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Science 4.0 as a Model of Scientific Activity in an Innovative Environment of Industry 4.0

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ABSTRACT

Technological innovations in the generation, storage, transmission, and processing of data have transformed traditional scientific activities and contributed to the accelerated development of the concept of "data-driven science." The article analyzes the image of Science 4.0 in a new format since organizing and managing scientific activities with the widespread use of the Industry 4.0 technological platform has become relevant here. A four-level classification of stages in the development of science and the use of e-Science as a technological platform for Science 4.0 is proposed. The essence of Science 4.0 is revealed in the analysis of works devoted to scientific research with broad involvement of the internet of things, cyber-physical systems, artificial intelligence, cloud computing, big data analytics, and other intelligent solutions. Implementation of the proposed concept contributes to an increase in the efficiency of scientific research and supports solutions for the operational management of science.

KEYWORDS

Artificial Intelligence, Big Data Analytics, Cloud Computing, Cyber-Physical Systems, e-Science, Industry 4.0, Internet of Things, Science 4.0

INTRODUCTION

Science and the knowledge it creates have played a key role in the development of civilization, stimulating progress and opening up new horizons of opportunity. Science provides tools to understand the world around us, develop technology, improve living conditions, treat diseases, and solve complex problems. It is a driving force in human history, shaping society, enriching culture, and promoting social development. For example, in the Stone Age, based on numerous observations and experiments, bronze and iron tools were created, which created the conditions for the transition of mankind to a completely new stage of development.

In the second half of the 18th century, processes of accelerating industrial production, known as the first industrial revolution, began in some countries of Western Europe and North America.

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Parallel to this growth in production is explosive progress in scientific discoveries and inventions. The continuous development of science, education, and production continues during the periods of the second, third, and fourth industrial revolutions. Today we stand on the threshold of a super-smart society 5.0, which is creative and human-centric. This new direction of development promises the integration of advanced technologies, smart use of data, and close interaction between man and machine. This era provides unique opportunities to improve lifestyles, improve education, and create more flexible and innovative environments for social interaction.

The fourth industrial revolution has been counted since 2011 when the Industry 4.0 concept was announced at the initiative of the German federal government with the participation of universities and private companies (Kagermann et al., 2013; Lee et al., 2015). Its main task was to develop and implement innovative information technologies in production systems to increase the efficiency and competitiveness of the national industry. Similar industrial modernization programs exist in other countries. For example, back in 2014, the State Council of China unveiled its ten-year national plan, "Made in China 2025", which aims to transform China from a global workshop into a global manufacturing power (Xu et al., 2018).

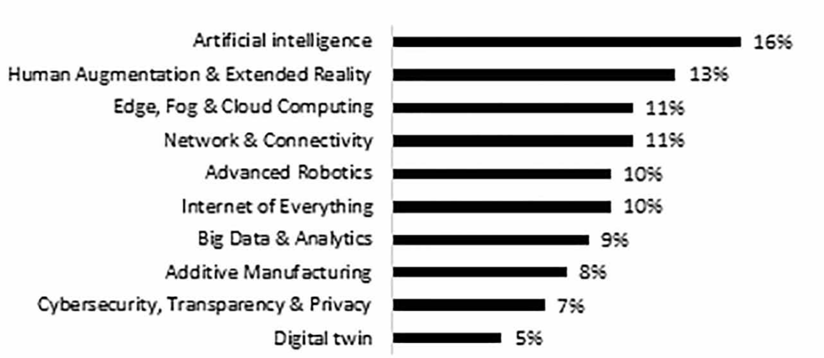
Industry 4.0 is characterized by a high level of sophistication and full networked integration of products and manufacturing processes. This concept represents a new industrial phase of production systems by integrating new and converged technologies that add value to the entire product lifecycle. Industry 4.0 is based on advanced manufacturing or the concept of intelligent manufacturing, that is, on an adaptable system in which flexible lines automatically adjust production processes for different types of products and changing conditions. This allows for increased quality, productivity, and flexibility and can also help to produce customized products on a large scale and in a sustainable manner with better resource consumption. The chart below (Figure 1) shows the top 10 Industry 4.0 trends impacting companies in 2024.

The use of artificial intelligence (AI) techniques across devices and processes is shaping the main trend in Industry 4.0. Collecting data through cloud and edge computing and developing cybersecurity solutions enables companies to create the building blocks for smart factories. Advanced robotics solutions, including autonomous mobile robots, cobots, and swarm robotics, as well as robotic software development, are also an important part of Industry 4.0 trends.

However, Industry 4.0, based primarily on innovative information and communication technologies (ICT) of the 21st century, contributes to the creation of new trends in the development and integration of science and education in general.

