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INDUSTRY 4.0 TECHNOLOGIES IN THE DESIGN OF RELIABLE SYSTEMS IN CHEMICAL ENGINEERING

Reliable systems engineering in chemical engineering is a multifaceted field that encompasses the application of principles to enhance the dependability and integrates various methodologies and tools to ensure the dependability and safety of chemical processes of chemical processes and systems. It is involves a variety of approaches, including reliability prediction and analysis, maintenance strategies, safety considerations, risk assessment, fault diagnosis, failure prevention, and optimization techniques. The evolution of reliability engineering has been driven by the increasing complexity of systems and the need for a quantitative framework to ensure industry system safety and risk analysis. The article showed the relationship between big data, AI and reliable systems engineering in chemical engineering. AI tools and techniques support the principles of reliability engineering to create more efficient, safe, and sustainable chemical processes and equipment. Artificial Intelligence enhances real-time surveillance and early detection of irregularities for fault identification and diagnostics, diminishing the likelihood of severe breakdowns and bolstering system dependability. New technologies are transforming the way chemical processes are designed, optimized, and controlled, leading to improved efficiency, cost savings, and increased industrial safety. Applying reliability engineering principles throughout the system engineering lifecycle, from concept to retirement, is essential for improving system performance and includes activities such as requirements development, design input, and reliability growth. This conception involves not only technical aspects of reliability and risk management but also embraces sustainability and the broader impact of chemical engineering on society and the environment.

Keywords: chemical engineering, circular economy, reliability engineering, fault detection, optimization, industry 4.0, process and product design, process control, sustainable development

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ТЕХНОЛОГІЇ ІНДУСТРІЇ 4.0 У ПРОЕКТУВАННІ НАДІЙНИХ СИСТЕМ У ХІМІЧНОМУ МАШИНОБУДУВАННІ

Надійна системотехніка в хімічній інженерії охоплює застосування принципів підвищення надійності та інтегрує різні методології та інструменти для забезпечення надійності та безпеки хімічних процесів, хімічних виробництв та систем. Вона включає різноманітні підходи, в тому числі прогнозування і аналіз надійності, стратегії технічного обслуговування, міркування безпеки, оцінку ризиків, діагностику несправностей, запобігання відмовам і методи оптимізації. Еволюція інженерії надійності була зумовлена зростанням складності систем і потребою в кількісній основі для сприяння безпеці промислових систем і аналізу ризиків. У статті показано взаємозв'язок між великими даними, штучним інтелектом та інженерією надійності систем у хімічній промисловості. Інструменти і методи штучного інтелекту підтримують принципи інженерії надійності для створення більш ефективних, безпечних і стійких хімічних процесів і обладнання. Штучний інтелект покращує спостереження в режимі реального часу і раннє виявлення порушень для ідентифікації та діагностики несправностей, зменшуючи ймовірність серйозних поломок і підвищуючи надійність промислових систем. Нові технології трансформують способи проектування, оптимізації та контролю хімічних процесів, що призводить до підвищення ефективності підпрємств галузі, економії коштів і підвищення промислової безпеки. Застосування принципів інженерії надійності протягом усього життєвого циклу має важливе значення для підвищення продуктивності і включає в себе такі види діяльності, як розробка вимог, проектування і підвищення надійності. Ця концепція включає не лише технічні аспекти надійності та управління ризиками, але й охоплює питання сталого розвитку і ширший вплив хімічної інженерії на суспільство та навколишнє середовище.

Ключові слова: хімічне машинобудування, циркулярна економіка, інженерія надійності, виявлення несправностей, оптимізація, індустрія 4.0, проектування процесів і продуктів, управління процесами, сталий розвиток

Introduction. Chemical engineering is a discipline within engineering that employs the tenets of chemistry, physics, and mathematics to examine the fundamental laws of energy, substance, and momentum change, as well as reactions, in order to harness energy and materials in a more effective, lucrative, and secure manner within the chemical sector. Currently, the chemical sector confronts a multitude of formidable issues, including scarcity of raw materials, elevated energy usage, and stringent safety and environmental regulations, compelling both the industry and research institutions to innovate and create novel technologies, catalysts, and substances.

