliveries.

– ensuring the timeliness and efficiency of the processes of supply and distribution of materials and equipment;

– increasing the efficiency of logistics operations and reducing costs for their implementation;

– ensuring security and protection of confidential information regarding logistics processes;

– support for a convenient and intuitive interface for users.

2. Functional requirements:

– The possibility of keeping records of goods, stocks and other resources;

– automated planning and coordination of logistics operations, such as supply, storage, transportation, and distribution of goods;

– a system for monitoring and tracking the state of logistics processes and material flows;

– analysis and reporting functions to support decision-making and optimization of logistics processes.

3. Non-functional requirements:

– Security requirements: ensuring the protection of confidential information and preventing unauthorized access to the system;

– performance requirements: ensuring the speed and efficiency of the system, especially in conditions of a large amount of data and a large number of users;

– availability requirements: ensuring the availability of the system during the entire working time without major interruptions or failures;

– scalability requirements: the possibility of increasing or decreasing the scale of the system depending on the needs of users.

These requirements form the basis for the development of an information system that will meet the needs and expectations of a special-purpose enterprise in managing logistics processes.

Precedence diagram

To reflect the role of this or that user in our IS, we will create a Use Case Model diagram.

A use case diagram is a diagram that describes the interaction between stakeholders and functions of an internal system. It explains what the system does and how actors use it, but does not explain how the procedure works internally. It helps define the system requirements so that stakeholders can understand the actions in the system.

In Fig. 7 presents an example of a precedent diagram.

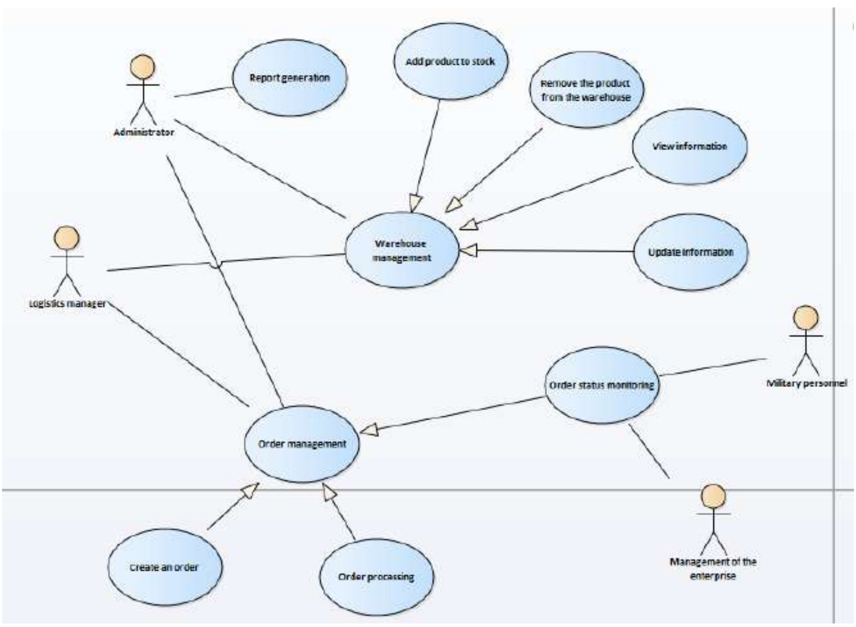

Figure 7. Precedents diagram

Source: designed by the authors

This diagram of precedents reflects the main functionality of the information system for managing logistics processes at a special-purpose enterprise. The system administrator can manage the warehouse, manage orders, and generate reports. The management of the enterprise can monitor the status of the order. The logistics manager is responsible for warehouse management and order management. Military personnel – a representative of the customer (an employee of the Ministry of Defense of Ukraine), who can also monitor the status of the order within the information system.

This case diagram provides an overview of the functionality of an information system for managing logistics processes in special-purpose enterprises. It helps to understand what actions can be performed by different actors and how they interact with the system. This diagram is a starting point for the further development of detailed specifications of the functionality of the system.

Databases and knowledge bases of IS

The information support of the logistics process management system at special purpose enterprises consists of various components that ensure the collection, processing, storage and distribution of information in the system. Here are some of the main components of information security:

1. Data sources: These can be various sources, such as sensors, barcode scanners, monitoring systems, databases, external information systems, etc. They provide information on various aspects of logistics processes.

2. Data collection and processing systems: These systems are responsible for collecting data from various sources, processing it, and preparing it for further use. They may include software to automate data collection and processing processes.

3. Databases and data warehouses: These components are responsible for storing information in a structured and organized manner. They provide reliable access to data and are used to store different types of information, from operational data to analytical data.

4. Analytics and reporting systems: These systems are used to analyze data, identify trends, and create reports and dashboards for management decision-making. They help identify problems, improve processes, and solve strategic tasks.

5. Access control systems: These systems are responsible for controlling access to information and ensuring data security. They define the access rights of users to different parts of the information system based on their roles and responsibilities.

6. Data Quality Assurance Systems: These systems are used to ensure data quality, and identify and correct data entry errors, duplication, and incompleteness.

These components work together to ensure effective and reliable information support of the logistics process management system. They provide the necessary information for making management decisions, support the optimal level of productivity and efficiency of logistics operations.

Databases and data warehouses are the basis for storing, managing, and accessing information in the logistics process management system at special-purpose enterprises. They provide reliable storage and effective access to all information necessary for optimal management of logistics processes. Here are some types of databases and their roles in the system:

1. Operational Databases: Used to store operational data, such as information about goods, orders, customers, warehouses, transportation, etc. These databases provide access to up-to-date information for ongoing operations.

2. Analytical Databases (Analytical Databases): Used to store data used for analysis and creating reports. These databases enable complex analytical queries and data sampling to identify trends and make strategic decisions.

3. Data Warehouses: Used to integrate and store data from various sources, such as operational databases, external data sources, monitoring systems, etc. These data warehouses are created to support analytical reporting and business intelligence.

4. Customer Databases: Used to store and manage information about customers, their orders, purchase history, and other data necessary for managing customer relations and fulfilling orders.

5. Geographic Databases: Used to store geographic data, such as maps, coordinates of warehouses and delivery routes, information on territorial restrictions, and other geographic aspects important for logistics processes.

These databases and data stores interact with each other and with other components of the system, providing access to information from various sources and allowing them to effectively perform various functions of management and analysis of logistics processes.

Thus, databases and data warehouses play a key role in the management system of logistics processes at special-purpose enterprises, providing reliable storage and effective access to information necessary for the performance of various management and analysis functions.

List of information objects created in the database:

– Table «Clients»: Client ID, First Name, Last Name, Contact Information, Order History, etc.;

– Table «Orders»: Order ID, Creation date, Customer, Products, Quantity, Order status;

– Table «Products»: Product ID, Name, Description, Price, Quantity in stock;

– Table «Warehouse»: Product ID, Quantity in stock, Received/delivered date.

– Table «Payments»: Payment identifier, Order, Amount, Payment date, Status;

– Table «Employees»: Fields: Employee ID, First Name, Last Name, Position, Date of Employment;

– Table «Events»: Fields: Event ID, Event Type, Date and Time, Notification, User ID;

– Table «Users»: Fields: User ID, Login, Password, Roles, Permissions.

The structure of the database being designed is presented in Fig. 8.

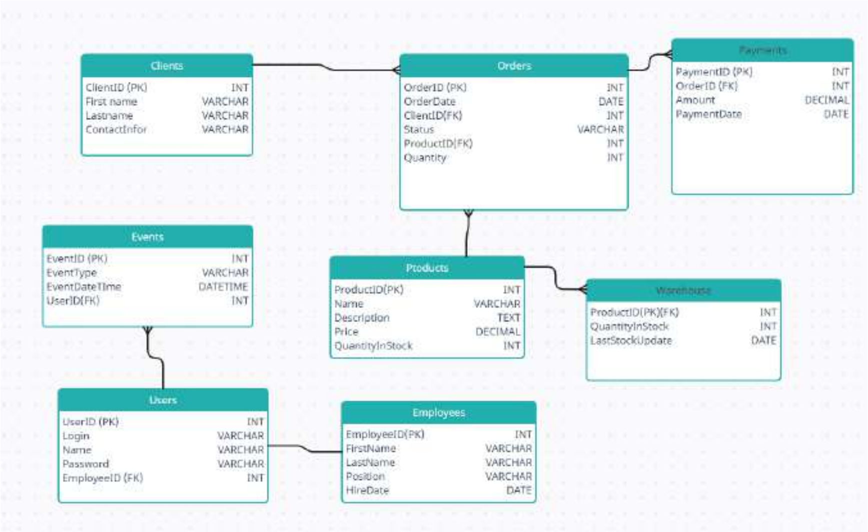

Figure 8. The logical level of the database structure

Source: designed by the authors

The DBMS chosen for this course project is SQLServer.

MS SQL SERVER is a database management system owned by Microsoft Corporation. Modern software products require appropriate technical characteristics of computer equipment. Before installing MS SQL, it is necessary to analyze the operating system. So, for the Windows 10 (64-bit) operating system, you can install MS SQL Server 2019 and MS SQL Server Management Studio. Windows 10 (32-bit) and Windows 7 (32/64-bit) operating systems will support only MS SQL Server Express 2014. MS SQL Server Management Studio is already built into the latter and does not need to be installed additionally. MS SQL Server Management Studio is an integrated environment that provides management of any SQL infrastructure.

This is modern software that allows you to manage the creation and use of databases, namely, insert, update, delete and select information [11]. All information is structured in a table, in which data about a specific object is written in rows, and columns contain information about its characteristics or properties. All tables are connected using primary and foreign keys, and the entire set of these tables is called a relational database. It should be noted that it is mandatory to normalize the tables – this is the arrangement of information according to the following rules:

– the order of rows and columns do not carry any information;

– there should not be identical lines;

– there should be only one value at the intersection of a row and a column, all columns are normal;

– the primary key must uniquely identify a row;

– columns that depend only on part of the primary key must be separated in separate tables;

– the dependence of several cells on other non-key cells is eliminated.

This accounting and analytical system ensures the administration of databases, the reliability of their storage, the safety of use, and the integrity of data. It is built on the language of structured SQL queries, which is used to create a declarative programming language. With its help, queries, updates, and management of relational databases are formed, database schemes and its modifications, and database access control systems are created. which allows the user to interact with databases (Fig. 9).

Today, the SQL language acts as a tool for data management in application programs (for example, Ispro – a software package for optimizing the management of enterprises and budget organizations of various profiles), it is used to create interactive queries, namely, it is responsible for the physical structuring and recording of data on disk, reading data from it, allows you to accept SQL queries from various DBMS components and user applications.

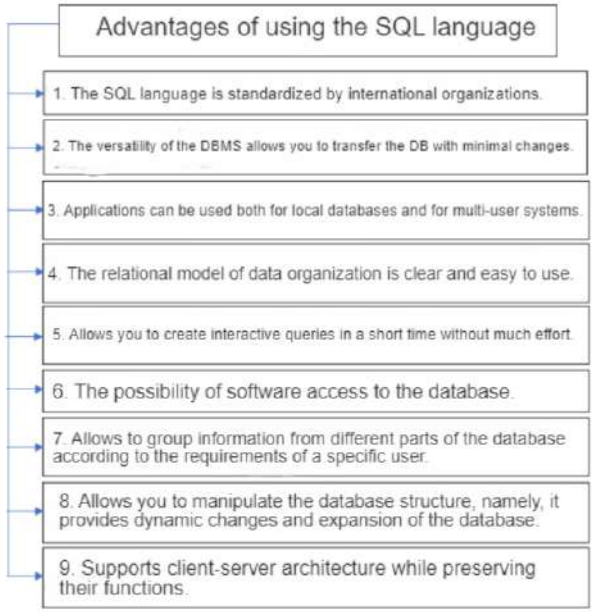

Figure 9. The main advantages of using the SQL language

*Source: [**Помилка! Джерело посилання не знайдено.**]*

Benefits of SQL Server:
– record high speed;
– fast obtaining of results both in the local and in the cloud network;
– advanced security features;
– hybrid cloud platform;
– intelligent data analysis.

Since SQL Server supports Transact-SQL, some changes must be made to query codes written in plain SQL.

IS software support

he software of the system for managing logistics processes at special-purpose enterprises is a key component and includes various modules and software components that provide automation and optimization of various logistics processes. Here are some basic software components of such a system:

1. Inventory Management System: A module for monitoring the availability of goods in warehouses, keeping inventory records, planning purchases, and moving goods.

2. Order Management System: A module for processing and fulfilling orders, tracking the status of orders, coordinating delivery, and returning goods.

3. Transportation Management System: Module for planning and organizing transportation, routing, cargo tracking, and delivery coordination.

4. Tracking and Identification System (Tracking and Identification System): Module for tracking the movement of goods through the logistics chain using barcode technologies, RFID, etc.

5. Warehouse Management System: A module for optimizing warehouse operations, including goods receipt, placement, storage, and shipment.

6. Analytics and Reporting System: Module for data analysis of logistics processes, generation of reports, identification of trends, and problem-solving.

7. Cost Management System: A module for monitoring and optimizing the costs of logistics operations, including the costs of transportation, warehousing, order processing, etc.

8. Customer Relationship Management System: A module for maintaining a customer database, processing orders, interacting with customers, and ensuring a high level of service.

Together, these software components help automate and optimize various aspects of logistics processes in a special-purpose enterprise. They provide a high level of efficiency, accuracy, and control over processes, which allows the enterprise to successfully perform its functions and tasks.

IS technical support

The technical support of the information system for the management of logistics processes at special purpose enterprises includes various components and infrastructure solutions that ensure the reliability, speed, and security of the system. Here are some key aspects of technical support:

1. Hardware:

– Servers: powerful servers to handle data and user requests.

– Computers and Workstations: Computers for users who use the system.

– Network equipment: switches, and routers for building a network and ensuring communication between system components.

2. Software:

– Operating Systems: Use of operating systems such as Windows Server, Linux to maintain servers.

– Databases: using databases such as MySQL, PostgreSQL, and Oracle to store and manage system data.

– Web servers: Installing web servers such as Apache, and Nginx to handle web client requests.

– Development platforms: using platforms such as Java EE, and .NET, to develop system software.

3. Networking:

– Internet connection: providing access to the system via the Internet for remote users and partners.

– Internal network: building an internal network for communication between system components within the enterprise.

4. Security:

– Authentication and authorization: establishing user authentication mechanisms and controlling access to different levels of the system.

– Data encryption: the use of encryption methods to protect the confidentiality and integrity of data during transmission and storage.

– Intrusion prevention: using intrusion detection and prevention systems to protect the system from intruders.

5. Backup and Recovery:

– Regular creation of backup copies of data to protect against loss of information in the event of an accident.

– Recovery plans: development and implementation of system recovery plans in case of unforeseen situations.

These are only some aspects of the technical support of the system, which can be important for the successful functioning of the information system for managing logistics processes. Each of them needs attention and proper configuration to ensure efficient operation of the system.

IS organizational support

Organizational support of the information system for managing logistics processes at special-purpose enterprises includes several aspects aimed at ensuring the effectiveness of the implementation, functioning, and support of the system in the organizational environment. Here are some key aspects of organizational support:

1. Strategic planning: Development of strategic plans for the implementation of the information system, determination of the purpose and goals of the project, and assessment of potential benefits for the organization.

2. Project management: Formation of the project team, distribution of duties and responsibilities, planning and control of work performance, determination of resources and deadlines.

3. Involvement of stakeholders: Involvement of management, employees, and other stakeholders in the system implementation process, ensuring their support and participation.

4. Organizational structure: Adaptation of the organizational structure for optimal implementation and effective functioning of the information system.

5. User training and support: Conducting user training on working with the system, providing technical support and consulting.

6. Change management: Management of changes in the organization related to the implementation of a new information system, problem-solving and implementation of improvements.

7. Monitoring and evaluation: Monitoring and evaluation of the effectiveness of system implementation, measurement of compliance of the achieved results with the strategic goals and objectives of the project.

8. Ensuring security: Protection of information and data, detection and prevention of possible threats and risks.

9. Resource management: Effective use of human, financial, and material resources for successful implementation and operation of the system.

These aspects help to create favorable conditions for the successful implementation and functioning of the information system in the organizational environment. They provide the necessary support and management of processes that allow the system to effectively perform its functions and achieve the strategic goals of the organization.

Prospects for further research

Further research in the field of information systems for managing logistics processes at enterprises can consider various aspects and directions. Some possible areas of further research include:

– Optimization of logistics processes: Research of new methods and strategies for optimization of logistics processes to increase efficiency and reduce costs.

– Use of the latest technologies: Research the implementation of the latest technologies, such as artificial intelligence, machine learning, and blockchain, to improve the management of logistics processes.

– Supply Chain Management: Study of supply chain management strategies and methods to ensure stability and efficiency of logistics processes.

– Standardization and integration of systems: Research the possibilities of standardization and integration of information systems for managing logistics processes between different enterprises.

– Risk management: Study of methods and approaches to risk management in the logistics chain, including risk analysis and minimization.

– Environmental sustainability: Researching the impact of logistics processes on the environment and developing strategies to reduce negative impact and increase environmental sustainability.

– Global trends: Study of global trends in logistics and their impact on special purpose enterprises and development of strategies for adaptation to changes.

These are only some possible directions for further research in this field. The development of information technologies and the growing complexity of logistics systems require constant scientific research and innovative approaches to solve the challenges facing modern enterprises.

Conclusions

This article analyzes logistics information systems, their role in logistics and production, and designed an information system for managing logistics processes at special purpose enterprises. The obtained results can be used in the use of a software product that must meet the specified requirements for both a special-purpose enterprise and a regular enterprise (for example, a metalworking enterprise). Also, the obtained results can be used in the design and creation of IS for managing logistics processes at enterprises based on the individual requirements and needs of the customer.

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INFORMATION CONTROL SYSTEM FOR BUSINESS ANALYTICS OF A SMALL ENTERPRISE

Today, our world is teeming with technology, having replaced manual labor and significantly enhancing our lives. Technology permeates every aspect of our existence, from simple gadgets like watches to complex computer systems and from household appliances like refrigerators to intricate server networks. We've grown accustomed to leveraging technology for tasks ranging from cooking and communication to entertainment and problem-solving. However, the perception of technology's value varies among individuals and across different fields, with some embracing it more readily than others. Yet, regardless of differing perspectives, technology remains a versatile tool capable of simplifying processes across various domains.

Among the many domains where technology intersects with our lives, the realm of work stands out as particularly significant. We spend a considerable portion of our time engaged in work, making it a prime area for technology integration. Within this sphere, the business sector, especially the role of analytics in small businesses, warrants closer examination.

In contemporary times, business intelligence has evolved into an indispensable component of organizations of all sizes and shapes. Information control systems play a crucial role, especially in small enterprises, enhancing efficiency, refining decision-making processes, and fostering business growth. However, small enterprises often overlook the importance of such systems, leading to several challenges, including resource constraints and a lack of awareness regarding their significance. This monograph aims to address these gaps by exploring the prerequisites, different types, and practical implications of business intelligence systems in the context of small businesses, shedding light on their benefits, challenges, strategies, and impact in today's digital age.

An overview of business intelligence in small businesses. An overview of business intelligence in small businesses reveals its essence as the organization's ability to make informed decisions and drive effective business development. A business intelligence information control system employs statistical analysis, predictive modeling, and data visualization techniques to investigate and interpret complex business data, identifying patterns, trends, correlations, and other relevant information crucial for strategic and operational decision-making. As defined by the Journal of Business Analytics, it is «a systematic thought process that uses qualitative, quantitative, and statistical computational tools and techniques to analyze data to gain insights to inform and support decision-making» [1]. We can say that the definition itself is quite voluminous, different authors interpret its aspects in different ways, but fundamentally, nothing changes – processing volumes of data and information using various methods to obtain valuable, practical, and useful information for further usage.

One of the key reasons why business intelligence is so important is its potential to improve decision-making processes. Traditionally, decisions have been made based on intuition and subjective judgment by individuals who, within their capabilities and knowledge, may unintentionally make wrong decisions. The business environment is becoming more complex each day and what was once the standard has become outdated, so relying on the decisions of responsible persons is no longer enough. The decisions of such persons should be made based on data, which will allow organizations to receive the necessary information in real-time and also to make more informed decisions. This approach is not new and it is still effective, especially in the time of active development of IT and AI. It is worth noting that according to Gartner research, 95 % of all decisions will be at least partially automated by 2025.

In addition, such a toolkit allows companies to quickly identify trends and patterns, helping them to stay ahead of competitors, as B. Dmytryshyn and M. Borovoy emphasize in their article. As they point out, «it is necessary to identify the facts of mismanagement, unproductive losses, and unjustified investments» [2]. In other words, not only examines how consumers and the market behave but also internal business procedures to find opportunities that could be hidden and dangers that could arise. For example, by analyzing data, companies can identify changes in the market, adapt their products or services to these changes, or move to another segment where there is less pressure from competitors.

Business intelligence tools also contribute to innovation in enterprises. Economic development can be considered cyclical, which is a general form of movement of the economy and the economy as a whole. This implies a change in the revolutionary and evolutionary stages of economic development, and economic progress and expresses the uneven functioning of various elements: fluctuations in business activity and a fall in market conditions, alternation of extensive and intensive types of economic growth [3].

Analytics tools affect operational efficiency. For example, in inventory management, when a lack of raw materials or data can lead to downtime, causing losses and loss of market position. By using statistical data, companies can predict this in advance, resulting in more efficient resource allocation, higher conversion rates, and ROI.

Business intelligence allows organizations to reduce risks and avoid potential threats. It is especially useful in risk management, optimization of business processes, implementation of innovative ideas, and process reengineering, as O. Guseva points out in her article [4].

Business intelligence information systems are gradually being implemented, which creates additional workplaces. This is not a direct benefit for the companies that use them but contributes to the development of the economy as a whole. That's why organizations are actively looking for people with the right skills – analysts.

However, no matter how attractive and wonderful the benefits of business intelligence information control systems look, many small businesses face challenges in implementing such solutions. These obstacles not only hinder the development of small businesses but can cause the nation's economy to grow more slowly. Since «a vital component of any healthy market economy is the active development of the small and medium-sized enterprise sector, which plays a crucial role in creating new workplaces, promotes economic growth and innovative development», as noted by the authors of the «Problems and Prospects for the Development of Small and Medium-Sized Business» [5].

Among the problems faced by small businesses, probably the most essential is the lack of resources, mainly limited financial resources, which are the main equivalent of all others, including hired labor, etc. Since the implementation of information control systems of business intelligence requires significant investments in technological infrastructure, software licenses, and qualified personnel or training of existing ones, these limitations often lead to a dilemma between cheap funds, credit, and business efficiency, which often leads to mediocre competitiveness.

The next problem, which is a consequence of the first one, is how to obtain the experience and skills that are necessary to implement and manage such a system. This is reflected in the ability to hire data analysts and system developers who have enough skills to meet the needs of a particular enterprise, while more qualified specialists are poorly retained by the enterprise due to lack of salary, or skills, or cannot be hired with the available funds.

A significant problem that small and even medium-sized enterprises often face is data quality. This problem generally emerges due to «temporary» or «alternative» solutions used by the enterprise. This leads to decentralized and poorly coordinated data sources and insufficient data management policies. Important data is typically dispersed across two or more systems, which makes integration and efficient analysis challenging.

Implementation always changes workflows, methods, ways, and rules for making and approving decisions. In turn, small businesses face resistance to change from employees who are «good» at traditional manual processes or don't possess the requisite digital literacy.

After a business intelligence information control system is put into place, scalability issues can occasionally occur as the number of consumers of enterprise can quickly increase due to new opportunities, which ultimately means there will be more data to deal with and could lower system performance or cause the infrastructure to become unable to handle the expanding volume of data and users.

Comparison of popular systems. The framework of a business intelligence information control system can currently be fitted by multiple similar systems. Despite their apparent similarity, these seemingly identical systems can differ greatly from one another in terms of not just the tasks they can carry out but also how well-suited each system is for a specific sector, what benefits and drawbacks each system has, and how widely used or highly specialized it is. In their writings, Vyganyailo S.M. and Viunenko O.B. discuss such systems, noting that they are separated not only by functionalities but also by the kinds of activities they carry out and the intent behind their use [6].

Some of the popular systems that have the appropriate functionality include the two leading systems Tableau and Power BI and two contenders Looker Studio and Domo. The functioning of these two groups is rather wide and not restricted to any particular field or analysis potential.

Tableau is a data visualization tool by Salesforce Inc. that helps to transform various information into different charts and graphs using interactive dashboards. Tableau is one of the leading and popular products that is simple, fast, and easy to use.

Among the advantages of Tableau:

- the most diverse data visualization capabilities of any vendor on the market, including graphs, panels, charts, tables, spheres, and many others, all linked together for easy and quick navigation;
- a very simple interface that is understandable without any technical knowledge;

● The multi-platform solution allows the use of the program not only on a computer but also on mobile devices, both platforms have very reliable user support to solve any problems.

Among the disadvantages of Tableau:

● Despite its ease of use, for more complex tasks or data representations, knowledge of SQL is required. The data presentation section can only convert text and digital data into graphical data, thus you will need to construct data queries for sophisticated queries and manually choose the data;

● When reports or views are stored in a new version, the previous versions vanish and cannot be retrieved, which causes issues with version control and the loss of historical data;

● The lack of automated report updating requires you to restart queries to build them every time, which wastes time.

Power BI is a set of software services that work within the Microsoft platform to transform a variety of data into visually appealing graphs and understandable tabular representations, where the sources can be any storage options, from local tables to huge services.

Among the advantages of Power BI:

● The biggest advantage of the service is the ability to connect, import, and analyze data from many different sources. The service allows you to connect and use data from Excel, XML, JSON, Facebook, data-cloud, Google Analytics, and many other formats and cloud services without much effort;

● Integration capabilities allow you to use the results of the analysis in many popular services without intermediate transformations, and also have an API that allows you to integrate the results directly into your website or email;

● Power BI is a set of software services that allows you to choose the most suitable option. The options include a free version with limited functionality, a SaaS version, an enterprise version, a mobile version, a server version, and a cloud version.

Among the disadvantages of Power BI:

● Complexity in usage causes issues with accessibility and comprehension; using the full capability of the complex programs demands specific skills in dealing with data and data models, without which it will be exceedingly difficult to utilize a system;

● The need for customization and the rather unintuitive interface requires some time to understand what is on the screen.

Looker Studio is a free cloud-based tool as part of the Google platform for transforming data into informative dashboards and reports.

Looker Studio provides not only tools for transforming data but also for analyzing it.

Among the advantages of Looker Studio:

● The main advantage is that it is a free service, although there is a paid version, which offers a fairly high level of data modeling, processing, and transformation. The toolkit includes functions for drill-down, filtering, transformation, report generation, etc;

● Because it is cloud-based, it can be utilized without the need for physical infrastructure and offers data security features including row-level protection, access control, backup and recovery capabilities, and interaction with other tools;

● Looker Studio provides an extensible platform that allows you to create custom data applications and embed Looker into other systems, offering APIs and SDKs for creating custom data and integrating features.

Among the disadvantages of Looker Studio:

● Fairly limited in comparison to others, which often makes the data difficult to understand;

● Data integration can be a problem when using sources that do not have an additional connector, such as local databases or data warehouses;

● The analysis and processing functionality is also limited, and it may not be suitable for the demands of medium-sized and larger enterprises, since it does not handle big volumes of data efficiently.

Domo analytics is a cloud analytics platform designed for large enterprises and small businesses. It has a wide range of features related to security, management, dashboard, reporting, and data analysis requirements.

Among the advantages of Domo:

● Domo is a cloud-based technology, so it’s quick and easy to set up and start using for business intelligence management;

● The service supports a wide range of cloud technologies, making it simple to include them in the workflow;

● is an easy-to-use service that does not require special technical skills to get started.

Among the disadvantages of Domo:

● Occasional problems when working with large amounts of data caused by a significant load on computing resources service, as its functionality makes it appropriate even for large organizations with a high flow of information;

● Questionable user support is a concern for customers, as even minutes of downtime in a business bring significant losses;

● Service gives functionality under the paid plan; thus, to obtain complete functionality, you have to pick the costliest option.

These systems appear to be the same at first look, yet there are significant differences. In certain aspects, each system outperforms the other, while in others it falls far short. Looker Studio is the most affordable option, but it has limitations in terms of how data is connected to the system, analyzed, and presented. Services such as Tableau have the best data presentation, and Domo or Power BI have connectivity that is far ahead, but in some cases, Domo and Power BI are very expensive.

Information control system of business analysis for small enterprises. According to the definition by O. Guida, «an information control system is a set of tools, methods, and performers that provide the necessary and sufficient information for the implementation of all activities of the management process» [7]. In general, several types of such systems are common in practice, namely: decision support systems and information control systems. The business intelligence information control system, in turn, belongs to the first category, although it may partially include the functions of the second, such as comparing two alternatives as a result of data analysis for different periods or by different categories.

Such a system should have the capabilities necessary for a small business to collect, store, organize, analyze, and deliver data and information in a way that supports and improves business decision-making. This, in turn, includes the technologies, processes, methodologies, and tools used to structure and utilize data for analytical purposes.

The system and its components can look like this (Fig. 1).

The data collection component is responsible for obtaining data from various internal and external sources, such as databases, data warehouses, etc. Data collection may often involve integration with other systems to ensure the accuracy, reliability, relevance, and timeliness of the data.

Databases, data warehouses, and cloud storage are examples of storage components.

Data systematization and harmonization is an essential part that involves converting data from many sources and formats into a single form. These technologies enable users to communicate with many databases, systems, and applications, resulting in a unified view of the information being stored.

Data governance is the set of rules, processes, and standards that control data quality, access, security, and conformity. Establishing a strong governance framework is vital for ensuring data integrity and producing more reliable analytical outputs.

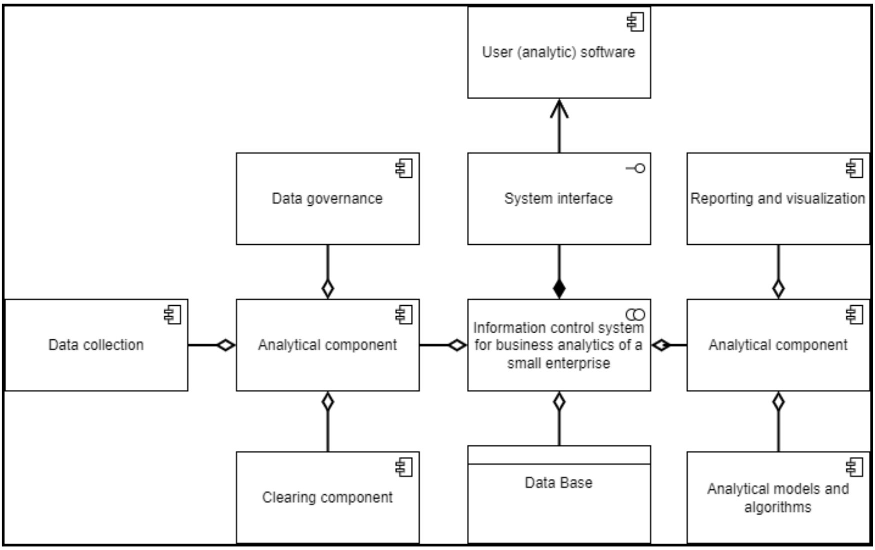

Figure 1. Graphical interpretation of system components

Source: developed by the authors

The cleaning component is required to remove any existing faulty data before it can be processed. This normally consists of cleansing, data validation, and sorting information that comes in. Proper data preparation procedures assist in optimizing this process and provide users with trustworthy and standardized data.

The system is built on analytical models and algorithms that provide meaningful information and results. Statistical analysis, machine learning, artificial intelligence, prescriptive, predictive, and descriptive analytics algorithms, among others, are examples of such techniques. These approaches and algorithms play a role in the development of prediction models, pattern recognition, and data-driven decision-making.

Displaying information in a relevant and visually appealing manner serves as essential for business users to successfully evaluate and comprehend data. Reporting and visualization methods make it simpler for people to understand data and exchange information by providing interactive dashboards, charts, graphs, and reports.

The user interface serves as a means of interaction between the system and the analyst and is responsible for the interaction with the end-user.

In general, small enterprises are quite limited in their capital, unlike large ones, so they usually use more affordable, universal, and less functional solutions when choosing any IT product. As noted by M.A. Saensus and G.S. Karnaukhova, «the low price of information technology equipment and ease of access to service are the most important criteria when choosing it» [8]. Thus, the system should be affordable, ensuring that the cost of implementation and maintenance is low-cost, so cloud-based solutions or open source are often a good choice, providing extensive features at a low price.

Small businesses often grow rapidly, especially when implementing solutions such as business intelligence management systems. To keep up with the expanding volume of data, the system must be scalable. As the organization expands, the system will gradually evolve without requiring big financial investments for expansion.

Small firms often do not have specialist teams or IT departments that can quickly understand the software, thus the system should be easy to use and accessible. The user interface should be straightforward, with minimum training necessary to operate effectively with the system. This will allow users to swiftly adapt the system's functionalities to current business processes.

The ability to integrate with different sources is a necessity for small businesses to consolidate data from different sources and make it possible to use the system's functionality, as small businesses often have many different solutions for each task.

The security of processed data is a key feature for all sizes and forms of business, so appropriate data protection standards, data and storage requirements, as well as backup, and protection against external and internal threats, should be used to ensure system reliability and trust.

Based on the characteristics discussed, we can identify several requirements that small businesses need:

● the system must be able to process large amounts of data and store it securely, use indexing and search functions to make data retrieval simple and efficient;

● the system should provide several analytical tools, such as predictive modeling, data mining, and statistical analysis, to identify prospects based on the collected data;

● the ability to generate on-demand reports and perform ad hoc queries is essential for small businesses that often need to evaluate specific scenarios or respond to immediate business requests, so an information control system should include a comprehensive reporting engine that allows users to retrieve and present data in real-time;

- the system should provide fast response times and the ability to process requests without significant delays;
- small businesses need to protect their data from unforeseen events such as system failures, so the system must have backup mechanisms to create copies of the data.

When implementing business intelligence information control systems, small enterprises emphasize their business processes. According to V.A. Tigareva and I.V. Stankevich, «the basis of all existing scientific views on the selection of indicators for assessing business processes of enterprises and organizations is the qualitative and quantitative approaches to the analysis of the object of study» [9].

Business intelligence tools and methods. Business intelligence tools and techniques refer to a wide range of technologies, methodologies, and software tools that help businesses discover, interpret, and present data in a meaningful way. They are designed to facilitate data analysis and make it accessible to users without advanced technical skills or in-depth knowledge of statistics.

It is important to understand that not everyone classifies tools and methods in business intelligence systems in the same way. Gartner identifies a set of business intelligence software tools as data warehousing tools, operational analytical processing systems, information and analytical systems, data mining tools, and query and report generation tools [10]. Capterra differentiates several categories, such as data visualization software, decision support software, analytical software, data mining software, web analytics software, risk management software, etc.

Using Garthner's magic square for 2023, we can see a comparison of such tools (Fig. 2).

Each of the platforms is assessed by Gartner using 12 criteria for 2023, along with two axes of vision completeness criteria. These criteria consider indicators such as product strategy, marketing strategy, sales strategy, vertical/industry strategy, innovation, geographic strategy, and so on.

All tools are organized into 4 squares.

Leaders demonstrate a clear understanding of key product capabilities and a commitment to customer success which is demanded by buyers in this market.

Contenders are well-positioned to succeed in the market, although they may be limited by specific use cases, technical environments, or application areas.

Figure 2. Gartner Magic Quadrant

Source: [11]

Visionaries have a clear or differentiated vision of their product, usually narrowly focused services that excel in one type of analysis or task, but struggle with more general ones.

Niche companies specialize in a certain sector or in satisfying the needs of specific cloud-stack consumers, but positions outside their specialization are weakening.

From this square, we can say that there are only 3 in leader and all of them are quite expensive for small businesses, among the narrowly focused tools there are already 9, but as noted earlier, small businesses often need wider functionality. There are still contenders and niche tools that are better suited for small enterprises.

Among the techniques used for the implementation of business intelligence information control systems, there are four categories or kinds of analytics:

● Descriptive analytics – according to the definition provided by E. Okpaku, «is the evaluation of past data to better understand company trends, which involves the effective use of a variety of historical data to create comparisons. The most commonly reported financial data, such as year-over-year price adjustments, month-over-month sales growth, number of users, or total revenue per subscriber, are products of descriptive analytics that show what happened in a company over some time» [12];

● Predictive analytics – in the article «How artificial intelligence will change the future of marketing», it is described as a branch of analytics that uses input data, statistical combinations, and machine learning to predict the probability of a certain event or group of events, forecast future trends or outcomes using available data with the ultimate goal of improving corporate performance [13];

● Prescriptive analytics – by D.B. Mishra, S. Naqvi, A. Gunasekaran, and V. Dutta can be described as an advanced approach to the use of advanced processes and tools for data analysis that uses complex mathematical and logical algorithms to provide recommendations, identify opportunities for optimizing processes and solutions [14];

● Diagnostic analytics is «a section of analytics that aims to answer the question 'Why did this happen? By using diagnostic analytics, companies can gain insight into the causes of patterns they notice in their data. Diagnostic analytics can include a variety of methods, including data mining and data analysis. To investigate the root cause of trends, companies may need to examine additional data sources, potentially including external data», as M. Holliday says [15].

Each type of analytics or category of methods serves a specific purpose and can be used in conjunction with others to acquire an in-depth knowledge of the present scenario using the data that is currently available.

All 4 categories are actively used in business intelligence information control systems. Large businesses tend to employ predictive and prescriptive analytics since they have access to enormous quantities of historical data and operate in several industries. For instance, in February 2023, the Starbucks coffee chain introduced a new line of coffee called «Oleato», which included olive oil. Unfortunately, the series failed as a result of an improper product mix, which cost the network money since customers decided against purchasing the line because of its adverse effects. Even though the product resulted in losses for a company of this size, they were insignificant in comparison to a small enterprise, where similar investments would have a considerable budget impact. Consequently, small enterprises attempt to utilize each of these categories, each of which is in charge of a different component and has a different complexity. (Fig. 3).

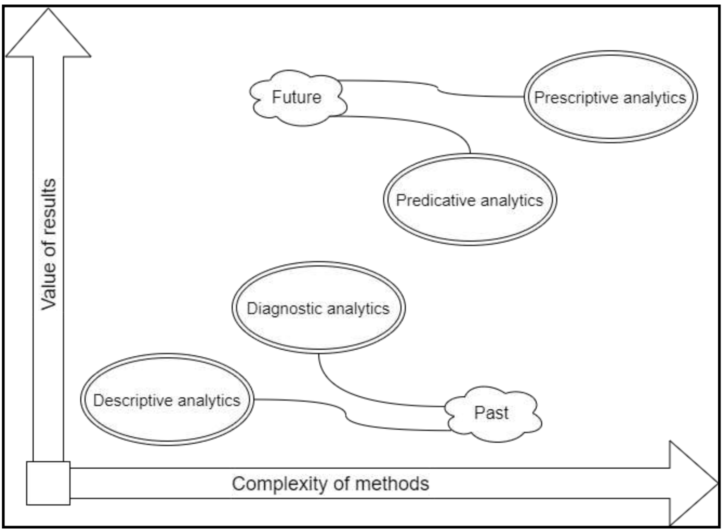

Figure 3. Categories of analytics methods

Source: developed by the authors

It is simple to understand the relationships between these categories based on the way they are shown. The relationship between complexity and effectiveness is linear; that is, from bottom to top, the value of the results produced by these approaches grows as the methods' complexity increases from left to right. It is also clear that each category of analytics or set of techniques provides information on the analysis of the past, such as product sales numbers, or anticipated future, such as individuals wanting to buy a specific type of product.

Descriptive analytics is a statistical interpretation used to analyze historical data and identify patterns and relationships between them. Descriptive analytics tries to describe an event, phenomenon, or outcome, which helps to understand the implications of past events and provides businesses with an ideal basis for tracking trends. The primary purpose of the approaches in this category is to answer the question «What happened?».

The advantages of this category of methods include the following:

● Historical understanding of the processed data allows businesses to look at the accumulated indicators and information from a retrospective perspective, which can help to see patterns, trends, and anomalies and in turn can help to make more accurate and correct decisions;

● Visual representation uses various techniques and formats of data output, such as charts, graphs, and tables, to help make enormous amounts of information more understandable. Such representations can be made use of to communicate key choices and ideas to stakeholders;

● Descriptive methods are simple to learn and apply, therefore they are frequently employed by non-technical workers like accountants. Furthermore, systems that make use of this kind of method frequently offer templates, because little or no experience is required to use the systems.

● The availability of hindsight is often used in conjunction with other groups of methods, usually to compare past and current KPIs, which facilitates monitoring of business performance;

● By identifying trends, patterns, and anomalies in historical data using descriptive analytics, companies can develop future strategies based on information and improve business processes without additional analysis.

The disadvantages of this category of methods include the following:

● Descriptive methods focus on analyzing and extracting value from historical data and do not provide predictive information. Although these methods allow us to see patterns, trends, and anomalies they cannot provide an understanding of whether they will remain or not;

● Descriptive approaches give data as-is, frequently without explanation for why data occurred or why trends or anomalies have emerged. Because context is absent, these approaches limit the company's understanding of the reasons for particular cases and demand the application of further methods;

● The category of descriptive methods often relies on structured data, which does not always provide a complete picture of events. The fact that these methodologies involve the extraction of unstructured, subjective, or qualitative data, further hinders one's understanding of significant elements that may have an impact on performance.

The main popularity of these methods in recent years has been driven by the development of Big Data technologies and the availability of these technologies, due to their implementation in cloud computing, which is usually more scalable and cost-effective in terms of infrastructure for enterprises. In addition, the development of cloud computing and the integration of more extensive and innovative data visualization tools have made descriptive analytics easier to use, allowing any individual or business to analyze data independently and enabling the use of descriptive methods by individuals without significant technical skills and knowledge.