It should also be noted here that throughout the history of mankind, science and education have been interconnected and developed in parallel. The interrelation and integration of science and education, as producers of new knowledge, have always been relevant and reflected in the research

Figure 1. The top 10 Industry 4.0 trends (based on Startus-insights, 2024)



of scientists. The main goals include the joint use of the scientific and educational potential of organizations with mutual interests and, first of all, in the field of training, advanced training, and retraining of personnel, as well as conducting joint scientific research, implementation research, improving management processes, etc.

Innovative solutions of Industry 4.0, the widespread use of its advanced technologies Internet of Things (IoT), Cyber-Physical Systems (CPS), AI, cloud computing, big data analytics, etc., have created new prospects for the qualitative transformation of traditional science and education. Along with this, ample opportunities have also emerged for the restructuring and integration of science and education as a corporate environment in the form of combining Science 4.0 and Education 4.0 in a single format (Fataliyev et al., 2023). Thus, it can be seen as an evolution of e-science and e-education, integrating information from the real and virtual worlds, taking into account the technological tools of the new digital era.

The purpose of this article is, in this context, to study the main trends in the organization of science and the conduct of scientific research, as well as to consider them against the background of the general ideas of Industry 4.0.

RELATED WORKS

The authors set out to study the environment of science and its change under the influence of the technological solutions of Industry 4.0. For this, the method of comparative analysis of related works by keywords was used. The results of a search in scientific databases for the term “Science 4.0” did not meet the authors’ expectations, since they assumed that this term included a different, more in-depth meaning than was found in the results obtained.

Hey et al. (2009) proposed the concept of four paradigms in the development of science: empirical, theoretical, computational, and e-science. These paradigms reflect the evolution of the scientific method and show how technological progress affects science. The latter paradigm, e-science, is particularly relevant in the context of Industry 4.0, where large volumes of data and advanced computing technologies play a key role.

Teif (2013) examines the concepts of Science 2.0 and Science 3.0. He proposed that the terms Science 2.0 and Science 3.0 were coined to describe a new generation of online tools for researchers to facilitate data sharing, collaboration, and publishing.

Spence (2018) views Life Science 4.0 as an environment for life science companies’ market offerings, business models, and new opportunities as the disciplines of health and technology merge into “medical technology.”

Pirner (2017) uses the term Science for All 4.0 for open science and citizen science, using the Internet as a communication medium.

The authors set themselves the task of combining disparate information regarding the application of Industry 4.0 technologies in the scientific environment to highlight the benefits reveal the essence of Science 4.0 and determine the direction of future development. Therefore, the works discussed below represent only a small part of the rich spectrum of research on the use of AI, CPS, Big data, etc., highlighting the diversity of approaches and methods in this area.

As analysis of sources has shown in recent years the scientific landscape has changed significantly, especially under the influence of AI. The rapid development of various AI applications is primarily due to the inability of humans to cope with the volumes of data used in decision-making and knowledge extraction. A paradigm has emerged in which the limited cognitive abilities of humans are inferior to the computing power of computers. This situation has spurred the opportunities, challenges, and potential research agenda arising from AI. Dwivedi et al. (2019) present the collective insights of some of the leading experts from the public sector, industry, and academia on various aspects of AI. The problems studied, and these perspectives open up great opportunities for AI applications in Science 4.0.

According to Wang et al. (2023), AI can help scientists generate hypotheses, design experiments, collect and interpret large data sets, and gain insights that might not be possible using traditional scientific methods alone. Some of the breakthroughs in AI that enable such applications include self-learning, deep learning, and generative AI techniques. These methods can leverage the enormous volumes of unlabeled data, the structure of scientific data, and the diversity of data modalities to generate new designs and solutions to scientific problems.

Note that the first known application of AI to solve scientific reasoning was the Heuristic-DENDRAL program. Another version of it, called Meta-DENDRAL, became the first expert system to form scientific hypotheses. For example, this expert system has proposed some ideas to explain the correlation between specific designs and the mass spectrum (Sparkes et al., 2010).

Banerji et al. (2010) proposed to use such a field of AI as machine learning in the morphological classifications of telescope images in the Sloan Digital Sky Survey DR6 astrophysics project. Senior et al. (2020) proposed to use deep neural networks in genetics to analyze the structure of proteins.

The topic of Big data and its integration with AI is of great interest to researchers. Big data analytics (BDA) develops a methodological analysis of Big data structures, which often fall into the following categories: volume, velocity, variety, veracity, and value. When combined with AI, BDA can transform the fields of manufacturing, healthcare, and business intelligence by offering advanced incentives within a predictive context (Shukla et al., 2019). In addition, health-related studies that have analyzed the impact and contribution of Big data and AI have argued that these technologies can significantly support diagnosis and prediction based on the health status of patients (Beregi et al., 2018).

For successful decisions in Big data structures, tools, and methods of data visualization are also used. In scenarios that take human perception and cognition limitations into account, a higher level of understanding and interpretation can be gained from analyzing and presenting data using AI technologies. However, the analysis and processing of complex heterogeneous data are problematic. Zhong et al. (2017) consider the possibility of extracting critical information and critical management information with intelligent AI-powered visualization tools.