Certain AI methodologies have been implemented in the processing sector. For instance, deep learning, an increasingly prevalent AI strategy, has proven its merit in identifying operational patterns, pinpointing malfunctions, and conducting hazard assessments during the refinement stages. Additional recent AI developments, such as reinforcement learning, statistical machine learning, and evolutionary algorithms, show potential in addressing challenges related to oil profiling, process simulation and enhancement, strategic decision-making, environmental awareness, and self-governing smart regulation for a range of issues in the chemical sector [1]. Consequently, it is both opportune and critically vital to profoundly amalgamate AI technologies with the chemical industry to attain superior catalysts, precise management, ideal planning, and operational strategies with the support of sensors, anticipatory comprehension, big data, and autonomous learning.

Current status of the problem. The development and implementation of a new model for the development of the chemical industry that would meet the current global neo-industrial changes and challenges within the framework of Industry 4.0 is an urgent scientific and practical task. Therefore, the study of the essence, features and global experience of modern transformations of chemical production in the context of Industry 4.0 is the basis of this study.

Industry 4.0 is one of the leading newest concepts of modern industrial development, which reflects the prospects and challenges of the massive introduction of Cyber-Physical Systems (CPS) into production and various spheres of human activity [2]. The term was coined in 2011 to describe the process of radical transformation of global value chains. The concept of Industry 4.0 (in the German version) was further developed as a coordinated initiative of the scientific community, business and government agencies to mobilize national resources to accelerate technological change and ensure Germany's strong international position in global industrial production [3]. At the same time, the sectoral aspect is of great importance in the development of scientific and applied issues of implementing the Industry 4.0 concept.

Today, the world is actively developing Chemicals 4.0, which can be viewed as an industry-specific notion for implementing the basics of the Fourth Industrial Revolution [4]. This represents a pioneering framework aimed at elevating chemical technologies, manufacturing, and markets to an unprecedented level by consistently integrating smart innovations along with information and communication technologies. The international chemical business leaders understand the enormous potential of Chemicals 4.0 and its importance for maintaining (increasing) strategic benefits in the near future and are making significant efforts to secure their dominant roles in the smart neo-industrialization processes [5].

Current active scientific and analytical research, practical developments, and industry discussions are centered on the substance and nuances of the Industry 4.0 concept within the chemical sector, the methods of its execution, potential impacts, strategies for employing specific (mainly digital) technologies, and the organization and advancement of chemical manufacturing through smart innovations. [6]. The specificity of chemical production lies in the large range of chemical products, which ensures their participation in various product chains.

The intrinsic facet of changes underpinned by Chemicals 4.0 pertains to the innovative overhaul and modernization of the chemical production process itself, encompassing its intellectualization, automation, digitization, and the integration of intelligent technologies. The contemporary methodology entails deploying information systems and digital innovations across the entire value chain, which includes modeling, designing, operating, logistics, and the management and monitoring of chemical processes [8]. Innovations created with the support and on the basis of information systems and technologies provide a reduction in product and technology development time (by 20-40%) and savings in related costs.

Chemicals 4.0 is transforming technologies, processes, operations, markets, and the rules of competition, while simultaneously serving as a catalyst and supplying the tools necessary to address other major trends, such as smart solutions for energy efficiency or tailored products and services [9]. Chemicals 4.0 is based on new technologies, in particular cyber-physical systems, but it should be viewed in a broader perspective - in terms of production growth, efficiency, new business opportunities and new business models [10].

A hallmark of Industry 4.0 is the concept of Smart Factories. According to the authors of [11], based from the provided definitions of CPS (Cyber-Physical Systems) and IoT (Internet of Things), a Smart Factory can be characterized as a manufacturing environment where CPS interacts with IoT, thereby aiding both humans and machines in executing their functions.

The Internet of Things (IoT) concept pertains to networks comprising objects equipped with embedded devices designed to transmit and exchange data between the physical world and computer systems [12]. IoT provides chemical businesses with new opportunities to launch new products, increase productivity and product quality, improve technical support, establish new partnerships, reduce costs, minimize supply chain issues, and improve safety [13].

For example, emergency shutdowns and unscheduled maintenance are a well-known problem in the chemical industry. "Smart technologies offer a solution to this problem based on predictive maintenance using sensors, analytics and real-time data, which allows for the prevention of failures and quick response to critical situations.

Other important features of Chemicals 4.0 are the processes of individualizing products and services and customizing production [14]. This allows for the use of long tail strategies, avoiding price competition and generating added value. As consumer interaction with the digital environment deepens, the ability to analyze individual preferences and thus customize offers is also growing.