Due to their popularity and many advantages, small businesses have gained a few benefits:

● Descriptive analytics provides small businesses with the ability to analyze data without the need for large specialized resources, which in turn allows them to get results at a lower cost than larger competitors who typically lack of functionality of these methods;

● Descriptive category techniques assist in breaking down small businesses' clients based on many different things, such as demographics or age, which eventually gives enough possibilities to understand their preferences and target audience behaviors and helps them to respond to the market better;

● Small businesses gain insight into their internal operations, identifying bottlenecks, and inefficient areas that need to be improved, which, in comparison with the availability and low costs, allows them to maintain a sufficient level of competitive efficiency.

Diagnostic analytics is characterized by methods such as drill-down, data discovery, data analysis, and correlations, which are used to identify behaviors, trends, and patterns to find out why certain events occurred and what led to the actual results. The primary purpose of the approaches in this category is to answer the question «Why did this happen?».

The advantages of this category of methods include the following:

● The ability to identify the causes of certain events or issues that have come up as a result of the company's operations. By evaluating and researching data from multiple sources, companies may establish what aspects affected the actual outcome as well as the main reasons why things had taken place the way they did. Diagnostic methods are important for creating solutions to recurrent problems and refining existing organizational strategies by identifying the causation;

● A deep understanding of the root causes provides the basis and opportunities for developing more informed and data-supported decisions to optimize business processes, decision-making efficiency, plans, etc.;

● Based on the investigated historical data, diagnostic analytics methods allow organizations to keep an eye on fluctuations in key financial indicators, identify the origins of these changes, assess current progress against previously defined goals, and augment descriptive analytics approaches;

● Methods of the diagnostic category are excellent for risk management, as they help to identify risks in advance and make decisions to prevent them before they occur. These methods are especially valuable in the short term, as they help to avoid most losses.

The disadvantages of this category of methods include the following:

● Diagnostic analytics approaches primarily rely on historical data that may not always precisely reflect current or future situations, which limits their use in dynamic and unstable business environments;

● Methods of this category of analytics require a deep understanding of data analysis tools and methodologies, which makes them less accessible for widespread use due to the skills of those who will utilize them;

● The process of data manipulation takes much longer than descriptive methods and requires more technical resources and specialized knowledge;

● Diagnostic methods require high-quality integrated data to obtain accurate results, so the requirements for data are somewhat higher than for descriptive methods.

Diagnostic analytics has become even more popular in recent years. This is primarily because of the rapid advancement of technology and the gradual digitization of business processes. The public now has wider access to diagnostic analytics methods thanks to the development of cloud solutions. However, particularly among small businesses has increased less than that of descriptive analytics methods due to the latter's greater complexity in analyzing «past» data and situations.

Due to the gained popularity and several advantages, small businesses have gained several advantages when using systems with diagnostic data analysis methods, such as:

● systems and tools for diagnostic analysis have become cheaper and more accessible to businesses with limited budgets compared to the previous decade;

● The availability of systems with diagnostic analytics has allowed small businesses to identify gaps and causes of these gaps in their operations, which has improved operational efficiency and using preventive methods in risk management;

● Diagnostic analytics may assist small firms in understanding the causes for fluctuations in client base patterns, changes in the market, and their revenue, allowing them to better adjust to the various scenarios;

● Understanding the causes behind certain events makes it simpler for small enterprises to join niche markets and achieve their business objectives and goals.

Predictive analytics uses statistics, data, and modeling techniques to predict the future, including various key indicators, trends, causes, and possible scenarios for the unfolding of events. Predictive analytics approaches use past and present data to uncover the future development and probability of specific occurrences, which aids in determining if something is beneficial or not. The primary purpose of methods in this category is to answer the question «What can happen in the future?».

Advantages of this category of methods include the following:

● Predicting future events is the main reason why this category is very popular, especially among large business players, as it provides an opportunity to predict the behavior of their target audience, market volatility, competitors' actions, etc. The analysis of many indicators, including but not limited to behavioral patterns, decisions of responsible persons, and investor sentiment, provides a solid understanding of the possible consequences of implementing certain decisions;

● Predictive analytics methods greatly improve operational efficiency in many areas, providing greater opportunities than descriptive and diagnostic methods;

● Effective risk assessment, management, and forecasting of occurrence and possibilities help to avoid fraud, business downtime, and significant losses by implementing preventive measures to avoid or at least mitigate risks;

● Predictive approaches, as opposed to descriptive and diagnostic data analysis, assist in the formation of more targeted strategies and plans. Adopt these methods in business operations to cover as many elements as possible at reduced costs and maximize the realization of benefits;

● With a highly accurate prediction of future events, chief executives may plan and cover potential niches on time, greatly surpassing their competition by designing better-performing strategies.

The disadvantages of this category of methods include the following:

● The quality of the data has a tremendous impact on the outcome. Models and neural networks utilized in the predictive techniques category might produce incorrect and misleading conclusions based on how outdated or biased the input data is;

● Predictive analytical techniques employ far larger amounts of data than descriptive and diagnostic methods, which causes issues with information gathering, storage, and processing in terms of privacy and safety. This occasionally creates concerns from stakeholders, imposing additional expenditures of funds to assure reliability as well as security through process validation of predictive models;

● Some prediction models and methodologies, such as deep learning algorithms, are exceptionally difficult for humans to fully understand and explain. This affects comprehending the cause-and-effect links as well as the model's predictions. If the results cannot be interpreted, there may be doubt on the part of responsible personnel, which leads to serious difficulties in making choices.

● Forecast models are based on historical data and assumptions that past patterns and relationships will continue. However, market dynamics, customer behavior, and external factors may change over time, making forecasts less accurate or outdated and requiring that new trends should be taken into account by regularly updating such models;

● Developing, managing, and maintaining effective predictive models is often resource intensive, especially in terms of highly skilled personnel, computing power, and data infrastructure, making it very difficult to implement and maintain for businesses with limited resources.

Predictive analytics has become an innovation in the modern world, revolutionizing the approach to decision-making and stimulating the growth of many areas and industries. Advanced information analysis methodologies, machine learning algorithms, and quickly expanding artificial intelligence-enabled organizations to get an in-depth understanding of cause-and-effect links, resulting in an innovative approach to traditional management and decision-making.

It can be said that all new ideas and achievements start with discovery and innovation in the hope of creating a viable idea where predictive analytics guides the process, trying to answer exactly when, where, how, and why a certain innovation will improve the current idea or concept. However, working with innovations is inherently unpredictable, and therefore often the results are disruptive or unviable, where it is very difficult to rely on intuition alone, and as a rule, it is simply impossible to analyze the data. As a solution to the problem, predictive analytics methods in information control systems are used, which, first and foremost, allow for gathering information before the idea becomes a reality, and second, allow for accurate information extrapolation, resulting in a variety of potential changes. Companies will quickly discover where the difficulties will be, what their nature will be, whether they can be overcome, and how they are going to be overcome. At this point, anyone can see the value of such technologies, which allow testing an idea with relatively small investments rather than blindly introducing innovation and praying it will have success; while such seemingly absurd ideas have achieved significant success, failure would result in catastrophic losses.

By being innovative when using systems with such methods, small businesses can gain advantages:

● Predictive analytics can precisely determine customer preferences and improve their experience on a small scale, making it useful for small businesses;

● Because of the minimal number of business processes that must be adjusted, small companies may swiftly adapt to their niche without spending substantial time and financial expenditures. This helps easily differentiate the company, especially in crowded markets;

● Reducing risk when implementing new business processes and ideas using predictive analytics methods is a significant advantage for small businesses, as they usually operate on a limited budget when any cost is critical.

Prescriptive analytics provides an advanced approach to data analysis that uses sophisticated mathematical algorithms and technology to provide practical recommendations for decision-making and is the fourth category of methods. Prescriptive analytics is closely related to all other categories and is often used as the final stage of any analysis, as the primary purpose of this category is to answer the question «What should be done next?» where the logical continuation is «to achieve the goal».

The advantages of this category of methods include the following:

● Gives proactive decision-making based on a thorough awareness of future possible situations. Prescriptive methods provide an integrated understanding of all possible scenarios by analyzing both historical and hypothetical data, as well as a combination of different factors;

● The ability to observe the complete chain of events helps companies develop far more effective tactics, as companies can identify the cause-and-effect links and what potential actions can lead to them.

● As a basis for innovation, prescriptive analytics allows for quick analysis of several situations at once, adaptation to new circumstances, and providing the most optimal solution, considering certain needs and goals;

● The maximum degree of risk management and operational planning is achieved when companies have a way to anticipate not only the best but also the worst cases and the routes leading there.

The disadvantages of this category of methods include the following:

● Implementation of prescriptive analytics requires significant financial and technical knowledge, as it involves complex mathematical modeling for the needs of the enterprise, development of algorithms and integration with existing systems, hiring entire teams of highly qualified specialists or cooperation with outsourced experts;

● To provide reliable results, prescriptive analytics methods need extraordinary volumes of data, which can be very costly for small and medium-sized businesses;

● The main problem with such analytics methods is that they rely on historical data and learn from it, so they can rarely provide real-time information, as it takes a certain amount of time from receiving the most recent data to being able to get results based on it.

Small enterprises can still benefit from using such technologies, despite their drawbacks and questionable availability:

● Prescriptive analytics methods are best suited for innovative development, so the use of such methods in small businesses can significantly increase competitive advantage, as more successful ideas will be implemented;

● Benefits in risk management and prevention for company operations, with the budget serving as one of the most crucial metrics for small enterprises.

Innovative approaches to system implementation. It can be clearly stated that at present, in the period of rapid development of information technology, better and more innovative approaches to the implementation of information control systems for business intelligence of small enterprises can significantly change not only the benefits and success of the introduction of entrepreneurship but also realize more appropriate ways and methods of introducing such systems into the work of a small enterprise.

The approaches to implementation may vary depending on specific needs, but they all have one thing in common, as R. Ode and R. Aivu write: «Data collection and data processing leads to new knowledge, and the result is new knowledge that has a positive impact on innovative business development» [16]. Such systems and methods are found in the space between gathering data and learning new things.

One of the simplest and most innovative approaches for small businesses is cloud-based solutions. With the cloud-based approach, computing services can be offered via the Internet, and data is stored, processed, and managed remotely with minimal need for business infrastructure.

Among the main advantages of the approach:

● The primary benefit of the cloud method is its accessibility, which, in contrast to alternative solutions, allows users to access the system from nearly any place on Earth with Internet connectivity, regardless of device;

● Cloud-based systems are usually well scalable and quickly adapted by enterprises to their requirements due to the absence of the need for physical devices, and additional investment into the volume of leased data storage, and computing power, which are usually much cheaper than physical counterparts;

● Most, if not all, cloud platforms include several safety measures for their services, resulting in rather dependable methods for encrypting, copying, and restoring data. This is partially because, under such systems, the risk is passed to an external organization that offers data storage or processing services;

● The last advantage would be a decrease in bureaucratic work associated with information management and processing. Small businesses frequently don't have the resources to implement work policies and principles; most operate under less complex and less successful policies, so the cloud approach also addresses this issue, as the leased resources in the systems have their own set of rules, which are typically far more advanced to what a small business can afford.

Among the disadvantages are the following:

● The transition to cloud solutions is quite difficult and requires attention because when choosing such a solution, enterprises want to move everything to the cloud problems with this transition begin to arise: partial loss of data, loss of processing functions, and long and careful planning of the migration process;

● Training employees to work with the new system will require time and money, and although this is one of the cheaper solutions, it is not free.

SaaS or software as a service or software lease is another approach to system implementation. This strategy requires the system to be implemented as a service that small businesses will pay for. Rather than buying the complete software product or any of its components, specific features or the system will be purchased for a predetermined amount of time, during which the business will be able to utilize the system to its maximum scale as per the terms of service, get the most recent updates, and concentrate on other important aspects of the business.

Among the main advantages of the approach:

● Because renting a system or its components is generally affordable, companies may pay for just a portion of the system they use or for a set length of time without having to make big initial financial expenditures;

- By partially paying for the system, the use of solutions based on this approach allows companies to scale if necessary by switching between tariffs and services received at any time without almost any other changes;
- With the SaaS model, nearly all technical issues and malfunctions are handled by the service provider, who typically offers all the assistance required for any issue related to their product;
- SaaS are easy to learn, as they provide detailed instructions on how to operate and do not require significant customization.

Among the disadvantages are the following:

- Most SaaS are off-the-box solutions, so they are sometimes limited in their ability to be customized to meet specific enterprise needs;
- This approach's modularity frequently prevents companies from accessing specific components or features without having to pay for the tariff plan that includes them.

The uniqueness of this method originates from the fact that, while «modularity» is a negative aspect, depending on the number and distribution of these modules, certain systems allow the creation of a plan that is most beneficial to a small business. Innovative SaaS services utilize a variety of analytics methods, including machine learning and artificial intelligence, to automate the majority of regular activities. This method allows firms to constantly adjust their information control systems without costly disruptions or re-implementation, while also providing integration with other critical business tools.

One of the approaches that has gained popularity is the concept of mobile-oriented solutions. This approach is focused on portable devices such as smartphones, tablets, and laptops, ensuring accessibility, efficiency, and convenience of business processes on these devices. This approach is also driven by the dependence on portable devices in both personal and professional settings.

Among the main advantages of the approach:

- Small businesses often have problems with physical infrastructure, which makes any investment in their hardware very expensive, so the mobile-first approach is often based on cloud-based solutions to ensure accessibility from any device with Internet access;
- A mobile-first approach is used to implement solutions that can provide easy access to important information, ensure uninterrupted communication, and simplify routine tasks. This also includes multi-platform solutions for such systems that are not limited to laptops or tablets;

● Multi-factor authentication, secure data transfer protocols, and remote wipe capabilities in case of device loss or theft help protect confidential business information.

Among the disadvantages are the following:

● The main problem with a mobile approach is the capability of the device from which the system is accessed. The capabilities and size of the screen and hardware may make a significant difference in the efficiency of usage on a smartphone, tablet, and laptop;

● Small interfaces in this approach typically place extra limits on the interface while developing the system, which might cause challenges when using and displaying system data.

Being innovative in implementing information control systems with a mobile-first approach can revolutionize the way small businesses work and operate, thanks to the ability to use the system on any device and adapt it to specific needs.

A centralized approach involves gathering data through integration and automation. The technique is not new in IT, but it enables diverse systems, storage, and technologies to be brought together. Integration tools, such as application programming interfaces, guarantee that data flows smoothly across multiple software programs, minimizing duplicate entries and decreasing human error, whilst automation eliminates all or part of time-consuming and repetitive operations.

Among the main advantages of the approach:

● Data centralization helps to ensure data integrity by eliminating inconsistencies that can arise from storing data in multiple locations, which provides opportunities to identify and correct errors;

● A centralized approach allows for efficient resource allocation and eliminates unnecessary duplication, freeing up space and optimizing data processing time;

● Centralization of data provides better security control and monitoring by working with a single source of data.

Among the disadvantages are the following:

● The centralized approach involves significant financial investments in the development and implementation of the system, including hardware, training, etc;

● Centralized systems may require significant changes to business processes and staff, which can lead to complex and time-consuming development and implementation plans;

● A centralized system may stop the functioning of a company in the case of issues, but it also becomes a potentially tempting target for attackers since it stores all information in one location.

Conclusions

Business intelligence information control systems are important tools for small businesses, providing functionality for analyzing and interpreting data to make informed decisions supported by data. However, small businesses often face many challenges and have specific needs when it comes to implementing such systems.

One of the common problems for small businesses is limited resources, both in terms of finance and technical and human resources. It is often impossible or extremely difficult for small businesses to allocate funds towards an IT solution or to hire qualified staff, to create or implement such systems, and then to maintain and adapt them. Another problem is the experience of operation and implementation, which is often lacking, so small businesses face excessive costs due to staff training, solving problems with integration with existing systems, and introducing an information culture of doing business. Therefore, as a solution, small businesses need to prioritize and focus on key items: during implementation, gradually investing only in the necessary parts of the systems, abandoning the currently ineffective ones, thinking over and creating appropriate staff training plans for working with innovations, develop an effective change management strategy to engage employees and increase the acceptance of the implemented system.

In terms of requirements, small businesses typically need systems that are affordable, accessible, easy to implement and use, require minimal maintenance, and offer gradual scalability as the enterprise grows. It is worth mentioning that, in addition to the fundamental requirements, system flexibility will be a significant advantage, easing the development and usage process.

When considering the factors that influence the choice of business intelligence management systems, organizational requirements, scalability, integration capabilities, data processing, and analytical capabilities are important, and they are especially important for small enterprises since they help them to determine whether a certain system is a good option and whether it can be used within their constraints.

To analyze data effectively, different systems support or offer different categories of analytics methods for small businesses. Descriptive methods allow businesses to understand situations that have already occurred without the need for specialized knowledge or experience. Diagnostic methods provide an understanding of why certain situations occurred that led to the current state of the enterprise, allowing you to obtain the factors that influenced the activity. The predictive category of methods will allow you to predict future trends, market behavior, customers, and the success of small business ideas, and prescriptive analytics will allow you to choose the best results and achieve them. It can be said that even the simplest systems can significantly increase the efficiency of small businesses and provide a comprehensive understanding in all aspects: from making simple decisions and conducting business to building long-term strategies and implementing innovative ideas, while more advanced solutions will allow you to understand the whole picture of events in detail.

When designing and implementing such systems, one or more approaches can be used, as each approach realizes certain advantages and has its drawbacks, using several of them at once can lead to comprehensive and reliable solutions, but at the same time can significantly complicate these processes. The cloud approach is particularly well suited to many other approaches, providing the basis for many systems that may not be able to purchase their own hardware and computing resources. SaaS makes it possible to differentiate one complex information control system into several components or modules, providing more attractive opportunities for small businesses due to the lower cost and the ability to select individual parts. The mobile-oriented approach will allow the system to be used on different devices, although it has limitations due to the performance of these devices. At the same time, a centralized approach will create a single system for the entire enterprise.

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MACHINE LEARNING VERSUS DEEP MACHINE LEARNING WITH THE USE OF BIG DATA INFORMATION CONTROL SYSTEMS

1. Effective configurations of classical machine learning with the use of Big Data information control systems

In its nascent years, artificial intelligence (AI) largely focused on rule-based systems that would make predictions using predefined sets of rules that had to be provided by a subject matter expert. However, these systems were fragile and relied on these «expert opinions», which eventually led to their falling out of mainstream use. As the scale and volume of data increased, these methods were replaced by a more data-driven approach – machine learning (ML).

ML is a set of algorithms and tools that help machines understand patterns in data and use that underlying structure to make inferences about a particular task. There are many ways in which machines seek to understand these basic patterns [1, 2].

ML is a class of methods for the automated creation of predictive models based on data. Machine learning algorithms turn a dataset into a model. Which algorithm works best (supervised, unsupervised, classification, regression, etc.) depends on the type of problem to be solved, the available computing resources, and the nature of the data [3–5].

ML algorithms can be described as learning an objective function f that best correlates the input variables X and the output variable Y: $Y = f(X)$.

It is not known what the function f is. After all, if it were known, it would be used directly, and not tried to learn with the help of various algorithms.

The most common task in ML is to predict Y values for new X values. This is called predictive modeling, and our goal is to make as accurate a prediction as possible.

ML is a subset of general AI and a general term for computers learning from data. It describes the intersection of computer science and statistics, where algorithms are used to perform a specific task without explicit programming; instead, they recognize patterns in the data and make predictions as new data comes in. supervised learning, unsupervised learning, and reinforcement learning.

After all, it is the method of learning that is most often used to classify machine learning into large categories: supervised, unsupervised, reinforcement learning, and learning with partial involvement of the «teacher», each of them has its own tasks of practical application in real conditions and its own distinguishing features and limitations.

In general, the ML process is based on the following steps:

1) preliminary analysis of the data set and the set ML problem, cleaning and preparation of data for use by the corresponding ML algorithm,

2) selection of the algorithm and setting, selection of its parameters;

3) data loading and model training;

4) testing and interpretation of the model;

5) implementation and use of the model for the automated solution of predictive tasks.

Unsupervised learning

While supervised learning requires input-output pairs (or labeled data), unsupervised learning algorithms use only input data (unlabeled data). Although this learning method is less intuitive, it is suitable for problems where we have little or no idea what our results should look like. The goal is to gain knowledge and find structure in the data.

The unsupervised ML algorithm processes unlabeled data, including finding different ways of presenting complex data to organize them or describe their internal structure, which simplifies their interpretation.

In unsupervised learning, there may be no target variable, i.e. the training data set does not have labeled data belonging to a certain class of predetermined data, i.e. «Teacher» (target variable) is absent. The algorithm independently determines correlations and connections based on the analysis and interpretation of all available data and draws conclusions based on them. The algorithm tries to organize the data in any way and describe its structure. The algorithm observes some similarities between groups of objects and joins them to the appropriate clusters. Some objects may be very different from all the clusters, and thus the algorithm assumes that these objects are anomalies. As more data is added for analysis, the algorithm's ability to make decisions based on that data grows, as does the accuracy of those decisions.

With only some arbitrary data at their disposal, sometimes untrained learning algorithms can be able to detect some non-trivial dependencies or even some kind of complex laws.

Teaching methods without a teacher solve the following tasks:

–clustering;

– dimensionality reduction;

– search for association rules (buyer basket analysis, etc.);

– detection of data anomalies.

ML without a teacher is also used as an auxiliary tool for the preparation of data sets for the subsequent correct solution of predicative tasks by machine learning algorithms with a teacher.

Supervised machine learning

Supervised learning uses a known/explicit relationship between inputs and output. This is where labeled data comes into play: the goal of the algorithm is to learn from the «correct answers» in the training data and use the insights to make predictions as new input is received.

The term «supervised learning» comes from the fact that we initially provided the algorithm with a data set in which «correct answers» were provided. This is a key difference in unsupervised learning.

Learning with a «teacher» functions only on labeled data and is currently the most developed and applicable type of ML. To implement it in practice, you need a task that can be formulated as a classification or regression analysis problem, as well as a sufficient set of labeled data. Learning with a teacher is the task of training the system on a training set of data that contains the necessary input and output values. The learning algorithm with the «teacher» by iteratively «fitting» the learning results to the training data set, searches for the most optimal parameters of the model (for further prediction of possible answers on other / new objects / records). The process continues until the algorithm reaches a given level of accuracy / performance (stopping criterion).

Supervised ML algorithms are divided into two main groups:

– if the set of possible answers is a real number, then this is a regression task;

– if the set of possible answers has a limited number of values, where these values are unregulated, then this is a classification task; in classification tasks, the machine learning program must draw a conclusion based on the observed values and determine to which category the new observations belong.

However, it is worth noting that to solve certain classes of problems in the conditions of semi-structured data – traditional ML methods require considerable effort and thorough human expert experience/understanding in a specific subject area precisely to obtain a qualitative classification or regression model after iterative training.

For example, to recognize animal images using traditional supervised ML, you need to do the following:

– manually correctly label hundreds of thousands of animal images

– configure the controlled ML algorithm to build a classification model on these labeled images

– test the trained model on a set of unknown images

– to determine why some results of the obtained model are inaccurate.

– according to the results of the previous step – expand/increase the input data set by marking new images to improve the accuracy of the model.

That is why – in supervised learning, the accuracy of the results improves only when you have a wide and sufficiently diverse set of data. For example, an algorithm can accurately identify black cats but not white cats because the training dataset contains more images of black cats. In this case, you will need to label more images of white cats and train the machine-learning model again.

Weak machine learning or semi-supervised machine learning

Weak machine learning is similar to supervised machine learning but uses both labeled and partitioned data. Labeled data are, in fact, sets of information units with labels (tags, variables) assigned to them. Unmarked data has no such tags. By combining learning techniques, these algorithms can learn to label unlabeled Big New Data. That is, such machine learning combines both approaches described above. This is an excellent opportunity to solve predictive tasks on large sets of new data. This method also allows a significant increase in the accuracy of the forecast using Big Data from ICS.

Weakl supervised learning, also called semi-supervised learning, is an ML paradigm that has grown in relevance and prominence with the advent of large language models due to the large amount of data required to train them. It is characterized by using a small amount of human-labeled data (exclusively for the more expensive and time-consuming supervised learning paradigm) and then a large amount of unlabeled data (used exclusively in the unsupervised learning paradigm). In other words, the desired output values are provided only for a small subset of the training data. The rest of the data is unmarked or inaccurately marked.

Technically, this can be thought of as first – performing clustering on new data and then labeling the clusters with old but labeled data, pushing the decision boundaries away from areas of high density.

Obtaining labeled data for a learning problem often requires the expertise of a skilled human expert or group of experts (e.g., to transcribe an audio segment, etc.) or to perform a series of physical experiments (e.g., determine the 3D structure of a protein or determine the presence of oil at a specific location, etc.). Thus, the cost associated with the labeling process can make large, fully labeled training sets infeasible, while obtaining unlabeled data is relatively inexpensive. In such situations, it is semi-supervised learning that can be of great practical importance.

Assumptions for semi-supervised learning: For any use of unlabeled data, there must be some relationship with the underlying distribution of the data. Semi-supervised learning algorithms use at least one of the following assumptions:

Assumption of continuity/smoothness. Points that are close to each other are more likely to have a common label. This is also commonly assumed in supervised learning and favors geometrically simple decision bounds. In the case of semi-supervised learning, the aforementioned smoothness assumption additionally gives the advantage of not constructing decision boundaries in partially labeled regions/areas with low density, so the training result can be valid when several points are close to each other but in different classes.

Clustering assumption: Data tend to form distinct clusters, and points in one cluster are likely to share a common label (although data that share a common label may span multiple clusters). This is a special case of the smoothness assumption and gives rise to feature learning using clustering algorithms.

Assumption of diversity: In reality, data typically have much less diversity than the theoretically possible space of values. In this case, studying diversity using both labeled and unlabeled data can avoid the curse of dimensionality. Training can then continue using the distances and densities defined on the particular dataset. The diversity assumption is also practically useful when multidimensional data are generated by some process that can be very difficult to simulate directly performing experiments, but this difficulty is overcome by the expert understanding that in a given set of input data when solving a specific analytical problem, the input dimensions have a limited number of degrees freedom (category values). For example, the human voice is controlled by several vocal folds, and the image of different facial expressions is controlled by several muscles. In these cases, it is better to consider distances and smoothness in the natural space of the specific generating problem, rather than in the space of all possible acoustic waves or images, respectively.

Reinforcement machine learning

Reinforcement learning is not similar to any of the above types of machine learning tasks because it is used in tasks where there are neither conditioned labeled data sets nor unlabeled data sets.

In reinforcement learning, an algorithm (also often called an agent in this context) learns by trial and error, using feedback from its actions. Rewards and punishments act as signals for desirable and undesirable behavior. That is, agents/agents learn from past experiences and change their approach in response to a new situation, trying to achieve the best possible outcome.

In other words, in reinforcement learning, the algorithm chooses an action in response to each data point and based on the results of its previous predictions (the learning algorithm receives a success signal that lets it know how successful the past decision was). Based on this signal, the algorithm changes its strategy to achieve the highest reward.

That is, reinforcement learning is a type of ML in which software agents must take actions in some environment to maximize some notion of cumulative reward.

Reinforcement learning is widely used to implement non-generative AI, that is, this approach to ML is most common in robotics, the Internet of Things, and in the industry of computer games without a description of the rules of the game. Its use can be promising in the modeling of game theory problems.

The main difficulty in applying this approach to ML is that the real world is very difficult to model with the necessary accuracy and adequacy, as a result of which a trained AI can perfectly perform tasks in a virtual environment, but be practically useless in real complex, dynamic, stochastic conditions of BIG DATA and also under the influence of the «curse» of their dimensions.

Machine learning vs deep machine learning vs artificial intelligence

Consider the following definitions to understand deep learning and machine learning and artificial intelligence.

AI is:

– property of intelligent systems/algorithms to perform functions that are traditionally considered a human prerogative;

– the science and technology of creating intelligent machines, especially intelligent computer programs

– techniques and algorithms that allow solving complex predictive tasks on large data sets.

ML is a subset of artificial intelligence that uses techniques and algorithms that allow computers to take advantage of opportunities to improve tasks.

Deep learning is a subset of ML based on artificial neural networks. The learning process is deep because the structure of artificial neural networks consists of several input, output, and hidden layers. Each layer contains units that transform input data into information that the next layer can use for a specific predictive task. Through the structure of an artificial neural network, deep learning is designed to identify patterns in large volumes of unstructured, categorical data. For this reason, deep learning is now being actively implemented in the operational and tactical management of business processes in various industries (health care, energy, finance, transport). Table 1 provides a more detailed comparison of these two methods.

Configuring effective Machine learning in Big Data conditions

ML uses a wide range of algorithms to transform datasets into predictive models. Which algorithm will work better depends on the problem being solved.

There is such a thing as the «No Free Lunch» theorem.

The bottom line is that there is no single algorithm that is the best choice for a particular task/data set, especially tutored learning.

For example, it cannot be said that neural networks always perform better than decision trees, and vice versa. The effectiveness of algorithms is affected by many factors such as the size and structure of the data set. In addition, each ML algorithm has its own style of inductive shift.

For this reason, one has to try many different algorithms, check the performance of each on a test data set, and then choose the best one. Of course, you need to experiment and choose the best ML algorithm for your problem/dataset. For a particular problem, it may be appropriate to experiment with several ML algorithms and select the best algorithm and tune it accordingly. If we draw an analogy when cleaning the house, you will most likely use a vacuum cleaner, a broom, or a mop, but not a shovel.

The recommendations offered in this lecture are general rules. Some should be adapted to a specific situation, and some can be violated. Don’t be afraid to use multiple ML algorithms simultaneously when processing and analyzing data.

Table 1

COMPARISON OF MACHINE LEARNING AND DEEP MACHINE LEARNING TECHNIQUES

	Machine learning	Deep machine learning
Approach to learning	Divides the learning process into smaller steps. Then the results of each step are combined into one overall result.	Conducts a single end-to-end training process on the entire data set in turnkey mode.
The process of configuring features and functions	It is necessary that functions and features are precisely defined and/or created by users.	Automatic recognition of input features, automatic search for high-level features from data and generation of new features and/or features
Equipment requirements	Can work on low-end computers. Does not require a large amount of computing power.	Depends on high performance computers. It essentially performs a large number of matrix multiplication operations. The GPU can effectively optimize these operations.
Task completion time	It takes relatively little time to learn, from a few seconds to several hours.	Usually, the learning process takes a long time because the deep learning algorithm involves many layers and iterations.
Input and output data	This data must be structured, the output value is usually a numerical value such as a rating or classification.	Input and output data can have several formats, including unstructured: for example text, image or sound.
The volume of the input data set	Small amounts of data can be used to generate predictions, but the learning algorithm may require a priori criteria.	To create forecasts, it is necessary to use large volumes of training data.

Source: developed by the author

Choosing an effective and appropriate ML algorithm depends on many factors, including the size of the data, the number and type of attributes (features), the quality of the data, the presence and amount of anomalies in the data, and understanding what answers the business needs based on that data. Attention should also be paid to accuracy, training time, a priori parameters of the algorithm, representativeness of the sample, and many other things. Therefore, choosing the appropriate algorithm is a complex expert decision based on business needs, specifications, experimental work, and analysis of available time.

Even the most experienced data scientists won't be able to tell you which algorithm will perform better without doing lots of experiments with different kinds of algorithms, their settings, and different data samples. Despite this, there are certain general methodological guidelines for machine learning algorithms that will help you find an effective algorithm suitable for your specific tasks and data.

Choosing an effective ML algorithm depends mainly on two different aspects of the data processing and analysis scenario:

– What should be done with the data? Specifically, what is the business question that needs to be answered, the type of problem of learning from past data (for example, is the problem categorical classification, predictive regression, cluster analysis, or anomaly detection?).

– What are the requirements for the data processing and analysis scenario? In particular, what is the accuracy, training time, linearity, number of parameters, and number of functions supported by the solution? That is, various accompanying requirements should be taken into account when choosing a machine learning algorithm. So, a list of the main groups of requirements for an effective machine learning scenario (and their details are given below in the text):

- Accuracy
- Study time
- Linearity
- Number of parameters
- Number and type of target functions

Accuracy in ML measures the effectiveness of the model in the form of the ratio of valid results to the total number of variants, that is, a set of industry metrics for accuracy assessment is calculated.

It is not always necessary to get the most accurate model possible. Sometimes an approximate answer is enough, depending on what the model is used for. If this is indeed the case – it is possible to significantly reduce the processing time by replacing with more approximate methods. Approximate methods also usually avoid excessive overtraining.

There are three scenarios for evaluating the accuracy of a trained model:

– creation of scores for training data to evaluate the model

– generating estimates for the model, but comparing these estimates to the values in the reserved test set

– comparing estimates for two different but related models using the same data set.

Study time. In supervised learning, learning refers to the use of historical data to create an error-free ML model. The number of minutes or hours required to train a model varies greatly for different algorithms. Learning time is often closely related to accuracy; one of them is usually an obstacle to the other.

Also, some algorithms are more sensitive to the number of data points than others. The analyst can choose a specific algorithm, as there are time constraints, especially if the data set is large.

Creating and using an ML model is usually done in three stages:

1. Configure the model by choosing a specific type of algorithm and then determining its optimal parameters.
2. Download a prepared dataset compatible with the selected algorithm. Connect the data and model to the model training module.
3. After training is complete, use the trained model with one of the estimation modules to make predictions based on new data.

Linearity in statistics and ML means that there is a linear relationship between a variable and a constant in a data set. For example, linear classification algorithms assume that classes can be separated by a straight line (or its approximation). Linearity is used in many classic ML algorithms. For example, linear regression algorithms assume that data trends follow a straight line. This assumption is only suitable for some problems, but reduces accuracy for others. Despite their shortcomings, linear algorithms are popular as a first strategy. They are usually algorithmically simple and quickly mastered. It should be remembered that using the linear regression method for data with a non-linear trend will lead to significantly more errors than necessary.

The number of ML algorithm parameters. Parameters are the controls that the analyst chooses when setting up the ML algorithm. These are certain settings that affect the behavior of the algorithm, for example: the permissible learning error or the number of iterations, options for the behavior of the algorithm in case of falling into a local extremum, etc. Training time and algorithm accuracy are often difficult to balance to obtain ideal algorithm settings. As a rule, algorithms with a large number of parameters take more time to experiment to find an effective combination of them.

It should be noted that in many applications for ML, a separate Model Setup Module is available. The purpose of this module is to select the optimal parameters for the machine learning algorithm. The module automatically creates and tests several models using different combinations of parameters. It compares metrics across all learning outcomes to find a good combination. However, the time required to train the model increases exponentially with the number of parameters. However, having a large number of parameters usually means that the algorithm has a lot of flexibility. And then it is possible to achieve very good accuracy of the trained model, provided that it is possible to find the right combination of ML algorithm parameter settings.

Number and type of target variables/functions. In ML, the target variable is the variable to be analyzed. For some data types and industries, the number of features/target variables can be relatively large compared to the number of data points. This is often the case with genetic or textual data.

A large number of features can slow down some learning algorithms, making the learning time very long. Support vector computers are particularly well suited for problems with a large number of functions. For this reason, they have been used in many information analysis applications for text and image classification. Vector computers can also be used to speed up the solving of classification and regression problems for ordinary data sets.

The selection of target variables occurs in the process of performing statistical tests on the input data taking into account the given output data. The purpose of such tests is to determine which columns are more predictive of the original data. in many applications for ML – The filter-based component selection module provides several options for selecting target variables and includes correlation methods such as Pearson correlation, chi-square value, etc. It is also worth using the service for automatic calculation of a set of evaluations of the importance of features for a specific data set if the functionality is available.

Data extraction and cleaning (ETL) technology for machine learning. Directly in Big Data, initially «clean» data does not exist. To be useful for ML, data must be heavily prepared and transformed. For example, you can:

• Review the data and exclude all columns that have a lot of missing data.

•View the data again and select the columns to be used for forecasting. (If you repeat this operation several times, you can select different columns.)

• Exclude all rows in which there is no data in the last columns.

• Correct obvious errors and combine equivalent values. For example, GB and Great Britain can be lumped into one category.

• Exclude rows with data that are outside the required range.

There is much more that can be done, but it will depend on the particular Data Set. This can be time-consuming for an expert, but if the data cleansing step in the machine learning pipeline is configured, it can be repeated using triggers later on if desired.

Coding and normalization of data for machine learning. To use categorical text data for machine classification, the text labels must be transformed into another form. There are two encoding modes.

The first is manual label numbering, each text label value is replaced by a number. The second is one-hot encoding, each value of the text label is converted into a column with a binary value (1 or 0). However, most machine learning platforms have features that do the coding themselves. Automatic one-hot coding is generally preferred, as manual label numbering can sometimes confuse the ML algorithm into thinking that the codes are ordered.

Also, to use numerical data for machine regression, the data usually needs to be normalized. This process is also often called scaling. Without normalization when calculating Euclidean distances, sets of numbers with large ranges may start to «dominate» unnecessarily, and «steepest» descent optimization may not converge. There are several ways to normalize data for ML, including minimax normalization, centering, standardization, and scaling to unit length.

Features in machine learning are individual measurable properties or characteristics of an observed phenomenon. The concept of «sign» is related to the concept of an independent variable, which is used in statistical methods such as linear regression. Feature vectors combine all features of one line into a numeric vector.

A major part of the art of effective feature selection is to select a minimal but sufficient set of independent variables that explain the task. If two variables are highly correlated, they should be combined into one or deleted. Some data transformations used to construct new features or reduce the dimensionality of their vectors are simple. For example, by subtracting the year of birth from the year of death, the age of death is obtained, which is the main independent variable for the analysis of mortality and life expectancy. In other cases, the preparation of signs may not be so obvious.

Hyperparameters for machine learning algorithms

The algorithms themselves have variables called hyperparameters. They are called hyperparameters because, unlike parameters, they control the operation of the algorithm, not defined weights.

The most important hyperparameter is often the learning rate, which determines the step size used when finding the next set of weights to optimize. If the learning rate is too high, the steep descent may quickly plateau or lead to a suboptimal local extremum. If the learning rate is too slow, the descent may stall and never fully converge.

Many other common hyperparameters depend on the algorithms used. For example, most ML algorithms have a stopping hyperparameter, such as the maximum number of epochs, maximum execution time, or minimum epoch-to-epoch improvement. Certain algorithms have hyperparameters that control the shape of their search. For example, a random forest classifier has hyperparameters for minimum samples to generate a leaf/branch, maximum depth, minimum samples when splitting, minimum mass fraction for a leaf, etc. Some ML frameworks provide automatic tuning of hyperparameters. Essentially, you tell the system which hyperparameters to tune, and possibly which metric to tune, and the system looks at those hyperparameters for as many runs as it's allowed (for example, Google Cloud hyperparameter tuning pulls the relevant metric from the TensorFlow model, so you don't you need to specify it.)

There are three approaches in automatic optimization of hyperparameters: Bayesian optimization, grid search, evolutionary optimization, and random search. As a rule, the most effective approach turns out to be Bayesian optimization.

It can be assumed that setting as many hyperparameters as possible will give a better result. However, this can be very expensive/time-consuming. With experience comes an understanding of which hyperparameters are most important for the data used in each specific case/problem and the algorithms selected.

The human factor in machine learning

Although data analysis and computational analysis may make us think that we are obtaining objective information, this is not the case; ML results are not always neutral. The shift in results introduced by the human factor affects not only the collection and systematization of data but also the algorithms themselves, which determine how ML will interact with this data.

Suppose there is a group of people collecting and labeling images for ML. She gets a task to collect images of flowers. If most people chose a rose for this image, the computer would not be able to classify a lily, sunflower, or violet as a flower.

Another example. Photographs of scientists were used as training data in ML. The computer received a set of images where the overwhelming majority of white men were represented. As a result, the machine could not properly classify people with different skin colors and women. Recent studies have shown that AI and ML programs have inherited racial and gender biases.

As ML is increasingly used in business today, undetected biases can cause systemic problems: based on prejudice, programs can prevent a person from getting a loan, finding an ad for a high-paying job, or even ordering a delivery.

In ML, the human factor can negatively affect other people, and it is now extremely important to be aware of this and strive to eliminate it. To do this, different people should be involved in the development, testing, and analysis of ML projects. Some developers request model monitoring and auditing from objective regulatory third parties. Others are creating alternative systems that can detect ethical biases in algorithms. Fighting «superstitions» in the field of ML is very important. To do this, you need to constantly raise awareness of possible problems, remember your own unconscious biases, and take them into account when collecting, preparing, and structuring data.

Automated machine learning

There is only one way to find out which algorithm or ensemble of algorithms will produce the best model in each case – to try all algorithms and their combinations. But if you also try all possible variants of data normalization and variants of functions, there will be a combinatorial «explosion».

Trying to do everything by hand is impractical, so ML tool vendors have put a lot of effort into releasing AutoML-class systems (so-called automated ML). The best of them combine parameter setting, algorithm selection, and data normalization. Hyperparametric tuning of the best model (or models) is often performed at later stages of the project.

Consider, for example, automated feature extraction, which is part of the complete AutoML workflow that provides optimized models. The workflow includes three simple steps that automate feature selection, model selection, and hyperparameter tuning. New high-level methods of automatic feature extraction from signals have appeared. Autoencoders, wavelet scattering, and deep neural networks are commonly used for feature extraction and data dimensionality reduction. Wavelet diffusion networks automate the extraction of low-variance features from real-time series and image data. This approach creates a representation of the data that minimizes within-class variation while maintaining the ability to distinguish between classes. Wavelet scattering works well when you don’t have a lot of data.

Hence, autoML is used to reduce human interaction and automate all tasks to solve real-world problems. This functionality includes the entire process from raw data to the final ML model. The goal of AutoML is to offer extensive learning techniques and models for non-ML experts. Remember, even though AutoML doesn't require human interaction, that doesn't mean it's completely superior to it.

Thus, the ML algorithms themselves are only part of the mosaic of machine learning. In addition to algorithm selection (manual or automatic), you will need to deal with optimizers, data cleaning, feature selection, normalization, and algorithm hyperparameter tuning.