However, the formation of Science 4.0 is not limited to the potential of AI and BDA to enhance the cognitive abilities of researchers.

Collection and storage of data are significant challenges. Modern scientific research can generate gigabytes or terabytes of data, forcing researchers to find places to store it. A complex drive farm large enough to hold this amount of data will take up most of the space. Cloud computing eliminates the need for hard drives in place, creating more room for experimentation or equipment (Althagafy and Qureshi, 2017; Nichols, 2019).

The robotic conduct of scientific experiments is another promising direction. Burger et al. (2020) are looking at the implementation of a robot scientist who can autonomously conduct experiments, analyze the results, and decide what to do next. The robot moves through the laboratory thanks to the LIDAR detection system, very similar to those used in autonomous vehicles, and is programmed with coordinates for several workstations on which certain tasks are performed.t. The robot moves through the laboratory thanks to a LIDAR detection system very similar to those used in autonomous vehicles and is programmed with coordinates for several workstations on which specific tasks are performed.

Scientists find virtual and augmented reality (VR and AR) technologies a promising tool in scientific research. VR replaces the physical landscape with a virtual one and thereby allows researchers to control experiments better. In essence, this means that VR will enable us to create a simulation of the environment with which we can interact without leaving our computer (Fox et al., 2019). For example, VR helps you observe the reactions of the human brain using the Virtual Maze Neuroscience app. This virtual environment allows neuroscientists to test how people respond to social interactions or use their spatial intelligence.

AR can meet users' needs for the digital presentation of information in real-time by displaying this information in users' physical environment. This environment will simplify the analysis of multidimensional datasets generated weekly or daily in a dynamic agronomic and climatological research environment (Singh, 2021).

The use of digital twins is also becoming a promising direction in scientific research. For example, in a project known as Destination Earth, a digital twin of planet Earth has been created, which will be a virtual display of as many processes on the planet's surface as possible, including the impact of humans on water, food, and energy systems. In addition, this will provide reliable information on extreme weather conditions and climate change (Voosen, 2020).

Häse et al. (2019) are exploring self-driving laboratories as an alternative to classical laboratories. Automated platforms based on machine learning, neurolinguistics programming, knowledge management, intelligent control, and BDA based on cloud services allow completely independent experiments in scientific laboratories. The creation of a self-contained laboratory is a multidisciplinary task that combines a wide variety of research areas. Machine learning and simulation techniques predict material properties and suggest new experiments, while robotics, AR and VR, and automated characterization techniques are used to conduct experiments and analyze results.

Villegas-Ch et al. (2019) investigated trends in the intelligent campus. This campus represents a cluster of infrastructures that include classrooms, libraries, laboratories, faculties, and computer systems where the university community can design activities for its learning.

It is also necessary to note the growing role of CPS applications in the environment of science (Fataliyev and Mehdiyev, 2019). These applications cover all steps from collecting, storing, processing, and analyzing research data. For example, the science prototype of a web platform integrates CPS services. It uses browser-based functional systems to create and operate a laboratory for remote experiments via the Internet using technical equipment and systems.

An additional impulse in the Science 4.0 environment will receive citizen science. Citizen science can help scientists collect and analyze large and diverse data sets, solve complex and interdisciplinary problems, increase public understanding and participation in science, and democratize and diversify the scientific process. Some examples of citizen science projects include monitoring biodiversity, measuring air quality, discovering new planets, and deciphering historical documents. It is proposed to use a network of drones of citizen scientists for integrated observations in various geographical areas to study the melting of polar ice, the migration routes of animals, and the impact of various pollutants on the global ecological situation (Mehdiyev Sh. and Mehtiyev A., 2018).

At the same time, Science 4.0 actualizes issues of cybersecurity (Suzen, 2020), personal data protection, and such a sensitive topic in the scientific community as plagiarism and priority in research. Blockchain technology can solve these problems. Furthermore, blockchain will make large parts of the research cycle open to scientific self-correction. This new approach to reproducibility in science has the potential to "cut waste and make more research results true." In addition, blockchain can reduce overhead costs, accelerate the scientific process, and stimulate innovation [Rossum, 2017; Bartling, 2019).

We also wanted to give an example of the convergence of science and production. For example, an automated drilling process is a closed-loop system that integrates real-time borehole and surface data with pre-drilling models. Given changing conditions, such a system modifies operating parameters, such as pump flow, hook weight, or drilling speed. In addition, the automated system refines the model based on real-time data, effectively simulating the decisions of an experienced drilling engineer who corrects for inaccuracies in existing estimates (Alguliyev et al., 2019).

Thus, the reviewed accompanying works confirm that Industry 4.0 has excellent potential for the development of science. At the same time, the reconstruction of science as a corporate environment of Science 4.0 based on Industry 4.0 solutions is relevant.

METHODOLOGY

This article focuses exclusively on problems related to the scientific field and considers the possible interpretation of the results obtained in the context of the educational environment.