Industry 4.0 aids chemical firms in optimizing their supply chains through enhanced process visibility within these chains, considering end-user requirements. Moreover, forecasting demand trends using Big Data enables the circumvention of the inherent excessive complexity in chemical markets, minimizes risks, and facilitates the rapid restructuring of production systems and supply chains [15].

Research methodology. This article is part of a study aimed at identifying opportunities to integrate Industry 4.0 technologies into the practice of chemical engineering as well as the chemical industry to facilitate the subsequent implementation of the circular economy. The scientific method used was related to the analysis of literature sources, articles and studies as well as existing industrial practices. It was a systematic approach to collecting, evaluating and interpreting scientific information. It was a systematic approach to collecting, evaluating and interpreting scientific information.

The process involved an extensive literature review to ascertain the present level of understanding in the field of study. Literature analysis included a critical examination of data, methodologies, results and conclusions. The review of research articles and studies emphasized scientific rigor, including reliability and validity of results.

The theoretical analysis conducted in this paper was based on a set of articles searched using a combination of the keywords "chemical engineering", "reliability improvement", "i4.0" and "Industry 4.0" in the Scopus and Web of Science databases. The analysis of existing production practices involved the assessment of efficiency, economy and safety of production processes, as well as their compliance with environmental standards and regulations. An important aspect was the identification of bottlenecks and areas subject to improvement and innovation, which also included the development and application of new technologies and optimization of production and business processes.

Research results. The primary characteristic of Industry 4.0 involves the digital overhaul across all economic sectors and specific business operations, coupled with the extensive deployment of cyber-physical systems (CPS) in manufacturing, the broad application of the industrial Internet of Things (IoT), and the utilization of artificial intelligence [1]. Within the industrial sector, the present phase of digital technology evolution is intricately linked to the concept of Industry 4.0. In our view, it represents a comprehensive and complex process of merging physical objects, human participants, intelligent machinery, and production lines into a unified automated information system.

In the Chemicals 4.0 environment, the boundaries of individual enterprises are shifting, and production and economic systems are becoming open and transparent. New technologies promote the development of various forms of integration, networking, and outsourcing processes. Unlike traditional approaches that involve the integrated management of horizontal and vertical synergies. Chemicals 4.0 introduces enhanced self-organized coordination via the Internet of Things, which is gathering pace and fostering flexibility along with a novel form of synergy.

Strategic emphasis is shifting to value chain networks and virtual partnerships. A crucial element of contemporary transformations is industrial digitalization. The chemicals sector is also undergoing profound digital changes: firms are digitizing essential functions within internal systems and across partnerships along the entire value chain. Furthermore, they are enhancing their product portfolios with digital attributes and launching innovative data-driven services. The above features of Chemical Industry 4.0 indicate a fundamental change in the principles of organization and management of chemical production and require the study and involvement of global experience in the implementation of smart industrialization. The distinction between these two approaches is presented in Table 1. These can be applied at various stages of the chemical value chain or integrated with one another.

When planning and implementing the Chemicals 4.0 concept, the entire set of transformational decisions and actions should be presented in the form of a multi-level structure in Table 2.

In Chemicals 4.0, traditional business boundaries are dissolving. The industry is moving from rigid synergies to flexible, self-organized coordination through IoT. Companies are digitizing internal operations and partnerships, enhancing products with digital features, and introducing data-driven services. These changes signal a fundamental shift in chemical production management, necessitating global expertise in smart industrialization.

Table 1 – The impact of Industry 4.0 on the chemical Industry

Main goals	Scope of action	Influence tools
1. The direction of influence is operational activity		
Improved perfor-mance	"Smart" production	Intelligent asset management: maximizing asset utilization and minimizing unplanned downtime
		Process management and control: minimizing product variability and improving quality
		Energy management: reducing energy costs and evaluating alternative energy sources
		Security management: real-time monitoring of assets, processes, personnel and products
		Production modeling: increasing the level of operator training, production planning and timely commissioning
Risk reduction	Supply chain planning	Security management: real-time monitoring of assets, processes, personnel and products
		Demand forecasting: adjusting production tasks according to changing customer requests
2. The direction of influence is business growth		
Obtaining additional income	Research and deve-lopment	Development of new products to increase revenues
		Advanced analytics for material selection
		4D printing for the development of modern materials
Generating new income	"Smart" products and services	Intelligent products for the use of chemicals
		Services for data transmission aimed at boosting current revenues
		Creating new revenue streams by directly integrating into customer operations