Once you've completed the above procedures and then built a quality model that will work with your data, it's time to use the model and then update it as conditions change. However, the management of machine learning models is a modern scientific and practical problem, and the results of its solution will be presented in future publications.

2. Deep machine learning parameters with the use of Big Data information control systems

In its nascent years, AI largely focused on expert systems based on knowledge in the form of production rules that solved mainly diagnostic problems, but also design-type problems (using previously manually collected and formalized knowledge/experience of human experts in a specific subject area). However, this type of intelligent systems had numerous shortcomings, including the subjectivity of experts' opinions, which ultimately led to their loss of mass popularity [6–10].

As the scale and volume of data increased, these methods were replaced by a more controlled and objective data-oriented approach – ML. ML is a set of algorithms and tools that help machines understand hidden patterns in data and use the structure and essence of these hidden patterns in the data/heuristics to perform logical inference/prediction for a specific task. Currently, there is a diverse range of such methods/algorithms by which machines seek to understand these basic patterns such as association, sequence, classification, clustering, regression prediction, and anomaly detection in data.

If we systematically consider the history of the development of computational analytics and analyze its perspective, deep learning is a further evolution and subdomain of machine learning. Thanks to the emergence of architectures with increased computing power and large sets of semi-structured and unstructured data, specialized architectures and corresponding deep learning algorithms can independently study hidden patterns in BIG DATA and even perform generative functionality.

A key technology in deep ML is artificial neural networks. Such connectionist architectures in cybernetics have existed for more than 70 years, but new cloud hardware architectures, specialized processors (GPU and TPU), and the rapid distribution and accumulation of BIG DATA have once again brought them to the forefront of artificial intelligence and information control systems in particular.

However, recently there has been a growing misconception that deep learning is a competing technology to classical ML. Deep learning is not the only possible approach, but rather a specialized separate class of algorithms and topologies that should be applied to a certain range of scientific problems and practical tasks, in particular in the field of information control systems.

In this subsection of the monograph, the results of research and a comparative analysis are given not only in relation to the above hypothesis but also the results of thorough research on the advantages, problems, and features of effective deep ML in the conditions of BIG DATA information control systems are presented.

Deep learning is a machine learning technique that:

– automatically extracts features (Feature extraction automatically identifies/selects the most discriminating characteristics of signals, which are more easily exploited by machine learning or a deep learning algorithm. Feature extraction is a very difficult to automate and time-consuming process of converting raw data into numerical features (for example, recognizing speech recordings) that can be processed while retaining the information in the original dataset.)

– learns hidden patterns directly from big data.

Such Big Data for deep ML can be not only texts, speech recordings or other signals that are tied to time, place, and frequency (for example, sound, time series, signals from various microphones and other sensors).

That is why deep learning is often also called end-to-end learning.

Although deep ML was first formulated in the last century, there are the following main reasons why the use of deep learning has grown dramatically in recent years:

First, deep learning methods are now more accurate and more objective than human experts, particularly in information control systems.

Second, deep learning requires significant computing power. That is why the emergence of high-performance GPUs and TPUs with parallel architectures are effective for deep learning. When combined with clusters or cloud computing, this allows development teams to reduce training time for a deep learning network from weeks to hours or less.

Third, in the past few years, large amounts of labeled data have become available for deep learning.

fourthly, the booming interest and, therefore, investments from the corporate and state scientific communities also contributed to the advancement in this area and the effective continuation of relevant research.

The vast majority of deep learning methods use architectures and learning algorithms of conventional artificial neural networks. Artificial neural networks attempt to mimic the human brain using a combination of inputs, weights, and biases. These elements work together to accurately recognize, classify, and describe objects in data.

Artificial neural networks consist of multiple layers of interconnected nodes, each layer building on the previous layer to refine and optimize prediction or categorization. This flow of computation through the network is called forward propagation. The input and output layers of a deep neural network are called visible layers. The input layer is where the learning model receives data to process, and the output layer is where the final prediction or classification is made. Each neuron in the hidden layer is connected to many others. Each synapse has a weight property that controls how much activation of that neuron affects others attached to it.

Another process, called backpropagation, uses algorithms such as gradient descent to calculate the errors in the predictions, then adjusts the weights and biases of the feature by moving back through the layers to train the model. Together, forward and back propagation allow the neural network to make predictions and correct any errors accordingly. Over time, the algorithm becomes more accurate.

Thus, in the learning process, the ANN performs iterative nonlinear transformations of the input data and uses the obtained results to create a black box model, and the learning iteration continues for many epochs with different experimental parameters until the result reaches an acceptable level of accuracy.

Considering the common features of shallow neural net and deep neural net described above, it is worth noting that deep learning is an evolution of classical machine learning. Although a conventional shallow artificial neural network with one or more layers can still make approximate predictions, an additional increase in the number of internal layers in a DNN can greatly help to optimize and improve its performance, even on unstructured big data. The term «deep» usually refers to the number of hidden layers of such a neural network. Traditional shallow neural networks contain only 2–3 hidden layers, while deep networks can have up to 150. Therefore, the term «deep» in deep learning is associated with these deep hidden layers, and this is where its effectiveness comes from. The choice of the number of hidden layers depends on the nature and complexity of the problem and the size and characteristics of the data set.

Thus, deep learning programs have many layers of interconnected layers of artificial neurons, with each layer building on the previous one to refine and optimize regression or classification predictions. This is similar to the way our human brain works to solve problems – it runs queries through various hierarchies of concepts and related questions to find an answer. It is the number of layers of data processing in the hidden layers through which the input data must pass that gave rise to the term «deep».

The simplest type of shallow neural network was briefly analyzed above. However, both deep learning algorithms are incredibly complex, and deep neural network architectures are very specific and variable for solving a range of very different problems. Therefore, it is appropriate to highlight six types of DNN architectures that have gained popularity and proven their effectiveness over the past 20 years. Long Short-Term Memory (LSTM) and Convolutional Neural Networks (CNN) are the two oldest approaches on this list, but also the two most used in a variety of applications.

Convolutional Neural Networks (CNNs), used primarily in computer vision and image classification applications, can detect features and patterns in an image, enabling tasks such as object detection or recognition.

Recurrent Neural Networks (RNNs) are commonly used in natural language and speech recognition applications because they use sequential or time series data.

The current research classifies deep learning architectures into supervised and unsupervised learning and introduces several popular deep learning architectures: Convolutional Neural Networks, Recurrent Neural Networks (RNN), Long Short-Term Memory/Supervised Recurrent Unit (GRU), Self-Organizing Map (SOM), autoencoders (AE) and restricted Boltzmann machine (RBM), deep belief networks (DBN) and deep stacking networks (DSN).

Machine and deep learning models are capable of different types of learning, commonly classified as supervised learning, unsupervised learning, and reinforcement learning. As outlined above, both classical machine learning and deep learning technologies use data to train, but the key difference is what data they use, how they process that data, and how they learn from it using which architecture configuration.

The fundamental questions of the theory of classical machine learning were revealed in their works by such scientists as Nils J. Nilsson, Trevor Hastie & Robert Tibshirani & Jerome H. Friedman, Pedro Domingos, Ian H. Witten & Eibe Frank, Ethem Alpaydin, David J.C. MacKay, Richard O. Duda and Peter E. Hart, Christopher Bishop, Stuart Russell & Peter Norvig, Ray Solomonoff, Kevin P. Murphy.

The main principles of the theory of deep machine learning were revealed in their works by such scientists as: Schulz Hannes & Behnke Sven, LeCun Yann & Bengio Yoshua & Hinton Geoffrey, Marblestone Adam H. & Wayne Greg & Kording, Konrad P., Deng L. & Yu, D., Zhang W.J. & Yang G. & Ji C. & Gupta, M.M., Bengio Yoshua, Bengio Y. & Courville A. & Vincent, P. LeCun Yann & Bengio Yoshua & Hinton, Geoffrey, Schmidhuber J., Hinton G.E. and other.

But the urgent question of an effective choice between machine and deep machine learning in information control systems, and the question of analyzing the advantages, problems, and features of deep machine learning on big data information control systems, remained unresolved.

Considering the above, the actual and initial goal of the current of this part of complex interdisciplinary collective scientific research was not only to propose recommendations for the choice between machine and deep ML in information control systems but also to propose methodological and practical recommendations regarding the advantages, problems and features of deep ML in scientific research and practical projects/tasks of information control systems.

Below are the results of the study of important differences between classic machine learning and deep learning technologies:

1. ML involves using thousands of data points, while deep learning uses millions of data points. Machine learning algorithms typically work well with relatively small sets of labeled and structured data. Machine learning algorithms are also better when data is scarce. Conversely, deep learning needs really very large amounts of unlabeled or partially labeled data that have semi-structured or unstructured data format to understand the data and perform better than traditional machine learning algorithms.

2. ML algorithms solve problems using explicit programming (algorithms for building decision trees and forests, finding association rules, finding regression equation coefficients, kNN, SVM and Naïve Baies classifiers, hierarchical and non-hierarchical cluster analysis, etc.). That is, classical machine learning offers a wide variety of

methods and algorithms that can be chosen depending on the specifics of the subject area/industry, your specific task, the nature of the structured data being processed, and the type of problem to be solved. However, deep learning algorithms solve all problems after a complex process of learning hidden deep layers of neural networks of special architectures and their further use in black box mode.

3. ML algorithms take relatively less time to train, from a few seconds to a few hours. On the other hand, deep learning algorithms take a long time to train an artificial neural network, from a few days to many months.

4. Classical ML provides the possibility of using very different methods/algorithms (algorithms for building decision trees and forests, finding association rules, finding coefficients of regression equations, kNN, SVM and Naïve Baies classifiers, hierarchical and non-hierarchical cluster analysis, etc.); while deep machine learning involves the use of exclusively artificial neural networks of special architectures.

5. Classical ML requires an interactive process of interaction with the analyst at all stages of the project, unlike deep machine learning. Deep learning networks do not require human intervention, as multi-level layers in neural networks contain data in a hierarchy of different concepts that eventually learn from their own mistakes, i.e. are capable of self-learning over time. However, even these can be misleading if the data quality is not good enough.

6. In classical machine learning and in deep machine learning, the quality and representativeness of the input data significantly affect the quality of such learning, however, given the minimal intervention of expert analysts in the auto ML mode of deep learning, the risks for it due to low-quality and incomplete data are much greater.

7. Classic ML with time and/or the appearance of significant changes (either systemic or force majeure) in the studied subject area requires re-training of the model – but exclusively on new sets of collected data, in which such changes should be reflected.

8. Since machine learning algorithms can learn only according to pre-programmed set criteria and require labeled data, they are not suitable for solving innovative complex scientific queries in free search mode, which involves a significant amount of unlabeled semi-structured and unstructured data (for example, deciphering and understanding completely unknown In other words, cases, where deep learning excels, include situations where there is a large amount of unlabeled data, a lack of domain understanding for feature discovery/extraction, or more complex problems such as speech recognition and NLP.

9. Classical machine learning does not require the same expensive high-quality computing machines and high-performance processors (GPU and TPU) as deep learning.

10. After all, many data scientists choose traditional ML over deep ML because of its superior interpretability or ability to understand solutions. On the contrary, deep learning models are complex, they work like a «black box», that is, it is difficult to explain the course of the decision and prove the result.

11. Deep learning is a subset of machine learning that is distinguished by the way it solves problems. Most ML application functions require an expert in the field to define. Deep learning, on the other hand, understands hidden functions incrementally, in an offline mode, thus eliminating the need for domain expertise and the systematic intervention of a human expert analyst. Because of this, deep learning algorithms take much longer to train than machine learning algorithms, which only take a few seconds to a few hours. However, the opposite happens during testing. Deep learning algorithms take much less time to run tests than machine learning algorithms, whose testing time increases with the size of the data.

12. Retraining for classical machine learning may turn out to be a more pressing problem on modern data sets, given the automatic ability of shallow hidden layers of a deep neural network to level the impact of noise and anomalies in big data and the ability of subsequent, deeper hidden layers to generalize to really big data.

The benefits of deep learning include the following:

1. Automatic learning/extraction of features/features from big data.

Deep learning systems can perform feature extraction from data automatically, meaning they do not need supervision to add new features. Deep learning algorithms can save time by not requiring humans to manually extract features from raw data. Deep learning will perform in auto ML mode most of the previous interactive «manual» data processing that is usually associated with machine learning. These algorithms can accept and process unstructured data, such as text and images, and automate feature extraction, removing some reliance on human experts.

2. Discovery/search for hidden regularities/patterns in big data.

Deep learning systems can intelligently and deeply analyze large volumes of data and detect complex patterns in images, text, and audio recordings of conversations, other signals, in order to extract hidden, non-trivial, and useful regularities/patterns.

3. Ability to effectively process and analyze highly variable/unstable/variable features in big data.

Deep learning systems can classify and sort data sets that have very large variations. Volatile/volatile data sets have large variations and/or noise.

4. Automatic marking/marking of new data.

Deep learning requires labeled/labeled data for training. After training, a DNN can independently label new data and identify different types, categories, or values of new chunks of data.

5. Effective processing of unstructured data.

Classical ML techniques find unstructured data, such as conversation recordings, difficult for automated processing and analysis because the training dataset can have infinite variations. On the other hand, deep learning models can take in unstructured data and make general observations without manually extracting features. For example, a neural network can recognize that these two different input sentences have the same meaning:

– Tell me how to make the payment.

– How should I transfer the money?

This does not necessarily mean that classical ML does not use unstructured data; it simply means that in this case, unstructured data requires a rather long, complex, and time-consuming procedure of pre-processing the input unstructured data for the purpose of manual extraction of features, their quantification, normalization, and organization into a structured format (which is acceptable for classical ML methods).

In turn, it is worth noting that simple architectures of deep neural networks are also able to process structured data if there is an appropriate amount of it.

6. Accuracy.

Adding additional hidden layers to DNNs helps optimize deep learning models to provide greater accuracy.

7. Faster debugging of AutoML mode compared to classical machine learning.

Compared to conventional machine learning processes, deep learning requires much less human intervention and manual experimentation and can automatically analyze types and volumes of data that classical ML cannot handle and analyze.

8. More efficient and functional unsupervised machine learning.

Deep learning models can learn and improve over time based on user behavior and their own experience. They do not require large variations of labeled datasets. For example, consider a neural network that automatically corrects or suggests words by analyzing your typing behavior. Suppose that a DNN has been trained on the English language and can check the spelling of English words. However, if the user often types/speaks non-English words like danke, a trained (according to your behavior and characteristics) deep neural network will automatically identify such common typos/spellings and errors and automatically and correctly correct them.

While deep learning has gained popularity over the past few years, it comes with its own set of challenges that the community is working hard to solve.

Deep learning projects and cases may also have systemic flaws and certain limitations, in particular:

The problem of biases and biases in input data for training and its verification. If a model is trained on insufficiently large and representative data that is obtained from different and independent sources, the data may contain biases and biases, and the trained model will reproduce these biases in its subsequent predictions. This is especially a threat to convolutional DNNs with an unreasonably large number of hidden layers – which can often be prone to overgeneralization.

Optimal configuration of DML hyperparameters, in particular learning speed. Choosing the optimal learning rate also becomes a serious challenge for deep learning models. If the speed is too high, the model converges too quickly, producing a not-always optimal and accurate model. If the learning rate is too low, the learning process may take too much time (and therefore exceed the operating budget). In addition, a suboptimal learning rate can lead the model to fall into local or sub-global optima. Another problem with slow learning rates is the threat of overfitting. However, even in the case of a deep learning model transfer strategy (which is currently a popular practice and seems to be able to solve the above threats), retraining a pre-trained deep neural network on new data will still require much more time and computing power than in the case of using classical ML.

High requirements for the global financial and operational parameters of the Data Center and its equipment. Multi-core high-performance specialized processors (GPU and TPU) and other related high-performance hardware are necessary to ensure the comprehensive cost-effectiveness of the DML project. However, this hardware not only requires significant investment but is currently in short supply. Complex conditions of a data processing center with such equipment should also take into account the main item of the operating cost of such projects – the price of electricity.

The need for large volumes of large-dimensional data, including and verified marked. To obtain high-quality DNNs in real conditions of big data, there is a need for a large amount of prepared data of the maximum dimension. And to solve regression forecasting problems in such conditions, it is even more difficult to satisfy the need for a large number of prepared and checked correctly/correctly marked/marked data of the maximum dimension. Obtaining which will be an expensive, difficult task that requires considerable time and labor costs.

The need for large amounts of high-quality data. Deep learning algorithms produce better results if they are trained on large volumes of high-quality data. Outliers, errors, lack of representativeness and adequacy of input big data, and other errors in big data – as a rule, will significantly affect the deep learning process. To avoid such problems, in the case of deep learning, data engineering, namely ETL/ELT, is very important and responsible. Such pre-processing of input big data for deep machine learning requires a lot of time, labor, and computing power.

Lack of multitasking/versatility of trained DNN in real conditions of its use over time. In order to obtain quality results from DML – machine learning problem statement, the relevant data for training and testing, as a rule, should be as specific/targeted/aimed at solving one specific narrow problem/problem as possible. This can lead to the loss of even the limited/conditional universality of the obtained model – and, therefore, to further limitations in the mode of using the trained DNN in real, current conditions (which will contain/reflect objective needs due to even a slight change in the macro environment of the organization/project/company with the passage of time).

Lack of adequacy of trained DNN with real new actual data. To obtain quality results DML – machine learning problem statement, suitable big data for training and testing must be cleaned and prepared. This can lead to the loss of even the limited/conditional universality/adequacy of the model trained on such data – and therefore to further errors in the mode of using the trained DNN on new, real, and relevant data, especially in the conditions of big data (which naturally will definitely contain anomalies and information noise that were filtered out in the ETL/ELT step before training the DNN).

Lack of transparency of deep machine learning results. While the algorithm looks at millions of data points to find hidden patterns during this training, it will likely be very difficult to understand how the neural network arrives at its decision. The lack of transparency in how DNNs process data in both training mode and usage mode makes it much more difficult for human experts to detect unwanted biases and explain predictions. Despite the fact that deep learning algorithms surpass the accuracy of human thinking, there is no clear and clear way to go back (conduct reverse reasoning – deduction) and justifications to explain how exactly, step by step, each made prediction was obtained on the basis of a new portion of input data. This makes it difficult to use DML in some types of scientific research, where the obtained result must be clearly explained and justified.

Behavioral fairness of reinforcement learning agents. Another aspect that tends to be problematic when using reinforcement learning models is the presence of meaningful/behavioral/systematic biases/distortions in the input data itself, which can lead to poor/suboptimal performance of the model trained on them due to its suboptimal learning trajectory. Software agents learning using a reward-based mechanism sometimes stop behaving ethically/fairly/ constructively because all they need to do to minimize the aggregate error is to maximize the reward they receive. In the literature, such an example is mentioned, when the software agent simply stopped playing the game and got into an endless cycle of collecting prize points. While this may be partially acceptable in a game scenario, wrong or unethical decisions can have profound negative consequences in the real world. Thus, it is relevant to have additional control of training results with reinforcement for obtaining balanced/constructive/ethical results. To this end, there are specialized open-source toolkits for detecting, investigating, and eliminating such systematic errors in deep learning algorithms and data. It is important for deep learning researchers and users to keep these potential issues in mind when planning and conducting reinforcement learning deep learning experiments.

Running deep learning algorithms on cloud infrastructure can overcome many DML problems. It is effective to use deep learning in the cloud to more effectively design, develop and train deep learning applications. Cloud computing services help make deep learning more accessible by making it easier to manage large data sets and train algorithms on distributed hardware.

Cloud services contribute to effective deep learning in the following aspects:

– provide access to large-scale computing power on demand, enabling model training to be distributed across multiple machines.

– provide access to special hardware configurations, including GPUs, FPGAs, and massively parallel high-performance computing (HPC) systems.

– do not require significant initial investments — because, in the conditions of using cloud technologies, analysts get access to modern equipment without buying it.

– help manage deep learning workflows — cloud services provide advanced features and templates for managing data sets and algorithms, training models, and their efficient deployment in production.

– increase the speed of DML. Experts and analysts can train deep learning models faster by using clusters of GPUs and CPUs to perform the complex mathematical operations required for your neural networks. Analysts can then deploy these models to process large volumes of data and produce increasingly relevant results.

– improve the accuracy of DML. High accuracy: Deep learning algorithms in the cloud computing mode can achieve state-of-the-art performance in various tasks in the field of information control systems, in particular, such as semi-structured text recognition and natural language signal processing.

– facilitate DML scalability.

With a wide range of on-demand resources available through the cloud, professionals gain access to virtually unlimited hardware resources to work with deep learning models of any size. Configurable deep neural network architectures can take advantage of multiple processors to smoothly and efficiently distribute workloads among different types and numbers of processors.

The main areas of application of deep learning in the field of information control systems can be divided into three areas: computer vision, natural language processing, / and reinforcement learning

In computer vision, deep learning models can enable machines to identify and understand visual data. Some of the major applications of deep learning in computer vision include:

– Object detection and recognition: A deep learning model can be used to identify and locate objects in images and videos, enabling machines to perform tasks such as self-driving cars, surveillance, and robotics.

– Image classification: Deep learning models can be used to classify images into categories such as animals, plants, and buildings. This is used in applications such as medical imaging, quality control, and image retrieval.

– Image segmentation. Deep learning models can be used to segment images into different regions, enabling the identification of specific features in images.

In NLP, deep learning can enable machines to understand and generate human language. Some of the main applications of deep learning in machine linguistics include:

– Automatic Text Generation – A deep learning model can learn a corpus of text and new text like resumes, and essays can be automatically generated using these trained models.

– Language translation: deep learning models can translate text from one language to another, making it possible to communicate with people from different linguistic backgrounds.

– Sentiment analysis: Deep learning models can analyze the sentiment of a piece of text, allowing it to determine whether the text is positive, negative, or neutral. This is used in applications such as customer service, social media monitoring, and political analysis.

– Speech recognition: Deep learning models can recognize and transcribe spoken words, enabling tasks such as speech-to-text, voice search, and voice-controlled devices.

In reinforcement learning, deep learning works by teaching agents to act in an environment to maximize reward. Some of the main applications of deep learning in reinforcement learning include:

– Games: Reinforcement deep learning models have been able to beat human experts in games such as Go, Chess, and Atari.

– Robotics: Deep reinforcement learning models can be used to train robots to perform complex tasks such as object grasping, navigation, and manipulation.

– Control systems: Deep reinforcement learning models can be used to control complex systems such as power grids, traffic management, and supply chain optimization.

Conclusions

For years, all individuals and legal entities have generated, registered and stored (in databases, repositories and data showcases) huge volumes of heterogeneous structured and semi-structured information (quantitative, qualitative, text, hypertext, transactional, geo-information, multimedia, meta-information, etc.) regarding all aspects of their business, technological and management activity. In addition, the rapid development and spread of Big Data, Web 4.0 and Web 5.0, IOT, augmented reality, blockchain in recent years caused an additional avalanche-like increase in stored data.

This big data contains a significant potential for finding and formalizing hidden new regularities (knowledge, patterns), which are the basis for making optimal and effective managerial and technological decisions, including in the field of marketing.

From these regularities and patterns (after their verification and interpretation), the corporate knowledge base is mainly formed, including and for expert systems and classic artificial intelligence systems, which should become an integral part of the innovative marketing management system of any company or enterprise.

In the modern conditions of the development of the global economy, and in connection with the emergence of new branches of economic activity in the field of informatization, the application of innovative technologies for the preparation, processing, analysis, and analytics of extremely large arrays of heterogeneous data leads to the obtaining of additional competitive advantages by users at the state, regional, branch and corporate levels of management, which is especially relevant in times of crisis [11–15].

Summing up the following interim summary of this work, it is worth noting that there are dozens of classical machine learning algorithms, varying in complexity from linear regression to deep neural networks. Until recently, these classical approaches using classical machine learning allowed us to achieve acceptable accuracy and quality, but in the context of structured ICST data.

The influence of big data ICST – has urgently actualized for classical methods of machine learning the need for their combination and their joint sequential/parallel use – in a hybrid-scenario mode, including using assembly technologies.

But even an experienced ICST expert will not say which algorithm (or their ensemble) in which configuration of parameters and variant of hybridization will work most effectively in a specific subject area for a specific task, without a complex of additional studies, a series of tests and tests.

To summarize from Chapter 2, deep learning is a subfield of machine learning that involves the use of deep neural networks to model and solve complex problems. Deep learning has made significant strides in a variety of fields, and its use is expected to continue to grow as more data and more powerful computing resources become available.

However, the emergence of new challenges associated with large semi-structured and unstructured data in information control systems does not allow classical methods/algorithms of machine learning to effectively and efficiently respond to the above-mentioned challenges.

In summary, we can say that it is the hybrid use of deep machine learning (which involves the use of deep neural networks of various specialized architectures) and classical machine learning methods in various ensemble modes (which will allow not only to solve modern problems of machine linguistics productively and quickly but also correctly) is appropriate for responding to the above-mentioned challenges and problems of big data analytics of information control systems [16–19].

All of the above results are becoming more relevant due to the already existing specialization and recent successes of hardware manufacturers for fast and more affordable deep machine learning (including in experimental modes to determine optimal machine learning hyperparameters and optimal machine learning configurations).

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USING BLOCKCHAIN TECHNOLOGIES TO CREATE DISTRIBUTED, SECURE CORPORATE SYSTEMS

Blockchain is a modern technology of distributed databases, which has gained general recognition as a promising direction in the development of information technologies and is widely used in a wide variety of industries. If in the early stages of development blockchain networks were mainly used as an infrastructure base for the circulation of cryptocurrencies, then currently blockchain projects are effectively implemented in the fields of trade, logistics, finance and banks, insurance, property rights, etc. [1–5].

New blockchain solutions are emerging for decentralized finance, infrastructure facilities, and public administration [6–9].

Many projects offer blockchain-based data analytics, distributed infrastructure to support artificial intelligence models, Data Science, the Internet of Things (IoT), etc. [10].

In addition to the expansion of the scope of application, research, and development of new technological and engineering solutions aimed at solving the problems of integration of blockchain networks of various levels, scaling of blockchain solutions are being carried out [11].

The above characterizes blockchain technologies as constantly developing and requiring the study of new directions and possibilities of their application, solving problems of their functioning, and analyzing optimal approaches to the development of complex distributed blockchain projects. These questions constitute the goals and objectives of this study.

Presentation of the main material

With the development of cryptography and blockchain technology, the infrastructure of cryptocurrencies is becoming increasingly complex, leading to the appearance of complex infrastructure objects. In particular, **cryptocurrency ecosystems** have emerged as an environment for the development and activity of digital cryptocurrency. The cryptocurrency ecosystem includes a wide range of products that are functionally interconnected and interact with one another, such as:

- a payment service that uses cryptocurrency wallets, own tokens, and smart contracts for conducting transactions in the system;
- decentralized finance (De-Fi), the components of which can be stablecoins, services for providing credits and attracting loans to solve various financial tasks of the ecosystem;
- a set of blockchain solutions for corporate use, which are created at the request of specific companies to solve their tasks;
- entertainment services, which may include proprietary social networks, non-fungible tokens (NFTs), and computer games.

The main modern cryptocurrency ecosystems are the BSC and Ethereum ecosystems. Following their example, new projects are developing, for example, Polkadot, Avalanche, Solana, and Cardano, which are expanding their infrastructure.

The cryptocurrency ecosystem provides its autonomy and is independent of external factors functioning in the blockchain system. The architecture and functionality of the ecosystem are gradually evolving with the addition of new elements and services.

An essential component of the blockchain technology, which ensures the safety, reliability and efficiency of the blockchain system, is its protocol.

The **blockchain protocol** is a set of rules and procedures that determine the order of interaction of participants with the system and with each other, transactions creation and control operations and the structure of their blocks in the blockchain, set algorithms for reaching consensus among participants regarding the right to record blocks in the blockchain. There is a large selection of consensus algorithms [1], the most famous of which is: PoW (Proof of Work) consensus, where network participants must perform complex computational tasks to write new blocks into the system; a PoS (Proof of Stake) consensus, where block validators are chosen based on the number of coins they own.

Blockchain protocols can be public or private with varying levels of access. Public protocols are available for use by anyone and ensure the openness and transparency of the blockchain. Private protocols are created for specific purposes, organizations, or enterprises and are limited to a group of participants with different levels of access.

Blockchain business models

The implementation of blockchain projects in various sectors of the economy and business creates the problem of developing appropriate organizational business models. The traditional business model mostly involves centralized management and vertical (hierarchical) relationships between management levels. In contrast, the blockchain model has a decentralized or distributed structure and mainly supports horizontal connections between nodes. However, in practice, blockchain can be used to store closed data with limited access rights. The requirements for secure storage and limited access to this kind of information often dictate the need for a closed, private blockchain and decentralized network. Thus, the blockchain business model suggests different approaches to building a blockchain network architecture and business management structure. The principle of business profitability remains common to the traditional organization of business and projects using blockchain, i.e., such enterprises must in one way or another bring income to their founders.

Taking into account the practical experience of developing and operating business projects based on blockchain technologies [12], the most common types of blockchain business models can be identified.

1. Business model of utility tokens.

A utility token is a digital token issued to finance the development of a blockchain project and to support its operation. Utility tokens can be used to gain access to products and services offered by a company and to increase its capitalization and generate profits.

The utility token business model is very common in the blockchain technology industry. There are a large number of decentralized finance and e-commerce blockchain networks developed using utility tokens.

2. Blockchain as a service (Baas).

The essence of the blockchain as a service (BaaS) business model is that an external service provider installs and configures all the necessary blockchain infrastructure for the client, as well as supports the operation of technological means, for a certain fee.

In addition, the provider controls such functions and tasks as network bandwidth management, rational distribution of resources, compliance with hosting requirements, and security measures. With BaaS, the customer can focus on the functionality of their blockchain instead of solving its infrastructure and performance issues.

3. Frameworks for blockchain projects.

The development and growth of interest in blockchain technology have resulted in an increase in the number of new blockchain projects in various industries. However, the development of an original blockchain project involves independent research and project work, the presence of highly qualified specialists at the enterprise, and large expenditures of time and money. Instead, designing based on blockchain frameworks is efficient and requires less cost. Related to this is the following blockchain business model.

A blockchain framework is a software framework or shell that simplifies the development, deployment, and maintenance of blockchain infrastructure and end-use cloud solutions. Usually, the framework contains only the framework of the blockchain and its basic modules, and all specific components are implemented by the developer on their basis. This ensures a high speed of development and guarantees the reliability and performance of the final product.

Currently, the industry offers a significant number of powerful blockchain frameworks, from universal Ethereum, Bitcoin, Hyperledger, and EOS to specialized Corda (enterprises and organizations, banks), NEM (trade), Quorum (banking sector), IOTA (Internet of Things). There is also research into new approaches to blockchain architecture, resulting in innovative frameworks such as Tendermint Core, Cosmos SDK, etc.

4. Blockchain-based software products.

Implementation of blockchain-based software products is designed to solve such problems of enterprises and organizations as secure data storage in decentralized (distributed) registers, optimization of infrastructure solutions, creation of financial settlement networks, etc.

The easiest way to solve such problems is to purchase a blockchain solution and integrate it into the information system of the enterprise or partner network. This business model refers to the activities of software development and consulting companies that create blockchain solutions and sell them to customer companies. The sale of blockchain solutions to other organizations is a profitable business, which, among other things, may involve the further provision of blockchain implementation, debugging, and support services.

On the other hand, it is much easier for companies to buy a ready-made blockchain solution that meets their requirements than to develop it in-house.

5. Professional services in blockchain technologies.

The business model of providing professional services in blockchain technologies is connected with the sale of blockchain solutions. These services are provided by leading development companies for startups or other enterprises and may include consulting, research and reengineering of business processes, development and implementation of a blockchain project, blockchain support and maintenance. Services may also include business auditing or the preparation of blockchain-related legal documents.

Blockchain technology services are provided by companies such as Deloitte, IBM, and others.

6. Payment for network usage.

Multi-functional open blockchain networks can provide users with the ability to perform a variety of jobs for a fee.

For example, the Ethereum network charges developers a fee to run decentralized dApps.

The Neo blockchain network enables transactions and creates decentralized solutions. In addition, it offers users other paid services, including a decentralized file storage system, an identity system, and a blockchain oracle system for providing information from external sources. Two cryptocurrencies are involved in the operations of the Neo blockchain network: the NEO token for voting on protocol changes and GAS for paying for computations on the network.

7. Peer-to-peer blockchain business model.

The peer-to-peer business model involves the use of peer-to-peer public blockchain networks for storing and exchanging data between users. Peer-to-peer networks enable end-users to interact directly with each other and use users' computing resources to store data. Payment for services can be made in different ways, such as tokens, commission payments, or BaaS.

Examples of the blockchain peering model are the IPFS interplanetary file system and the Filecoin blockchain platform, which is focused on data storage and exchange.

8. Corporate blockchain.

The development of blockchain technology and decentralized and distributed blockchain systems created an information and technological basis for the implementation of a decentralized management model of enterprises and organizations. A significant number of enterprises of various sizes, from small startups to corporations and consortia, are emerging that use blockchain networks as a technological base for the formation of management and data storage infrastructure. This approach to business organization is called the corporate blockchain business model.

Corporate blockchain is most often implemented in the fields of finance, property rights, logistics, and identification. One example is the banking consortium R3CEV (an association of more than 70 of the world's largest banks and financial companies), created using blockchain technology in the field of finance.

Let's consider some of the blockchain business models in more detail.

Token economy

The business model of utility tokens involves the use of functions and properties of tokens (mainly utility tokens) of cryptocurrency platforms to perform various business operations, generate profit, and stimulate end users of blockchain projects. Another well-known name for this business model is the token economy.

Tokens are digital assets that are created in blockchain networks and represent a certain asset, function, or utility. The peculiarity of tokens is the absence of their own blockchain, which is why they can function only on the networks of other cryptocurrencies.

In the context of specific software, a token is a programmable monetary unit attached to the blockchain and involved in the operation of a smart contract. In the business world, a token is defined as a unit of value that an organization creates to independently manage its business model and allow users to interact with its products while facilitating the distribution and sharing of rewards and benefits for all stakeholders.

Depending on the functions, the following **types of tokens** are distinguished:

- utility tokens – are used for circulation within decentralized applications (for payment, receiving part of the profit). Decentralized applications (dApps) are digital applications based on smart contracts that run on blockchains. They implement a wide range of services and functions from games to finance, social networks, etc.;
- governance tokens – provide the right to participate in voting on the further development of the blockchain system and in reaching consensus;
- security tokens – perform the functions of securities (confirm the right to own a share of the project and are similar to investment agreements);
- stablecoins – assets whose exchange rate is tied to the value of a certain asset, most often, fiat currencies – dollars, euros, and others (the largest representatives are USDT, USDC);
- wrapped tokens – a copy of a crypto-asset issued in another blockchain against the pledge of the original coin. This type of token makes it possible to expand the possibilities of using cryptocurrency, for example, to trade on decentralized exchanges that do not support the original cryptocurrency (for example – Wrapped Bitcoin, WBTC);
- digital currencies of central banks – issued and fully regulated by the central bank;

- non-fungible tokens (NFT) – unique digital objects in the form of images, audio, or video files, which are used for special purposes (collecting, avatars, etc.).

In the business model of the token economy, management and utility tokens play the most prominent role.

A **governance token** is a digital asset whose owners can participate in decision-making regarding the development of a blockchain project within the framework of a decentralized autonomous organization. Voting can be done on the following blockchain management issues:

- determining the amount of commissions related to operations in the blockchain and their distribution among participants;
- creation and replenishment of the project development fund;
- grants to system developers;
- changes to the user interface, etc.

In decentralized financial applications (DeFi), governance tokens can not only be used for voting, but also bring profit to their owners in such types of business as staking, landing protocols, and profitable farming.

Staking is a way of receiving passive income from blockchain systems that use the Proof-of-Stake (PoS) consensus algorithm and its variants. Its essence is to block a certain number of tokens in the wallet to obtain the right to participate in the use of the corresponding blockchain and receive income for it.

The lending of cryptocurrencies means the owner providing his assets (coins or tokens) for management or a loan on the landing platform. Other users or traders can borrow these assets at a set interest rate or other terms. Lending can be considered a form of decentralized finance (DeFi).

Types of cryptocurrency lending include deposit and loan lending. With deposit lending, users can deposit their cryptocurrency assets on the platform and receive rewards in the form of interest rates. Lending is a process where users can borrow tokens in exchange for collateral (such as other digital assets).

Another type of lending is unsecured, in which the user can get a loan without collateral, but must repay this loan. The rules of collateral less lending fix decentralized financial protocols, for example, Aave or Compound.

It is also possible to automate the landing process. For this, decentralized protocols are used, which make it possible to take a loan or lend assets without direct interaction with other users. Such protocols use smart contracts to automate processes in DeFi decentralized finance systems.

An example of such a solution on the WhiteBIT platform is the WhiteBIT lending service, which automates the lending process with appropriate interest rates. Lending on the stock exchange provides an opportunity to lend assets to the platform in accordance with the chosen plan with a fixed rate and other conditions.

Another lending model is shared lending pools, in which users pool their assets and then share profits or costs in proportion to their contribution.

Yield farming involves placing cryptocurrency (tokens) in liquidity pools or on deposits. When tokens are sent to liquidity pools, the owner earns a profit from trading transaction fees. When tokens are placed on deposits, the owner is credited with interest on issuing the deposited tokens to borrowers.

Yield farming is linked to the development of decentralized finance. Users contribute their tokens to the liquidity pool, thus supporting the functioning of the DeFi platform. Such users are called liquidity providers (LP).

Liquidity Pool is a decentralized application (dApp) in which all funds are stored using a smart contract. When liquidity providers contribute their tokens to a liquidity pool, they receive a defined reward or a percentage of the revenue from the core activity of the DeFi platform that hosts the liquidity pool.

The liquidity pool powers the DeFi market, where any user can borrow or lend various tokens. All users when using DeFi platforms pay a fee, which is used to pay liquidity providers for their contributions to the pool.

The value of governance tokens depends on market conditions, as well as the quality of the platform on which they are used. Cryptocurrency exchanges determine the ratings of governance tokens by the level of market capitalization (Fig. 1).

Governance tokens play an important role in the development of decentralized blockchain projects, as they are a tool through which various participants can join the work of a decentralized organization and exercise influence over the direction of its development.

Utility tokens are crypto-assets intended for special purposes of use in specific cryptocurrency ecosystems. Sometimes utility tokens provide access to blockchain infrastructure or use of a product, but more often they are used to perform certain transactions, pay fees, receive benefits and income, make expenses, and fund projects.

The value of utility tokens depends on the quality of the corresponding blockchain project and the relevance of the operations in which they are involved.

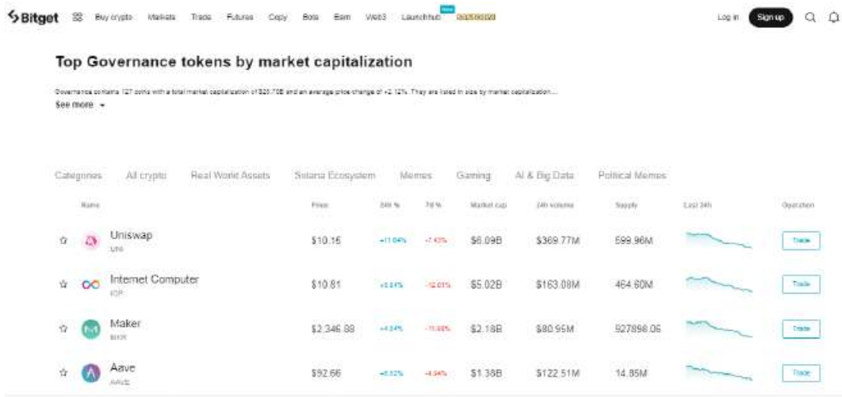

Figure 1. Rating of governance tokens on the Bitget exchange

Source: [13]

For example, utility tokens MATIC of the Polygon ecosystem are spent on payment of transaction fees. The Basic Attention Token (BAT) is designed to reward Brave browser users for viewing ads and also serves as a means of payment to advertisers.

Owners of the BNB token receive a discount on trading fees on the Binance centralized exchange and are also able to support new projects on the Launchpad platform. Also, this token is a key element of the BNB Chain decentralized blockchain ecosystem and is used to pay transaction fees.

The $EDU token ensures the operation of the Open Campus protocol and contributes to its development. At its core, the Open Campus Protocol is a blockchain project for the creation and distribution of educational content, which provides students with access to a variety of educational content, and teachers with additional opportunities to receive income and recognition for their work.

Blockchain as a Service (BaaS)

Blockchain as a Service (BaaS) involves the creation of corporate blockchain solutions based on the use of cloud blockchain applications and services of service companies. BaaS providers provide paid services for setting up blockchain implementation, deploying and maintaining network nodes, supporting internal services, security and hacking protection protocols, resource allocation, network bandwidth, and performance management, etc.

There are certain criteria for choosing a BaaS provider capable of providing an optimal blockchain solution, such as:

- fast initialization;
- server services;
- identification and access management;
- smart contracts;
- choice of blockchain structure and tools.

Fast initialization essentially means the ability to quickly and without unnecessary complications install and deploy blockchain networks and effectively manage this environment. Blockchain network support requires the provider to choose the optimal combination of database, browsers, firewalls, application servers, and hardware. At the same time, the provider's work is complicated by the following factors:

- complex installation that requires detection and correction of errors;
- network environments that are difficult to maintain and administer;
- the need to use the latest tools;
- the need to integrate inflexible systems and environments that need to be fixed;
- non-standard situations in system deployment;
- lack of hardware support for all projects;
- configuring functions between production, testing, and development.

Potential BaaS customers face the task of finding an experienced provider capable of providing:

- fast deployment of the blockchain network without an excessive number of errors;
- reliable data backup solutions in case of emergencies;
- addition of the blockchain platform without server failures;
- provision of technical support service in case of self-deployment;
- the possibility of returning to the previous version of the system without data loss in case of errors and interventions;
- high speed of deployment of the blockchain network.