The research methodology is based on the synthesis of the conceptual model of Science 4.0. This synthesis is possible thanks to the analysis and synthesis of works devoted to the application of key technologies of Industry 4.0 in the scientific environment. To do this, an extensive search of scientific databases was carried out. Additionally, to identify the relationships and indicators of science and industrial revolutions, a comparative historical analysis of the extensive information accumulated in this field was performed. Considerable attention was paid to exploring the value of data for the scientific community, and e-science was chosen as the technological basis.

As a result of the research, Science 4.0 is presented as a system that combines interconnected intelligent subsystems. These subsystems interact with each other and with the external environment, using material, technical, and information resources to achieve their goals. The proposed methodology also proposes the application of the smart city concept for the effective management of scientific infrastructure, personnel, unique equipment, etc. This is aimed at maximizing the potential of research groups in improving the Science 4.0 concept.

The goal of the proposed concept is to increase the efficiency, reliability, validity, and reproducibility of scientific research using the principles of Industry 4.0. The idea is also to take advantage of technological progress to improve scientific practices and create a more modern and innovative scientific environment.

The Emergence of Science 4.0 in the Context of Industry 4.0

It should be noted, that at the end of the XVIII - the first half of the XIX century, the process of intensive interaction between science and technology begins, and a particular type of social development arises, which is commonly called scientific and technological progress. The evolution of science is directly related to the improvement and development of means and methods for solving problems such as collection (registration) and storage of information, processing (logical and computational tools) transfer (dissemination) of acquired knowledge. If we turn to the history of science, we will note that in pre-industrial society, up to the 18th century, science developed on its own. The community's needs became the driving force that caused changes in science and contributed to the gradual transformation of science into an immediate productive force more and more. Thus, it can be assumed that the main achievements of science and technology formed the basis of industrial revolutions. At the same time, industrial revolutions stimulated new scientific directions, and there was an adaptation of science to the needs of society. Nevertheless, the priority of science and technology in industrial revolutions is still contested. Some scholars argue that skilled and talented artisans without scientific training were mainly responsible for essential inventions; others, referring to the James Watt steam engine, believe that the link between science and the most important designs of the period was fundamental (Gráda, 2016).

Here are some other examples. Henry Maudslay's invention, who created a self-propelled caliper, made it possible to manufacture parts with an accuracy of a fraction of a millimeter and laid the foundation for modern mechanical engineering (Gilbert, 1971). The emergence of machines caused the need for metal. Improvements and inventions by Henry Cort of puddling and rolling processes (1784) as the best way to convert coke pigs into wrought iron have gained progressive importance for their time (Harris, 1988). These processes required large quantities of coal to be used in pig iron production, and coal mining became the leading industry in England in the first industrial revolution.

The scientific discoveries of Michael Faraday, James Clerk Maxwell, and other scientists in electromagnetism laid the foundation for the production of electricity, electric motors, lighting fixtures, and more (Baigrie, 2007).

Based on the analysis of the industrial revolutions that have taken place, the following classification of the stages of the evolution of science in interconnecting to the industrial revolutions can be proposed.

Science 1.0

The first industrial revolution (Industry 1.0, from the middle of the 18th century) is traditionally associated with inventions such as the textile machine and the steam engine. This period is characterized by the appearance of the first gauges (manometers, thermometers, etc.) and the introduction of mechanical automation. Technological changes stimulated the growth of experimental sciences, as new opportunities for more precise and systematic research became available. The processes introduced in the first industrial revolution required deep knowledge of mechanical engineering, metallurgy, and other engineering disciplines. The use of mechanical devices and sensors has become widespread in industry, allowing data to be collected and processes to be controlled more efficiently.

Science 2.0

The second industrial revolution brought many fundamental scientific discoveries, including electricity, magnetism, general relativity, and many others. The telegraph, telephone, and X-ray machines were the result of advanced scientific research. Scientific laboratories of that time began to be equipped with modern technologies such as electrical sensors and equipment. These tools allowed scientists to conduct more precise and complex experiments, which helped expand the boundaries of knowledge in various fields of science. Scientific discoveries have become the basis for modernizing educational programs and teaching methods. The widespread use of electronic and distance technologies, such as audio and video lessons, has become part of the process of popularizing science and education. The emergence of radio broadcasting and television during this period enabled the general public to gain access to scientific knowledge and discoveries, strengthening the connection between science and education.

Thus, the second industrial revolution became a time of intense interaction between scientific research and education, promoting not only the development of science but also the improvement of teaching methods and the accessibility of scientific knowledge to society.

Science 3.0

Science 3.0 associated with the third industrial revolution (Industry 3.0) in the 1970s, was largely defined by the development of microelectronics, computer technology, programmable logic controllers (PLCs), and robotics. This period also saw the widespread introduction of computer modeling into scientific research and the creation of the Internet, which led to significant changes in the relationship between science and education.