Table 2 – Solution architecture in the context of chemical industry transformation

Level	Content of transformations
Integration of technologies	IoT platform integration, including technology, data architecture and scalability
Data management	Data integration and validation, big data infrastructure, management
Advanced analytics	Intelligent data analysis, modeling, optimization
Digital interface	Delivery of information to the point of use is flexible and customer-oriented
Business imperatives	Marketing and production strategies, ways to rebuild the operating model for value delivery

Chemical plants are characterized by the following technologies:

- Data Science involves mathematical and algorithmic techniques tailored for the effective creation of digital twins. It encompasses a collection of methods and practices aimed at addressing complex issues and analyzing data, including: design, modeling using machine learning techniques, evaluation and verification, visualization;
- ERP systems based on SAP – a designer of interconnected modules of production process management. The SAP ERP enterprise resource management system offers all the essential functions for implementing self-service information services and SAP ERP analytics;
- A corporate information system founded on ERP (enterprise resource planning) methodology is designed to attain optimal business process management;
- APC or Advanced Process Control;
- Drones, also known as UAVs (Unmanned Aerial Vehicles), vary in configuration depending on the industry of the facility and the tasks they are designated to perform.

These technologies at industrial enterprises contribute to improving the quality of manufactured products, organizing the process of document flow, reducing production costs, reducing a range of risks and losses, while also streamlining business operations [16].

In addition, there are a number of Industry 4.0 technologies that are of most interest to the chemical and petrochemical industries. The main tools and technologies of Industry 4.0 to improve the efficiency of enterprises in the chemical and petrochemical industry:

- Automation and robotics. Manufacturing systems featuring three or more degrees of freedom, utilizing sensors and artificial intelligence for enhanced functionality.
- Distributed ledger technologies (blockchain) involve algorithms and protocols for decentralized storage and processing of transactions, structured as a sequence of interconnected blocks, without the capability for their subsequent alteration.
- Big Data. Technologies for gathering, processing, and storing large and rapidly changing arrays of both structured and unstructured information, necessitating specialized tools and methodologies for handling them, including real-time data management.
- Artificial Intelligence refers to a combination of software and hardware that, with a certain level of autonomy, can perceive information, learn, and make decisions based on the analysis of large datasets, including the imitation of human behavior.
- 3D printing. Additive technologies for equipment improvement.
- Wireless Communication Technologies encompass methods for transmitting data via a standardized radio interface, eliminating the need for wired system connections.
- New manufacturing technologies. Technologies aimed at enhancing the efficiency of resource utilization, as well as the design and manufacturing of individual items.
- The Industrial Internet refers to data networks that link devices within the manufacturing sector, equipped with sensors and capable of interacting with each other and the external environment autonomously, without human intervention.

Recommendations for successfully building a Chemicals 4.0 solution architecture are as follows.

The starting point of transformation should be those areas, processes, products and supply chains where the company has significant experience and competencies and a good understanding of the sources and ways to attract new ideas, and then move on to newer and more complex areas of activity;

To fully realize the potential of Chemicals 4.0, it is necessary to create a multifunctional team, as the competencies required in the architecture are in different functional areas;

It is necessary to form an appropriate ecosystem and be an active part of it, since the application of Big Data infrastructure and the use of Chemicals 4.0 opportunities require large amounts of relevant information, most of which should come through partner networks;

Open standards, which are shared among producers and are platform-independent, are the basis for horizontal and vertical integration, and thus ensure unimpeded exchange of information across value chains;

Due to close cooperation with ecosystem partners, cyber risk management, including data protection, should become an important element;

An appropriate strategy should be the basis for transformations in the direction of Chemicals 4.0, which should be well correlated with the overall business goals;

Developing a business strategy, it is necessary to take a global view and look for global operational perspectives through global value chains.

Exploring the utilization of Industry 4.0 technologies further, we can examine the integration of artificial intelligence technology within the framework of automating production processes. The idea of automation is by no means new, but its content has changed dramatically over time. At first, at the first stage of automation, it was about mechanization of the process.