A BaaS blockchain service provider should provide an enterprise's need for **server services**, including the integration of core functions and technologies. These functions include control over the preservation of application data and user data within the blockchain platform. A scalable network environment must provide an appropriate level of performance, data flow management, computing resources, monitoring tools, and mechanisms to protect against network intrusion. If the enterprise already uses data transmission networks, integration of server services into the existing network architecture and the use of blockchain software can be provided without replacing network equipment.

There is a need for the creation of blockchain systems with permissions at enterprises within the scope of their activities. These can be open (public) or closed (private) blockchains. In an open blockchain with permissions (Public Permissioned Blockchain), the right of access is confirmed by authorized participants: management bodies or employees, and government institutions. Users have the ability to view the data, but particularly important information may be hidden. In a closed blockchain with permissions (Private Permissioned Blockchain), the functions of administration and coordination of procedures are performed by a single body. The register information is closed to third parties. In permissioned blockchain networks, issues of granting access rights to the system must be resolved.

Identity and Access Management (IAM) combines a set of technologies and software products that manage the lifecycle of accounts and user access to enterprise information resources. When creating a blockchain network with permissions at the enterprise, the BaaS provider must ensure its integration with the IAM infrastructure designed to manage digital or electronic identification data and certificates, the organization of a role-based access architecture with restriction of rights to view, read and write data.

Also, the task of the BaaS provider is to define and implement the appropriate consensus algorithm. For the most part, a simple Proof of Authority mechanism is most suitable for permissioned blockchains.

Smart contracts in a blockchain network are primarily used to describe business logic, such as setting conditions for the transfer of assets or documents between users and describing penalties in case of violation of the conditions. The means of deploying smart contracts are provided to users as part of the respective blockchain platform and cannot be changed. However, working with them can be quite difficult for specialists at the enterprise. Therefore, they should choose BaaS providers that support the development and testing of smart contracts in the blockchain network being created.

An effective design approach is considered to be one in which the BaaS provider provides support for choosing **the optimal blockchain structure using alternative sets of blockchain deployment tools**. This will make it possible to avoid rigid frameworks and ensure the flexibility of the system development process, creating conditions for creating its optimal version. Network monitoring tools to detect malicious nodes and network performance monitoring tools will be useful when operating a blockchain.

The most famous BaaS providers

1. **Microsoft Corporation** is a well-known BaaS provider that uses the Microsoft Azure platform to develop blockchain solutions. The advantages of this platform are the speed of deployment and relatively low cost of the created system, built-in tools for development, and ease of configuring functionality. Microsoft Azure offers three types of network topologies. The first is the Dev/Test topology, which works only with a virtual machine and is used mainly by system developers. A single-member topology is suitable for an organization that does not have separate branches and divisions. Nodes of such a network can be created, for example, on different production lines. A topology with several members is appropriate in networks of corporations and consortia with a territorially and functionally branched management structure.

Features of the Microsoft Azure blockchain platform:

- the ability to track goods using voice and SMS interfaces;
- the Internet of Things is integrated into the platform, with the help of which you can easily track the location of the shipment or any type of product;
- using the ERP system, you can manage the main business processes and communicate with the main participants;
- high speed and efficiency, as well as reduced cost of blockchain deployment.

2. **IBM Corporation** has a significant number of implemented BaaS projects, while the IBM platform comes with a set of ready-made solutions. IBM uses its own cloud infrastructure that is integrated, fully functional and ready to deploy. Blockchain can be used as an application of the IBM system, which simplifies its integration and management of the interface and the system as a whole.

Built on the Linux Foundation’s Hyperledger Fabric, the IBM Blockchain Platform (Fig. 2) is a comprehensive managed BaaS platform available in multiple environments, including the IBM Cloud, local environments, and third-party cloud environments. Using the platform, participants can manage, design, operate and develop the network with the strictest performance and security requirements. IBM blockchain projects are fast and efficient and can be configured for various implementation options from small businesses to multinational corporations.

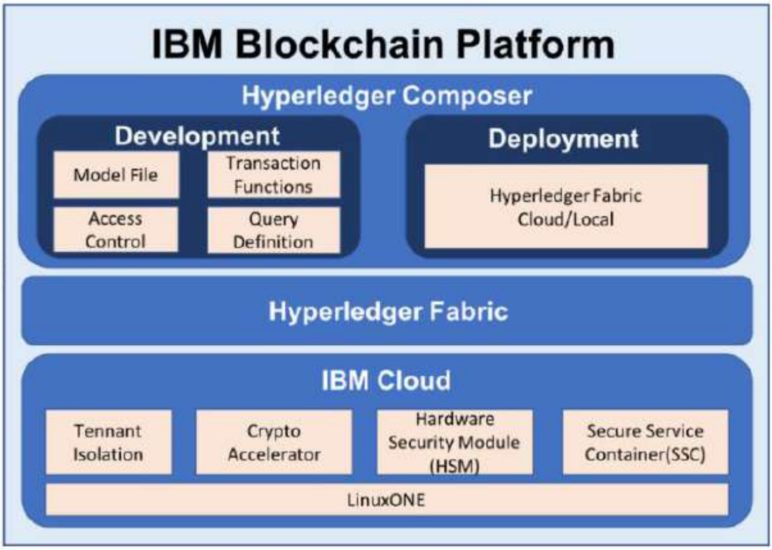

Figure 2. IBM Blockchain Platform architecture

Source: [14]

Features of the IBM blockchain platform:

- comes with an effective environment and modern application development tools, which can be configured online, from a public or local environment;
- blockchain solution management system provides activation tools for new channels, participants, smart contracts, and network systems;
- the blockchain network is a productive, reliable, and operational solution with the capabilities of rapid deployment, heavy loads, and disaster recovery.

3. **Oracle** offers a comprehensive distributed ledger technology platform with the ability to securely share information with business partners. Also, an enterprise can join another organization to deploy its own blockchain. The platform supports a composite multi-layer architecture model and provides automatic updates. Blockchain technology supports a reliable consensus mechanism, and smart contracts integrated with a cloud service.

Oracle cloud blockchain solution features:

- all authorized participants can see data updates in the registry, but access to nodes may be limited based on their ranking;
- consensus depends on the decision of a subset of network users;

- Similar to public blockchains, recorded transactions cannot be changed or deleted in the Oracle registry;
- technology provides reliable encryption to protect confidential data.

Frameworks for blockchain projects

The use of frameworks for blockchain projects significantly increases the efficiency of their development, ensuring a high speed of work and the quality of the solution. Currently, development companies offer a large number of frameworks and tools for creating blockchain applications for various purposes. Let’s consider some samples.

The **Ethereum framework** is an open-source platform for creating and deploying decentralized applications (DApps) that work on the basis of smart contracts.

The basis of the Ethereum framework consists of key components:

1. The Ethereum Virtual Machine is an environment for running DApps written in one of several popular programming languages. They do not require the use of a separate framework for each language or application and can run on the same blockchain.
2. Smart contracts are a computerized transaction protocol for the development and operation of decentralized projects (decentralized DApps, decentralized DeFi finance, decentralized autonomous DAO organizations) without the involvement of regulatory authorities. The program code of the smart contract is executed automatically subject to compliance with certain conditions prescribed in it.
3. Decentralized DApps that use smart contracts for various purposes: guaranteeing the transfer of values, affixing digital signatures, forecasting in stock markets, etc.
4. A set of software solutions aimed at improving network performance and scalability [1].

Hyperledger frameworks

The Hyperledger Foundation Consortium was founded by the Linux Foundation with the support of IBM, Intel, and SAP Ariba to support the open development of centralized and decentralized industry blockchain projects to address enterprise challenges.

The most famous Hyperledger frameworks:

1. **Hyperledger Fabric** is a platform created jointly with IBM and Digital Asset as a plug-and-play technology for developing large-scale blockchain applications. Fabric is designed primarily for integration

with projects that require the use of distributed ledger technologies. The framework provides an opportunity to create a modular architecture with the distribution of roles between network nodes, the execution of smart contracts (chain code), a flexible mechanism for reaching consensus, and other services. Hyperledger Fabric smart contracts support Golang (Go), Java, and JavaScript, making them more flexible than conventional smart contracts.

2. **Hyperledger Sawtooth** – a modular platform (developer – Intel company), which is mainly used for tokenization of logistics and sales chains. Sawtooth implements a consensus algorithm based on Proof-of-Elapsed-Time (PoET), in which the right to generate a new block is granted to the first node that has waited for it during a randomly selected period of time.

3. **Hyperledger Burrow** is a blockchain client with a built-in virtual machine that can work on the basis of Ethereum specifications. The tool was developed by Intel and Monax.

4. **Hyperledger Iroha** – development of the Japanese company Soramitsu, focused on creating mobile applications.

5. **Hyperledger Indy** is a project of the Sovrin Foundation, the main function of which is digital authentication in systems based on distributed ledgers.

The **Corda framework** is implemented as a distributed platform with private access, whose smart contracts run within the Java Virtual Machine (JVM). Corda was developed by the R3 consortium to record, monitor, and synchronize transactions between financial institutions. Corda’s consensus algorithm uses notary nodes to verify and sign contracts. Information about transactions is not broadcast to all nodes of the network but is available only to nodes that have a confirmed legitimate interest in the assets involved in the transaction. This approach, as well as the absence of mining, saves network resources and contributes to its scaling.

Peer-to-peer blockchain business model

The Interplanetary File System (IPFS) implements a peer-to-peer blockchain business model. IPFS is a hypermedia protocol and decentralized content management system based on data distribution. For data identification, the system uses data hashes (ID), calculated based on the internal content of the data.

IPFS is a development of the Protocol Labs company and belongs to the concept of Web 3. The interplanetary file system works on blockchain technology, using hundreds of thousands of nodes to ensure the necessary bandwidth of the network. Nodes connect to each other using a peer-to-peer network and jointly place files in the global space. The IPFS protocol performs the same tasks as HTTP (Hypertext Transfer Protocol) but does not use a centralized server.

Another infrastructure project for data storage and exchange by Protocol Labs is the Filecoin system, which also uses a peering blockchain business model. Filecoin is a blockchain platform of the Web 3 concept, focused on decentralized data storage based on the IPFS protocol with built-in economic incentives for users.

The security and verification of data stored in the Filecoin network is ensured by two consensus algorithms: Proof-of-Spacetime (PoSt) and Proof-of-Replication (PoRep).

Miners are responsible for storing and providing data on the Filecoin network. Native cryptocurrency FIL is used to incentivize data storage.

In order to become a Filecoin user, you should pay for storing your files on the network, or, conversely, add your own data storage equipment to the network and receive a reward in FIL cryptocurrency for this. A special provider fulfills data requests for a fee set in the market. In addition to payments for data storage, miners receive rewards for creating blocks.

Corporate blockchain (enterprise blockchain) is an integrated blockchain solution designed to support the business processes of an enterprise. The essence of corporate blockchain is to create a distributed ledger of data that promotes transparency, security, and efficiency of business operations.

Implementation of blockchain in enterprises and organizations can be carried out on a different scale and using various means. Accordingly, there are different views on the organization of the corporate blockchain business model. According to the means used, the following types of corporate blockchain models are distinguished [12]:

- smart contracts – involve fixing the terms of doing business in smart contracts. The model is characterized by low levels of automation and complexity;
- open network enterprises – an association of smart contracts, that have more complex functionality, coordinate their activities with suppliers and partners, and develop network connections. This model is characterized by a low level of automation and high complexity;
- autonomous agents – software objects that provide services, are capable of functioning autonomously without direct user instructions, and can interact interactively with other software agents and users. Agents are able to make an independent choice of action, determine a way to achieve a goal and respond to a change in the environment.

Functions of an autonomous agent may include performing transactions and payments, purchasing resources, searching for information, and more. Autonomous agents are characterized by a high level of automation and low complexity;

- distributed automatic enterprises – a combination of open network enterprises and autonomous agents. Such a model can function without or with minimal human involvement. Operations are automated and described in smart contracts, and staff tasks and performance indicators are regulated. The company optimizes relations with customers, improving services and products. The interests of shareholders are also maximally satisfied. The model has high levels of automation and complexity.

According to the level of access to blockchain content, the following types of corporate blockchains are distinguished.

1. **Private blockchains** are blockchain networks intended for use in one organization. Access to such a network is limited, which ensures a high degree of data protection. They are used to manage and store private data and conduct internal operations and business processes within the company.

2. **Consortium blockchains** are systems managed by a group of organizations in which participation and access to data are jointly regulated. They provide a certain level of control and privacy when sharing data and resources. Consortium blockchains are used in healthcare for collaborative management of medical data, in the banking sector for interbank transactions, and in logistics and supply chains to coordinate and track goods between different organizations.

3. **Hybrid blockchains** combine elements of private and public blockchains, providing controlled access and data transparency. They provide privacy and control over certain data while providing access to selective information on an open network. Hybrid blockchains are used in areas where a combination of privacy and transparency is required, for example, in real estate for registration of transactions, in public services, etc.

4. **Public blockchains** are decentralized networks open to all participants. They allow any user to participate in the use of the network.

The generalized scheme of the corporate blockchain model can include elements of different levels (Fig. 3).

Elements of the physical level will have a place in the enterprise blockchain models for processing data about physical objects (logistics, object identification, access restrictions, etc.). This level provides capture and processing of signals from various reading devices, such as radio frequency identification (RFID), IoT sensors, QR codes, etc.

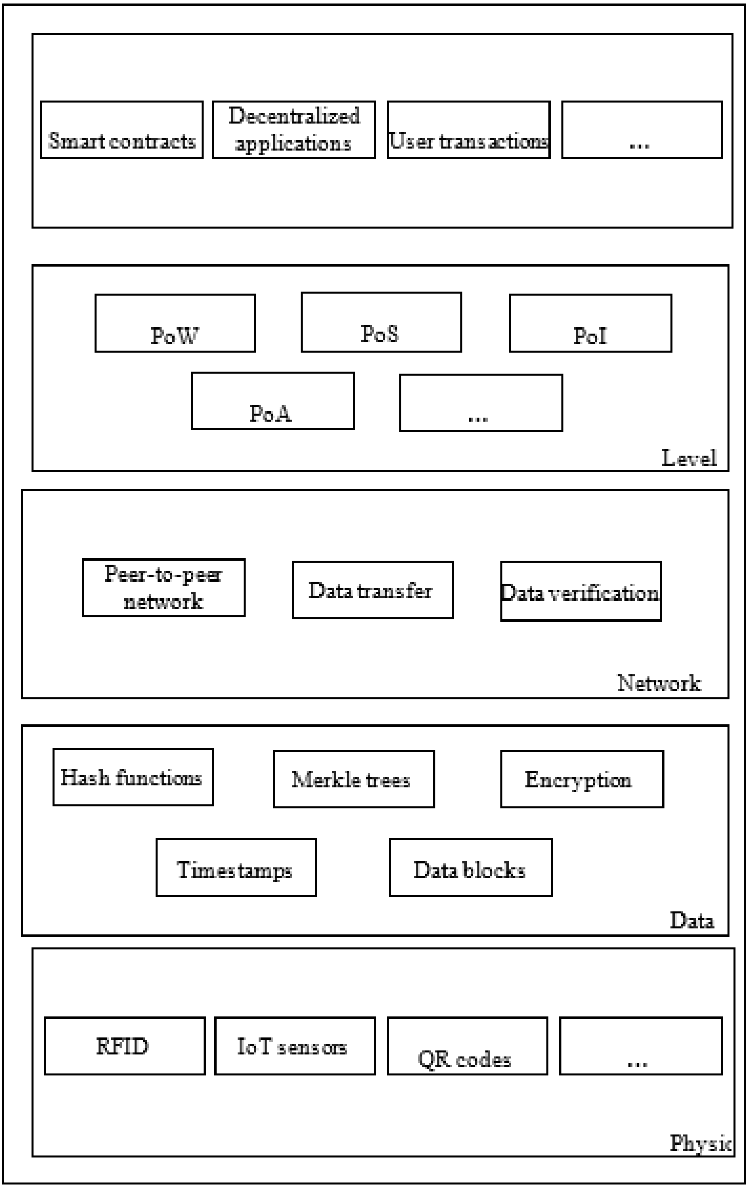

Figure 3. Scheme of the corporate blockchain

Source: developed by the author

The data level is intended for the preparation of data blocks, in particular, data selection, calculation of Merkle trees, hash functions, fixing of time stamps, data encryption, etc. [1].

At the network level, after authentication and authorization of the data sender and receiver, a connection is made to the distributed peer-to-peer blockchain network.

The level of consensus is used to determine the order in which transaction blocks are added to the blockchain. For this, an appropriate distributed consensus algorithm is used, such as Proof-of-Work (PoW), Proof-of-Stake (PoS), Proof-of-Importance (PoI), Proof-of-Authority (PoA), etc. [1].

The application level supports the operation of application programs and smart contracts, which, depending on the profile of the enterprise, implement certain data processing procedures.

The development of complex corporate blockchain systems is based on the concept of blockchain layers.

The **concept of blockchain layers** arose due to the need to overcome the bandwidth limitations of blockchain networks. The need to store a copy of the registry in each node of the blockchain increases data security, but significantly reduces computer resources, which has a bad effect on network bandwidth and scalability. In addition, the more decentralized a network is, that is, the more nodes it has to reach consensus, the slower it works. These contradictions have formed the so-called blockchain trilemma, the essence of which is that it is currently impossible to create a perfectly decentralized, scalable, and secure blockchain at the same time. More specifically, the blockchain trilemma suggests that decentralized networks can only provide two of the three benefits at any given time of decentralization, security, and scalability.

To solve this problem, it was proposed to create a blockchain ecosystem with several layers, each of which has a specific purpose.

Layer L0 (crosschain infrastructure)

The infrastructural objects of the L0 layer provide opportunities for the interaction of blockchains with each other, namely:

– support the transfer of assets between different blockchains;

– make it possible to develop one application on several blockchains (thanks to standardization);

– enable fast and cheap transactions on cross-chain exchanges with the support of communication protocols (for example, IBC).

For example, the Polkadot protocol enables the transfer of data or assets between blockchains by connecting to the main Polkadot network (Relay Chain).

In the Cosmos network, blockchains can interact with each other in a decentralized manner, thanks to the fact that they are built using the Cosmos open-source tools Tendermint, Cosmos SDK, and IBC.

L1 (transaction layer)

The first layer includes blockchains that can conduct transactions without involving another network. Because layer 1 blockchains are characterized by the blockchain trilemma, they typically only implement two of the three properties (decentralization, security, and scalability) well. To solve this problem, L2 layer solutions are used. In addition, due to the large number of first-level blockchains, the problem of transferring assets from one blockchain to another arises, which is solved using the L0 layer.

Examples of L1 layer blockchains are Bitcoin, Ethereum, etc.

L2 (trilemma solution for L1)

The L2 layer consists of special solutions integrated with L1 that solve for L1 one of the problems of the blockchain trilemma, usually the scaling problem.

The following tools are used in the L2 layer:

– state channels – exchange of transactions outside the blockchain with subsequent recording of the result in the blockchain (usually implemented by a multi-signature smart contract);

– nested blockchains – operation of L2 blockchain (for example, more scalable due to a less secure consensus mechanism) over L1;

– rollups – combining several transactions and processing them in the L1 network;

– sidechains – a hybrid of a nested blockchain and a state channel, which are used to process a large number of transactions together.

Examples of L2 layer solutions:

– Polygon – a sidechain-based scaling tool for the L1 Ethereum network;

– Optimism – a scaling solution based on convolution technology for the L1 Ethereum network.

L3 (applications and application infrastructure)

The L3 layer is often called the application layer. This is the layer that hosts decentralized dApps and the protocols that make the applications work.

Examples of L3 layer applications are Uniswap decentralized exchange and Orbs single backend for cross-chain applications.

Note that some programs can belong to several layers at the same time. For example, OmniLayer, a platform for trading digital assets and currencies, built on top of Bitcoin, can be classified as L2 and L3 layers of the ecosystem.

Security problems of information systems based on blockchain technology

The development of blockchain technologies at different times took place at different rates – from rapid with excessive expectations to gradual with a balanced assessment of the technology's capabilities. As a result, it is now possible to observe the wide spread of information systems based on the blockchain in various fields, such as financial services, logistics, property rights, socio-political sphere, etc. The main factor contributing to this spread is the assessment of blockchain technology as safe and reliable for data storage.

Indeed, the security of the blockchain is due to the very technological features of its construction. The technical infrastructure of the blockchain is based on a peering network with equal rights and a single access protocol for participants. Each network node keeps a copy of the transaction block registry. The data inside the block is protected from changes by a hash calculated by the Merkle tree method. In addition, each block contains a hash calculated using the hash value of the previous block using SHA-256, KECCAK, etc. algorithms. Blocks in the blockchain are located in the chronological order of their creation and have a corresponding time stamp. The order of entering data blocks into the registry is determined based on the consensus algorithm. Authentication of transactions is provided by asymmetric encryption systems with private and public keys and other algorithms. These security measures mostly prevent the risks of changing or losing blockchain data.

However, despite the developed security system, blockchain solutions cannot be considered completely invulnerable to malicious interventions [15, 16].

In particular, for blockchain solutions there is a risk of a «51 % attack», the essence of which is that a group of participants can gain control over the network by owning 51 % of its power. Thus, they can influence the addition of new data to the blockchain. For blockchain projects with a small number of participants, this vulnerability is quite significant.

In distributed financial blockchain systems, there is a danger of double spending, when the same funds will be involved in two transactions. At the same time, the violator can either pay twice with these funds, or return the amount to another account with the help of a second transaction.

One of the scenarios of double spending is a Race attack, when a hacker sends funds to the seller's address and to another address simultaneously from different addresses. The seller, seeing an unconfirmed transaction, can send the product. However, in the mining process, only one of the two conflicting transactions will be accepted, so the seller may not receive payment for the product.

Another method of double spending, but already with the participation of the miners, is the Finney attack. A miner records his transaction in the block he generates for the blockchain, and at the same time sends his other transaction with the same funds to the network. In this way, two blocks with conflicting transactions appear in the network, which leads to branching of the chain.

To protect against such attacks, before sending the goods, you should receive confirmation of the transaction from at least 6 nodes, in addition, the seller should disable incoming connections with paying nodes to receive confirmation from other nodes. Also, for the sake of security, it is recommended to maintain incoming and outgoing connections only with known nodes, which prevents the introduction of false information to the node and the leakage of data about the state of the chain, which this node processes, to attackers.

The Blockcypher platform adds a special trust attribute to the transaction to counter the threat of double spending, which is calculated based on the analysis of two characteristics: the format and behavior of the transaction. The format includes input and output transaction data, their history, and signature type. Behavioral analysis refers to the nature of the transaction's progress over the network and changes in its parameters over time.

In the Dash cryptocurrency, double spending is protected by the InstantSend service, which sends a transaction to 7–10 random master nodes, which block transaction inputs for a certain time and thus prevent the reuse of funds involved in them.

The Timejacking attack exploits a theoretical vulnerability in Bitcoin's timestamp processing. During the attack, the hacker modifies the node's network timer and forces the node to accept an alternative blockchain. This can be achieved if an attacker adds several fake peers with inaccurate timestamps to the network. However, the timejacking attack can be prevented by limiting the acceptance time ranges or by using the node's system time [16].

The Sybil attack consists in the fact that the attacker launches several nodes in the blockchain chain at once. A blockchain network has no trusted nodes and each request is sent to a certain number of nodes. The victim node is surrounded by fake nodes that close all their transactions. Finally, the victim becomes open to double-cost attacks.

Another threat is related to the risk of loss or theft of private access keys to the blockchain network. Typically, users use a private and public key to connect to the network and authenticate. In case of loss of private key, the user loses access to his assets in favor of an attacker who can appropriate them. Also, even if there is evidence that the keys have been lost or stolen, the owner will not be able to restore them if he has lost the access password to the corresponding service.

The openness of data in blockchain applications can negatively affect data security. For example, in the Bitcoin network, all addresses and transaction data are open to network users and third-party visitors. With the help of matching information and special algorithms, fraudsters can determine the user's identity and use this information for malicious purposes.

In many cryptocurrencies, the transactions made are irreversible, that is, there is no mechanism for their cancellation. If these transactions are fraudulent, this leads to significant problems. One way to prevent unreliable transactions is to use multi-signatures. Multi-signature is a scheme for the implementation of an electronic signature, which assumes that a certain number of electronic signatures (keys) from the list of possible electronic signatures of network users must be used to confirm the authenticity of the transaction. The description of multi-signature conditions is carried out using the built-in scripting languages of cryptocurrencies.

The advantages of blockchain technology led to its use in the field of the Internet of Things to store data about IoT objects and systems. With the development of IoT, an increase in the number of devices connected to the network leads to an increase in the security risks of system operation. There are threats in IoT systems: Sibyl attacks (violation of confidentiality, unreliability of data transmission); communication authentication and security issues; problems with distribution of trust keys and allocation of addresses for devices; and the problem of tracking offenses [15].

Blockchain technology can provide unified and multi-factor authentication of IoT devices based on decentralized authentication rules and logic. With the help of smart contracts, you can set effective and simple access rules for the authorization of connected IoT devices. In addition, in order to protect confidential data, you can specify in smart contracts the conditions, time, and rules for access to data by certain users or devices.

Therefore, developers of blockchain solutions, using the inherent advantages of this technology in terms of information security, should take into account the possible «weaknesses» of each project and apply appropriate data protection measures.

Conclusions

As a result of the study, the main directions of the development of blockchain business models were determined, and their characteristics and implementation examples were given. A multi-level structure of the corporate blockchain model is proposed. Problems of blockchain decentralization, scaling, and security are identified and approaches to their solution are described. Prospects for further research are related to the problems of integration and compatibility of blockchain solutions, as well as the possibilities of using blockchain technology in the global network Web 3, in the Internet of Things IoT, etc.

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SECTION 6
INNOVATIVE APPROACHES TO THE DEVELOPMENT OF TECHNOLOGIES FOR BUILDING SPECIALIZED COMPUTER SYSTEMS

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UNMANNED AERIAL VEHICLE CONTROL SYSTEMS

With the rapid development of computer technology, caching, sensors, communication, and control, unmanned aerial vehicles (UAVs) are attracting increasing interest in military, industrial, and social circles. Currently, UAVs are used in various fields such as military operations, early warning for air defense, border control, prevention tasks, monitoring and mitigation of natural and man-made emergencies, radiation and chemical reconnaissance of territories and specific objects, long-term aerial observation of critical infrastructure objects, rescue operations at industrial sites and maritime areas, geological exploration, monitoring of traffic, logistics, and communication, etc. Among various applications, UAV communication can provide long-range communication, high maneuverability, flexible deployment, and low-latency information transmission, thus it is of great importance for the future wideband efficient communication network.

In article [1], trends in the development and application of UAVs for addressing tasks related to prevention, monitoring, and mitigation of emergencies are investigated.

In work [2], several UAVs are simultaneously utilized for communication with a ground station, and the achievable throughput under line-of-sight conditions is investigated.

Many UAV projects over the past twenty years have focused on system management, such as flight control, trajectory design, and orientation adjustment. In fact, control and communication are tightly intertwined in UAV systems. For instance, altering the orientation of a UAV can affect the direction of data communication. Moreover, obstacles and communication interference can be significantly reduced by adjusting the spatial positioning of UAVs. Additionally, UAV navigation formulates a three-dimensional (3D) dynamic topology. All these factors stimulate the integration of communication and management for UAV systems to enhance their productivity.

This paper highlights the capabilities and challenges of UAV management systems. It describes methods of control and communication, principles of channel modulation for control, flight tracking for single or multiple aircraft, and autonomous operation mode. An analysis of implementation methods and decision-making by a UAV swarm is provided. Proposed are architectural solutions for the development of a comprehensive UAV management system and the use of innovative information technologies in managing military drone groups.

Methods of UAV control. The architecture of UAV construction may vary depending on requirements and tasks. Experience in building such aircraft shows that in the context of their management, there are two main elements: the first is executive, which includes the aircraft itself with the powerplant and control mechanism; the second is command, responsible for task setting for the flight, decision-making, if necessary changing the flight program, and correcting the aircraft's movement in case of deviations from the specified trajectory [3]. When building a UAV control complex, the command element or part of it is placed outside the aircraft and connected to the executive element through a transmission line.

The greatest difficulties arise during the creation of the control system. This is associated with the need for the UAV to perform tasks in conditions of autonomous flight, i.e., to have a fully functional closed-loop control system (CS). Therefore, the CS must address the following tasks:

- Stabilization of object motion parameters relative to external obstacles of various natures.
- Analysis of external data by onboard means and determination of the priority target for movement.

- Calculation of the optimal trajectory to reduce travel time and UAV resource expenditure.
- Control and maintenance of the specified trajectory.
- Real-time computational operations to implement UAV control algorithms [4].

It should be emphasized that the main function solved by the CS is the control of the motion of the UAV's center of mass and its angular movements.

To visually describe the motion of a quadcopter model, it is necessary to select coordinates for the specified position. The quadcopter model is typically defined with respect to the frame of the body B and the ground E, as shown in Fig. 1 [5]. Let the vector [x y z] denote the position of the device in the inertial reference frame, and the vector [φ θ ψ] denote the orientation of the quadcopter in space using three angles: yaw – ψ, pitch – θ, and roll – φ. Here, m represents the total mass, g is the acceleration due to gravity, and l is the distance from the center of each rotor to the center of gravity.

The paper conducts an analysis of autonomous, non-autonomous, and hybrid control systems based on the general provisions outlined in Article [6].

Autonomous control systems are characterized by the fact that motion control signals are generated by equipment located entirely onboard the UAV, and after launch, they do not receive any information from a control point. These systems operate according to a predefined program.

There are two methods of obtaining control signals. The first method of autonomous systems involves calculating, before takeoff, how the main parameters of UAV motion, which determine the trajectory, should change over time. The resulting time functions are input into specialized control system devices as set values or programs. During flight, the devices continuously compare the actual values of the specified parameters with their calculated values. In case of deviation, they generate corresponding control signals. The second method of autonomous systems involves installing equipment on the UAV that continuously measures its coordinates in space. These coordinates are automatically input into the onboard computing device, which, according to a predetermined program, calculates the control signal magnitude. In this case, a specific trajectory is not predefined, and its calculation depends on the current coordinates. Such systems do not affect obstacles artificially created and have an advantage in controlling UAVs with long flight distances [7].

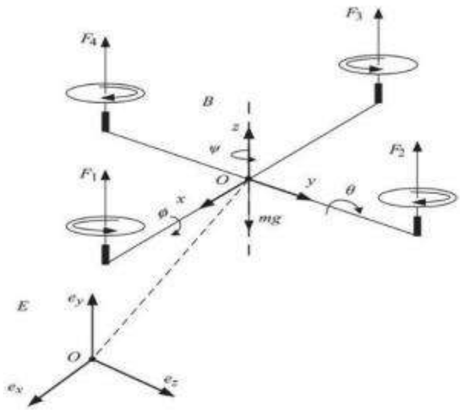

Figure 1. Basic Quadcopter Model

Source: [5]

The general structure of an autonomous UAV control system is shown in Fig. 2.

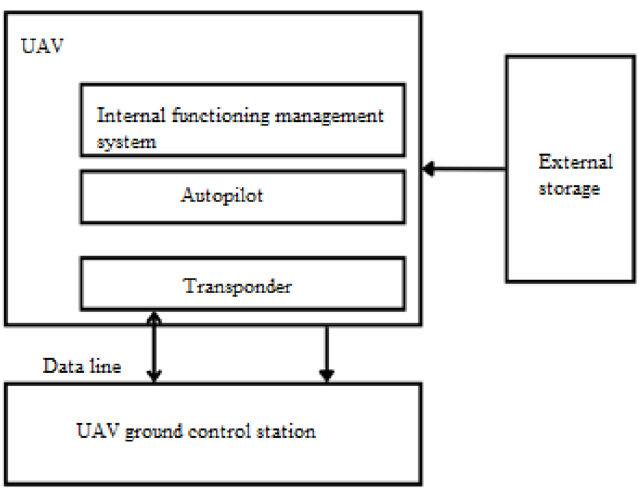

Figure 2. Structure of an Autonomous UAV Control System

Source: [7]

To utilize an autonomous UAV control system, it's necessary to create an internal subsystem for the operation of the aircraft. This subsystem is designed to implement algorithms for the operation of internal systems and devices of the UAV in order to achieve the set task objective. Essentially, it performs local control functions in the airspace.

The determination of the UAV's own coordinates is constantly carried out through the standard operation of the satellite navigation receiver. In real conditions, it's essential not only to determine the object's location but also to produce an effective response to this location. These processes within the system can be conditionally divided into three categories:

- Monitoring process: where the system records the object's location over time.
- Monitoring extension process: where, in addition to location recording, the system generates an internal response.
- Data transmission process back to the onboard system: where the system receives external data processed at the observation point and transmitted back to the UAV for its movement correction.

One of the methods of UAV control is the so-called «manual» method, as depicted in Fig. 3. This control method can be classified as non-autonomous control systems because an operator can intervene in its operation. In this scenario, control is directly carried out by the UAV's actuators, with the control station transmitting desired deflection angles for the control surfaces and powerplant operation modes. For UAVs requiring high speed and maneuverability, rapid transmission of control commands from the control station to the aircraft is necessary. However, the «manual» control method also demands a high level of intervention from a professional operator in the UAV control process, necessitating their high concentration and training [7].

The next control method, known as navigation control [7], is depicted in Fig. 4. It falls under the category of hybrid control systems, where operators do not intervene in the system's operation, but an external navigation control system may intervene to correct deviations from the specified route. In this control method, commands for deviations are not transmitted to the UAV. Instead, waypoints relative to the Earth's surface are set. This method involves transferring some computations from the control station to the UAV itself. All calculations regarding the detection of deviations from the planned trajectory are performed onboard. This further reduces the load on the radio link, where only changes to the navigation program, such as changes in the route relative to the previously planned one, are transmitted. In case of any deviations from the specified trajectory, the navigation processor can independently develop a set of commands for motion correction without the involvement of an external control point. However, this control method increases the requirements for the navigation processor hardware, including memory, processing power, and software.

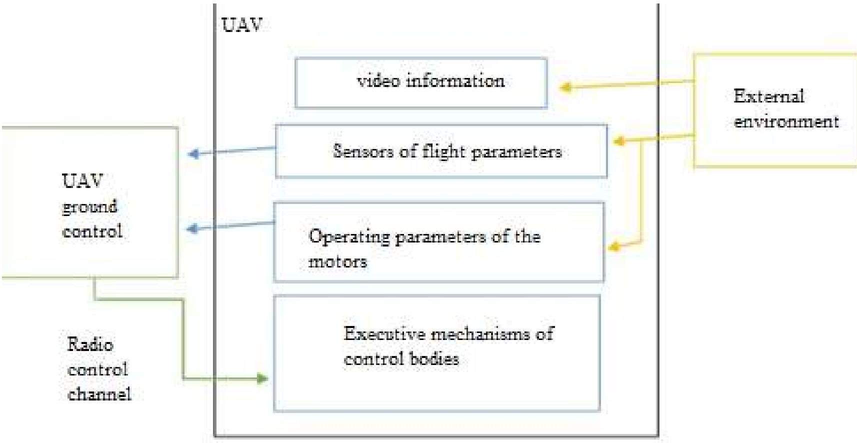

Figure 3. Structure of a control system based on the «manual» method of UAV control

Source: [7]

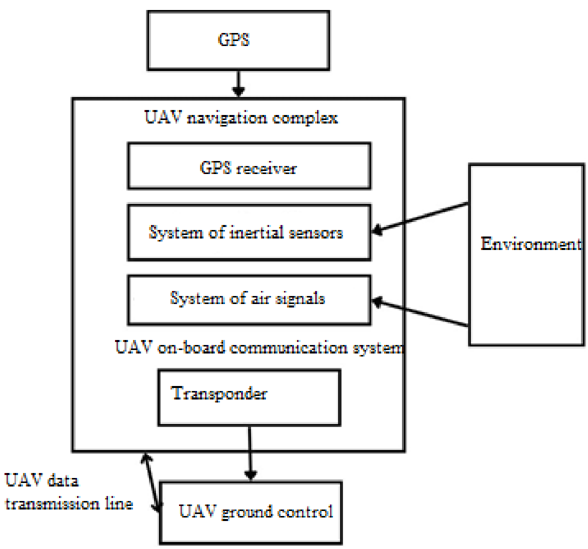

Figure 4. Structure of the navigation control method for UAVs

Source: [7]

In this case, the onboard navigation and control complex includes the following components:

- GPS receiver: receives navigation information from the GPS system.
- Inertial sensor system: determines the orientation and motion parameters of the UAV.
- Air data system: measures altitude and airspeed.
- Onboard communication system: operates within authorized radio frequency ranges and facilitates data transmission from the aircraft to the ground and vice versa.
- UAV transmission line: various types of antennas performing communication tasks.

The UAV navigation complex thus enables flying along a specified route, changing the route assignment, or returning to the starting point upon command from the control point. It facilitates waypoint navigation, orbiting a specified point, autonomous tracking of a selected target, stabilization of aircraft orientation angles, maintaining specified altitudes and flight speeds, collecting and transmitting telemetry information about flight parameters and the operation of target equipment, and software control of target equipment devices. Data transmitted from the aircraft to the ground include telemetry parameters and live video and photo feeds. Data transmitted to the aircraft contain commands for controlling the UAV and target equipment.

Information obtained from UAVs is classified according to the level of threat. Classification can be conducted by the operator or the onboard computer (autopilot) of the UAV. For the onboard computer, the software includes artificial intelligence elements used to develop quantitative criteria and gradations of threat levels. These criteria can be formulated expertly and formalized to minimize false alarm signals [8].

Communication and control for various UAV applications. Due to the advantages of high mobility and easy deployment, UAVs are expected to be widely used in wireless communications in the future. Typical UAV communication scenarios are shown in Fig. 5, including but not limited to:

- Hotspot coverage: Using UAVs as aerial base stations can enhance wireless coverage for hotspots such as railway stations, stadiums, office workplaces, fairs, etc., due to the additional spatial freedom provided from the sky.
- Coverage extension: UAVs can be deployed for users without communication infrastructure, such as remote mountain settlements

and ocean voyages. It can also be used as emergency communications for areas of natural disasters where the infrastructure is completely destroyed.

- Relay communications: UAVs can act as relays between two specific users, which is especially important for military conditions where commands need to be delivered timely between a remote command center and border troops.
- UAV-to-satellite communications: UAVs can communicate with satellites during navigation, meaning communication with a satellite while in motion, and the UAV must constantly point the beam at the satellite to maintain communication.
- Multi-UAV collaborative communications: Multiple UAVs can cooperate to create a wireless aerial network and cover a large area, where techniques from coordinated multi-point terrestrial cellular networks can be used to improve system productivity.
- Swarm communications: A swarm consists of a large number of mini-UAVs and is primarily used in combat applications. Since mini-UAVs are densely packed, the swarm forms a virtual massive array and can be coordinated to enhance spectrum efficiency.

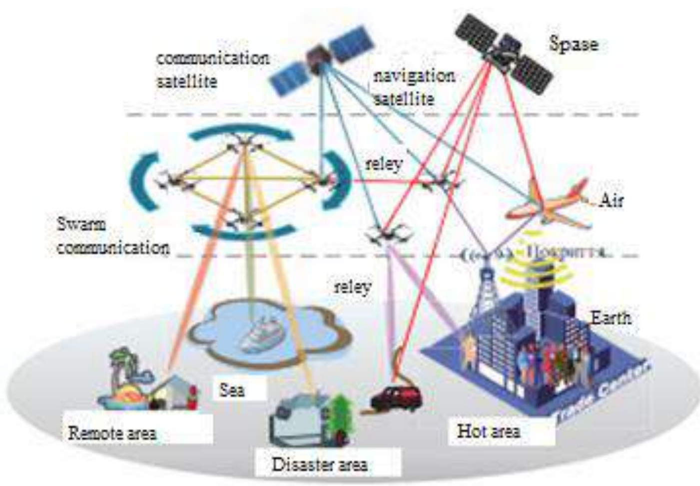

Figure 5. Integrated air-space-ground network

Source: Developed by the authors based on [10]

The UAV system mainly consists of the communication subsystem, flight control system (FCS), and aircraft subsystem. The communication subsystem is responsible for transmitting information, while the FCS manages the UAV's navigation, which comprises sensors such as GPS and an inertial measurement unit (IMU). The FCS is typically housed within the fuselage frame, where the xb, yb, and zb axes indicate rightward, forward, and upward directions, respectively.

The aircraft subsystem fulfills the control requirements from the flight control system to support UAV navigation, with its fuselage typically serving as a local geodetic frame. Thus, the xn, yn, and zn axes indicate northward, eastward, and downward directions, respectively. The corresponding flight control system and communication subsystem of the UAV are illustrated in Fig. 6 (a, b) [10].

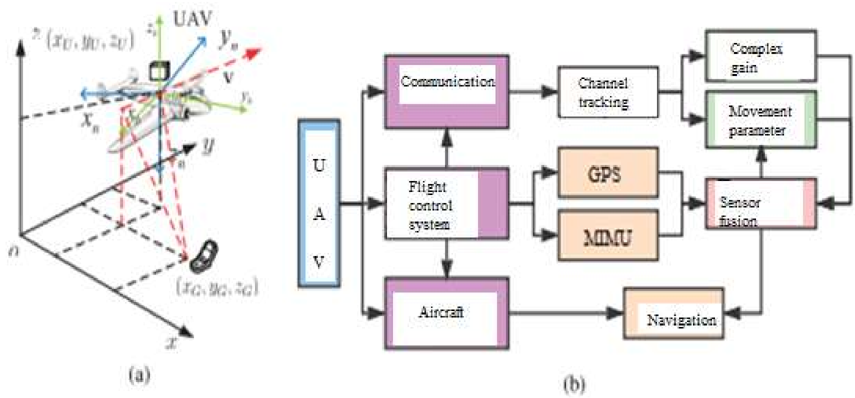

Figure 6. Integrated UAV Communication and Control System.
(a) Channel Model. (b) Channel Tracking Strategy

Source: Developed by the authors based on [10].