The advent of microelectronics, computing, and robotics has greatly improved scientific research capabilities and led to greater precision and efficiency in experiments.

PLCs made it possible to automate production processes, which also affected scientific laboratories, where the introduction of automated systems became standard.

Computer modeling methods have become widely used in scientific research, allowing scientists to analyze complex processes and conduct virtual experiments. This accelerated and strengthened the development of various scientific disciplines, including physics, chemistry, biology, and engineering.

The advent of the Internet has created a new “telecommunications” perspective for the scientific community.

Electronic science (e-science) became a phenomenon of this period, stimulating online collaboration, knowledge sharing, and research through the global network.

Science 3.0 has supported and improved educational processes by providing students and researchers with access to modern technologies and information resources.

Educational institutions have begun to actively use computer technologies and network resources for teaching and research.

Thus, the third industrial revolution, with its technological innovations and the development of the Internet, has significantly influenced the relationship between science and education, improving the efficiency and accessibility of training, as well as stimulating international scientific cooperation.

Science 4.0

Science 4.0 driven by the fourth industrial revolution (Industry 4.0) since the beginning of the 21st century, is characterized by the strong integration of innovative technologies such as IoT, CPS, AI, Big Data, smart automation, and others. These technologies have become the basis for changing the nature of scientific research and its relationship with education.

They made it possible to more accurately collect and analyze data, which improved the quality and productivity of research, and also significantly speeded up the processes of conducting experiments and collecting information.

The nature of Science 4.0 is data-driven. Data mining, data science, and computational science are becoming key components of research activities. According to surveys, data scientists spend the majority of their working time preparing and processing data. (Herwig et al., 2021). Up to 80% of a data scientist's time is spent aligning, cleaning, and contextualizing data, and setting up test data sets. Data scientists must repeat these basic work tasks daily because there are an unlimited number of possible and different data formats, many of which are unusable or non-standardized. As a result, only about 20% of a highly skilled data scientist's time is available to create training sets, write algorithms, build and refine models, and provide knowledge.

Science 4.0 stimulates the convergence of various fields of knowledge, as Industry 4.0 technologies penetrate all areas of scientific activity, which in turn leads to the emergence of research at the intersection of disciplines, creating new areas of knowledge. Education in Science 4.0 adapts to the use of new technologies and approaches in scientific research. Students' training includes working with data, using AI and other technologies, and preparing them to actively participate in the scientific community.

Science and Education on the Industry 4.0 Platform

Integration problems of science and education on the Industry 4.0 platform cover a wide range of different areas of activity and manifest themselves in a wide variety of forms (Fataliyev et al., 2023). The main ones include the following:

- integration and development of network infrastructures under the single name National Research and Education Network (NREN) to provide advanced ICT services to the research and educational community;
- integration, development, and management of information infrastructures and resources of data centers;
- sharing of existing e-resources, e-libraries, and the development of multipurpose new smart resources;
- automation of sharing processes with the widespread use of IoT, CPS, AI, Big data analytics and other advanced technologies, new generation equipment and devices, and the development of new smart systems for various purposes;
- organization and expansion of joint activities, participation of scientists in the education process, and the inclusion of teachers and students in the scientific research;
- high-quality support for the scientific and educational process and management;
- ensuring integrated security (cybersecurity and cyber resilience);
- personnel management and training of a new type of personnel focused on the digital reality of the challenges of Industry 4.0 (smart scientist, smart researcher, smart teacher, smart student).

Data as the Driving Force of Science 4.0

It should be noted that data has always been of particular value in scientific work, providing the basis for understanding the world through observation, experimentation, and analysis. However, in the era of Science 4.0, data has become even more important due to the increase in data volumes, development of processing technologies, and Big data analysis capabilities. This opens up new perspectives for a deeper understanding of phenomena, as well as for refining or obtaining new knowledge of solutions in various fields of science. Knowledge is well-structured data and metadata. One of the main components of the general system of knowledge is scientific knowledge, which is understood as the basic scientific picture of the world since it describes the laws of its development. Scientific knowledge is usually considered at two levels: empirical and theoretical. Each of these levels uses its specific research methods and is of equal importance for scientific knowledge as a whole.

Empirical knowledge arises from direct contact with reality through observation or practice, and science is based on empirically proven facts. First, at the practical level, facts are collected, initially systematized, and classified. Empirical knowledge then allows the formation of empirical rules, patterns, and laws that are statistically inferred from observed events. The main methods of practical knowledge include experiment, observation, measurement, comparison, and description of the data obtained.

The essence of theoretical knowledge is to describe, explain, and systematize empirically determined processes and patterns and embrace reality.

At both levels of scientific knowledge, problems arise with storing, processing, and analyzing large volumes of data collected from research. Data of particular relevance to research are classified as observational, experimental, and computational data. In addition, big data also has usage frequency, life cycle, and other properties. This data is also a source of tacit knowledge and extracting knowledge from it has always been a pressing issue.