From the beginning of the last century, the use of electricity and knowledge of electrical engineering and electronics came to the fore. This was the second stage of automation. Today, in the third stage, there is an increasing emphasis on computing and information technology, leading to the digitization of the product development and manufacturing process. This direction is a new area of industry development that is just beginning to unlock its potential. Currently, many companies are already using AI to automate production processes, but the process is far from complete. AI technologies include computer vision, image segmentation, text tasks, working with spreadsheet data, time series, optimization tasks, recommendation systems, and much more. The process of introducing artificial intelligence into production automation tools can be divided into several stages:

1. Analyze the company's needs and identify areas where AI can be applied to automate production.
2. Selecting the right technologies and tools to implement AI in manufacturing processes.
3. Developing and testing prototypes of the AI system to be used in manufacturing.
4. Implementation of the AI system into the production environment and training of personnel on the new technologies.
5. Evaluating the effectiveness of the AI system and its impact on manufacturing processes, and adjusting the system according to the results of the evaluation.
6. Continuous improvement of the AI system and its adaptation to changing market conditions and consumer needs.

It's crucial to highlight that the implementation of AI technologies into production requires significant financial and time costs, so companies should carefully assess their capabilities and needs before starting the implementation process. However, if implemented correctly, the use of AI can significantly improve a company's efficiency and competitiveness.

First of all, industrial automation means a significant increase in the reliability and efficiency of production. Not only does it reduce the ongoing costs of production in the medium to long term by transferring operations that could previously only be performed by humans to machines, it also reduces the number of errors that occur. The focus of AI applications in industry is on automating product development, production planning and manufacturing processes. The primary goals are: increased productivity, more flexible production, shorter production times, easier human labor, lower price, and improved quality.

To supplement and/or replace human skills or actions, technical devices switch between humans and machines to enable a more autonomous production process. Technical equipment refers to the fields of sensors/actuators, regulation, control, information, communication, management and/or robotics. Some industries with great potential for automation are listed as examples: automotive; mechanical engineering; food processing; medical technology; chemical and pharmaceutical industries.

Let's delve deeper into some of the applications of AI in automation across industries. In the manufacturing sector, AI plays an important role as its integration into production allows workers to focus on higher value-added jobs, avoiding repetitive and tedious tasks, increasing reliability and efficiency and simplifying the entire production system. Artificial intelligence-based systems are the next step after robotics to increase productivity and minimize production costs.

The application of artificial intelligence in factory automation offers tremendous opportunities to improve the efficiency and quality of manufacturing processes. However, challenges and limitations related to lack of expertise, data security issues, and ethical considerations must be taken into account. Transformation of economy and production processes in the conditions of Industry 4.0 is connected with the revolution of intelligent production and introduction of cyber-physical systems. At the same time, it creates numerous challenges for enterprises, technologies, human resources, and challenges in socio-technical systems. These challenges must be addressed with appropriate methods and tools. In addition, the interaction between people and machines requires the right concepts - efficient and safe.

An example of such modern integration is the use of interfaces at chemical and petrochemical enterprises using the NAMUR standard.

NAMUR modules (Normenarbeitsgemeinschaft für Mess- und Regeltechnik in der Chemischen Industrie) are used in the chemical industry to standardize and increase the reliability of measurement and process control [17]. They ensure compatibility between different devices and automation systems, which is particularly important in complex production environments.

The main application possibilities of NAMUR modules include:

1. Measurement and control. They are used to monitor parameters such as pressure, temperature and level to maintain optimum conditions in reactors and industrial plants.
2. Interfaces for sensors. NAMUR modules often serve as interfaces between sensors and control systems, ensuring accurate data transmission and minimizing interference.
3. Process safety. NAMUR standards help ensure process safety by reducing the risk of accidents and improving equipment protection.
4. Quality Management. The use of NAMUR modules helps to improve product quality by accurately controlling production processes.

These modules help to improve efficiency and safety in the chemical industry, which makes them an important element of modern automated systems.

Here is the list of some specific examples of NAMUR modules in the chemical industry:

1. Tank level monitoring. NAMUR level sensors are used to measure the level of liquids in tanks. They

provide accurate data for control systems to maintain optimum liquid levels and prevent overfilling of tanks.

2. Reactor pressure measurement. NAMUR modules are used to connect reactor pressure sensors to monitor pressure during the reaction process and ensure safety.

3. Temperature sensors. NAMUR temperature sensors are often used in chemical processes to monitor the temperature in reactors, which is critical for maintaining the necessary conditions for chemical reactions.