Traditionally, FC and communication subsystems are implemented separately. However, communications and control are closely linked in UAV systems. Control can be utilized to adjust both trajectory and orientation to achieve better communication outcomes, while communications, in turn, can enhance the accuracy of UAV control. These facts motivate the integration of communication and control for UAV systems to increase productivity.

Communication and control for a single UAV. During UAV navigation, its orientation constantly changes, affecting the direction of the beam and degrading communication quality. Therefore, control actions such as orientation adjustment should be jointly developed with communications to reap the full benefits in UAV system productivity.

Let's explore key integration techniques of communication and control for UAV systems, including UAV channel modeling, channel tracking using control systems, and joint beam tracking with mechanical and electrical adjustments.

Modeling the UAV channel. The communication channel of UAVs has several unique characteristics that differ from terrestrial communications due to constant navigation during flight. For instance, numerical measurements indicate that the UAV channel without line-of-sight contact operates with more obstacles compared to line-of-sight communication. Meanwhile, the UAV channel experiences constant Doppler effects and encounters significant time-varying selection effects [9]. Additionally, direct line-of-sight communication makes communications vulnerable to obstacles.

To support high-speed data transmission or wireless backup connections, the frequency range of waves (30–300 GHz) should be used in UAV communications, which can provide gigahertz bandwidth. Additionally, due to the short wavelength of millimeter waves, a large number of antennas can be placed on small UAVs, providing a significant spatial advantage to combat large losses in the millimeter wave range.

The communication system of UAVs with millimeter waves using an $M \times N$ uniform planar array (UPA) was considered as an example. It has been shown previously in [11] that broadband transmission with a large number of antennas can encounter frequency-dependent spatial steering vectors, also known as beam misalignment effects. The channel in the l-th block in the frequency domain can be described by a geometric model as follows [10]:

$$H(l,f) = \frac{a}{[D]^{Y}} e^{-j2\pi f dlNbTs} A(\varphi, \theta, f, fc), \qquad (1)$$

where *Nb* is the number of symbols in each block, α is the complex channel coefficient, *D* is the distance between the user terminal and the UAV, γ is the large-scale fading coefficients, *fd* is the Doppler shift, *Ts* is the sampling interval, *fc* is the carrier frequency, φ is the azimuth angle relative to the plane of the antenna array, and θ is the zenith angle relative to the plane of the antenna array. Additionally, A(φ, θ, *f*, *fc*) is the frequency-dependent spatial steering vector, where the element (*m*, *n*) is given by the expression [10]:

$$A(\varphi, \theta, f, fc) = e^{j\frac{2\pi d}{\gamma c}[(m-1)sin\varphi cos\theta + (n-1)sin\varphi sin\theta](1+\frac{f}{fc})}. \qquad (2)$$

It's worth noting that the azimuth angle φ and zenith angle θ change with the orientation of the UAV, thus affecting the channel values. In this case, the traditional channel transmitter structure will not work.

For massive Multiple Input Multiple Output (MIMO) systems, the large channel size increases the complexity of channel estimation. However, according to the 3D geometric model (1), the high-dimensional channel can be determined using several physical parameters such as *fd*, *D*, φ, and θ, as well as the complex value α. Therefore, estimating the high-dimensional channel can be simplified to estimating these parameters. Typically, the feedback channel can be directly obtained from the transmission channel in a Time Division Duplexing (TDD) system due to the reciprocity of the channel, which however does not occur for a Frequency Division Duplexing (FDD) system. Interestingly, a unique property of UAV communications is that the parameters φ and θ are not sensitive to frequency, while *fd* has an explicit connection with φ, θ, and *f*. Thus, even for an FDD system, most of the feedback channel parameters can be obtained directly from the transmission channel, requiring only a very small number of pilot signals to estimate the feedback channel coefficient α. This means that not only can the complexity of channel estimation be significantly reduced, but also TDD/FDD transmission protocols can be unified.

Channel tracking in the flight control system is crucial for UAV communications during continuous navigation, especially when using a large number of antennas in millimeter-wave bands. According to the channel model (1), the large-scale channel is determined by only a limited number of parameters such as α, fd, D, φ, and θ. Since most of these parameters are associated with the physical movement and position of the UAV, the flight control system can be utilized to simplify their acquisition and reduce the training load during tracking.

A simple way to implement channel tracking based on the flight control system is as follows: parameters related to the UAV's movement are first derived using sensor fusion of GPS and MIMU, and then several pilot signals are sent to estimate the remaining channel parameters. Meanwhile, a Kalman filter can be used to improve real-time and accuracy of channel tracking in UAV systems. The corresponding channel tracking procedure is illustrated in Fig. 6(b).

Beam tracking with combined mechanical and electrical adjustment is crucial for communication with artificial satellites using UAVs to formulate directional beams towards desired terminals, achieving significant spatial advantage and overcoming signal loss. For example, two distant UAVs must constantly adjust their respective beams towards each other to facilitate inter-UAV communications.

Another typical scenario is communication with an artificial satellite using UAVs, where the UAV must adjust its beam towards the target satellite. However, UAV navigation leads to constant changes in orientation, directly affecting the direction of the spatial beam. Although electric beamforming can be relied upon, sometimes incorrect UAV orientation can misdirect the beam beyond the antenna's pattern.

One possible solution is to use mechanical control for physically changing the direction of the array plane and assisting in beamforming [12]. However, since orientation sensors have limited accuracy to reduce production costs, there are generally systematic errors and measurement inaccuracies. In this case, mechanical adjustment can roughly direct the spatial beam towards the target satellite. Therefore, electrical adjustment is additionally applied to calibrate the beam direction. To ensure the beam is directed accurately, one way is to maximize the received signal power at the UAV side. In this case, a multi-layered approach to beamforming can be used, which sequentially introduces perturbations to phase shifters and maximizes the received signal power. Simultaneous perturbation using the array structure can also be utilized to accelerate convergence speed. The explicit representation of beam tracking with combined mechanical and electrical adjustment is shown in Fig. 7.

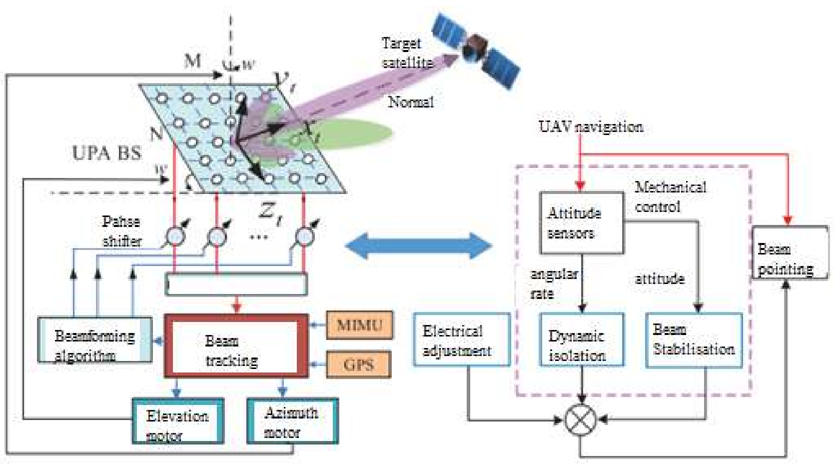

Figure 7. Beam Tracking with Combined Mechanical
and Electrical Adjustment for Satellite Communication of UAVs

Source: Adapted from [10] by the authors

Communication and control with multiple UAVs. Communication in complex missions and harsh conditions encourages the deployment of multiple UAVs. Since communication between multiple UAVs is a cutting-edge technology, it is extremely important to develop innovative communication technologies to support high-reliability remote commanding and control of multiple UAVs.

Cooperative communication and self-positioning. The communication system among multiple UAVs utilizes a large number of UAVs with one or multiple antennas to support ground users, which offers several advantages:

- The number of antenna arrays is not limited by the size of the UAV, while communication among multiple UAVs can collectively provide high spatial resolution.
- Beamforming in any three-dimensional direction can be effectively implemented by fully utilizing the mobility and flexibility of multiple UAVs, thereby dynamically increasing the spatial gain of the antenna array through UAV positioning adjustments.
- Communication reliability is significantly enhanced through the cooperation of multiple UAVs, as damage to one UAV will not affect the overall effectiveness of communication.

The typical communication system among multiple UAVs is depicted in Fig. 8 [10]. Unlike traditional ground communications, a virtual MIMO – Shared UAVs face several new challenges. For instance, the relative positions of different UAVs are dynamic and unknown, making it difficult to determine the position of UAVs and ensure stability and reliability of communication among multiple UAVs. Additionally, all deployed UAVs must be time-synchronized, and the virtual array requires calibration, with all UAVs maintaining connectivity for information exchange. These requirements demand precise positioning, control, and cooperative communications.

Ways to Manage a Group of UAVs. The organization of UAV group management can be implemented through centralized, hierarchical, decentralized, or mixed methods.

Centralized management of a UAV group can be implemented through various methods, each with its own advantages and disadvantages. The advantages of centralized management include simplicity of organization and algorithmization, as well as the ability for global optimization of the group’s actions to achieve the set goal. However, centralized management may have disadvantages such as low system robustness, limited range of radio communication, and complexity in management due to the need for redundancy and handover control.

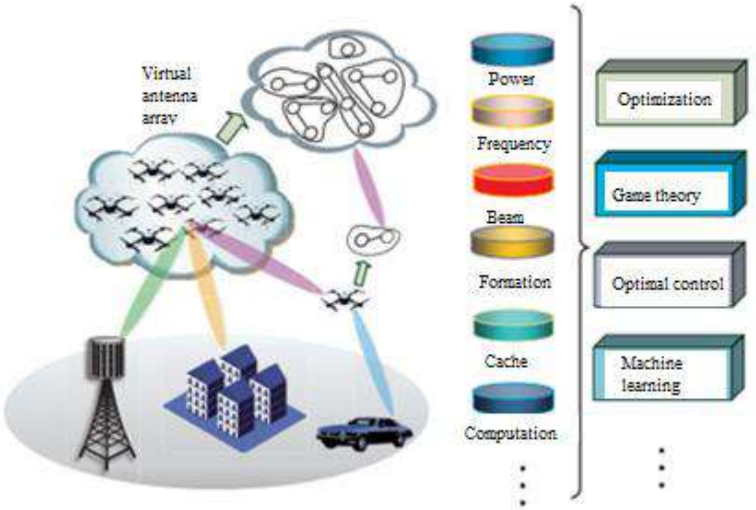

Figure 8. Multi-UAV Communication with Resource Sharing

Source: Developed by the authors based on [10]

The hierarchical method of management is applied in the interaction between the ground control center (GCC), the leader of the UAV group, and individual units within this group. This approach can have two main implementation variants:

- The leader of the UAV group has direct communication with each unit in the group, controlling their actions directly.
- Establishing a hierarchy of subordination, where the UAV leader is superior to other units, and the other units in the group are subordinate to the leader. This is especially relevant in the construction of mobile UAV groups.

The leader of the UAV group often has greater resource capabilities, which allows reducing the communication range requirements for most units in the group.

The drawbacks of the hierarchical management approach are similar to those of centralized management. However, this approach allows reducing the volume of data transmission and increasing the speed of response to changes in the environment since in the decentralized management method, each UAV in the group has significant responsibility and performs a range of functions:

- Determination of position and motion parameters: Each UAV autonomously determines its own position and calculates its motion.

- Exchange of state data with other UAVs: Each aircraft in the group exchanges information about its state and actions with other aircraft.
- Adjustment of own actions: After receiving information, each UAV can adjust its actions to accomplish the assigned tasks.
- Implementation of own behavior strategy: Each aircraft has its own strategy of actions, which it implements while cooperating with other UAVs to achieve the group's common goal.

Hierarchical management has high resilience and allows for scalable management processes. However, it is complex to coordinate and achieve optimal results due to the need for significant computational and telecommunication capabilities on board UAVs and the high level of management dynamics and interaction between aircraft. Therefore, reliable functioning of communication channels is required for effective communication between UAVs in conditions of high dynamic network topology.

In the mixed mode of management, elements of centralized and decentralized management are combined. For example, at certain times, group UAV management may be conducted through a ground control center or a lead UAV in the group, while at other times, it may be decentralized, with each UAV making decisions independently. This approach is particularly characteristic of military UAVs as it allows for effective management of a group of aircraft in various situations. The mixed mode of management enables a balance between centralized coordination and decentralized decision-making, making it effective in variable and complex conditions typical of military operations.

In the cycle of managing a group of UAVs, the following stages are implemented:

- Gathering information about the group of UAVs (T_gather): the ground control station (or UAV leader) collects information about the status of each UAV; each UAV also gathers information about the status of other UAVs identified by the coordination algorithm; the information may include position coordinates, motion parameters, communication channel status, payload level, and other status parameters.
- Analysis of group status information (T_analyze): each UAV subsystem analyzes the collected information; the task execution subsystem determines the degree of task completion by the group of UAVs and the need for control influence.
- Decision-making (T_decide): each subsystem makes decisions according to its goals and management objects; the decision can be made centrally through the ground station or decentralized by each UAV in cooperation with others.

• Decision dissemination and execution (T_broadcast and T_execute): the decision is disseminated to the executors (the group of UAVs or a specific UAV) and executed.

This cycle of UAV group management allows for information gathering, analysis, decision-making, and its execution, taking into account the current state and tasks of the group, as illustrated in Fig. 9.

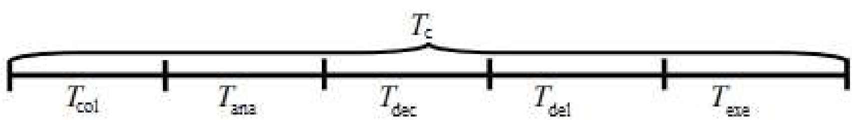

Figure 9. UAV Group Management Cycle

Source: Developed by the authors

It's important to note that the management cycle time Tc includes the time for implementing all components: Tc = T_collect + T_analyze + + T_decide + T_deliver + T_execute and will vary for each of the control subsystems.

The organization and management of communication within a group of UAVs can lead to various network topology configurations (see Fig. 10), which in highly dynamic conditions can result in a significant increase in control traffic and data transmission delays between the vehicles.

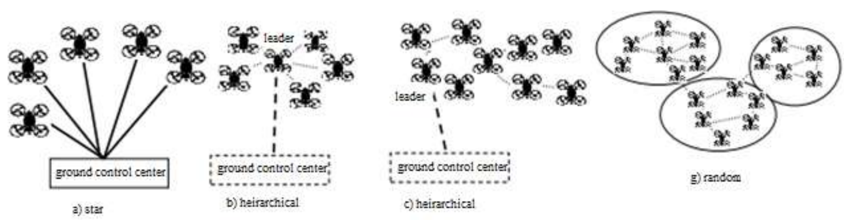

Figure 10. UAV Network Topology Variants

Source: Developed by the authors

The «star» topology (Fig. 10a) is characterized by a centralized management method, where there are direct individual radio communication channels between the control center and each UAV. UAVs are interconnected through the ground control center, and only the channel between the control center and each UAV is configured. This topology is easily scalable, and data transmission delays are minimal. However, it has its drawbacks, such as loss of interaction between nodes in case of control center failure and limited radio communication range.

The hierarchical topology reflects the hierarchical management method. In Fig. 10b, a scenario is depicted where the control center manages a UAV leader, to which individual UAVs are directly subordinate (in this case, the network topology between the leader and the UAVs takes the form of a «star»). Fig. 10c shows the interaction between the control center, the UAV leader, and the subordinate UAVs in a hierarchical structure (the network topology between the leader and the subordinate UAVs takes the form of a «tree»).

During swarm movement, a random topology is most characteristic, where each UAV in the network functions as a wireless router to maintain connectivity with other UAVs (this is known as flying ad-hoc networks, FANET). Fig. 10g illustrates an example of a random topology of three groups of UAVs.

Data transmission delays between UAVs depend on various factors, including the network diameter and its topology, the number of relay hops in data transmission routes, the quality of communication channels, the volume and intensity of traffic, and the management methods employed. The high mobility of UAVs, the type and number of antennas, and the differences in distances between UAVs significantly affect the quality of the radio channel. At the channel level, the choice of channel resource allocation method among UAVs, and at the network level, the method of building and maintaining data transmission routes, significantly affect the throughput and latency of data transmission, which is critical for real-time applications. Therefore, the communication system must take into account the technical characteristics of UAVs, the size of the UAV group, the diversity of network topologies, the type and intensity of traffic, and have its own control system.

Management of UAV Group Movement. Managing the flight of a UAV group proves significantly more complex compared to controlling individual UAVs, as it involves not only directing the movement of each UAV but also considering their mutual positioning within the group. There are two main modes of UAV group movement:

- Formation flight mode involves the orderly movement of a UAV group in a specified spatial configuration, such as a wedge, grid, lattice, chain, and other formations collectively referred to as a formation. In this mode, a hierarchy is established between leading and trailing UAVs. The objective of the UAV group flight management system is to coordinate the control of each UAV to ensure the effective achievement of group objectives, considering the designated trajectory and safety. A drawback is that trailing UAVs depend on the leaders, so the failure of the leaders can lead to the dissolution of the formation. The formation of the UAV group construction model is based on constraints such as energy capabilities, maneuverability, and mutual placement. The flight trajectory can be flat or spatial, with or without trajectory intersections, in closed-loop or open-loop formations. UAV control in this case may take the following form:

$$u_i(t) = \sum_{i \neq j}(r_j(t) - r_i(t)) + b_{ij}, \tag{3}$$

where $ui(t)$ – is the control input for the i-th UAV, $ri(t)$ – is the position vector of the i-th agent, $rj(t)$ – is the position vector of the neighboring j-th UAV, bij – is the specified relative position of the i-th and j-th UAV in the coordinate system.

- The swarm movement mode involves the collective motion of a decentralized, self-organized group of UAVs, without the necessity of adhering to a specific geometric configuration. This mode can be more flexible in unforeseen situations. Swarm control methods in a group of UAVs are based on the imitation of natural behavior, where each UAV implements a decentralized control method and exchanges information with its nearest neighbors. Each UAV makes decisions based on collected data about the surrounding environment and information from other UAVs. Communication with the control center is established only when necessary to obtain information about the tasks facing the group. During swarm interaction, each UAV determines distances to neighboring UAVs and autonomously adjusts its course to maintain the necessary distances between them. The speed control of each particle in the particle swarm optimization method is determined by:

$$v_i(t) = v_i(t-1) + a_1 rnd()(pbest_i - x_i) + a_2 rnd()(gbest_i - x_i), \tag{4}$$

where $v_i(t)$ is the velocity of the i-th particle, $v_i(t-1)$ is the velocity of the i-th particle in the previous iteration, x_i is the position of the i-th particle, $rnd()$ is the random value function [0…1], a1 and $a2$ are constant accelerations, $pbest_i$ is the best-found point of the i-th particle, and $gbest_i$ is the best point found among all particles in the swarm.

In the next iteration, the values of the best points are updated, and the cycle repeats. One of the most common methods for solving the problem of swarm movement today is the potential function method. The essence of the method lies in determining the control law for UAVs based on artificial forces, depending on the potential function or potential force fields, which either attract or repel UAVs. The control influence in this case can be calculated as:

$$u_i = \sum r_{il} > r_o\, c_1 r_{ij} + \sum r_{il} \leq r_o \frac{c_1 r_{ij}}{r_{ij}^2}, \tag{5}$$

Where *rij* is the distance vector between the *i*-th and *j*-th agents, *c*1 and *c*2 are adjustable constants, *r*0 is the radius of the force field (when *rij* ≤ *r*0, agents repel each other, when *rij* > *r*0, agents attract each other).

Decision-making in the context of collective UAV operation entails certain characteristics:

- Incomplete and conflicting knowledge: Each UAV has limited information about the external environment.
- Diversity of goals and roles: UAVs may have different goals and perform various roles within the group.
- Distributed and dynamic nature of action planning: Action planning for the UAV group is a distributed and dynamic process.
- Challenges of reliable communication: Effective management of the UAV group requires reliable communication among them.

The essence of group management lies in defining and coordinating the collective actions of autonomous UAVs to achieve specific objectives. These objectives may include minimizing target detection time, maximizing damage to the enemy, maximizing throughput for telecommunications platforms, and so on.

For managing a group of UAVs, multi-agent systems (MAS) are often used, which allow for effectively addressing complex multi-factor tasks, especially in dynamic and distributed environments. In such systems, each UAV acts as an individual agent with its own software and hardware for situation assessment, decision-making, and interaction with other agents.

The main functions addressed by specialized software of a UAV group agent include:

- Location determination: agents can use sensors and other means to determine their location in real time.
- Task completion assessment: agents can assess the degree to which they have completed their tasks and the group's common objectives.
- Information exchange: agents interact with each other, exchanging information about their status, perceived situation, and decisions made.
- Action adjustment: agents can adjust their actions based on received information and changes in the situation, ensuring adaptability and flexibility in management.

The collective management method is an effective approach to managing a group of UAVs because it allows each UAV to independently make decisions and interact with other agents to achieve a common goal.

The main principles of this method are:

• Autonomous control of each UAV: Each UAV independently formulates its actions based on the received information and the group's objective.

• Coordination of actions: The actions of each agent are coordinated with other group members to achieve an optimal solution. This is based on information about the overall goal, environmental conditions, and actions of other agents.

• Optimality of actions: Each agent seeks to maximize the objective function when making decisions in the current situation, ensuring maximum benefit for the group.

• Dynamic management: Optimal management is determined over the nearest time interval in the future and is reviewed as needed, providing adaptability to changes in the environment.

• Compromise solutions: Acceptance of compromise solutions is allowed, taking into account the interests of all group members, even if it requires giving up some advantageous actions.

The collective management method enables a group of UAVs to effectively tackle complex tasks by coordinating their actions and working together to achieve a common goal. This allows harnessing the full potential of each agent and achieving optimal results in conditions of uncertainty and change.

In theory and practice of MAS, various coordination methods are employed to ensure effective interaction among UAVs. Some of the most well-known methods include:

• Coordination through shared rules of group behavior: Agents interact while adhering to common rules or standards of behavior.

• Coordination based on information exchange at the meta-level: Agents exchange information regarding their state, surroundings, and objectives, enabling them to coordinate their actions to achieve a common goal.

• Teamwork: Agents can work as a team, where leadership and task allocation are based on hierarchy or a specialized management structure.

• Coordination in conditions of agent competition: Agents compete with each other but still cooperate to achieve a common goal, competing for resources or resolving conflicts.

Regarding the characteristics of intelligent agents, they include traits such as:

• Collegiality: the ability to engage in collective, goal-oriented behavior for the purpose of solving common tasks.

• Autonomy: the capability to independently address local tasks without centralized control.

• Activity: the capacity for proactive actions aimed at achieving shared and local goals.

• Informational and locomotive mobility: the ability to actively move and acquire information to cooperatively address tasks.

• Adaptability: the capacity to automatically adjust to changes in the environment.

Designing trajectories and resource allocation. Properly designing the trajectory of UAVs can enhance communication productivity by reducing the distance to desired users while increasing the distance to obstacles. Therefore, effective utilization of UAVs' high mobility is key to unlocking the full potential of UAV-based wireless networks. On the other hand, due to the limited power of UAVs, valid resource allocation strategies such as power, frequency, beamforming, formation, trajectory, caching, dynamic topology, and computational resources need to be developed to ensure efficient wireless communication networks based on a fleet of UAVs, as shown in the previous Fig. 8. In [13], joint trajectory and transceiver design for wireless communication networks using a fleet of UAVs is investigated, where the minimum throughput for all users is maximized by optimizing the scheduling of communications among multiple users and power management.

Resource allocation significantly impacts UAV swarm networks, and a practical performance metric can be established as the time required to serve all planned users. Therefore, one possible approach to formulating the multi-UAV deployment problem (Fig. 8) could be the minimization of the total time to serve all planned users. However, the objective function may not be convex, and the optimization task may be challenging to solve. In this case, an iterative algorithm can be a practical approach that divides the objective function into separate minimizations of transmission time and flight management time. Initially, the transmission time, as it is associated with the received antenna array gain or equivalently with the array formed by the multi-UAVs, can be reduced by optimizing the spacing and placement of UAVs. Then, the flight management time is dynamically optimized using UAV trajectory design and speed control according to optimal locations.

Integration of machine learning and multi-UAV communications can be a promising approach for achieving near-optimal deployment of UAVs and intelligent communications. Specifically, Extreme Learning Machine (ELM) or Support Vector Machine (SVM) methods can be used to capture complex relationships between UAV deployment and resource allocation. Meanwhile, novel bio-inspired intelligent optimization algorithms can enhance spectrum efficiency through deep resource allocation optimization.

Analysis of methods for implementing autonomous navigation systems for UAVs. Accurate positioning of UAVs in space requires the availability of signals from the Global Navigation Satellite System (GNSS). The absence or suppression of these signals can complicate the determination of UAV coordinates and hinder the execution of planned routes. Ensuring autonomous flight is an important task in UAV control system development. Despite the variety of navigation methods, the development of autonomous navigation systems remains relevant. One of the key tasks in UAV utilization is to carry out flight programs independently of various unforeseen circumstances that may arise during flight. The task of automatic flight control of UAVs is associated with the development of autonomous navigation systems and a comprehensive control system.

Key methods of autonomous navigation systems for UAVs. Modern autonomous navigation systems, which allow UAVs to perform flights in autonomous mode when satellite navigation is unavailable, include the following systems:

1. Optical-electronic navigation involves the use of techniques that process imagery of the terrain to determine coordinates and orientation by analyzing visual data such as photographs, videos, and object images. This method compares stored data with snapshots of territories using current visual data for precise determination of absolute coordinates, achieving high accuracy through the analysis of a large database of snapshots. Such a system allows UAVs to autonomously navigate and orient themselves in space by detecting and comparing contour points of identified objects with the surrounding environment.

2. Video navigation relies on calculating the distance traveled by the UAV through analysis of video materials obtained from onboard cameras. The process involves automatically detecting numerous key points in each video frame and tracking their movement from frame to frame, providing information about the drone’s trajectory. A large number of such key points ensures high accuracy in determining direction, speed of movement, and orientation in space. However, using

video navigation as the primary means of autonomous navigation without relying on satellite systems may face limitations. Issues may arise during the processing of monotonous surfaces, poor lighting conditions, and unfavorable weather conditions.

3. Navigation using laser scanning employs a method where digital terrain data is utilized to enhance the accuracy of determining the UAV's position, thereby addressing some of the limitations associated with video navigation. By comparing the obtained data with a digital terrain model, precise localization of the UAV in space is facilitated. A notable feature of this method is its ability to operate in low-light conditions due to the use of a laser altimeter. However, the technique is inefficient over water and sandy surfaces.

At the same time, it should be noted that the application of these autonomous navigation methods alone cannot fully ensure reliable UAV coordinate determination in a completely autonomous mode, considering the mentioned limitations. Therefore, it is recommended to consider integrating the mentioned navigation methods with inertial navigation systems and artificial intelligence elements. Such a comprehensive approach will enhance the accuracy and reliability of UAV position determination in various external conditions.

A strapdown inertial navigation system (SINS) utilizing MEMS technology provides a crucial foundation for supporting stable and independent UAV flight, even in cases of external signal loss or data outage. Such a system is fully autonomous and does not rely on external landmarks or connection to GNSS. Its operation is characterized by the use of sensors such as accelerometers for measuring accelerations, gyroscopes for capturing angular velocities, and magnetometers for determining orientation relative to the Earth's magnetic field, enabling precise determination of UAV motion parameters, including its velocity, distance traveled, and angular orientation.

A MEMS-based strapdown inertial navigation system (SINS) is a fundamental component for ensuring highly effective control and navigation of UAVs. The overall schematic of a SINS demonstrates the interaction between the main system blocks responsible for gathering and processing navigation information. The capability of a SINS to provide information at high frequencies and independently of external information sources makes it indispensable for autonomous UAV control systems, especially in conditions where access to satellite navigation systems is limited or unavailable. Integration of orientation and navigation systems at the sensor level is a key factor in improving the accuracy of determining UAV orientation parameters. This approach combines data from various sources, such as inertial sensors, magnetometers, and barometers, enabling a more comprehensive and accurate representation of the UAV’s state and position in space, as shown in Fig. 11.

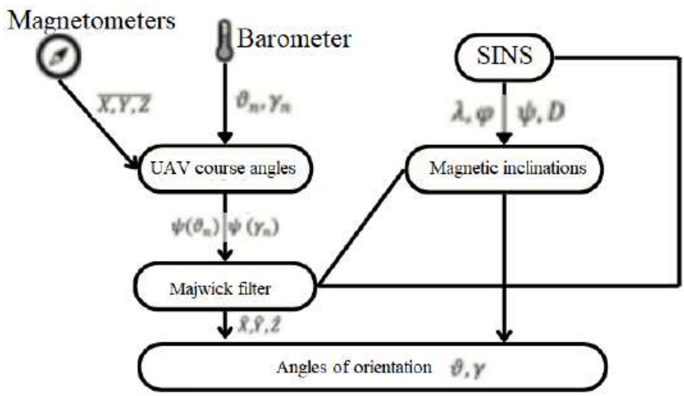

Figure 11. Integration Scheme of UAV Orientation and Navigation Systems

Source: [14]

Architectural solutions for the development of an integrated UAV control system

The absence or suppression of these signals can make it difficult to determine the UAV’s coordinates and prevent it from following its planned route. Ensuring autonomous flight is an important task in the development of UAV control systems. Despite the diversity of navigation methods, the development of autonomous navigation systems remains relevant. One of the key tasks in the use of UAVs is to carry out the flight program regardless of various unforeseen circumstances that may arise during the flight. The task of automatic control of UAV flight is associated with the development of autonomous navigation systems. The integrated UAV control system includes a global navigation system based on GNSS, a set of autonomous UAV navigation systems, an integrated database system, a data warehouse, a knowledge base, a decision support system, a set of sensors for determining flight characteristics, data transmission lines, a control center, Fig. 12.

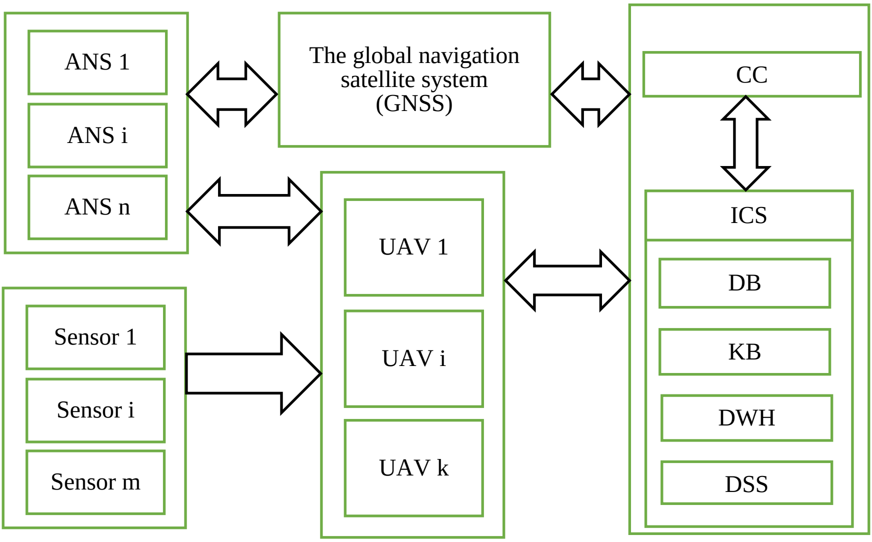

Figure 12. Integrated UAV control system

Source: Developed by the Authors

Multi-drone systems for military and military purposes. The history of mankind consistently confirms the thesis, but it does not cover that current wars are a global threat to our humanity, in addition to the greedy inheritance of the ruin of civil infrastructure and wealthy people Such expenses often stimulate the development of important areas of science and IT. The full-scale war of the russian federation against Ukraine has caused the rapid development of the so-called «military» robotics and, especially, digital technologies for drones for military and secondary purposes (MSP) – air, dry land, water, and underwater. It is clear that since the full-scale invasion of russia into Ukraine on February 24, 2022, the proliferation of various military drones has overturned the most extreme speculations and forecasts of experts and has accumulated even more widely in military spheres – surveillance, security, control, direct combat operations, logistics, transportation, etc.

The general topic of drones, both individual UAVs and group drone systems (GDS), is inherently multi-disciplinary, and comprehensively covering this topic is quite a difficult task, so we will consider the key aspects of this topic – drones as IT equipment, the architecture of drone

CS with the appropriate software and the possibility of implementing GDS on the example of demining technologies.

According to the types of military units and personnel and the number of weapons, various configurations of military software are possible for different groups of specialists when interacting with drone systems, including other necessary functions – logistics, repair, testing, replenishment of ammunition, training, etc. Table 1 presents one of the possible versions of the classification of modern drones (or drone systems), which allows further differentiation of the main types of software, including operating systems, communication software, simulators for training, and other types of additional software according to various categories of communication and IT equipment (VR glasses, video-photo cameras, location, and sensor equipment, radio and network equipment, multiple consoles, terminals, etc.), to which they are oriented according to the terminology of combat operations and the purpose of military units and types of weapons.

Table 1

CLASSIFICATION OF DRONE SYSTEMS MSP (unmanned aerial vehicles, uavs*)

Category	*Subcategory*	*Group*	*Models***	*Notes*
Military purpose	Intelligence	Copters/planes	Leleka-100, Furia, Valkyrie, PD-2, Raybird-3, Shark, Kazhan, Sirko, Mavic are similar	Including for use at night, on land, and water
	Strike drones	Kamikaze (copters/planes)	Molfar, Kolibri, Shrike, KH-S7, Maluk, Mavic similar, etc.	
		With ammunition reset (so-called bombers)	Banderik-K, Vampire, Baba Yaga, PD-2, Heavy Shot	
		With a rocket weapon	Bayraktar TB2+, Switchblade, Roadrunner, etc.	including intelligence
		Multi-drone systems (or flocks/swarms of drones)	SAKER SCOUT drone systems (the combined system accommodates the flagship reconnaissance drone and several Kamikaze drones)	Using AI, night mode

End of the table 1

Category	*Subcategory*	*Group*	*Models***	*Notes*
	Demining	Special groups and models of demining drones with various configurations of attached equipment (with active or passive sensor equipment)		Flying drones, for land and water, use of AI and virtualization technologies.
	Transportation	Evacuation of the wounded	Malloy (T150, T400, T80 models), ground drones Broshniv, Termit	Flying drones and for land.
		Logistics	Precision Payload Delivery System, (PPDS), ground drones Broshniv, Termit, etc.	
Civil purpose	Sports, entertainment, tourism, private video, toys	A large number of commercial groups and species	DJI Mavic, Autel, Phantom, Mini, Air, etc., Xiamen, Ryze Tello, BetaFPV, LYRZ, Yuneek, KS11, E99 Max, KF615, Explorer, Visuo, Timyhawk, NAZIM, Hubsan, etc.	Various configurations of parameters and attachments for flying drone models.
	Agricultural sector	Special models by appointment	According to the names of companies (Amazon, Google, etc.) in the fields of courier delivery and transportation.	Flying drones and for land (transportation of goods, orders in the city, etc.). Models of drones for the Cg-Ge subcategory can be used to perform demining tasks using AI and virtualization technologies.
	Courier delivery			
	Security and protection of territories (including fire safety)			
	Cartography, geo-exploration (subcategory Cg-Ge)			
	Scientific research			

Source: Developed by the Authors

* – The term «unmanned» for UAVs has a conditional meaning, i.e., the use of drones involves the involvement of two or more pilots, controllers, etc. categories of personnel for cooperation, flight training, and remote control.

** – The vast majority of drone models come with various sets and configurations of system and application software – Android, IoS, Windows, Linux/Unix, specialized OS, and other system and application software.

The categories of drones presented in Table 1 (military and civilian) are characterized by the use of various combinations of OS and software configurations, which are determined by their functionality, and sometimes it can be a combination of several of the mentioned types of OS together. The most common software configuration is a combination of Android and Windows OS, since the «drone + smartphone or tablet (or console + VR glasses)» complex is the main most numerous civilian subcategory «Sports, entertainment, tourism ...» with dual capabilities (incl. military) use.

Therefore, in these conditions, group drone systems should become the main factors for increasing the efficiency (effectiveness) of drone weapons, along with the need to develop and introduce appropriate software, focused on «flocks» or «swarms» of drones of various categories of air traffic control. Expert assessments make it possible to conclude that the field of air traffic control systems has a chance for successful development only under the conditions of deployment, production, and introduction of a powerful software industry with innovative and creative solutions of these CS for multi-drone systems, development of special mathematical and algorithmic support in the field military robotics.

It is clear that there are significant differences in terms of ensuring the safety of flying vehicles and performing the corresponding tasks of the two specified classes of CS (military and civilian), but in terms of controlling the multitude of these devices, the presence of many similar tasks, principled decisions, and similar algorithmic components should be recognized. It should be noted that both categories of GDS, as components of large flight CS, mainly and primarily provide for remote control and monitoring modes in the process of performing their flight tasks, when the main management functions are performed by experienced personnel: for military GDS – in command and operational points, and for civilians – in airport control centers. Today, it is also necessary to admit that the topic of GDS as autonomous robotic complexes is at the stage of research and formation of fundamental theoretical principles and methods, some aspects of which are considered in this subsection.

The multidisciplinarity of the subject of GDS and their SU, mentioned above in this subsection, can be summarized (Fig. 13) using the example of the most common types of architecture of group drones, which were considered above, the characteristics and parameters of these systems, and the specifics of research and their implementation in MSP practice. A characteristic feature of all the components of the GDS presented in the figure is that the vast majority of them (more than 50 %) are currently at the stage of active research, experimental development, and test trials due to the extremely high complexity and complexity of the GDS system.

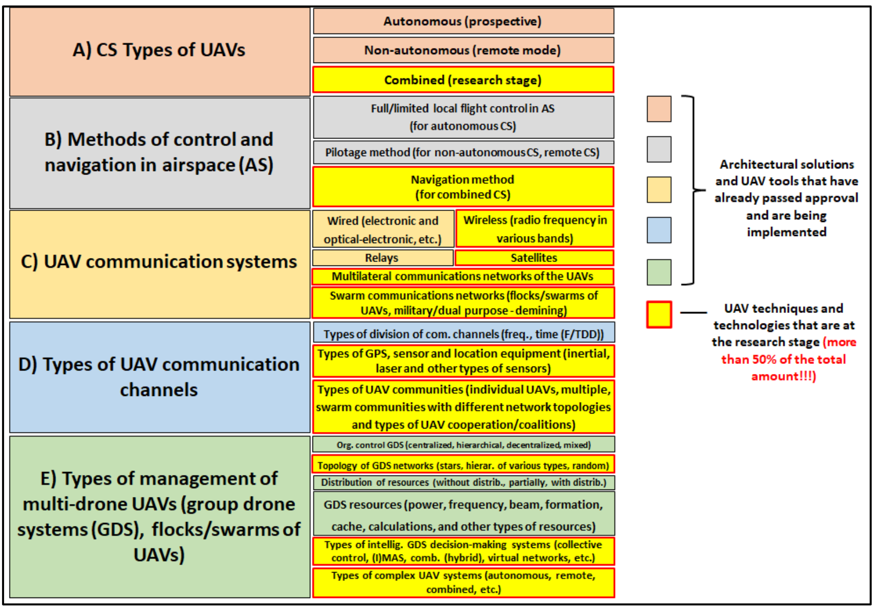

Figure 13. Architecture of GDS management systems, methods, technologies, parameters, and state of research

Source: Developed by the Authors

Information technologies of demining using GDS are a typical topic of MSP multi-drone systems. It is well known that mine detection is an ongoing and growing problem that affects millions of people around the world due to the enormous danger that mines pose to people. In 2016, an average of 23 people worldwide lost their lives or were seriously injured by landmines or other explosive remnants of war every day. Approximately 61 countries and vast areas around the world are still contaminated by landmines (including underwater ones), and thousands of people continue to live with this daily threat of loss of life or limb [15]. It is clear that the issue of demining is critically relevant for Ukraine, a decade has passed since the beginning of the war with Russia, and since February 2024, as a result of already full-scale aggression on the part of Russia and the intensification of military operations, Ukraine has become the most mined country in the world, and this process continues since the active phase of the war on the territory of our country has been going on for the third year already.

Mine detection occurs using a variety of methods, most commonly using active sensors, including ultra-wideband (UWB) radar equipment. Experience shows that although active landmine sensors are often used for performance reasons, they can cause unintended detonations of landmines because they use generated and reflected electromagnetic signals. Another way to detect mines without detonating mechanisms is to use passive detectors. This subsection of the monograph considers a model for creating an optimal structure of a neural network with the Adam optimization algorithm for effective mine classification based on magnetic field sensor data that can be obtained and used with the help of specialized drones or GDS for runway demining.

It is assumed that GDS (flocks or swarms) consist of a certain set of drones (UAVs, for land use, etc.) of different categories and subcategories (Table 1), which are able, thanks to the specific capabilities and architectural characteristics of their complex CSs, to integrate in various combinations of cooperation /coalitions (Fig. 13) to fulfill MSP tasks (in our case – demining technologies). The principle in this context is the choice of the basic concept of the construction of the GDS control system, which for all its architectural components (types of control systems – A), B), C), D), D) in Fig. 13) provides opportunities for consolidation and integration of all resources of drone systems at all stages of research, testing, approval, and implementation. Of these basic concepts shown in Fig. 14, the two most promising ones are multi-agent systems (or intelligent MAS) and technologies of virtualization of GDS networks, among which in this subsection certain priority is given to the second approach as the most promising one. Today, IT virtualization, which represents a large number of different approaches to cloud computing (cloud computing), allows to systematically solve the vast majority of the tasks of building complex SUs of the GDS, while the ideology of MAS faces certain limitations.