The relationship between data and knowledge is depicted in the well-known DIKW (Data, Information, Knowledge, Wisdom) knowledge pyramid model. It is one of the fundamental and widely accepted models used in defining data, information, and knowledge (Frické, 2019).). The pyramid displays an information hierarchy of levels, where each tier adds specific properties to the previous story:

- At the bottom is the level of available data.
- Information adds context.
- Knowledge adds “how” (mechanism of use).
- Wisdom adds “when” (terms of use).

The implicit assumption is that data create information, information used to develop knowledge, and knowledge used to create wisdom. Based on this pyramid, it can be assumed that scientific activity is characterized by the collection, storage, processing, transmission, and analysis of scientific data, scientific description, and forecasting based on models, the intellectual organization of scientific activity, and the management of science.

Thus, data is becoming a leading factor in science. Meanwhile, Science 4.0 itself is characterized by large amounts of data, and working with information is its primary trend. Thus, to summarize, we can conclude that “science is driven by data.” It should be noted that in the scientific method, there is a transition from single observations to large-scale data processing. At the same time, the application of Industry 4.0 technologies in the scientific environment leads to a rapid increase in the flow of scientific data. Traditionally, data has been stored in disparate storage locations within an organization or the cloud. However, Big data has made the task of keeping and hosting all data relevant, including structured, semi-structured, and unstructured data. It has become one of the reasons for the emergence of data lakes and their development. The storage strategy depending on the frequency of use in this environment can be adopted, as shown in Figure 2.

This organization of storage and management of data in its original form provides scientific organizations and researchers with the flexibility to analyze. Furthermore, the use of data from heterogeneous sources allows for the generation of actionable ideas, the amount of extracted knowledge grows, and thus the quality of scientific research improves (Byrraju, 2020).

There is also an urgent need to improve the infrastructure to support the reuse of scientific data. It should be noted that science requires data to be Found, Accessible, Interoperable, and Reusable (FAIR) in the long term. Wilkinson et al. (2016) discuss the development of sufficient and measurable sets of principles called FAIR Data principles. They intended to serve as a guide for those wishing to increase the reusability of their data stores. The FAIR principles emphasize enhancing the ability of machines to search for and use data automatically and support the reuse of data by individuals. In addition, these principles imply effective management of scientific data and their rational use.

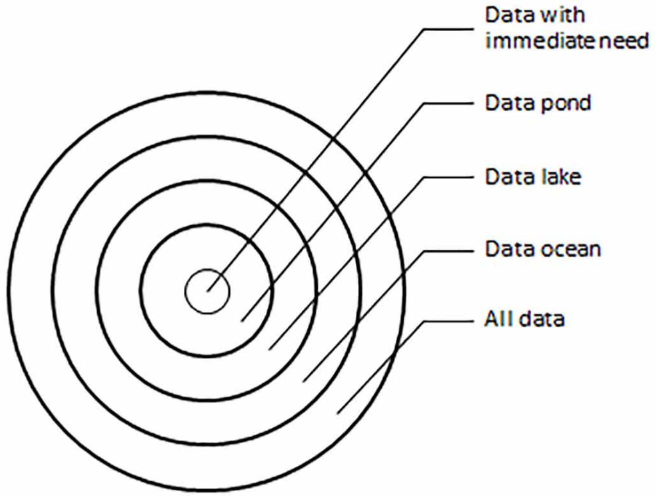
Digital twins have added value to scientific data. The digital twin reflects a two-sided dynamic display of the investigated processes and virtual models. In particular, this is the virtualization of physical objects (Qi and Tao, 2018). The physical function is evaluated, analyzed, predicted, and optimized by virtual means. In this way, the digital twin facilitates effective interaction between the various stages of research, enabling iterative optimization.

E-Science is a Technology Platform for Science 4.0

The study of the origins of Science 4.0 made it possible to conclude that it is directly related to computer technology. The rapid development of computer technology, the improvement of software tools, work on AI, the creation of the Internet, advances in microprocessor technology, etc., have created great opportunities for their integration into the scientific environment.

The e-science program, launched in the U.K. in 2000, has played a significant role in spreading this innovation. Research shows that the first integration of traditional science with a virtual e-science environment is associated with the Defense Advanced Research Projects Agency's ARPANET (Roberts, 1988). The term e-science itself was first coined in 1999 by John Taylor, General Director of Science Councils in Great Britain, and covers new methods of collaborative scientific research, including computer modeling and the organization of a virtual experimental environment (Hey and Trefethen, 2002).