4. Interfaces for analyzing product quality. NAMUR modules can be used to connect analyzers that monitor the quality of end products to ensure compliance with standards.

5. Alarm signaling systems. NAMUR sensors can be integrated into safety systems that signal when permissible parameters such as temperature or pressure are exceeded, allowing a timely response to potential threats.

These examples illustrate how NAMUR modules help to ensure process reliability and safety in the chemical industry. The main advantages of NAMUR modules are:

- Reliability. The standard ensures reliable connection of sensors and transmitters to process monitoring and control systems.
- Ease of installation and maintenance. NAMUR modules are designed to be easy to install and maintain, which further simplifies operation.
- Standardization. NAMUR modules conform to industry standards, so they provide compatibility with various types of equipment and devices, making them a versatile solution for a variety of applications.
- Cost-effectiveness. Using modules reduces equipment and maintenance costs through standardization and reliability.
- Flexibility and scalability. The NAMUR module provides flexibility in customization and scalability, allowing for easy integration into a variety of control and monitoring systems.
- Security. NAMUR compliant standards ensure the safety of equipment and processes, which is important for industrial applications.

The NAMUR module can perform several modes of operation depending on the specific task or requirements of the system being automated.

The main modes of operation include:

- Signal conversion, where the module can convert signals from sensors or other devices into standardized signals that comply with NAMUR regulations.
- Signal amplification - in some cases, signals from sensors or other devices may be too weak to process correctly. The NAMUR module can amplify these signals to ensure that they can be reliably recognized and transmitted.
- The signals are filtered to improve their quality and eliminate interference.
- Diagnostics. The NAMUR module can be equipped with diagnostic functions that help to determine the status of connected devices and detect possible problems in the system.

NAMUR modules are thus widely used in the chemical and oil and gas industries, where reliable and efficient connection of sensors and transmitters to process automation systems is required.

Using modular automation of process modules (e.g. Package Units) can be realized through the usage of so called Module Type Packages (MTP) in order to increase the flexibility of the production. The MTP contains a vendor neutral and functional description of the process module automation. It can be generated by the engineering tool of the module. Through a simple import of the MTP into the process control engineering of the production plant the module can be easily integrated. For example by using MTP the HMI of the module, which contains all static and dynamic information, can be generated automatically within the process control system. Furthermore the MTP offers the possibility of a service based control. The NAMUR specifies the MTP together with the ZVEI.

Modular automation solutions increase the productivity, efficiency and availability of production plants used in the fine chemical, specialty chemical or pharmaceutical industries. NAMUR modules play an important role in improving the efficiency and reliability of industrial production processes. They enable companies to reduce costs, improve product quality and ensure compliance with safety and regulatory standards.

Conclusions. Therefore, chemical companies can leverage Industry 4.0 technologies to enhance business operations via digital transformation, streamline production processes, and optimize the flow of materials and energy. They can also bolster safety measures, solidify market standings through the creation and production of intelligent products, harness collective expertise and vast data through collaboration along value chains, and explore avenues for business expansion with cutting-edge materials, intelligent chemicals, and innovative service propositions. The chemical industry plays a crucial role in the contemporary global economy that successfully accepts and implements the ideas of smart manufacturing. The industry views intelligent technologies as key drivers for enhancing the productivity, competitiveness, and safety of chemical manufacturing, supplying innovative materials to other economic sectors, and fostering environmental harmony.

The theoretical and applied aspects of Chemical Industry 4.0 are being actively developed. The highlighted aspects of Chemical Industry 4.0 underscore the necessity for a radical transformation in business models and the organization principles of chemical production, anchored in the systematic adoption of smart innovations and information technologies. The analysis and generalization of the international experience of implementing the Chemicals 4.0 concept at the micro level allowed us to focus on the tasks of strategic selection and building solution architecture. It was found that the effectiveness of smart transformations is largely determined by new synergistic factors. Further research in this area will be associated with the development of the concept of "smart" neo-industrialization of industry.

Also we can outline some actionable steps that can be taken by policymakers and industry stakeholders [18].

In conclusion, the adoption of Industry 4.0 technologies is rapidly changing many sectors of the economy and offers new opportunities for industrial automation and quality control. Manufacturers have the capability to refine supply chain management and logistics, resulting in enhanced efficiency, reduced expenses, and better product quality. This will foster innovation and growth within this vital segment of the global economy.

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