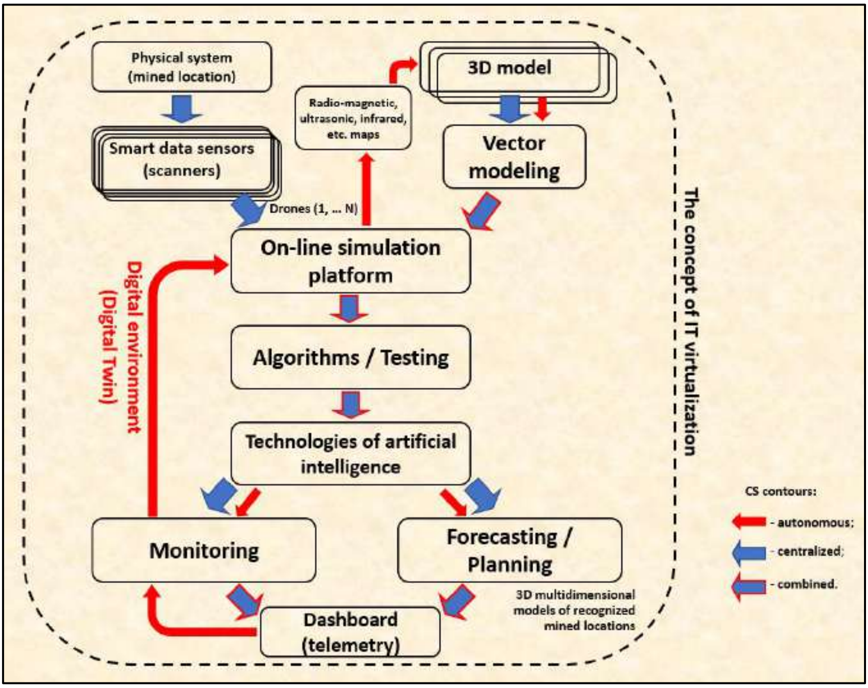

Figure 14. Global architecture of the digital double (DT) of the GIS for demining

Source: Developed by the Authors

The presented approach to building a neural network [23] allows you to set the task of increasing the accuracy of mine detection to a limit of more than 99 % as a virtualization concept, which is structurally implemented in the Digital Twin (DT) format in the form of a GDS CS for demining territories, and technologically it can be a variety of versions and combinations of individual cloud services (IaaS, PaaS, SaaS, and XaaS). In our case, virtualization is conceptually implemented in the DT environment within the contour of the GDS control system mainly as its combined instance, which allows, on-demand and by necessity, to obtain an autonomous or centralized version of the drone control system. The key advantages of virtualization and cloud computing fully reveal the real prospects of multi-drone systems and technologies:

– Scalability – cloud platforms allow for rapid scaling of control systems to handle large amounts of data within a cooperation/coalition of large numbers of drones, which is the basis for effective control of large drone swarms. A typical tool for implementing scalability on cloud platforms is Docker technology, which provides optimal construction and deployment of container-type software.

– The balance of cloud computing between the control loops of multi-drone systems – the combined loop of the CS allows you to quickly adapt to various types of autonomous and centralized control.

– Real-time data exchange – facilitates rapid data exchange between drones of various purposes and command centers, which increases the coordination and reactivity of swarm architectures.

– Disaster Recovery – Cloud services provide high availability and disaster recovery, which is critical for missions that depend on drone cooperation/coalitions.

– Analytics and computational data processing – cloud platforms are focused on the use of powerful analytical tools for data processing (including multidimensional, graphical, geo-informational, etc.) received from GDS, which helps in making informed decisions for their management systems.

– Collaborative computing – opportunities for cooperation between drones, allowing them to exchange resources and perform joint calculations (including for AI and neural network technologies), which increases the efficiency of swarm interaction.

Most of the mentioned advantages of virtualization allow the deployment of appropriate technologies and software aimed at a wide range of tasks for MSP multi-drone systems, including for demining technologies using AI methods and neural networks. The practice of demining proves that the classical methods of detecting and recognizing mines no longer provide the necessary level of reliability and efficiency in solving these tasks, and all this requires the involvement of passive detectors for demining based on modern IT tools, such as neural networks and 3D modeling methods for the implementation of territory virtualization tasks for demining based on DT concepts.

Usually, mine detectors can be divided into two groups: active and passive. Active detectors send a signal to the search object and the mine is detected by the reflected signal. These detectors demonstrate high detection accuracy, but there is a fairly high risk of detonation of the mine mechanism. The main principle of operation of passive mine detectors is aimed at detecting anomalies of the magnetic field, in particular those created by mines. Similar detectors demonstrate lower detection accuracy but are safe [16]. This subsection presents a neural network model to increase the effectiveness of passive mine detectors based on GDS for building 3D DT models of demining areas.

It should be noted that similar IT demining studies already have experience using machine learning algorithms to classify detected mines using magnetic field anomalies. One such example is the classification of landmines using a custom-tuned convolutional neural network called an autoencoder, and researchers were able to achieve an accuracy of 93 % and an AUC of 98 % [17]. The work [18] investigated the use of the k-NN algorithm for mine detection, where the main data were obtained from a sensor network consisting of 32 magnetic sensors. The best classification accuracy result in this study was 91.66 %. Also interesting is the result of the study [16], which describes an approach to the classification of mines using passive detection sensors based on the hybrid k-NN model, while the accuracy of 98.2 % of successful detection of 5 common types of mines was achieved.

The purpose of the materials presented in the subsection is to develop a model of passive detection and classification of mines based on a neural network and magnetic field sensors with an accuracy of 95-98 %, which is the allowed interval for demining technologies. The main toolkit of neural networks used for building, testing, and approbation of the model is multi-class classification, standard machine learning algorithms, determination of the optimal topology of the neural network for selected configuration parameters of the demining system, the method of Bayesian support vectors, decision trees, etc. [19–20].

The formal formulation of the problem is as follows: let X be the set of object descriptions $X = \{V, H, S\}$; V is the value of the anomaly of the magnetic field around the mine in volts; H is the height of the sensor above the ground where the mine is located; S – soil type; $Y = \{0, 1, 2, 3, 4\}$ – a set of numbers (or labels) of classes corresponding to the types of mines: *«Null»*, *«anti-tank mine»*, *«anti-personnel mine»*, *«booby-trapped anti-personnel mine»*, *«M14»*, respectively (Table 2). The task of classification consists of finding the appropriate mapping operator $Y^{*}\colon X \rightarrow Y$ for any objects (in our case – min) that are not included in the training sample with the minimum norm in the Euclidean space (see formula (6) in table 3).

Before the classification process, it is necessary to solve the problem of generating new values in the sample, since the sample size is 45 (values of magnetic field anomalies at a depth of 26–34 cm with soil types in the «Dry-Humus» interval for each of the 5 types of mines). The generation of new values for the sample is necessary for the neural network to acquire generalizing properties during training, that is, the size of the training set N must satisfy the ratio (7).

Table 2

PARAMETERS OF THE DEMINING CLASSIFICATION MODEL

Input data			*Output data*
Voltage	*Height*	*Soil type*	*Mine type*
Value of FLC100 output voltage	Distance between sensor and soil	Categorical value of 6 different soil types	Categorical value of 5 most common landmines

Source: [23]

Ratio (7) in the statement of the problem (Table 3) allows you to determine the order of values and the distribution of the training set into subsets – «training», «validation» and «testing». One of the approaches to solving this subproblem is the generation of pseudorandom values (8) using the normal distribution function (9) [21], where it accepts two parameters: μ and σ [23] and in the case of our classification, the values of μ and σ are the values of V_i and σ_e, respectively.

Table 3

STATEMENT OF THE PROBLEM, FORMALIZATION OF MINE CLASSIFICATION, AND MAIN PARAMETERS OF THE NEURAL NETWORK OF THE DEMINING MODEL

№	*Indicators and formalization of NN*	*Parameters*
1.	The basic classification mapping for any objects not included in the training sample with the minimum norm in the Euclidean space $Y^*: X \rightarrow Y$: $min\|y * -y\|$, (6)	y – target classifier; y^* – neural network classifier [22].
2.	The size of the training set N: $N = O\left\{\frac{N_{w_{ij}}}{\varepsilon}\right\}$, (7)	N – the size of the training set; $N_{w_{ij}}$ – the total number of free parameters of the neural network (number of synaptic connections, including bias); ε – permissible error of the neural network during classification;

End of the table 3

№	*Indicators and formalization of NN*	*Parameters*
3.	Normal distribution function *p(V)*: $p(V) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(V-\mu)^2}{2\sigma^2}}$, (8) $V_i^* = rand(V_i, \sigma_e)$, (9)	V_i – the value of the magnetic field anomaly at altitude H_i and S_i soil type; V_i^* – the new value of the magnetic field anomaly at altitude H_i and S_i soil type; σ_e – mean square deviation of the Earth's magnetic field anomaly; $rand(V_i, \sigma_e)$ – a pseudo-random value generation function based on a normal distribution function. The function accepts two parameters: μ – arithmetic mean, and σ – mean square deviation [16]. In this case, the values μ and σ are values of V_i and σ_e, accordingly.
4.	The root mean square deviation σ_e: $\sigma_e = avg(\sigma_i), i \in \overline{\{1; 15\}}$, (10)	σ_e – root mean square deviation of the Earth's magnetic field anomaly; σ_i – mean square deviation of the Earth's magnetic field anomaly at altitude H_i; i – takes on values from 1 to 15, because, according to research [16], this is the distance at which the intensity of the mine's magnetic anomaly is not recorded.
5.	The normalized value of magnetic field anomaly *V'*: $V' = \frac{V-\bar{V}}{\sigma_V}$, (11)	*V'* – the normalized value of magnetic field anomaly; *V* – the initial value of the magnetic field anomaly; $\bar{V}$ – the average value of the magnitude of the magnetic field anomaly; σ_V – mean square deviation of the magnitude of the magnetic field anomaly.
6.	The element y_i of the output vector of probabilities of the object's relation to each of the mine classes: $y_i = f_{softmax}(\sum_{l=1}^{7} w_{li} f_{relu})\left(\sum_{j=1}^{7} w_{ij} f_{relu}\left(\sum_{k=1}^{3} w_{jk} x_k\right)\right)$ (12)	y_i – element of the output vector of probabilities of the object's relation to each of the mine classes, $f_{softmax}$ – activation function *Softmax*, f_{relu} – activation function *ReLU*, w_{li} – element of the weight matrix between the second hidden layer and the output layer, w_{ij} – element of the weight matrix between the first and second hidden layers, w_{jk} – element of the weight matrix between the input layer and the first hidden layer, x_k – element of the input vector of mine characteristics.

Source: Developed by the Authors based on [23]

The pseudo-random new values calculated after generation will receive values that are closer to the values in the training sample as the arithmetic mean and based on the mean square deviation of the Earth's magnetic field anomaly. The mean square deviation is calculated according to formula (10). Data preprocessing consists of the following actions: normalization of magnetic field anomaly data, coding to soil type, conversion of mine class labels into a numerical value, and then coding. The normalization of magnetic field anomalies is calculated by the average value and the root mean square deviation according to formula (11) [23].

Coding is applied to soil type, as this data is categorical and soil type takes 6 values: «Dry and Sandy», «Dry and Humus», «Dry and Limy», «Humid and Sandy», «Humid and Humus» and «Humid and Limy». According to studies [16], the type of soil affects the classification of mines, so pre-processing of the data for use by the neural network is necessary. When testing the neural network, the One-Hot-Encoding type was used, which converts a variable into a vector of binary variables of size n, where n is the number of unique values of this variable. The algorithm converts the soil values into a vector of 6 values. The position corresponding to the soil type is 1, and all other positions are 0 [23].

In the process of solving the classification problem, a neural network with two hidden layers was created. In fig. 15 presents a neural network model where the size of the input layer is 3, the size of the first hidden layer is 7, and has the activation function «ReLU», the second hidden layer has the same characteristics as the first, and the output layer has the size 5 and the activation function «Softmax». The neural network uses the Adam optimizer, a categorical cross-entropy loss function, and an accuracy metric. The output of this neural network will be described by equation (12), which is presented in Table 3 and makes it possible to build a matrix of the resulting data in mine recognition tasks. In the future, this matrix will be the basis for the operation of the GDS management system in the DT format for the implementation of demining technology.

The initial sample consisted of 45 samples that were taken during the study mentioned above. This sample size is insufficient for further training of the neural network, so it was expanded to 9000 samples using the normal distribution function as described in the problem statement. Of these 9000 samples, 70 % were allocated for training, 15 % for validation, and 15 % for testing. As a result of the calculation of anomalous voltage values for various types of mines, a so-called heat map is built, which displays the error matrix of the results of the neural network classification based on test samples (Fig. 16). In the diagram, the X-axis is responsible for the samples that have been classified, and the Y-axis is the actual values [23].

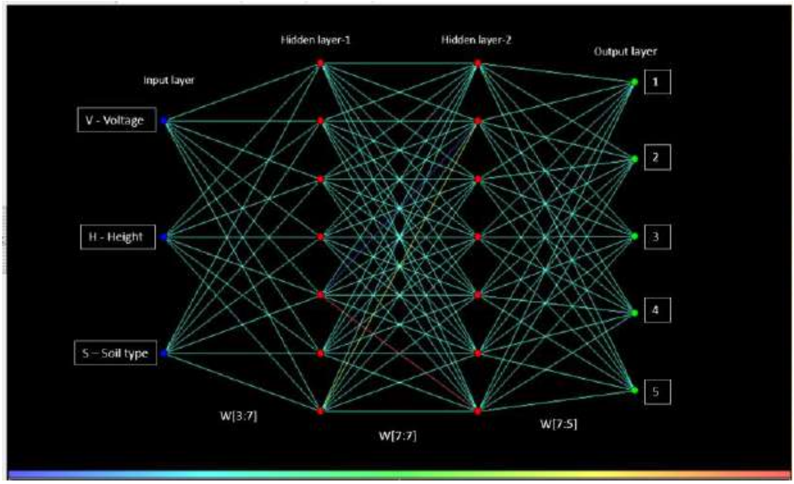

Figure 15. Neural network with a model of 2 hidden layers

Source: Developed by the Authors

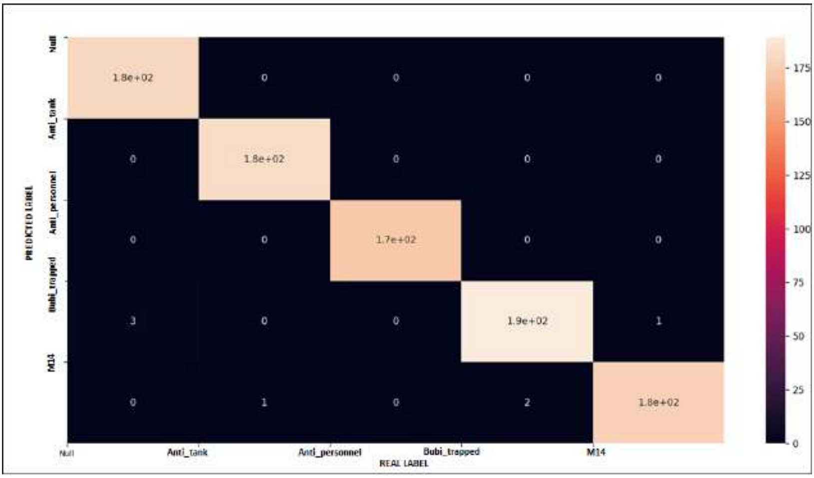

Figure 16. Confusion matrix of the neural network model

Source: [23]

Approbation of the built mine classification model and experiments with different parameter values were performed on a neural network with one and two hidden layers. Network performance was evaluated using accuracy and AUC metrics. Adam, RMSprop, and SGD optimizers were used to select the best ones, and the optimizers were evaluated using the Accuracy metric, the results of which are presented in Tables 4 and 5.

Table 4

ACCURACY SCORE OF NEURAL NETWORK MODELS BY EACH OPTIVIZATOR

Optimizers	*1-layer NN*	*2-layer NN*
ADAM	0,9790	0,9923
RMSprop	0,9790	0,9856
SGD	0,9695	0,9812

Source: [23]

Table 5

ACCURACY AND AUC SCORE OF NEURAL NETWORK MODELS

Metric	*1-layer NN*	*2-layer NN*
Accuracy	0,9790	0,9923
AUC score	0,9870	0,9953

Source: [23]

The resulting error values can be seen from the table. 4 and table. 5, show accuracy indicators for the proposed neural network model and are higher compared to research materials [16–18] by 2–7 %. The One-Hot Encoding algorithm was used as a data preprocessing method for the proposed normalization and variable encoding methods.

The presented topology of the neural network with the 1st and 2nd hidden layers ensures the classification of mines with an accuracy of 97.9 % and 99.2 %, respectively, using magnetic field sensors. It is shown that the number of correctly predicted classes for each mine type can improve the 5 % target margin of error to 2 %.

The confirmed performance of the two-hidden-layer neural network with the Adam optimizer is 1.3 % higher than the one-hidden-layer model, while the performance of the two-hidden-layer neural network with the Adam optimizer is higher than the performance of the same neural network with the RMSprop and SGD optimizers by 0.67 % and 1.11 % respectively.

As a result of developing demining technology based on GDS, a 3D online map is created in Digital Twin format with the marking of mines on the map and parallel marking of mined locations (physically, special flags), which is then used by personnel together with special robotic equipment for the final disposal of explosive objects.

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SPECIALISED COMPUTERISED VEHICLE MANAGEMENT SYSTEMS

The history of the automotive industry can be traced back to the late 19th century when the internal combustion engine was invented. Major milestones include Henry Ford's development of mass production technologies in the early 20th century, which revolutionized the industry and made cars more affordable for the general public.

The automotive industry is divided into different categories based on the type and purpose of vehicles:

- Passenger vehicles;
- Commercial vehicles;
- Two-wheeled vehicles;
- Special vehicles;
- Luxury vehicles;
- Powerful vehicles;

Each of these segments meets different market needs and diverse consumer preferences. The automotive industry is constantly evolving to meet changing demands by introducing new technologies and design innovations across these different vehicle categories. However, the industry is currently facing several challenges that reflect the complex and rapidly changing nature of the global market. A number of significant issues have been identified, including:

Technological disruption: The automotive industry is undergoing a significant technological transformation, with advances in electric vehicles (EVs), autonomous driving, connectivity, and artificial intelligence. Adapting to these technologies requires significant investment and poses challenges in terms of research, development, and infrastructure.

Introduction of electric vehicles: While electric vehicles offer environmental benefits, the automotive industry faces challenges in terms of developing infrastructure for charging stations, improving battery technology, and the cost of electric vehicles. The transition from traditional combustion engines to electric vehicles necessitates significant investment and presents traditional automakers with a pivotal decision.

Autonomous driving challenges: The development and deployment of autonomous vehicles confront regulatory, safety, and ethical challenges. Addressing issues such as liability in the event of accidents, regulatory frameworks, and public acceptance is of paramount importance for the successful integration of autonomous driving technology.

Supply chain disruptions: Disruptions such as trade tensions, natural disasters, the global pandemic of COVID-19, and war can affect the supply of critical components, leading to production delays and increased costs.

The automotive industry is currently undergoing a phase of transformation driven by rapid advances in automotive systems and technology. As vehicles become increasingly connected, autonomous and dependent on complex software, the need for comprehensive regulations and standards is paramount. This evolving landscape requires adherence to best practices that ensure the safety and interoperability of vehicle systems. In this context, compliance with established standards ranging from safety and cyber security to human-machine interface and wireless connectivity is key. It is of significant importance to consider the key best practices related to the regulations and standards that govern on-board systems. The comprehension and implementation of these best practices represent pivotal steps toward fostering innovation while prioritizing the safety and reliability of automotive technology in a rapidly changing environment.

Compliance with safety standards such as ISO 26262 [1] for functional safety in road vehicles is of paramount importance. Manufacturers must integrate safety into the entire automotive system development process in order to identify and mitigate potential risks.

As the connectivity of in-vehicle systems increases, compliance with cybersecurity standards becomes crucial. ISO/SAE 21434 [2] is a recently established standard that focuses on the cybersecurity of road vehicles. Implementing robust cybersecurity measures helps to protect against potential cyber threats and ensures the integrity of vehicle systems. Furthermore, standards that ensure interoperability and compatibility between different automotive systems are vital.

For example, standards such as AUTOSAR (Automotive Open System Architecture) provide a framework for developing standardized software architectures, thereby facilitating interoperability between different automotive systems. Ensuring a safe and convenient interaction between drivers and vehicle systems is of critical importance. Compliance with HMI standards, such as ISO 15005 for in-car audio warnings, helps to develop intuitive interfaces that minimize distractions. It is important to note that onboard systems often collect and process sensitive data. Compliance with data privacy regulations, such as the General Data Protection Regulation (GDPR) in

Ukraine and Europe, is crucial to protecting the privacy of vehicle occupants. Manufacturers must take measures to protect and handle data responsibly.

The basis of data transmission is the communication systems in cars, including V2X (Vehicle-to-Everything) communication, which must also comply with wireless communication standards. Standards such as IEEE 802.11p for wireless access in the transport environment provide reliable and secure communication between vehicles and infrastructure [3]. However, as the number of vehicles receiving software updates remotely increases, compliance with OTA update standards becomes increasingly important. Ensuring that updates are delivered safely and reliably helps prevent potential vulnerabilities and keeps vehicle systems up and running.

The Internet of Things (IoT) is similarly situated concerning automobiles in terms of implementation principles and cybersecurity issues. The protection of both the physical and cyber spheres is a crucial aspect of the development of the sector.

IoT devices, which encompass a range of items, including smart thermostats and industrial sensors, frequently lack robust security features. Many are designed with convenience and functionality in mind, rather than strict security protocols. This renders them susceptible to a variety of attacks, including:

- Unauthorized access: Weak authentication mechanisms or default credentials can permit unauthorized users to access and control Internet of Things (IoT) devices. Hackers can exploit these vulnerabilities to penetrate deeper into the network or gain unauthorized access to sensitive information.
- Data leakage: IoT devices collect and transmit a vast quantity of data, including personal and sensitive information. Insecure encryption or insecure data transfer protocols can lead to data leaks, exposing system and user data. The potential for IoT devices to serve as entry points for viruses, trojans, botnets, and other forms of malware is a significant concern. Once compromised, these devices can be used to carry out large-scale cyberattacks or engage in illegal activities such as distributed denial of service (DDoS) attacks.

In addition to cyber threats, compromised IoT devices can also pose a «physical» threat to other devices. For instance, attackers may exploit connected infrastructure systems, such as smart locks or industrial control systems, to cause physical damage or disrupt the functionality of a system.

Fig. 1 shows the classification of attacks on Internet of Things devices [5].

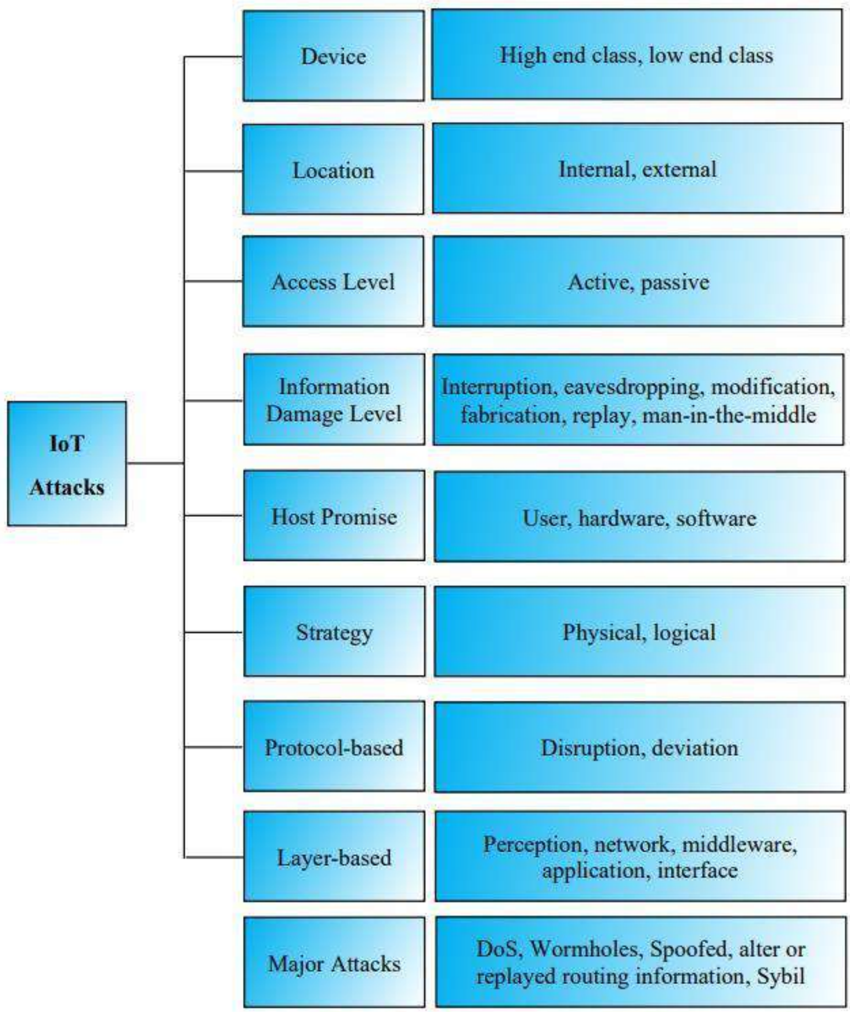

Figure 1. Classification of attacks on IoT devices

Source: [5]

To effectively mitigate the risks associated with IoT devices, a multi-layered security approach is essential. This approach should include physical and cyber security measures such as strong authentication (multi-factor), data encryption, regular system updates, access segmentation, implementation of intrusion detection systems (IDS) and network traps (honeypots), and physical restriction of access to devices.

As a general guideline, regular security audits and penetration tests should be conducted to assess the resilience of the IoT segment and identify areas for improvement or change in security mechanisms.

Securing any system requires full and close cooperation between stakeholders. Industry standards and regulatory frameworks play a crucial role in establishing minimum security requirements for both IoT devices and the automotive industry.

Harmonization of regulations and standards on a global scale is beneficial for the automotive industry. Efforts by organizations such as the United Nations Economic Commission for Europe (UNECE) aim to establish global technical regulations for vehicle safety and environmental performance. Rigorous testing and certification processes, such as those established by regulators and industry organizations, are essential to verify that in-vehicle systems meet the standards set. This helps to ensure that systems are reliable and safe in real-world conditions. In-vehicle systems should be designed to be continuously monitored and updated to address new threats and challenges. Software should be regularly updated and patched to improve driver and passenger safety and to address any control system vulnerabilities.

Artificial intelligence and neural networks are gaining momentum and are being used by several companies to autonomously control electric cars. Neural networks detect patterns in data that help the car learn to recognize traffic lights, trees, curbs, pedestrians, road signs, other cars, and other elements of the environment.

AI solutions are being integrated into devices to enable intelligent decision-making and automation. However, the use of artificial intelligence also presents security challenges, including the potential for aggressive attacks and data poisoning. Implementing robust security controls and auditing mechanisms is critical to mitigate these risks.

Speech recognition systems based on neural networks are one of the innovative technologies being integrated into modern cars. They allow the driver to use voice commands to make phone calls, change radio stations, or play music. Such functions help to create a comfortable driving experience without distracting the driver from driving and the situation on the road.

Of course, the use of neural networks is not limited to this. Large companies and start-ups have started to develop their own autonomous models and autopilots. Leading companies include Audi, BMW, Ford, Google, General Motors, Tesla, Volkswagen and Volvo. Most systems use a combination of different sensors (visual, ultrasonic, and radar) to analyze traffic to improve driving. The sensors provide good visibility in all weather conditions, high-quality images, and close-range object detection. Their integration enables the vehicle to read signs, park, and react to the traffic around it.

At their core, vehicle control systems operate on a simple feedback loop. The sensors are the eyes and ears of the system, collecting information about the state of the vehicle, such as engine speed, vehicle speed, wheel speed, steering angle, and even external factors such as temperature, road conditions, lighting, etc. They send this information to the control unit (ECU). They send all this data to the control unit (ECU). The ECU is the brain of the system, processing the data received from the sensors and using it to make decisions about how to adjust the car's behavior in accordance with the driver's decisions. Modern cars have several separate ECUs for different systems, such as the engine, brakes and transmission.

The ECU itself cannot do anything, it sends signals to the car's control mechanisms, which are the muscles of the system that carry out specific commands from the ECU to adjust things like fuel injection, brake pressure, or steering angle.

For example, a generalized steering control scheme for a car is as follows (Fig. 2 [6]). Given the specifics of each car, this scheme may differ, but in a schematic format for the total number of vehicles, it is currently unchanged.

It is worth considering the example of car control systems. Currently, such a board may be partly a development board or a capability assessment board. The use of such boards is growing rapidly in the IoT and automotive industries, where development platforms such as Arduino, Raspberry Pi, and NXP offerings play a key role. These platforms provide developers with the tools and resources they need to create innovative solutions for a wide range of applications, from smart home devices to connected vehicles.

Arduino (Fig. 3 [7]) is renowned for its simplicity and versatility, making it an ideal choice for prototyping IoT devices and sensor-based applications. With an easy-to-use development environment and extensive community support, Arduino allows developers of all skill levels to quickly bring their ideas to life.

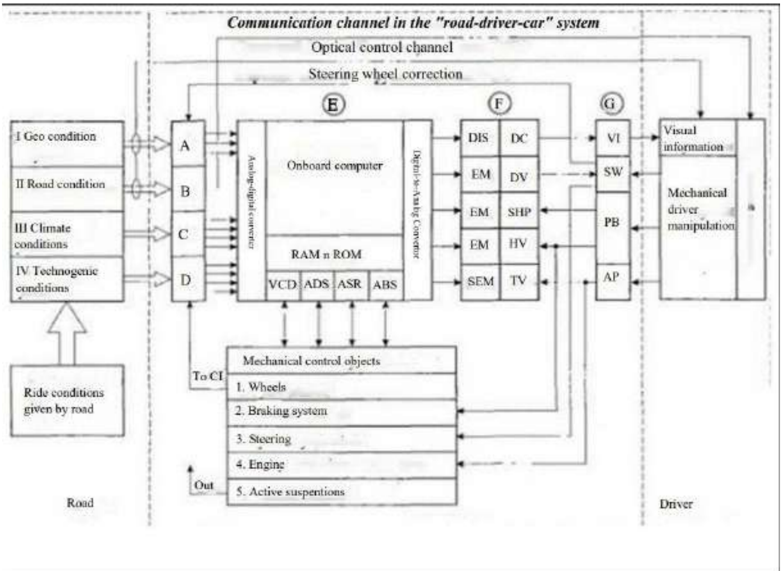

Figure 2. Scheme of electronic control of the car steering wheel

Source: [6]

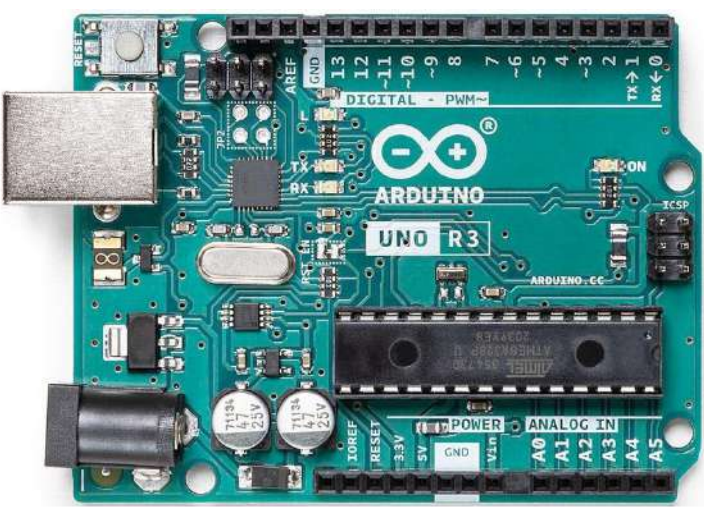

Figure 3. Example of the Arduino-uno-rev3 board

Source: [7]

In the IoT, Arduino boards are commonly used to collect sensor data, control actuators, and communicate with other devices via wired or wireless connections. Whether it's for monitoring environmental parameters, controlling home automation systems, or creating wearable gadgets, Arduino's modular approach allows it to be adapted to a wide range of use cases.

In the automotive sector, Arduino is being used to prototype vehicle diagnostics, GPS tracking systems, and telematics solutions. Developers are using Arduino's flexibility to create custom vehicle monitoring and control systems, enabling innovation in areas such as driver assistance, vehicle infrastructure connectivity, and in-car entertainment.

The Raspberry Pi offers more processing power and connectivity than the Arduino, making it well-suited for IoT and automotive applications that require more processing or multimedia capabilities. Equipped with a Linux-based operating system, the Raspberry Pi can act as a small server, gateway, or edge computing device in an IoT deployment.

In IoT projects, Raspberry Pi is typically used for tasks such as data aggregation, analysis and visualization. Developers use its general-purpose input/output (GPIO) pins to interact with sensors and actuators, and its networking capabilities enable communication with cloud services and other IoT devices.

In IoT projects, the Raspberry Pi (Fig. 4) is typically used for tasks such as data aggregation, analysis, and visualization. Developers use the general purpose input/output (GPIO) pins to interact with sensors and actuators, and its networking capabilities enable communication with cloud services and other IoT devices.

Figure 4. Photo of Raspberry Pi 4 2018

Source: [5]

In the automotive sector, Raspberry Pi serves as a platform for developing infotainment systems, dash cams and vehicle monitoring solutions. Its ability to run multimedia applications and connect to external displays makes it a versatile choice for enhancing the in-car experience, as well as supporting vehicle diagnostics and data logging functions.

NXP Semiconductors offers a range of microcontrollers and microprocessor solutions designed specifically for IoT and automotive applications (Fig. 5. [8]). These platforms offer advanced features such as real-time processing, hardware security, and automotive-grade reliability, making them ideal for mission-critical applications.

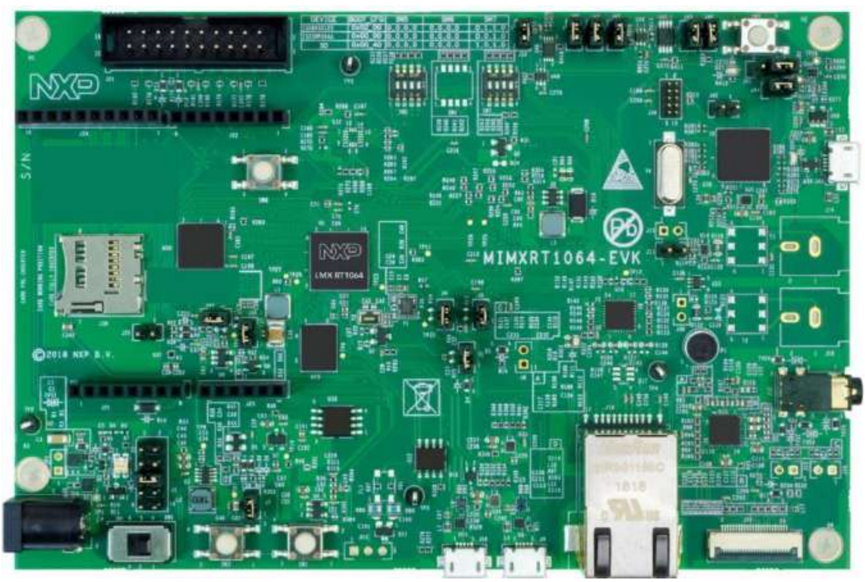

Figure 5. An example of an NXP development board

Source: [8]

In IoT projects, NXP platforms are used for edge computing, industrial automation, and smart city initiatives. With built-in support for communication protocols such as Bluetooth, Wi-Fi, and Zigbee, NXP’s offerings enable seamless connectivity and interoperability in IoT ecosystems.

In the automotive industry, NXP’s automotive-grade microcontrollers power advanced driver assistance systems (ADAS), vehicle electrification solutions, and connected car platforms. These platforms integrate safety-critical features such as functional safety and secure communications to meet the stringent requirements of today's vehicles.

Arduino, Raspberry Pi, NXP, and similar platforms are being used to create innovative solutions for both IoT and automotive applications. Whether it's prototyping new IoT devices or developing advanced automotive technologies, these platforms allow developers to unleash their creativity and contribute to the advancement of these rapidly evolving fields.

As IoT and automotive applications continue to grow, the need for flexible, scalable and reliable development platforms will only increase. By harnessing the power of platforms such as Arduino, Raspberry Pi, and NXP, developers can accelerate innovation, streamline development workflows, and bring transformative ideas to life in the IoT and automotive sectors.

If we look at a professional board used as an engine ECU, it is typically a complex system (Figure 6 [9]) that monitors and adjusts various engine parameters such as fuel injection, ignition timing, and air intake to optimize performance and efficiency. The data from each engine stroke can be compared with the previous one, taking into account environmental variables, to produce an 'ideal' optimization of the engine.

Figure 6. Motor control unit

Source: [9]

An example of such a block diagram for motorcycle engine control from NXP Semiconductors is shown in Fig. 7 [10]. The difference in logic between motorcycle and car engine control is insignificant in terms of the parameters collected to optimize performance, as they are generally the same in both cases.

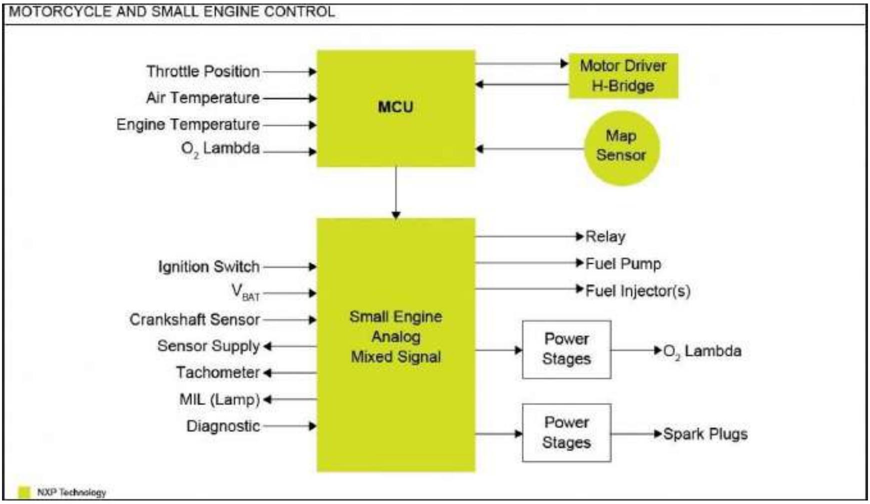

Figure 7. Diagram of the engine control unit

Source: [10]

There is a noticeable difference in the principles and mechanisms of control. For comparison, we can look at the diesel engine control scheme shown in Fig. 8 [11].

A diagram of an engine control unit can show various components that can collect a wide range of information, from the speed and position of the crankshaft at a given time to the moment and force of detonation when the air-fuel mixture is combusted in the cylinder block. The diagram also shows the actuators responsible for various systems, such as the exhaust gas recirculation valve or the valve timing system.

The electronic control unit itself can be divided into:

- A microprocessor that uses sensor data to calculate the necessary adjustments to the engine.
- Memory: Stores software and data.
- Power supply: Provides power to the microcomputer.

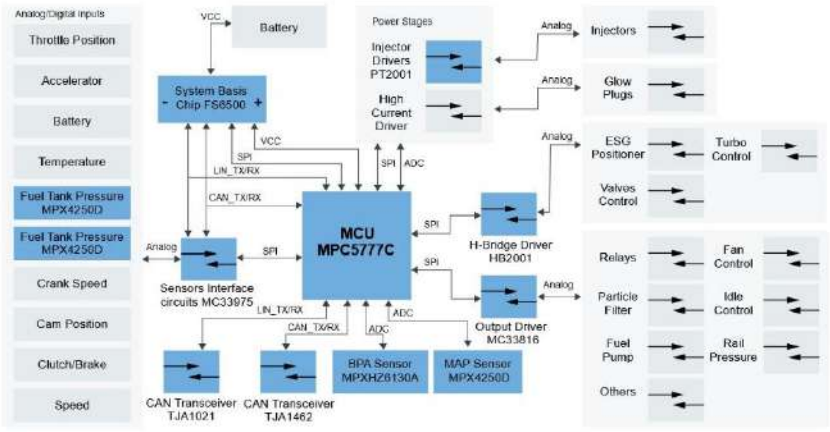

Figure 8. Schematic diagram of the NXP board

Source: [11]

Also, all the lines in the diagram are connection lines – wires that connect sensors, actuators, and other components.

Other components include

- Fuses and relays
- Diagnostic connectors
- Alarms and indicators

It is important to note that the circuitry of the engine control unit can vary significantly depending on the specific make, model, year and revision of the vehicle.

There are also separate systems controlled by a separate microcomputer, such as Electronic Stability Control, a system designed to prevent skidding and loss of control during cornering or evasive maneuvers. This system can already monitor data from the gyroscope and accelerometer if they are installed separately in the cabin or under the bonnet (Fig. 9 [12]).

This system prevents loss of traction during acceleration, especially on slippery surfaces. It can also track the acceleration of each wheel separately according to the speed of the car itself. A diagram of how such a system works is shown in Fig. 10 below [13].

Another such system could be Adaptive Cruise Control, which is no longer a novelty in the automotive industry, but it is almost impossible to imagine a car without it. The latest cars are equipped with an electronic cruise control system that maintains a safe distance from the car in front and automatically adjusts the speed without the driver's intervention.