Figure 2. Data storage strategy (based on Gorelik, 2019)



In a broader sense, e-science is based on two main fundamental tasks: the restructuring of the existing scientific environment by the requirements of the information society and the use of ICT in this environment (Alguliyev et al., 2015). Solving these problems requires an integrated approach. This approach involves monitoring ICT use in scientific activities, research monitoring and management, ensuring information security, and developing scientific, theoretical, and practical foundations for introducing electronic technologies. Furthermore, solving these tasks will allow achieving the following results (concerning the academic community of the Republic of Azerbaijan):

1. The national program "e-Science" will be brought into line with world standards as the study of world experience, adjustments to informatization of science based on monitoring, and improvement of the regulatory framework.
2. Accelerated development of the material and technical base; creation of local networks of scientific organizations and provision of high-speed Internet; creation of a unified scientific network connecting scientific organizations of the AR, and its integration with international scientific networks.
3. Development of a security strategy.
4. Creation of information resources for various purposes.
5. Solutions for the organization of a researcher's workplace are directly related to the use of ICT in scientific activities and tasks covering the activities of research teams.
6. The creation of new scientific relations based on the online environment in various fields of science.
7. The integration with international scientific organizations.
8. The formation of scientific and information spaces.
9. The creation of computing tools based on supercomputers, grid, and cloud technologies to solve problems that require significant computing and storage resources.
10. The issues of commercialization of science, etc.
11. The implementation of the training of scientific personnel in modern ICT and the organization of technical and software services.

Thus, e-science is perceived as a complex system with technical and technological components such as infrastructure, generation, collection, storage, processing, retrieval, analysis, transmission, data presentation, etc.

Summarizing the above, we can conclude that the approach outlined in (Alguliyev et al., 2015) provides the basis for accepting e-science as the technical and technological basis of Science 4.0.

Conceptual Issues of the Problem of the Science 4.0 Forming

This section analyzes the possibilities of Industry 4.0 when creating new organizational structures for scientific activities. Along with traditional research structures, virtual scientific institutions, scientific clusters, scientific networks, and science parks have been created. With the development of technology, the emergence of such new quality structures will continue. Science 4.0 finds simple solutions to technical, technological, economic, and other problems.

Consider a hypothetical innovative science on the example of the Azerbaijan National Academy of Sciences (ANAS). In general, ANAS coordinates and carries out its activities in several scientific areas: 1) technical, physical, and mathematical sciences; 2) chemical sciences; 3) earth sciences; 4) biological and medical sciences; 5) humanities; 6) social sciences.

Here the authors suggest some analogies with the concept of a smart city. With this approach, ANAS represents a corporate environment with an appropriate physical infrastructure: telecommunications networks, data centers, research laboratories, buildings, electricity, logistics, etc. In this corporate environment, for successful scientific activities, it is also necessary to provide:

- for buildings - uninterrupted power supply and water supply; climate control; access control; building security and video surveillance; material and equipment management; equipment monitoring; building management, hazard detection, and warning, etc.;
- maintenance of network resources, facilities, and equipment; network monitoring and cybersecurity; electronic services; constant diagnostics, etc.;
- management and security of information support of science;
- integration of Industry 4.0 tools into the research environment.

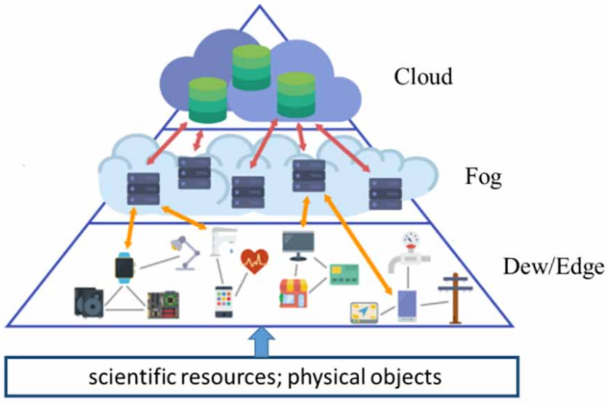
In this case, the role of intelligent maintenance increases. Zheng et al. (2020) propose an intelligent service framework and discuss its key components. It is an AI and IoT service platform that combines the collection, transmission, and storage of real-time data using wireless sensors and Big data technologies, continuous learning, and deployment of machine learning models.

Note that sensors are the primary source of data in science infrastructure. Recently, there has been an avalanche-like growth and an increase in the number of IoT devices equipped with them (Bogue, 2014). The extraction of knowledge from the collected raw data, and the critical development of requirements for the efficiency and productivity of the tasks being solved caused the need to bring data processing closer to their localization. These problems are solved by transferring analytics to the boundary level of calculations of fog and dew (Atlam et al., 2018; Rausch and Dustdar, 2019; Rao et al., 2015; Rababah and Eskicioglu, 2021). According to the generally accepted decentralized model of information processing, it is proposed to use the following universal multi-level block diagram, which is shown in Figure 3.

Applications in Science 4.0 can be grouped by data source as follows:

- Simultaneously, the growing number of mobile devices connected to 5G networks leads to a faster increase in data collected. Sources of primary data are at the level of a physical object. These include sensors, IoT devices, special equipment, security systems, etc. The data from these sources, especially from the IoT, represents a large amount of data continuously generated at high speed in real-time. Applying mobile Edge-AI techniques to solve this data type, especially in 5G networks, enables quick and comprehensive data analysis for better decision-making (Wang et al., 2019).
- Virtual data sources. As the main components of the information support of science, this group represents many sources with valuable knowledge on science management. These include digital libraries, scientific publications, multipurpose information systems, and electronic resources.

Figure 3. Universal multi-level block diagram of information processing



The practical results can be achieved through the use of automated agents based on Edge-AI methods in decision-making

Based on the above, the conceptual model of Science 4.0 can be proposed, as shown in Figure 4.

The proposed Science 4.0 concept provides a high degree of interaction between its main smart objects, the generation of Big data, and the integration of these objects with the BDA. It solves the functions of science management, such as forecasting and planning, organization, coordination, control, etc. Smart objects can be dynamically reconfigured for high flexibility, while BDA can provide global feedback and coordination for increased efficiency. Thus, it will allow practical problem-solving within the framework of Science 4.0.

It should be noted that the formation of Science 4.0 based on a single concept is a complex problem and requires financial, regulatory, technical, and technological support, and therefore should be carried out in stages. Here should be considered following:

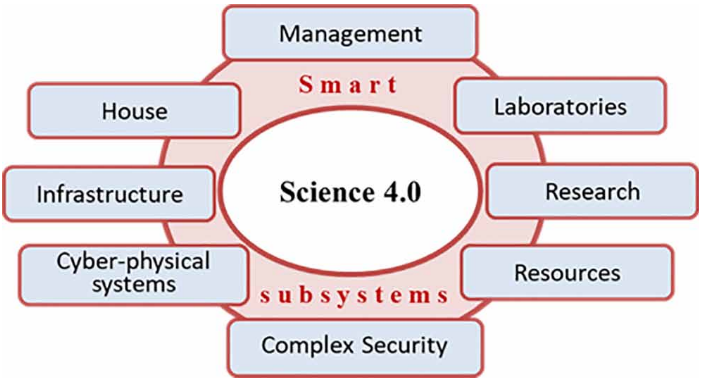
- development of network and computing infrastructure, data warehouses following new requirements;
- introduction of a new generation of intelligent sensors, actuators, wireless sensor networks, AI amplifiers, graphics processors, parallel processing processors, etc.;
- special software;
- development of systems for their purpose;
- development of scientific activity and management of science taking into account new requirements;
- ensuring information security, etc.

In conclusion, we note that when implementing the Science 4.0 concept, the projection of the following Industry 4.0 features is possible: interoperability, modularity, flexibility, virtualization, decentralization, optimized decision-making in real-time, etc. real-time access to data at the right time and in a suitable space has dramatically improved collaborative research projects to develop vaccines globally.

Eventually, the ongoing research and practical achievements in the above areas will (Fataliyev et al., 2023):

- accelerate the integration of science and education, transforming them into a single social institution, and consolidating their mutual development;

Figure 4. Generalized conceptual model of Science 4.0



- ensure the efficient use of facilities and resources, including infrastructure, and e-resources;
- increasing the effectiveness of science, education, and management;
- expand the introduction of the results of scientific research in education, thereby developing high-level human capital;
- improve the quality and effective management of science and higher education, as well as preschool and general education, etc.

The introduction of advanced technologies under Industry 4.0 will ensure higher productivity, greater flexibility, better control and optimization of processes, sustainable development, and other benefits to these institutions.

CONCLUSION

In this article, to define the format of Science 4.0, articles related to the applications of significant Industry 4.0 technologies, such as IoT, CPS, AI, Big data, and other intelligent solutions, in science have been collected and analyzed. The main focus is on:

1. A discussion of the mutual impact of industrial revolutions and science.
2. The formation of modern data-driven science.
3. The transformation of the e-science technology platform into Science 4.0.

The large-scale application of information technologies in industrial production, reflected in the concept of Industry 4.0, has a decisive impact on all spheres of human activity: economy, public administration, and social sphere. At the same time, in the scientific field, it directly affects both the research processes and the use of research results in the form of innovations, as well as the management of science and the interaction of science and society. The article developed conceptual issues of the formation of Science 4.0 based on the e-Science platform by the requirements of Industry 4.0. A classification of the stages of the evolution of science about the industrial revolutions that have taken place is proposed. An analysis of related works on the application of the main technologies of Industry 4.0 in science, such as IoT, CPS, AI, Big data, etc., confirms that Industry 4.0 opens up new prospects for the development of science. Reformatting the traditional research environment under Science 4.0, and improving the efficiency of process management, allows the integration of modern technologies to solve problems related to the use of research resources. It should be expected that discussions among the scientific community about the prospects of the so-called Industry 5.0 will create the preconditions for a more effective application of scientific research in solving global problems. It will also provide unique opportunities to create a more sustainable, harmonious, and intelligent society.

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