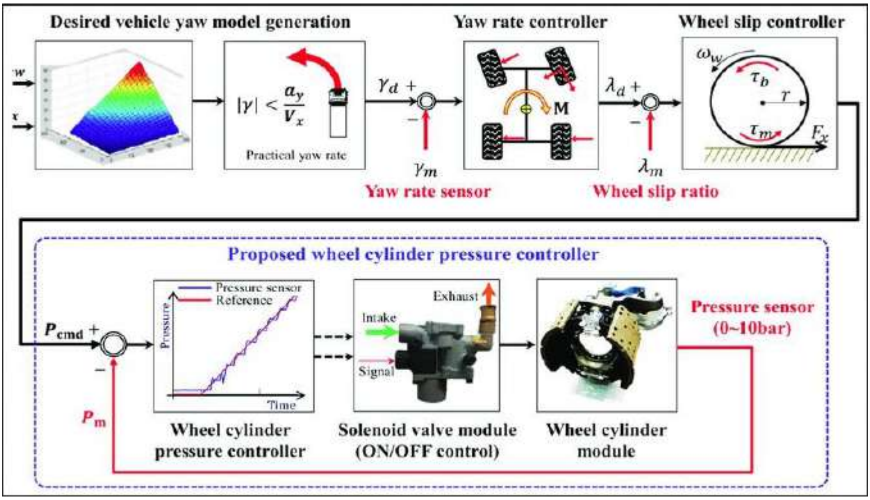

Figure 9. Control system

Source: [12]

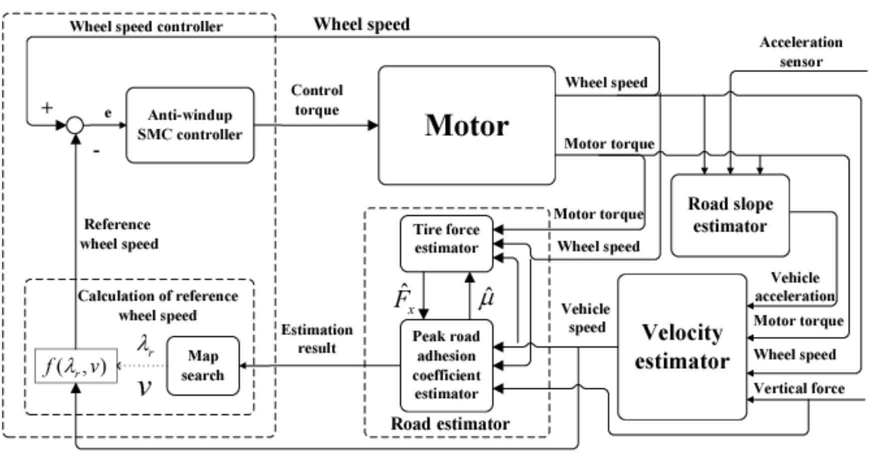

Figure 10. Schematic diagram of the control system

Source: [13]

Typically, such a system uses lidar, sonar, and cameras that can be installed on a car. In addition, given the capabilities of artificial intelligence and neural networks (Fig. 11 [14]), there are more and more cases where these are being used for adaptive cruise control.

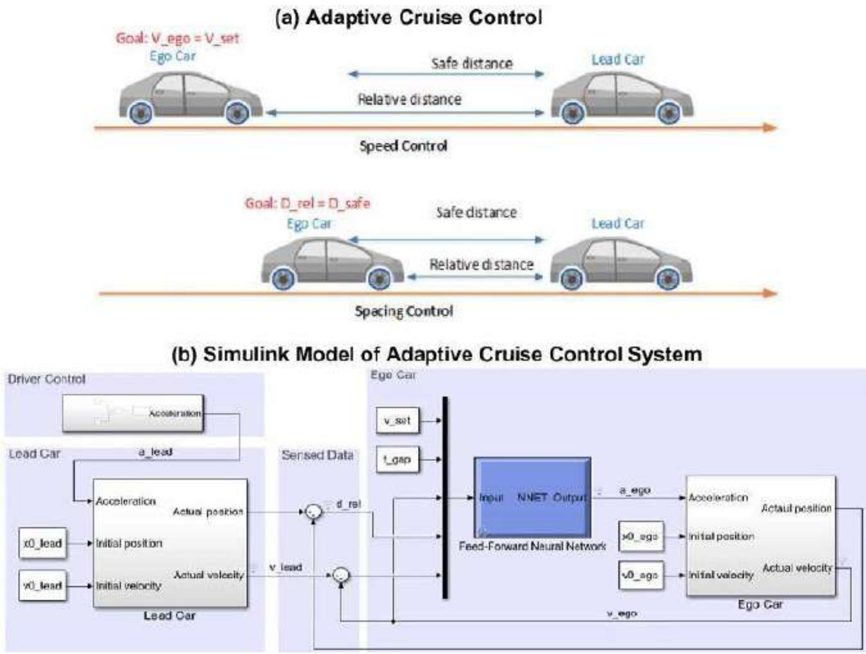

Figure 11. An example of calculating the system operation using lidars

Source: [14]

As technology advances, vehicle control systems are becoming more complex and integrated. We can expect even more automation and driver assistance features, paving the way for self-driving cars in the near future.

The introduction of artificial intelligence in the automotive industry will not only benefit vehicle manufacturers, but also automotive suppliers, car rental companies and all companies involved in the automotive industry and supply chain.

By using AI-based control systems, the automotive industry can harness the full potential of artificial intelligence and collect data from multiple resources and sensors to control machinery, manage inventory, conduct operational planning, and help users drive safely [15]. Using machine learning technologies, an automotive control system can also predict malfunctions in autonomous vehicles and take corrective action before an accident or potential accident occurs.

In general, this helps such systems operate at a high level of performance, saving the driver time and money. On average, a person takes over car maintenance in an emergency or when a problem arises that does not require a lot of labor. Machine learning algorithms collect data from AI sensors embedded in the vehicle, monitor the health of car parts, and display information when a part needs maintenance. In this way, the driver can take preventative action by contacting a technician for maintenance and inspection to avoid a breakdown or accident.

Artificial intelligence and deep learning models based on automotive applications offer a wealth of valuable insights and analysis to accurately determine driver behavior. By using these sensors and AI systems, driver behavior can be easily detected and warning signals can be issued to prevent accidents. In addition, if the driver is distracted by any circumstance, AI signals can also alert the driver and give them early warning to protect themselves using real-time driver distraction detection techniques.

In conclusion, dedicated computer-based vehicle management systems play an important role in the modern automotive industry, helping to improve safety, efficiency, and driving comfort. In particular, the use of dedicated computer control systems enables the implementation of intelligent traffic management strategies that help to reduce congestion and improve mobility on the roads. Automated systems can respond to a variety of situations on the road, providing fast and effective solutions to avoid accidents and optimize traffic flow.

Specialized computer control systems are becoming not only a key element in the evolution of the automotive industry but also an important factor in creating a safe, efficient, and intelligent transport environment. With their introduction, modern vehicles will be better adapted to the needs of the modern world, offering a balanced combination of technical progress and a high level of safety.

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BANK'S CLIENT IDENTIFICATION SYSTEM WITH THE USE OF IOT TECHNOLOGIES

Introduction. Financial institutions have long been an essential part of our lives. It is impossible to imagine the modern world without the Internet, and the Internet without financial transactions. It is worth remembering that Dan Cohn, a 21-year-old economist with a degree in economics, sold a music CD to his friend who was more than 300 miles away in 1994 by making an online payment. This was the trigger for the further development of the Internet, as well as various security protocols, such as SSL (Secure Sockets Layer) and, later, TLS (Transport Layer Security) [1].

The organization of banking and financial services is the basis for the economic development of many countries, and information technology (IT) helps to manage services and facilitate the scaling of banking institutions' operations [2]. Information technology is the driving force behind all economic activity, and thus an efficient banking system will make money move faster, leading to faster growth. The banking industry is adopting technologies to support its rapid development, such as service-oriented architecture (SOA), customer relationship management (CRM), business process management (BPM), web content management (WCM), document management systems (DMS), etc.

Although banks have to manage money, its safety, and correct profitable functioning, as well as its flows – card-to-card transfers, payroll, SWIFT payments, etc. – the clients are the customers of this process. Money depositors have a lot of demands on banks, such as deposit insurance, transparency of operations, financial stability, compliance with international standards, accessibility of services, confidentiality of information, and fraud protection.

The last two points are critical as much as any other. Unfortunately, it cannot be said that maintaining compliance with these requirements is an easy task for a bank, as confidentiality and fraud protection are not only the responsibility of financial institutions but also of clients. For example, according to a study by the EMA Association, in 2022, losses from online fraud and social engineering methods in Ukraine reached UAH 1 billion, which is 96 % more than in 2021 [3]. According to the association, fraudsters most often used cash payments from the government, international organizations, well-known Ukrainian companies, and banks as a lure.

Fraud schemes. Existing ATM fraud schemes have evolved significantly with the development of technology and the improvements in ATMs. Criminals are constantly developing new methods to exploit the vulnerabilities of ATMs, terminals, and the people who use them:

– Skimming [4]. It remains one of the most common and effective methods of ATM fraud. Criminals attach a device to the card slot of an ATM to read data from the magnetic stripe of a debit or credit card. A hidden camera or keypad pad can also be used to capture the user's PIN. The stolen data is then used to create counterfeit cards for unauthorized transactions;

– Shimming. A more advanced version of skimming that targets cards with a chip. A shim is a paper-thin device with a microchip and flash memory that is inserted into a card slot to intercept data from the card's chip. This method is more sophisticated and harder to detect than traditional skimming;

– Vishing or phishing through ATMs. In most cases, fraudsters find out the name and phone number of a banking user through leaks, open databases (such as IE), call them, and, using social engineering, force them to either provide their bank card number, CVV2, and PIN or provide a temporary (one-time) password – OTP – to conduct a fraudulent transaction.

In some cases, fraudsters may install entirely fake ATMs or modify existing ones. When customers use such ATMs, their card details and PINs are immediately available to fraudsters. To prevent the use of such devices, ATMs should be used only in crowded places and near cameras, such as shopping malls, shopping centers, and other public places.

It should be noted that fake ATMs cannot be fixed by upgrading current systems, as it involves the assembly and commissioning of a full-fledged model of the banking system by criminals. However, we can work on modernizing the system to fix the first problem – skimming.

As follows from the description of the relevant fraudulent schemes, they are not based on the vulnerabilities of banks and other financial institutions but rather on the human factor, poor awareness of bank customers about fraudulent scams, social engineering, and a rather weak customer identification system when working with payment terminals or ATMs.

Another important component for further work is to understand the difference between the processes of identification, authentication, and authorization:

– *Identification* is the procedure of recognizing a subject [5]. This can be achieved using a user ID (e.g., login), process ID, etc. The claimed credentials must be unique so that different entities in the system can be distinguished.

– *Authentication* is the process of proving that an entity is who it says it is [6]. For this purpose, passwords, secret phrases, PINs, digital signatures, biometric data, or other data that will allow verification of the identity are provided.

– *Authorization* is the process of verifying rights and specifying access levels for an individual user of an information system. Authorization is applied to a person who has already been identified and authenticated within the system and is waiting for access rights to work with individual modules of the system or the IS as a whole.

The purpose of this study is to innovatively upgrade banking systems to a) increase customer protection against fraudulent schemes; b) reduce the impact of bank cards and phones on customer identification; c) significantly improve the quality of authentication, the process of verifying that a person is really who they say they are; d) improve customer experience when working with upgraded banking systems.

Updating ATMs and terminals is critical to ensuring a high level of security, as it allows for the early detection and elimination of potential software vulnerabilities, reducing the risk of fraud, hacker attacks, and other cyber threats. On the other hand, hardware upgrades also contribute to an improved customer experience, as the latest technology and functionality provide more convenient, faster, and more efficient service.

Current state. The process of identifying customers at ATMs has evolved significantly since the advent of ATMs. This evolution has been driven by the need to increase security, improve user experience, and reduce fraud.

The first ATMs required a physical card with a magnetic stripe and a PIN to authenticate the user. This method was simple and revolutionary for its time, allowing bank customers to conduct financial transactions without the involvement of a teller. While PINs provide a basic level of security, they are vulnerable to various forms of fraud, including shoulder surfing, card skimming, and more sophisticated attacks.

Recognizing the need for multi-layered security, the banking sector has moved to two-factor authentication (**2FA**) models. These models combine something the user knows – a PIN – with something they have – a mobile device. Indeed, customer security and fraud protection when using terminals and ATMs have increased, but there is still room for fraud.

One common threat is surveillance, where fraudsters watch or record the victim entering their PIN at an ATM. Even in the case of 2FA, if a fraudster gets the card and manages to intercept the PIN, the only barrier is the phone factor, which can also be bypassed if the phone is not secure. **SEPIA** (Secure-PIN-Authentication-as-a-Service) has been proposed to protect users from over-the-shoulder attacks and partial surveillance, but requires additional hardware such as Google Glass to scan QR codes, which may not be very common or practical for all users [7].

Many 2FA systems use SMS to send OTPs to the user's phone. However, SMS messages can be intercepted using methods such as SIM spoofing, where an attacker convinces the mobile operator to change the victim's phone number to a SIM card under their control, thus receiving OTPs intended for the victim. In 2016, it was proposed to improve the security of ATMs and card transactions using SMS-based protection, and the corresponding scheme of interaction between the client and the bank is shown in the diagram below (Fig. 1).

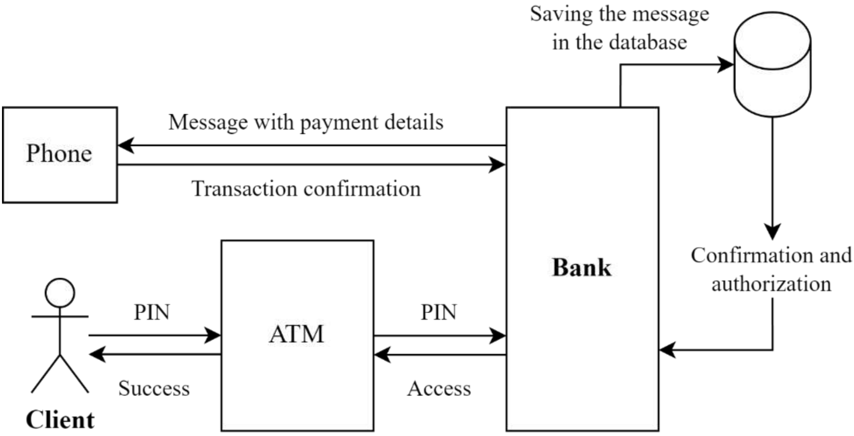

Figure 1. The 2FA model proposed in 2016

Source: [8]

In this process, the user has to insert the card and write his or her PIN code in the ATM or terminal, which in turn transmits this to the banking systems, which send an SMS to the phone with the transaction data and the OTP itself. The user confirms the transaction by entering the OTP into the ATM or confirms the transaction via mobile phone. The confirmation information is stored by the bank and leads to the customer's authentication and authorization. The banking system then transmits the information about granting access to the customer and sends a success message to the ATM or terminal. The relevant work did not consider the vulnerabilities inherent in SMS as a secure channel. The human factor was also not considered.

It is important to keep in mind that the effectiveness of 2FA at ATMs depends on user behavior. Users may choose weak PINs, share their OTP codes, or become victims of phishing attacks that compromise their credentials. In addition, technical issues, such as delays in receiving OTPs, can affect the user experience.

To overcome the limitations of PIN-based authentication, researchers, businesses, and financial institutions have begun to explore biometric authentication methods. Biometric identifiers, such as fingerprints and facial patterns, offer a higher level of security because they are unique to each individual and difficult to copy.

The application of even more security layers has led to the emergence of **MFA** (Multi-factor authentication) (Fig. 2). Accordingly, 2FA is a specific type of MFA.

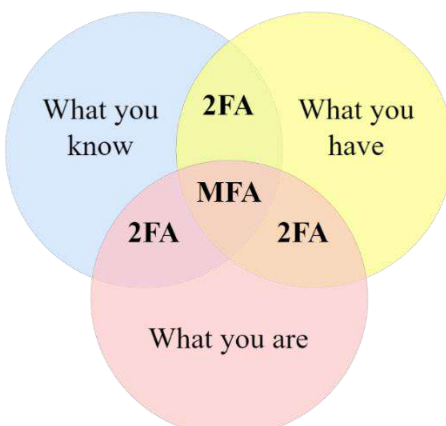

Figure 2. Authentication factors

Source: [9]

These authentication factors are usually divided into 3 types [9]:

– Something you know (e.g., a password, secret question, or PIN);

– Something you have (e.g., a cell phone, card, or token);

– Something that is a part of you (biometric data such as fingerprints).

One of the first and most widely accepted biometric methods in ATMs was fingerprint recognition. In the study «ATM Card Security Using Bio-Metric and Message Authentication Technology», published in 2018, the authors emphasized that the integration of fingerprint recognition with PIN verification significantly increases security during ATM transactions [10].

To implement the proposed modernization of ATMs and payment terminals, a combination of current and newly developed customer identification tools should be used. It is proposed to use an NFC reader, a touchscreen display for entering PINs and other data, as well as biometric sensors – a fingerprint scanner and a camera.

Main research.

Using biometrics. The use of biometric data will allow customers to be authenticated without the use of PINs and mobile phones that are vulnerable to fraudulent attacks. Moreover, the use of a high-resolution camera will also allow working with the Diia system, which is used to identify and authenticate citizens at the state level.

The use of these particular technologies is related to their popularity in everyday life – we protect our mobile phones with a fingerprint or face pattern. A fingerprint is the most common method of biometric identification; to use it, you only need to get a scanned fingerprint from a person using a suitable scanner. The device can be optical, capacitive, or ultrasonic.

Different types of fingerprint scanners work on different principles and have their advantages and disadvantages. For example, optical scanners use light to create a visual image of a fingerprint. When the finger touches the scanner, light reflects off the print and forms an image that is analyzed by the system. Optical scanners are relatively reliable and can be affected by dirt or moisture on the finger. Whereas, capacitive scanners use the electrical properties of the skin to create an image of the fingerprint. They create an image of a fingerprint by measuring changes in capacitance at different points on the sensor. These scanners are sensitive and accurate but may be less effective in the presence of moisture. The most expensive solution is ultrasonic scanners, which use high-frequency ultrasonic waves to create a detailed 3D image of the print. The waves bounce off the finger and are received by a sensor, allowing the system to determine the pattern of the print based on the time it takes the waves to return. Ultrasonic scanners are effective even when fingers are wet, and are considered one of the safest and most accurate.

The role of IoT in the banking sector. The integration of Internet of Things (IoT) technologies into the banking sector has significantly transformed processes, making them safer, more efficient, and more user-friendly. IoT technologies relevant to banking cover a wide range of devices and systems designed to collect, transmit, and analyze data in real time, which contributes to improving the quality of service and security measures [11].

IoT devices, such as smartwatches and fitness trackers, have opened up new opportunities for customer identification and authentication in the banking sector. These devices can communicate with banking systems via Bluetooth or NFC (Near Field Communication) for seamless and secure transaction authentication. Earlier in this paper, we mentioned a system that uses wearable devices such as Google Glass for secure PIN authentication at ATMs, demonstrating the innovative use of this type of device in banking.

Smartphones and mobile applications have become a central element of the IoT ecosystem in the banking sector. Banks use mobile devices for two-factor authentication, where a transaction initiated through an ATM or online platform requires additional verification using a one-time password sent to the customer’s mobile device. This method adds an extra layer of security to customer identification and transaction authorization.

IoT technologies can minimize lengthy customer waiting times and reduce overcrowding in bank branches, thereby increasing customer satisfaction [12].

Although the IoT offers innovative solutions, security remains a serious concern for customers. There is a growing risk of cyber threats in the banking, finance, and insurance (BFSI) sector due to the introduction of IoT devices [13]. Customers are increasingly aware of the potential for hacking and data leakage, which may affect their trust and willingness to use IoT banking services.

Customers’ perceptions of the use of IoT in banking are generally positive, especially in terms of convenience and efficiency. However, security concerns and a lack of awareness of IoT capabilities may hinder their adoption.

Implementation risks. There are also implementation risks for this project, such as technical shortcomings, laws, and acceptance of the new identification system by the target users – customers of banking institutions who use ATMs in their daily lives.

New technologies, especially those based on IoT and biometric data, may be prone to technical failures, flaws, or security vulnerabilities. Changes in legislation, especially those related to personal data protection and regulating the use of biometric data, may create legal risks for the bank. The processing of biometric data requires a very high level of protection. In addition, there is a risk that customers may not accept the new system due to unfamiliarity with the technology or privacy concerns.

To address and mitigate the risks (Fig. 3) associated with the implementation of a biometric customer identification system, it is important to develop a comprehensive approach that takes into account technical, legal, and social aspects.

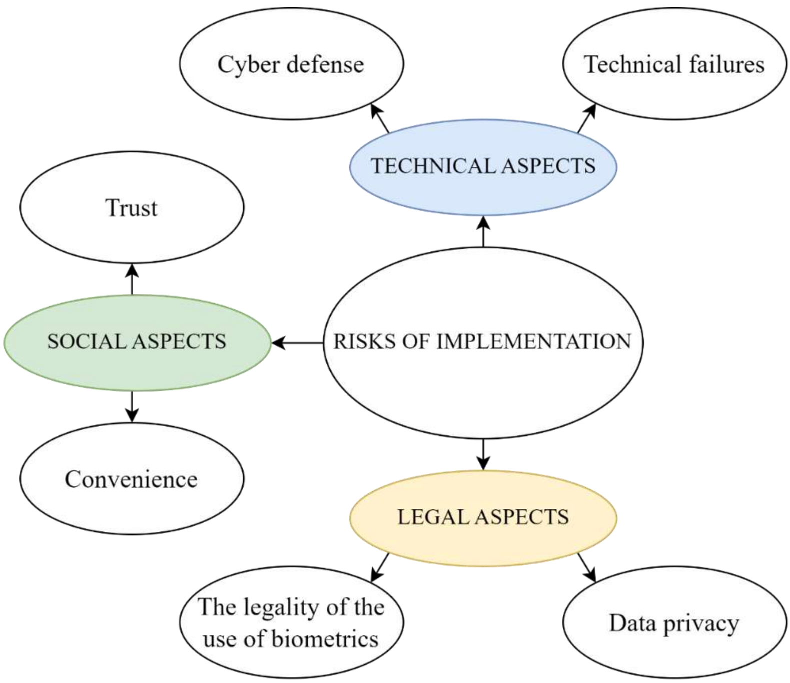

Figure 3. Risk cloud of implementing a new identification system

Source: developed by the authors

In terms of technical risks, the key is to implement an effective cybersecurity strategy. This includes using reliable and proven software, updating it regularly to protect against the latest cyber threats, and implementing modern cryptographic technologies to protect biometric data. In addition, it is important to provide an emergency response plan that will allow you to quickly resolve possible problems, ensuring the continuity of the system.

Concerning legal risks, it is necessary to ensure that the system is fully compliant with applicable laws, especially in terms of personal data protection and regulation of the use of biometric technologies. This involves close cooperation with the legal department to closely monitor changes in legislation and make timely adjustments to the system.

In addition to technical and legal aspects, customer relations play an important role. The strategy of customer relations within the framework of the implementation of a new biometric customer identification system should be comprehensive and aimed at ensuring a high level of trust and acceptance by customers. The main goal of such a strategy is not only to inform users about the new system, but also to reassure them about possible security and privacy concerns.

First and foremost, it is important to start by thoroughly informing customers about the benefits and features of the new system. This can be done through various communication channels, such as emails, information brochures, social media, the bank's website, and direct inquiries at bank branches. It is important to ensure that the information is accessible and understandable to all customer segments, including those who may not be very familiar with the latest technology.

Next, you need to emphasize security and privacy aspects. This includes a detailed explanation of how biometric data is collected, processed, and stored, as well as an explanation of the measures taken to protect this data. It is also important to inform customers about their rights and opportunities to control the use of their personal data.

Another key element is to provide customer support. This can be ensured by establishing a support team that will answer customers' questions and help them solve any problems related to the use of the new system. Additionally, training or workshops can be organized for customers who want to learn more about the system.

In addition, it is important to collect feedback from customers after implementation. This may include analyzing reviews on social media. Using feedback will help to improve the system and increase customer satisfaction.

Assessment of the system quality. Several criteria can be used to assess the degree to which a bank's customer identification system using IoT technologies and biometric data achieves its goals (Table 1). These criteria help ensure an objective assessment of the system's effectiveness. They should consist of quantitative and qualitative criteria that are separated from each other and characterized by identifiers such as scale type, unit of measurement, and range of values. Such an approach will help to formulate clear and understandable criteria that will allow for measuring the success of the system.

Table 1

SYSTEM SUCCESS EVALUATION CRITERIA

Parameter	Type	Measure	Range
System security (Quantitative)	Interval	Number of successfully repelled unauthorized access attempts	From 0 to maximum recorded attempts
Identification reliability (Quantitative)	Relative	Percentage of authentic users successfully identified	From 0 % to 100 %
Processing speed (Quantitative)	Interval	Seconds are required to process the transaction	From one second to a maximum time
System stability (Qualitative)	Relative	Percentage of availability time out of total uptime	From 0 % to 99.99 %
User satisfaction (Qualitative)	Ordinal	Satisfaction score	From 1 (low satisfaction) to 5 (high satisfaction)
Compliance with regulatory requirements (Qualitative)	Ordinal	Degree of compliance	From 1 (non-compliance) to 5 (compliance)

Source: developed by the authors

The implementation of a prototype solution begins with the design of the architecture of the corresponding system. According to the task, the necessary components of this system are the following:

- ATM or terminal (ATM);
- Customer identification system:
  - System core that connects the modules and acts as a «Gateway»;
  - Wi-Fi module or other network adapter for communication with the server or network bridge for communication with the server through the ATM or terminal network adapter;
  - Fingerprint sensor;
  - High-resolution camera (1080p).
- Server with server software that serves ATMs and terminals;

- A database that stores data on customers, terminals, and financial transactions for further transfer to integration banking, interbank, and central systems.

When starting to work with the system, identification will take place – the bank's client must attach his card to the NFC reader, the identification system will receive the necessary information from the card and check it against the control data in the system – the card must be valid, active and serviced by the corresponding terminal (Fig. 4).

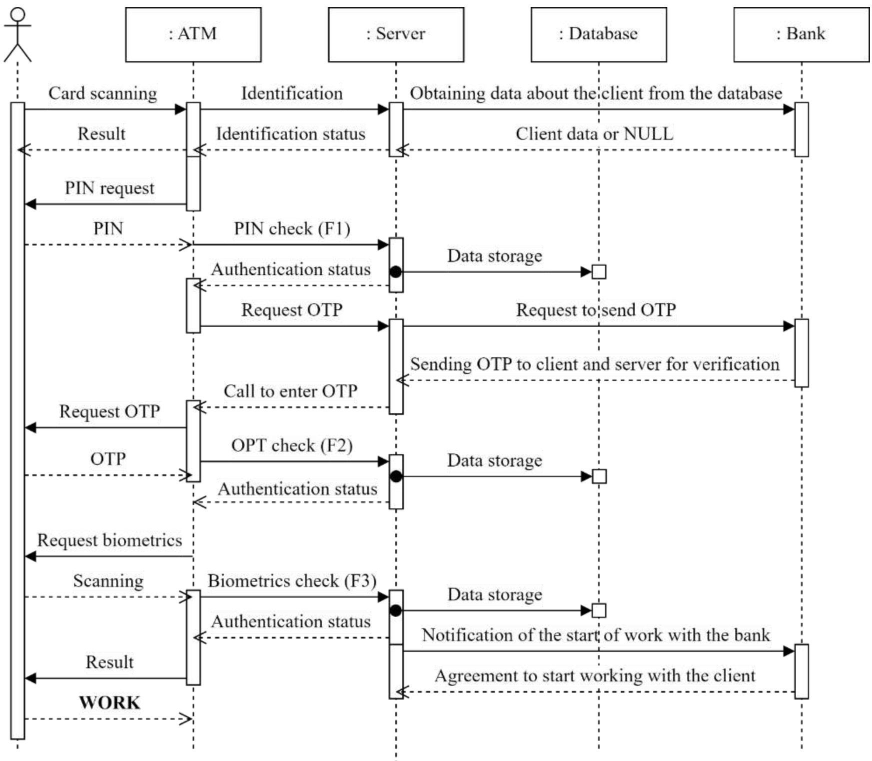

Figure 4. Scheme of identification and authentication of a bank customer using IoT technologies and biometric data as a factor of MFA

Source: developed by the authors

Then the system will start the authentication process. During the authentication process, the client must confirm that he or she is the person he or she claims to be by placing a finger on the fingerprint sensor or scanning his or her face using a camera. The relevant biometric data will be transmitted to the server in encrypted form, after which the user will either be authorized to use funds and perform any other card transactions or receive a message that his or her identity has not been confirmed. In case of problems with authentication, the client will be able to make 2 more attempts. In case of unsuccessful completion of the process, the client should be notified by phone or email. If all three attempts are unsuccessful, the card will be blocked until the customer contacts the bank branch.

Following the above components and identification scheme, the system architecture can be formed (Fig. 5).

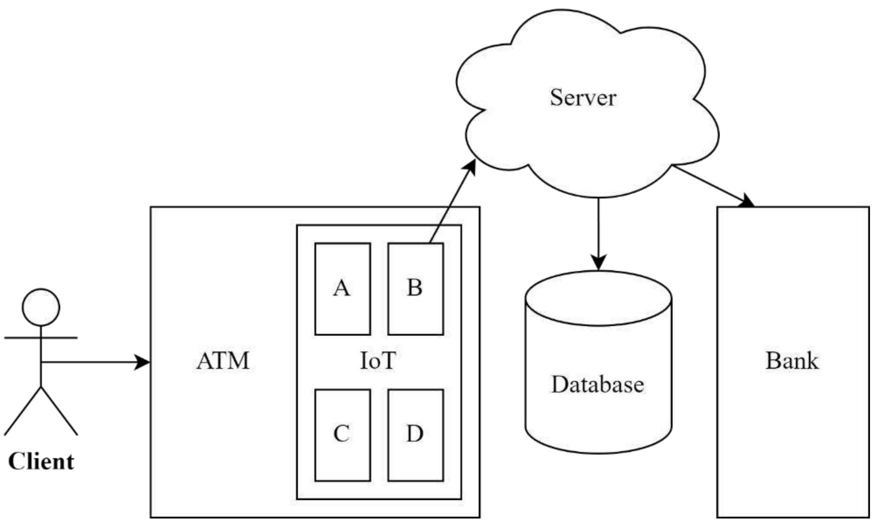

Figure 5. System architecture, where A – system core (Gateway), B – network module, C – fingerprint scanner, D – video camera

Source: developed by the authors

Building a module for customer identification and authentication. To create the corresponding component, it is proposed to use a system based on Raspberry Pi 3 or a newer model. Among other components, the necessary elements of the system, as mentioned earlier, are a camera – Raspberry Pi Camera Module 3; a fingerprint sensor – Adafruit Fingerprint Sensor Module, Waveshare UART Fingerprint Sensor (E) or Waveshare Capacitive Fingerprint Reader (B); reader of cards and other IoT devices (phones, watches with NFC technology) – MFRC522

RFID Reader; display not less than 7 inches, for example, LCD 1024x600 HDMI QLED Capacitive Touch Screen. In this case, the network module is available on the computer itself.

The proposed modules were chosen for several reasons. For example, the camera module of the third version, like the second version, is widely used in tasks related to face recognition because it has a high resolution. This camera has a 12-megapixel IMX708 sensor with HDR and phase detection autofocus with a wide-angle lens and an infrared filter.

The Waveshare Capacitive Fingerprint Reader is a great choice for projects requiring biometric authentication. This module is designed to provide fast and reliable fingerprint recognition using advanced capacitive fingerprint technology.

The mentioned display is high quality, made using QLED Quantum Dot Display technology, which makes this display bright, with rich colors, and pleasant to use.

The use of a touchscreen display, RFID reader, and biometric sensors in an ATM without a keyboard and card slot significantly reduces the risks of skimming, shimming, and vishing. Skimming, which involves illegally copying information from the card's magnetic stripe using special devices, becomes impossible because there is no physical card slot. Instead, the RFID reader allows for contactless identification, which eliminates the possibility of setting up overlays.

Shimming, a fraud technique that involves inserting a thin device inside the card slot to intercept the data of the integrated circuit (chip), also becomes ineffective. It is proposed to leave the reader under the thin part of the ATM body. Since the proposed ATM design does not have card slots and convex RFID readers, there is simply no place to install such a device.

In the case of vishing, which often involves attempts to obtain personal information through fake messages or calls, the use of biometric sensors greatly improves security. Biometric authentication, such as fingerprint recognition, provides a unique way to identify a person that cannot be easily stolen or replicated by fraudsters. Thus, even knowing a PIN or one-time password will not allow fraudsters to access user accounts.

The security enhancement is enhanced by the use of a touchscreen keyboard on the display for entering PINs, where the digits change their location, making it difficult to attempt to intercept the code through visual observation or the installation of other malicious devices. This feature not only increases the security of data entry but also reduces the risk of successful social engineering techniques to steal information.

Creating a database for the system. It is proposed to use MySQL since this database is one of the most popular database management systems, and its choice for designing a database for the bank's customer identification system can be justified for several reasons. MySQL is known for its high speed of operations and reliability. This is especially important for financial systems where speed and accuracy are critical parameters.

What's more, MySQL supports large databases and provides scalability, making it easy to expand the system as the number of users or data increases. MySQL has several built-in security features, including data encryption, user authentication, database-level access control, and the ability to configure SSL to ensure a secure connection. MySQL is also regularly updated to provide bug fixes, performance, and security enhancements. Also, a large community of developers and users provides significant support and resources to solve any problems. Based on the specified requirements for the respective database, its structure may include the following tables and fields:

- Table client:
  - client_id (INT, PRIMARY KEY, AUTO_INCREMENT);
  - first_name (VARCHAR);
  - last_name (VARCHAR);
  - email (VARCHAR);
  - phone (VARCHAR);
  - account_number (VARCHAR);
  - card_number (VARCHAR).
- Table ATM:
  - atm_id (INT, PRIMARY KEY, AUTO_INCREMENT);
  - location (VARCHAR);
  - manufacturer (VARCHAR);
  - The table may also contain other technical information about the ATM, such as the date of commissioning, the date of the last maintenance, or certain other statistics necessary for the proper functioning of the system.
- Table atm_audit_log:
  - log_id (INT, PRIMARY KEY, AUTO_INCREMENT);
  - client_id (INT, FOREIGN KEY);
  - atm_id (INT, FOREIGN KEY);
  - action (VARCHAR);
  - timestamp (DATETIME).
- Table transaction:
  - transaction_id (INT, PRIMARY KEY, AUTO_INCREMENT);
  - client_id (INT, FOREIGN KEY);

- atm_id (INT, FOREIGN KEY);
- amount (DECIMAL);
- type (VARCHAR);
- timestamp (DATETIME).

- Table otp:
  - otp_id (INT, PRIMARY KEY, AUTO_INCREMENT);
  - otp_code;
  - time_to_live – password lifetime in seconds, which is added to the value of the time of the creation of the corresponding password to check relevance;
  - created_at – password creation time.
- Table biometric:
  - biometric_id (INT, PRIMARY KEY, AUTO_INCREMENT);
  - client_id (INT, FOREIGN KEY);
  - biometric_data (BLOB);

It is suggested that you create the following relationships between tables:

- client_id in the atm_audit_log, transaction, otp, and biometric tables is a foreign key that refers to client_id in the client table.
- atm_id in the atm_audit_log, transaction, and otp tables is a foreign key that refers to atm_id in the atm table.

Using the appropriate technical description of the database tables, as well as the relationships between them, you can create an EER diagram [14] of the database using the MySQL Workbench tool (Fig. 6).

The database creation script generated with the use of Forward Engineering tools will allow you to create a database instantly instead of writing all database queries manually. This database structure will allow you to efficiently store and process information about customers, transactions, and ATM activities, and ensure secure storage of biometric data.

When a user starts using an ATM or terminal, the necessary information is read from the user's card or device, such as card number, account number, card expiration date, etc. This information is enough to identify the customer, and accordingly, the customer's information is searched in the database. This information contains the PIN code for the card, which will allow authentication by the first factor – the user must enter the code. An audit record will be created in the atm_audit_log table about the result of entering the PIN code.

After entering it, the user will receive an OTP, this code will also be saved in the database, and a record will be created in the ATM based on the results of its entry. The last step, if the previous two were successful, is to obtain biometric data from the client – a fingerprint or face.

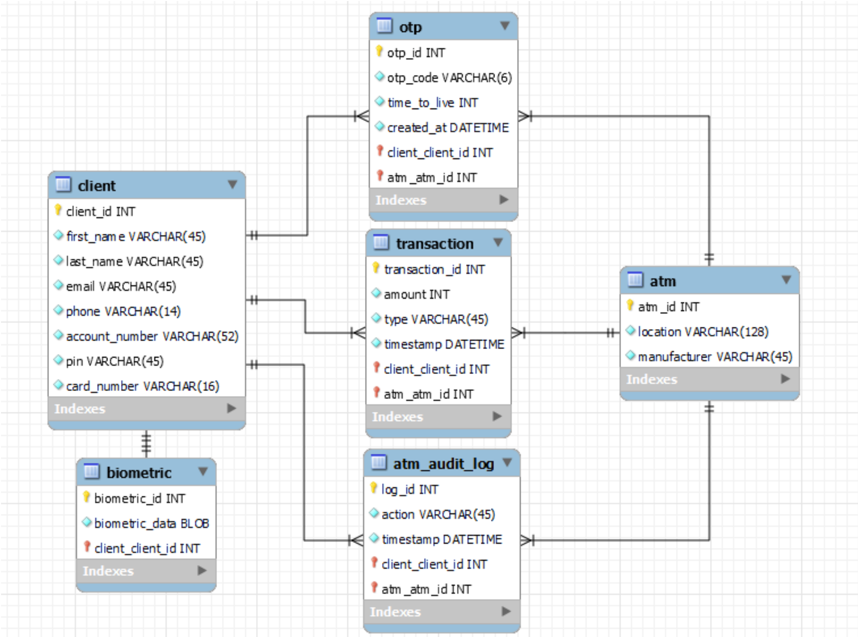

Figure 6. EER database diagram

Source: developed by the authors

Creation of the system's server software. The Java programming language was chosen for its development, as it has proven to be the best in corporate and industrial software development, and is also often used in the banking sector due to its high security and constant updates. For the rapid development of the REST API, the Spring Framework was chosen, which allows you to quickly create and run software created in the Java programming language.

To connect to the database, it is recommended to use the suitable MySQL Connector J and to work with the database – Spring Data JPA. This approach will allow you to easily and quickly connect the database to the project, provides convenient tools for configuring the database, and allows you to conveniently write database queries, even without using SQL.

After writing the program code (Fig. 7), you need to deploy documentation that will serve as an explanation for the newly created API.

```java
@RestController
@RequestMapping("/api/authentication")
@RequiredArgsConstructor
public class AuthenticationController {
    private final AtmService atmService;

    @PostMapping("/pin")
    public Boolean verifyClientPIN(@RequestBody ClientPinVerificationRequest request) {
        return atmService.verifyClientPIN(request.getClientId(), request.getAtmId(), request.getPin());
    }

    @PostMapping("/otp")
    public Boolean verifyClientOTP(@RequestBody ClientOtpVerificationRequest request) {
        return atmService.verifyClientOTP(request.getClientId(), request.getAtmId(), request.getOtp());
    }

    @GetMapping("/biometrics")
    public byte[] verifyClientBiometrics(@RequestParam int clientId, @RequestParam int atmId) {
        return atmService.getClientBiometrics(clientId, atmId);
    }
}

@RestController
@RequestMapping("/api/clients")
@RequiredArgsConstructor
public class ClientController {
    private final AtmService atmService;

    @GetMapping
    public Client getClientData(@RequestParam String account, @RequestParam int atmId) {
        return atmService.getClientDataByAccount(account, atmId);
    }
}

@RestController
@RequestMapping("/api/transactions")
@RequiredArgsConstructor
public class TransactionController {
    private final AtmService atmService;

    @PostMapping
    public Transaction saveTransaction(@RequestBody TransactionRequest request) {
        return atmService.saveTransaction(request.getClientId(), request.getAtmId(),
                request.getAmount(), request.getAction());
    }
}
```

Figure 7. Code of controllers

Source: developed by the authors

This will allow you to develop software for the identification and authentication system faster, as the developer will be able to see HTTP methods, input and output parameters, and errors. To create documentation, you should refer to Spring Doc (Fig. 8).

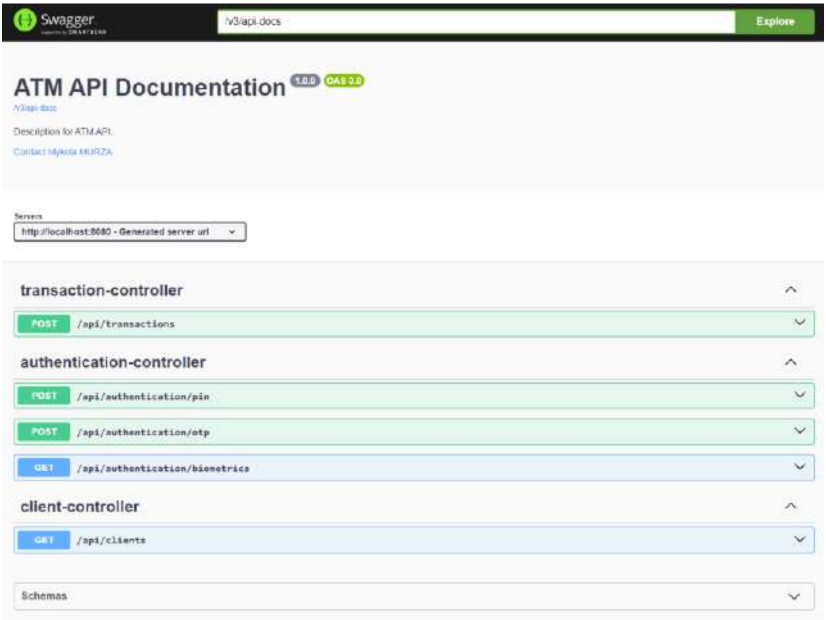

Figure 8. Project documentation

Source: developed by the authors

The full code base of this software solution is available at the link on the GitHub platform – https://github.com/MykolaMurza/atm-server.

Prospects for further research. The use of the Internet of Things in the banking sector is not limited to security, but also to operational efficiency. Research on the implementation of smart energy management systems (SEMS) in ATMs across India demonstrates how the Internet can be used to manage and reduce energy consumption, resulting in significant cost savings and other environmental benefits [15]. By using IoT sensors and real-time data analytics, banks can optimize the energy consumption of ATMs, especially those located in remote or less accessible areas.

The introduction of IoT technologies in the banking sector can also affect consumer confidence. IoT-enabled banking services that offer convenience, security, and personalized experiences can significantly increase customer satisfaction and loyalty [16].

The integration of IoT technologies into the banking sector, including the development of smart ATMs, opens up numerous opportunities to improve security, operational efficiency, and customer service. By leveraging IoT, banks can not only secure transactions and manage risk more effectively but also offer innovative services that meet the ever-changing needs of their customers. As the banking industry continues its digital transformation, IoT is becoming a key enabler of future innovation.

Conclusion and results of the study. The banking sector is actively developing and implementing the latest technological solutions, as this allows it to maintain high standards of customer service, guarantee additional security, and earn more money by selling new services. Among such innovations in the sector and the digitalization of individual processes, there should always be room for the development of systems that allow banks and other financial institutions to improve customer protection against fraud, as it is steadily and gradually growing.

To effectively combat fraud, it is not enough to develop a system. This issue is quite acute among customers of different banks in Ukraine and around the world, but it is the customers who must understand the risks associated with performing financial transactions both on the Internet and when using ATMs or terminals. Today, there are several popular fraudulent schemes: skimming – replacing card readers and keyboards with fraudulent ones to save customer data; shimming – replacing RFID card readers or creating an overlay on them to save customer card data; vishing – forcing a user to transfer card data, PIN and/or OTP to fraudsters to perform a terminal operation using social engineering methods or threats.

To solve this problem, it was proposed to use multifactor authentication (MFA). Unlike authentication in the original sense, it implies obtaining from the user what he knows – a password – what he has – a phone number (OTP) – and what is part of it – a fingerprint or face image. This approach will provide an additional layer of customer protection.

Creating ATMs without a physical keyboard and using only an RFID reader in a flat body allows you to solve these problems, since it is no longer possible to replace the keyboard, reader or make a substrate for the RFID reader, and one OTP is not enough, since biometric data is required.

Accordingly, the user's path to using their own data should be supplemented by an additional step, namely the use of biometric data. The introduction of IoT technologies based on Raspberry Pi will allow this to be done efficiently, since all the necessary components can be interconnected within each ATM, and connect the system to the server software, which, in turn, will have a database and the ability to communicate with banking systems.

It is proposed to use the MySQL database for the system, as it has good support and is considered to be a sufficiently reliable database. Tables should be created to store current customer information necessary for the system to function, as well as to store information about ATMs, transactions, OTP, and a table containing audit records containing all information about the actions performed.

The next step is to develop the software. In this step, it is recommended to use Java and Spring Framework for quick deployment and simplified software support. It is necessary to create a REST API that will meet the requirements – provide customer information, allow customers to authenticate by PIN and OTP, and will be able to transfer biometric data for further processing.

Technological developments in the banking sector, especially those related to security and fraud protection, are necessary and open to further innovation.

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DEVELOPMENT OF INNOVATIVE INFORMATION TECHNOLOGIES OF SEMANTIC SEARCH, PROCESSING, AND VISUALIZATION OF ELECTRONIC DOCUMENT MANAGEMENT SYSTEMS IN THE BANKING SECTOR

The introduction of access keys to a bank client's personal account increases resistance to unauthorized access, however, it has a number of disadvantages, including the need, instead of remembering a password, to securely store a file with an access key on a mobile phone or computer, which ultimately makes it impossible for a bank client who has lost a computer to consciously log in or phone due to blackouts and inability to turn on own device.

As an alternative to access keys, a neural network of artificial intelligence for playing chess, reinforced by semantic search AMAZON KENDRA, is offered. The idea is that the combination of the chess game is unique and can be the key that the banking institution sets as verification for entering the personal account, this eliminates the need for the bank client to use access keys, instead, it is enough to remember the game of chess and pronounce it with his voice, the artificial intelligence neural network with semantic search AMAZON KENDRA will be responsible for verifying and establishing the authenticity of the person. The innovative development of the banking sector in the direction of modeling the implementation of information technologies to support innovative bank products and services is extremely important. In this direction, scientific research (R&D) is carried out at Vadim Hetman State University, in particular, on the topics: «Development of methods and technologies of intellectual management of organizational structures in the conditions of the digital economy» state registration No. 0119U002604»; «Modeling of processes of implementation of information technologies supporting innovative products and services of banks, state registration No. 0122U001987» (research supervisor, Doctor of Economics, Prof. Ustenko S.V.). According to the current results of these works, scientific articles have been published in international monographs [1, 2, 3, 4]. The relevance of the research topic is determined by the fact that in market conditions banking products and services play a key role in the functioning of the financial system and market. This leads to the urgent need to build intelligent information systems for the interaction of banking institutions with the user, the involvement of artificial intelligence, in particular neural networks.

The main feature and innovation of such systems is that they have the property of machine learning and with each new training the system improves its performance [5]. In information and communication systems and technologies for supporting the information security of banking activities and conceptual approaches to the sustainable development of Ukrainian banks based on the general principles of banking education, the main ones of which are the principles of integrity, stability, digitization, and structural-logical connections of elements and the banking system as a whole, which requires a generalization of approaches to model studies and technologies for using banking systems [4]. The work is devoted to the study of the conceptual basis of the processes of information provision of digital educational activity, which does not take into account the production (operational) sphere of activity of enterprises and organizations [5]. Publications provide approaches, trends, and factors of economic growth in the most technologically developed countries [6, 7, 8, 9]. Technological development is one of the important factors of economic growth and includes the use of a set of production technologies and scientific methods that must be taken into account for a reasonable analysis and assessment of banks' activities. At the same time, there is an urgent need to develop a general (conceptual) model for assessing the bank's efficiency, which could take into account the key performance indicators of several bank subsystems, in particular operational, economic, financial, management, information technology, etc. [6, 8]. The implementation of the conceptual model in each bank will allow the system level to conduct model experiments to assess the effectiveness of the functioning and development of the bank, to develop practical recommendations and ways to improve the efficiency of Ukrainian banks, to take into account the implementation of banking services provided to bank clients.

Since the beginning of 2014, the banking system of Ukraine has experienced one of the biggest crises in its history. In terms of banking assets as a percentage of gross domestic product, Ukraine's banking sector was similar to Poland's. However, by 2016, bank closures and reduced lending led to a sharp reduction in the role of banks in the economy. Today, Ukrainian banks lag far behind many European banks. As of October 2020, out of 180 banks operating at the beginning of 2014, the National Bank of Ukraine declared 104 insolvent or liquidated, which is almost 60 % of the country's banks. It should be noted that the assets of some Ukrainian banks in 2014 were overstated due to the concealment of loans to related parties, but many banks, unfortunately, did not have the opportunity to model and forecast the impact of internal and external destabilizing factors on the financial institution, which leads to the search for tools and approaches for strategic analysis, performance evaluation and development of banks. Banks are at the epicenter of these changes. Technological developments and social changes have a deeper and more immediate impact on the financial industry than on most other sectors, as its primary raw materials are information and money. Money, in turn, can be dematerialized and turned into accounts, in other words, into data that can be stored, processed, and transferred in real time with little cost [1, 2].

The banking sector is beginning to experience the transformations that other information sectors have undergone. This is largely because banking has historically been a highly regulated industry subject to close supervision and control by government authorities. However, the transformation of the industry is not only inevitable but also gaining momentum every day. The main reason is that the technological revolution introduces new ways of doing business every day and increases the potential to reduce costs, and the number of users who resort to non-traditional methods of banking continues to grow. Another reason for the transformation is that the current crisis is causing changes in different directions. Banks are perceived as the «culprit» of the recession, and rightly so, as many institutions made very serious mistakes and chose to ignore the basic principles of banking: prudence, transparency, and even honesty. As a result of these mistakes, many banks faced serious difficulties, with some banks failing and others undergoing complete restructuring, usually financed with public funds.

The colossal amount of taxpayer funds invested in banks caused serious damage to the reputation of financial institutions and the entire industry in the eyes of ordinary citizens. The crisis also triggered a process of radical changes in banking regulation: credit limits, increased capital and reserve requirements, the need for large investments to improve risk and compliance systems, etc. All this comes down to a decrease in income and an increase in expenses, in other words, to a decrease in the current and future profitability of financial institutions. Banks must respond to the new demands of their customers and society, and meet this challenge with a damaged reputation, lower profits, and slower growth rates of traditional banking business. Such a situation requires a radical transformation: banks must radically revise the way they interact with clients and make a qualitative leap in efficiency. To a certain extent, the increase in efficiency will be achieved due to the sharp consolidation of the banking sector, which has already begun. But the true transformation of the industry will be achieved through the broad and above all, intelligent use of technology as part of a continuous process of innovation.

In recent decades, banks have been among the most important users of information and communication technologies, which they adopted considering two main goals: to reduce costs and optimize processes to increase profits, and to develop communication channels that differ from the usual ones. With the development of banking, the Internet has become a leading source of information, indispensable business communication, and even a forum for personal relationships: now more than a billion people around the world use various social networks. The Internet also contributes to the fragmentation of banks' production chains, facilitating the outsourcing of services. Banking services offered by cloud computing are a breakthrough in universal access to data storage and processing at very low costs and will have far-reaching consequences. The use of the Internet has also increased significantly due to the development of mobile phone technology. Thanks to these new devices, almost 4.5 billion people are online and have almost universal access to some level of information services, which has a huge impact on productivity [4, 10]. Mobile phones are equipped with more and more powerful and diverse functions, which will gradually be included in other devices, additional services, and services of banking systems («Internet of things», «Internet banking»). The methodology of researching the processes of functioning and development of banks is based on general analysis and principles of bank development and takes into account a comprehensive approach to researching the processes of effective development of banks [4]. A comprehensive approach to the study of bank development processes is focused on the holistic development of all processes, not individual processes, which contributes to the comprehensive development of the bank. This approach allows taking into account the information technology aspects of banking services, developing new banking products, and using modern information technologies and banking systems. The basis of the information and technological support of banks is the process of implementing digitalization as a tool for the development and scaling of the bank. Digitization is the direction of development of banks regarding the implementation of modern digital technologies, aimed at the transition to automated digital technologies, controlled by real-time intelligent systems in constant interaction with the external environment beyond the boundaries of one bank, with the prospect of unification on a global scale, the Internet of Things and Services network. Today, the first steps in the implementation of digitization are the introduction of such technologies as machine learning, blockchain systems, AR technologies (augmented reality), AWS cloud technologies (cloud technologies), and large data processing systems (data processing) [9, 2, 3].

To improve the security of a bank client's account, it is proposed to use the Amazon Kendra system to obtain the results of a semantic search in connection with a neural network of artificial intelligence for a game of chess. Amazon Kendra is a document search and indexing interface. Amazon Kendra can be used to create an updatable index of various types of documents, including plain text, HTML files, Microsoft Word documents, Microsoft PowerPoint presentations, and PDF files. It has a search API that can be used from several client applications, including websites and mobile applications, other services are integrated with Amazon Kendra.

For example, you can use Amazon Kendra search to run Amazon Lex chatbots and provide answers to user queries. Amazon S3 can be used as a data source for your Amazon Kendra index. AWS Identity and Access Management can also be used to manage access to Amazon Kendra resources.

Amazon Kendra consists of the following elements:

1. Index provides a client-side search API. The index consists of source documents.

2. Documents to be indexed are stored in the source repository.

3. The data source synchronizes the documents of your source repositories with the Amazon Kendra index. It is possible to synchronize your data source with the Amazon Kendra index to update the index with new, updated, and deleted files from the source repository.

4. Document Add API, which directly adds documents to the index.

Benefits of using Amazon Kendra:

1. Get answers in natural language: you can use simple keywords to search. Amazon Kendra will return the best answers to your query, whether your answer is in a document, FAQ, or PDF. Amazon Kendra will also provide suggested answers rather than going through a long list of documents.

2. Content Access: With Kendra, it's easy to access content from various repositories like SharePoint, Amazon S3, ServiceNow, and Salesforce into a centralized index that lets you search all questions in your data and find the exact answer.

3. Fine-tuning search results: it is possible to fine-tune search results by manually adjusting the importance of data sources or by using custom tags.

4. Deployment in just a few clicks: With just a few clicks, we can set up an index, connect relevant data sources, and start using Kendra to find answers to our questions.

Amazon Kendra users can ask the following types of questions or requests:

1. Factual questions are simple who, what, when, and where questions, the answers to which are based on facts that can be given in a single word or phrase.
2. Descriptive questions are questions with a single line, section, or full text as the answer.
3. Search by keywords – when the purpose and scope of the question are unclear. Amazon Kendra can determine user intent from a search query and return results that match the user's expected value.

Amazon Kendra is a widely used service defined as an intelligent search (ML) service powered by machine learning. Amazon Kendra redefines business search for user websites and applications so that their employees and customers can quickly find the information they need, even if it is located in multiple locations and content repositories within the company. With Amazon Kendra, users can stop sifting through large volumes of unstructured data and instead find relevant answers to their queries when they need them. Because Amazon Kendra is a fully managed service, there is no need to configure servers and train or install machine learning models. Use natural language queries in addition to basic keywords to get the information you need. Whether it's a text snippet, an FAQ, or a PDF document, Amazon Kendra will provide the exact answer from it. Instead of searching for exact answers in huge lists of documents, Amazon Kendra offers suggestions in advance. Amazon Kendra is also defined as a service that offers intelligent search capabilities for websites and applications. With this service, employees can easily identify the material they need, even if the data is stored in multiple locations, and get the right answers to their queries when they need them.

Amazon says goodbye to browsing through long lists of links and browsing through articles in the hope of finding something that will help users. Natural language search capabilities, unlike traditional search technologies, provide the answers users are looking for quickly and accurately, regardless of where the content is stored in their company, so they find relevant answers quickly. Amazon Kendra easily aggregates content from content repositories such as Microsoft SharePoint, Amazon Simple Storage Service (S3), ServiceNow, Salesforce, and Amazon Relational Database Service (RDS) into a centralized index using Amazon Kendra. It allows users to quickly search all of your enterprise data and find the most accurate answer, thus centralizing access to knowledge. The deep learning models used by Amazon Kendra have been pre-trained in 14 industries, helping to produce more accurate answers in a variety of business use cases. Users can also fine-tune search results by directly prioritizing data sources, authors, or relevance, or by applying custom tags, thus customizing search results. Compared to traditional search solutions, Amazon Kendra is quick to configure, allowing users to access Amazon Kendra's advanced search capabilities more quickly. Without any programming or machine learning skills, users can simply create an index, link relevant data sources, and launch a fully functional and customizable search interface with just a few clicks of the mouse, and thus it deploys with just a few clicks of the mouse. As with any data discovery tool, metadata is key. The S3 databases and tables available in the AWS Glue data catalog will be used.

We will present the method of service operation

To make information searchable through Amazon Kendra, you need to prepare the metadata (that is, the database and table names in the AWS Glue data catalog) in a format that can be indexed in Amazon Kendra. It's very easy with boto3's AWS Python SDK. See boto3's AWS Python SDK example below (see Fig. 1):

```
def get_all_glue_tables():
««««
Function to get all tables in AWS Glue Data Catalog
««««
glue_tables = []
kwargs = {}
response = glue.search_tables(**kwargs)
glue_tables.extend(response['TableList'])
while 'NextToken' in response:
token = response['NextToken']
kwargs['NextToken'] = token
response = glue.search_tables(**kwargs)
glue_tables.extend(response['TableList'])
return glue_tables
```

Figure 1. AWS Python SDK Example by boto3

Source: [11]

With metadata added as documents to Amazon Kendra, it's time to experience data discovery. The first query was to find user session data. For this, Amazon Kendra returned the correct results along with a suggested answer that matched what we were looking for. In addition, based on the metadata and Facet configuration in Amazon Kendra, I can filter the columns I am interested in or the types of tables (Fig. 2).

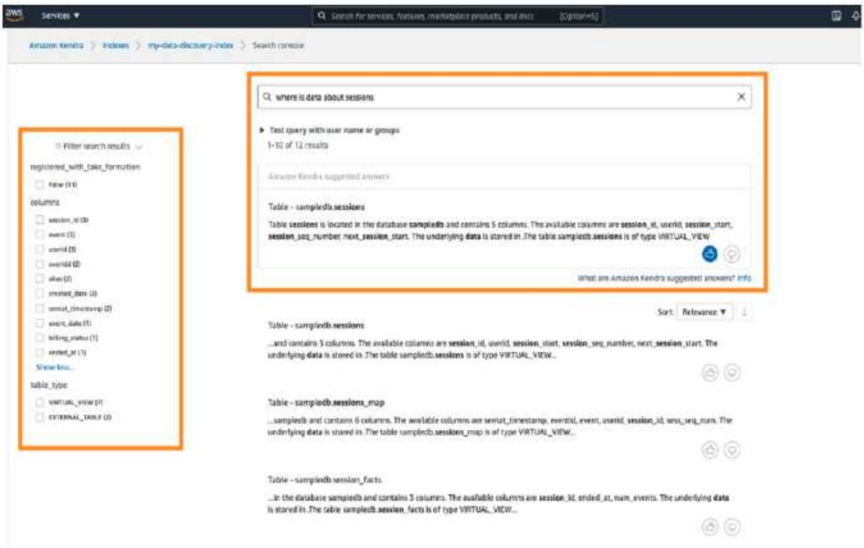

Figure 2. Searching for user session data

Source [11]

After examining the session data, the task is to view the data available for conversion. So the question to Amazon Kendra is, «Where's the conversion data?» We immediately see the result, as can be seen in Fig. 3.

Finally, we can see the tables with the event Id column to know which tables or views to combine for analysis (Fig. 4).

Search allows you to ask questions in natural language. eg «Where is eventide used?» or «Where is the conversion data?». This capability makes it easy for anyone to find the relevant data they need for analytics. Thus, the time required to search for data is reduced.

Finding semantic images for articles using Amazon Rekognition, Amazon SageMaker Foundation Models i Amazon OpenSearch Service

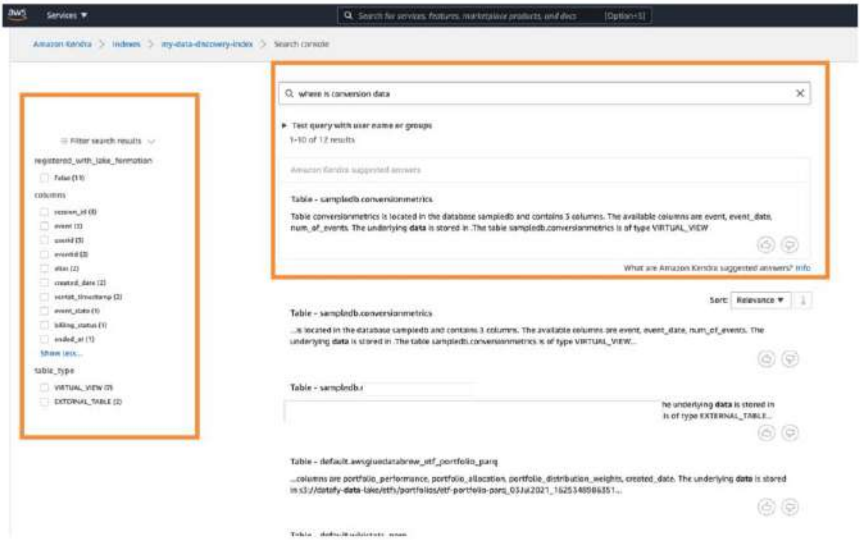

Figure 3. Data available for conversion

Source [11]

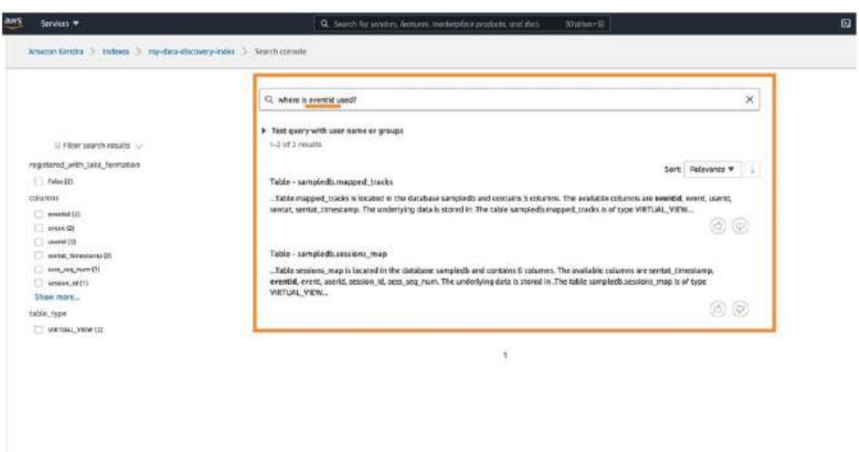

Figure 4. Tables with the event Id column

Source [11]

Digital publishers are constantly looking for ways to optimize and automate their media processes to generate and publish new content as quickly as possible.

Publishers may have repositories containing millions of images, and to save money, they need to be able to reuse those images in articles. Finding the image that best matches an article in repositories of this scale can be a time-consuming, repetitive, manual task that can be automated. It also relies on proper tagging of images in storage, which can also be automated (see Aller Media Finds Success with KeyCore and AWS for a customer success story) [11].

The paper demonstrates how to use Amazon Rekognition, Amazon SageMaker JumpStart, and Amazon OpenSearch Service to solve this business problem. Amazon Rekognition makes it easy to add image analysis capability to your applications without any machine learning (ML) experience and comes with various APIs to perform use cases such as object detection, content moderation, face detection and analysis, and text and celebrity recognition. which we use in this example. SageMaker JumpStart is a low-code service that includes out-of-the-box solutions, notebook examples, and many state-of-the-art, pre-trained models from public sources that can be deployed with just one click to your AWS account. These models are designed to be deployed securely and easily via the Amazon SageMaker API. The new SageMaker JumpStart Foundation Hub makes it easy to deploy large language models (LLM) and integrate them into your applications. OpenSearch is a fully managed service that makes it easy to deploy, scale, and manage OpenSearch. The OpenSearch service allows you to store vectors and other data types in an index and offers rich functionality that allows you to search documents using vectors and measure semantic relatedness, which we use in this publication.

The ultimate goal of this post is to show how you can output a set of images that are semantically similar to a given piece of text, be it an article or a TV synopsis.

The following screenshot shows an example of using a mini-article as search input instead of using keywords and being able to display semantically similar images.

The solution is divided into two main parts. First, you extract hashtag and celebrity metadata from images using Amazon Rekognition. You then create metadata embeddings using LLM. You store celebrity names and embed metadata in the OpenSearch Service. In the second main section, you have an API to query the OpenSearch Service index for images using OpenSearch's intelligent search capabilities to find images that are semantically similar to your text.

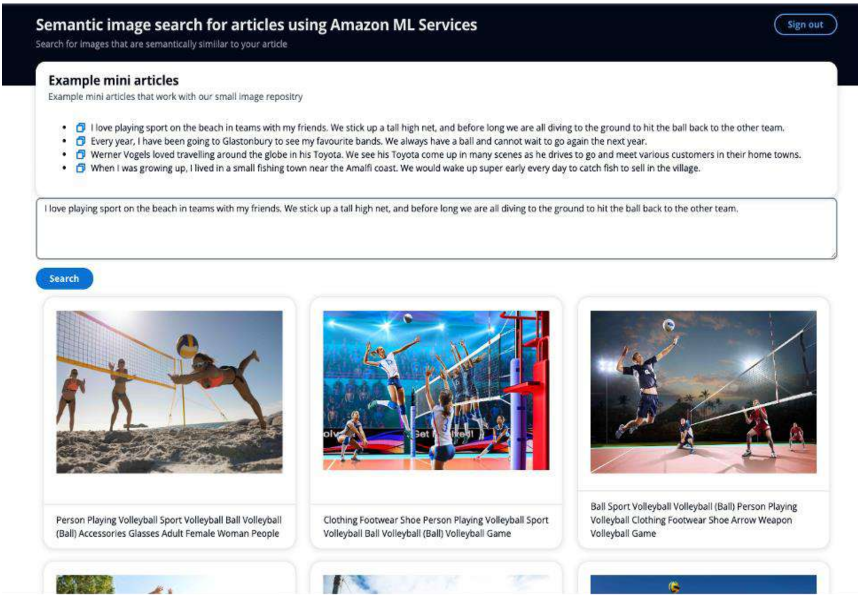

Figure 5. Example of using a mini-article as search input

Source [12]

This solution uses our event-driven services Amazon EventBridge, AWS Step Functions, and AWS Lambda to orchestrate the process of extracting metadata from images using Amazon Rekognition. Amazon Rekognition will make two API calls to retrieve the tags and celebrities from the image.

The Amazon Rekognition celebrity detection API returns an array of elements in response. For this post, you use the following:

1. Name, ID, and URLs – The celebrity's name, Amazon Rekognition's unique ID, and a list of URLs, such as a link to the celebrity's IMDb or Wikipedia for more information.

2. MatchConfidence – a match confidence metric that can be used to control API behavior. We recommend that you apply an appropriate threshold to this metric in your application to select the desired operating point. For example, setting a threshold value of 99 % may eliminate more false positives, but may miss some potential matches.

In the next call to the Amazon Rekognition tag discovery API, it returns an array of elements in response. The following sequence was used:

1. Name – the name of the detected label.
2. Credibility – the level of credibility of the label assigned to the detected object.

A key concept in semantic search is embedding. A word embedding is a numerical representation of a word or group of words in vector form. If you have many vectors, you can measure the distance between them, and vectors that are close in distance are semantically similar. So if you generate the metadata embeddings of all your images, and then generate the embeddings of your text, such as an article or TV synopsis, using the same model, you can find images that are semantically similar to your given text.

SageMaker JumpStart has many templates available for creating inserts. For this solution, you use Hugging Face's GPT-J 6B Embedding. It creates high-quality embeds and has one of the best performance scores according to Hugging Face's evaluation results. Amazon Bedrock is another option, still in preview, where you can choose the Amazon Titan Text Embeddings model to generate embeds.

A pre-trained GPT-J model from SageMaker JumpStart was used to generate the embedded image metadata and store it as a k-NN vector in your OpenSearch Service index along with the celebrity name in another field.

The second part of the solution is to return to the user the top 10 images that are semantically similar to their text, be it an article or a TV synopsis, including any celebrities if present. When choosing an image to accompany an article, you want the image to resonate with relevant points in the article. SageMaker JumpStart includes many summary models that can take long text and boil it down to the main points of the original. For the generalization model, you use the AI21 Labs generalization model. This model provides high-quality summaries of news articles, and the output text can be approximately 10,000 words, allowing the user to summarize the entire article in one go.

To determine if the text contains any names of potentially celebrities, you use Amazon Comprehend, which can extract key entities from a string of text. You then filter on the Person entity that you use as the search input.

Next, you take the summary article and create an embed to use as another search input. It's important to note that you use the same model deployed on the same infrastructure to create the article embed as you do for the images. You then use Exact k-NN with a scoring script so that you can search two fields: celebrity names and a vector that captures the semantic information of the article. Refer to this post which describes the capabilities of the Amazon OpenSearch Service vector database, the scalability of the Score scenario, and how this approach to large indexes can lead to large delays.

The diagram below (Fig. 6) illustrates the architecture of the information search solution

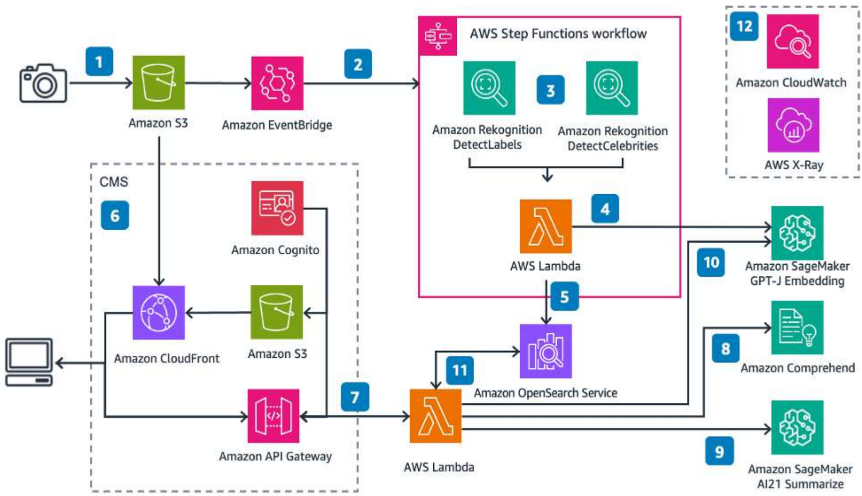

Figure 6. OpenSearch architecture

Source [12]

We will explain by numbered labels:

1. Uploading the image to the Amazon S3 bucket.

2. Amazon EventBridge listens for this event and then triggers the execution of the AWS Step function.

3. The step function takes an input image and extracts the celebrity label and metadata.

4. The AWS Lambda function retrieves the image metadata and creates the embed

5. The Lambda function then inserts the celebrity name (if any) and the embedding as a k-NN vector into the OpenSearch Service index.

6. Amazon S3 contains a simple static website served by the Amazon CloudFront distribution. The user interface (UI) allows you to authenticate with the Amazon Cognito application for image searches.

7. Sending text information through the user interface.

8. A subsequent Lambda function calls Amazon Comprehend to detect any names in the text.

9. The function then summarizes the text to get relevant points from the article.

10. The function generates embedded summary text information.

11. The function then searches the OpenSearch Service image index for any image that matches the celebrity name and the k-nearest neighbors for the vector using cosine similarity.

12. Amazon CloudWatch and AWS X-Ray provide end-to-end workflow visibility to alert you to any issues.

Technology for obtaining and storing key image metadata

Amazon Rekognition's DetectLabels and RecognizeCelebrities APIs provide you with metadata about your images-text labels that you can use to form sentences to create an embed. The article provides text input that you can use to create an embed.

There is also an option to create and save embedded words

The following figure shows the construction of our image vectors in 2D space, where for visual aid we have classified the embeddings by their main category.

It is also possible to create an embed of this newly written «text» article so that it can be searched in OpenSearch or the closest images to the article in this vector space. Using the k-nearest neighbors (k-NN) algorithm, we determine how many images to return in the search results. When zooming in to the previous Fig. 7, the vectors are ranked based on their distance from the article, and then the K-nearest images are returned, where K is 10 in this example.

OpenSearch can store large vectors in an index and also provides a function to query the index using k-NN to be able to query the vector to return the k-nearest documents that have closely spaced vectors using different measurements [Fig. 8]. For this example, cosine similarity was used.

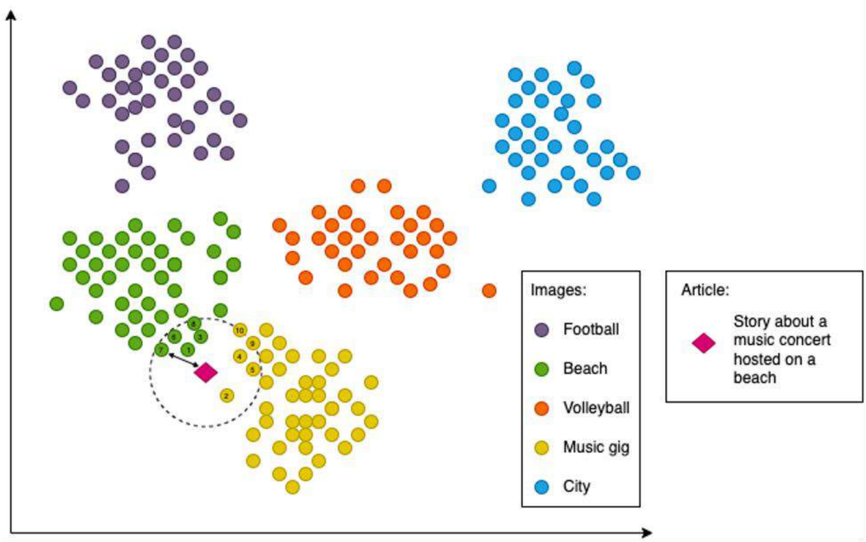

Figure 7. Construction of vectors
of our images in 2-dimensional space

Source [12]

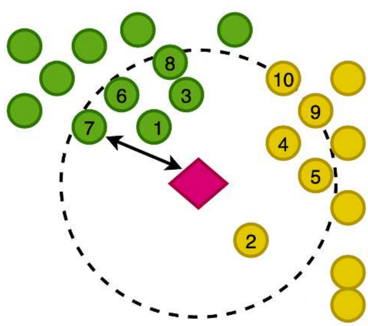

Figure 8. Vectors are ranked based on their distance from the article

Source [12]

Next, we will determine the names in the article.

Used Amazon Comprehend, an artificial intelligence natural language processing (NLP) service, to extract key objects from the article. This example uses Amazon Comprehend to extract entities and filter on the

Person entity, which returns any names Amazon Comprehend can find in a journalist's story, with just a few lines of code:

```
def get_celebrities(payload):
response = comprehend_client.detect_entities(
Text=' '.join(payload[«text_inputs»]),
LanguageCode=«en»,
)
celebrities = ««
for entity in response[«Entities»]:
if entity[«Type»] == «PERSON»:
celebrities += entity[«Text»] + « «
return celebrities
```

This example uploaded an image to Amazon Simple Storage Service (Amazon S3), which ran a workflow that extracted metadata from the image, including tags and any celebrities. You then convert this extracted metadata to embedded metadata and store all this data in the OpenSearch Service.

In the future, we will summarize the text article and generate embedding.

Summarizing an article is an important step in making sure that word embedding captures the important points of the article and therefore returns images that resonate with the topic of the article.

The AI21 Labs Summarize model is very easy to use without any prompts and only a few lines of code:

```
def summarise_article(payload):
sagemaker_endpoint_summarise =
os.environ[«SAGEMAKER_ENDPOINT_SUMMARIZE»]
response = ai21.Summarize.execute(
source=payload, sourceType=«TEXT»,
destination=ai21.SageMakerDestination(sagemaker_endpoint_summarise)
)
response_summary = response.summary
return response_summary
```

The GPT-J model was then used to create the embedding.

```
def get_vector(payload_summary):
sagemaker_endpoint =
os.environ[«SAGEMAKER_ENDPOINT_VECTOR»]
```

```
response = sm_runtime_client.invoke_endpoint(
EndpointName=sagemaker_endpoint,
ContentType=«application/json»,
Body=json.dumps(payload_summary).encode(«utf-8»),
)
response_body = json.loads((response[«Body»].read()))
return response_body[«embedding»][0]
```

Then we search for our images in the OpenSearch service. Below is an example fragment of this query:

```
def search_document_celeb_context(person_names, vector):
results = wr.opensearch.search(
client=os_client,
index=«images»,
search_body={
«size»: 10,
«query»: {
«script_score»: {
«query»: {
«match»: {«celebrities»: person_names }
},
«script»: {
«lang»: «knn»,
«source»: «knn_score»,
«params»: {
«field»: «image_vector»,
«query_value»: vector,
«space_type»: «cosinesimil»
}
}
}
}
},
)
return results.drop(columns=[«image_vector»]).to_dict()
```

The architecture contains a simple web application that represents a content management system (CMS).

For an example of a text article, the following data were used:

«Werner Vogels loved to travel around the world in his Toyota. His Toyota is shown appearing in many scenes as he drives to meet various clients in their hometowns [Fig. 9].'

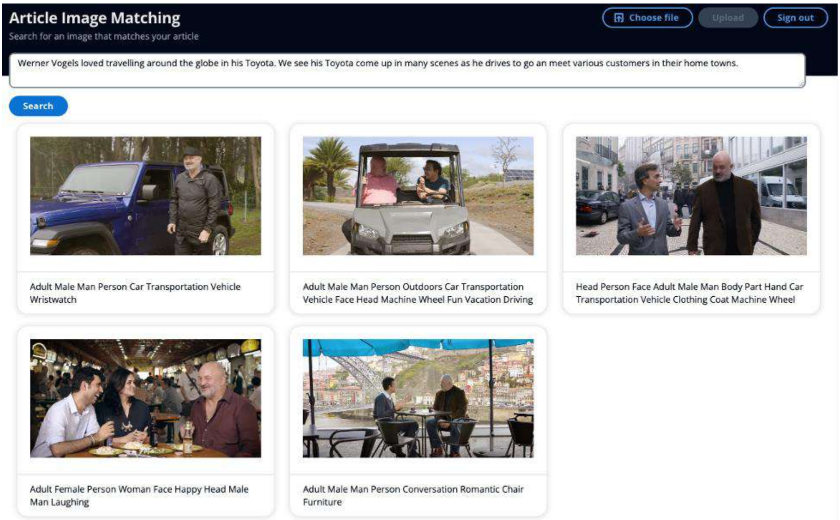

Figure 9. Matching in search result images

Source [12]

None of the images have metadata with the word «Toyota», but the semantics of the word «Toyota» are synonymous with cars and driving. So this example demonstrates how you can go beyond keyword searches and return semantically similar images. In the UI screenshot above, the caption below the image shows the metadata extracted by Amazon Rekognition.

The paper also demonstrated how to incorporate this solution into a larger workflow where they used the metadata they had already extracted from their images to start using vector searches along with other key terms such as celebrity names to get the best resonant images and documents for of your search query [12].

Thus, image recognition can be applied to recreate the process when a user tries to log into a banking application.

Modern IT enterprises are faced with the challenge of providing seamless access, search, capture, and organization of rapidly expanding knowledge that is often scattered across disconnected data sources. Transformative technologies such as generative artificial intelligence and semantic search are radically changing the way businesses organize, discover, and use these knowledge resources.

A subset of generative artificial intelligence known as large language models (LLMs) excels at understanding and extracting valuable insights from unstructured data. On the other hand, semantic search represents a new era of context-sensitive capabilities that dig deeper into the essence of search queries, providing accurate and highly relevant results.

Together, generative AI and semantic search form an integrated ecosystem for intelligent knowledge management. In this publication, we describe how generative artificial intelligence and semantic search can be used to improve productivity and efficiency by democratizing advanced search capabilities and generating useful information.

As business digitalization accelerates, the value of effective knowledge management continues to grow. However, like any significant technological advance, the implementation of these technologies presents certain challenges. The complexity of LLM and semantic search requires a modern data strategy and specialized technical skills.

TensorIoT is an AWS Advanced Tier Services partner and AWS Marketplace seller with many AWS competencies, including machine learning and conversational artificial intelligence. TensorIoT enables digital transformation and greater resilience for customers through Internet of Things (IoT), AI/ML, data and analytics, and application modernization

Generative Artificial Intelligence: Knowledge Extraction and Understanding Generation

Large language models such as Amazon Titan Text, Anthropic Claude, or OpenAI GPT4 are a subset of generative artificial intelligence that work with text input (also known as prompting) and output. These models can analyze and summarize vast amounts of Internet-scale data, including news, articles, books, financial data, open customer reviews, social media comments, and more.

Based on this knowledge, the models can perform several actions, such as generating text, answering questions, and synthesizing rich content into concise summaries. This helps improve operational efficiency, productivity, and overall customer engagement across a variety of use cases.

For example, masters can condense large research articles into concise abstracts, thus allowing researchers to quickly grasp key points without having to read the article in its entirety. Another example is sentiment analysis in e-commerce; LLMs can sift through thousands of reviews to help e-commerce websites understand customer sentiment about their flagship products and make quick, informed decisions.

Amazon Bedrock is a fully managed service that builds foundational models (FMs) that include Amazon LLMs as well as leading AI startups through an API. This allows you to choose from a wide range of LLMs the model that best suits your use case.

In addition, Amazon SageMaker JumpStart provides pre-built open-source FM files from Amazon and other leading AI companies that are suitable for a wide range of problems to help you get a head start on your machine learning journey.

Semantic search: precise information navigation

Semantic search significantly improves information retrieval by understanding the meaning and context of words in search queries and documents. Thus, it can provide highly relevant and accurate results. Also, semantic search goes beyond traditional keyword search because, unlike conventional search methods that rely solely on exact matches, semantic search understands the context and meaning of words (semantic relationships) and complex relationships within data (syntactic relationships joints). This results in search tools becoming more intuitive and efficient as they can retrieve more accurate results (increased precision) and miss fewer relevant results (improved recall) [12].

The work also provided the architecture of the bank account access program using chess from Amazon Kendra to improve search results, which is presented in Fig. 10.

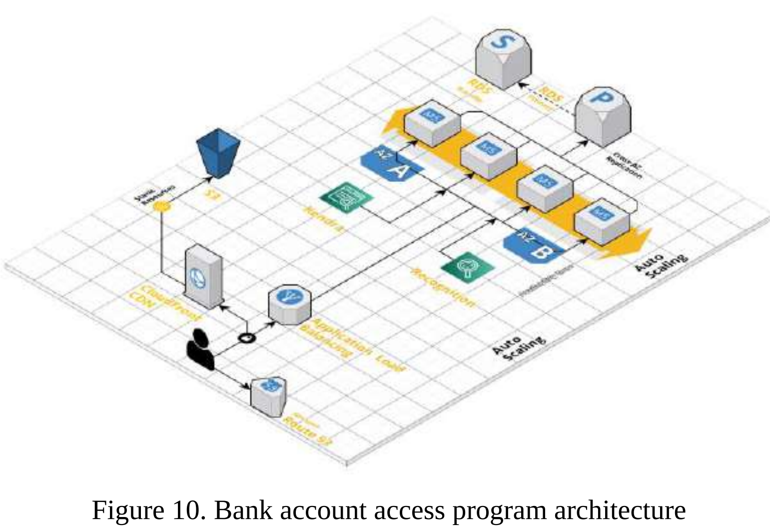

Figure 10. Bank account access program architecture

Source: developed by the author

Conclusions

In the work, a study was conducted regarding the use of various types of innovative technologies for the semantic search of textual and graphic information on the example of the AMAZON KENDRA service. The method of semantic search of objects of textual and graphic information based on the use of vectors and the similarity of vector elements, based on the distance between vector elements, is provided. Text and image information retrieval, indexing, and ranking options were demonstrated to facilitate efficient and relevant similarity-based information retrieval, resulting in comprehensive and accurate results.

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