UDC 622.23:621.926 **doi: 10.20998/2079-0821.2025.02.09**

M. V. PIDDUBNYI, S. P. KRIVILEVA

STRATEGY FOR DIGITAL TRANSFORMATION OF CHEMICAL ENGINEERING IN UKRAINE DURING WAR

This article delves into the concept of Industry 4.0 as a transformative force in modern manufacturing, with particular focus on its impact on Ukraine's chemical engineering and mechanical industries. It explores the core technologies driving Industry 4.0 – including cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), big data, and cloud computing – and emphasizes how their implementation can drive productivity, efficiency, and innovation in manufacturing processes. Special attention is given to enterprises within Ukraine's chemical engineering sector, highlighting the specific challenges they face amid the ongoing 2014–2025 war with Russia, which has severely damaged industrial capacities in the northern, eastern, and southern regions of the country.

The study identifies how the adoption of Industry 4.0 technologies is not just an opportunity but a necessity for Ukraine's industrial recovery and international competitiveness. Through a comprehensive SWOT analysis, the article evaluates internal strengths (such as skilled human capital and integration with the global IT sector), weaknesses (including limited financial resources and outdated infrastructure), opportunities (such as access to EU programs and export potential in dual-use technologies), and threats (from war-induced destruction, investor insecurity, and brain drain). Special focus is placed on how enterprises in chemical engineering machinery can benefit from technological foresight, digital transformation, and circular economy principles to rebuild and modernize in a sustainable way.

In this context, the article calls for systemic government support, strategic investments, and deeper cooperation between industrial enterprises, research institutions, and international partners. It also stresses that the country's long-term success in adopting Industry 4.0 technologies depends not only on overcoming internal barriers but also on winning the war and ensuring political stability. By leveraging its engineering potential and adopting future-oriented industrial policies, Ukraine can align its key sectors with global technological standards and position itself as a competitive player in the post-war industrial economy.

Keywords: chemical engineering, industry 4.0, digitization, technologies, modernization, SWOT analysis

М. В. ПІДДУБНИЙ, С. П. КРИВІЛЬОВА

СТРАТЕГІЯ ЦИФРОВОЇ ТРАНСФОРМАЦІЇ ХІМІЧНОЇ ІНЖЕНЕРІЇ УКРАЇНИ ПІД ЧАС ВІЙНИ

У статті розглядається концепція Індустрії 4.0 як потужний фактор трансформації сучасного виробництва, з особливим акцентом на її вплив на підприємства хімічного машинобудування та механічної галузі в Україні. Аналізуються ключові технології Індустрії 4.0 – кіберфізичні системи, Інтернет речей (IoT), штучний інтелект (AI), великі дані та хмарні обчислення – та підкреслюється, як їх впровадження сприяє підвищенню ефективності, гнучкості та інноваційності виробничих процесів. Особливу увагу приділено підприємствам хімічного машинобудування в умовах триваючої війни з Росією (2014–2025), яка призвела до руйнування цілих промислових кластерів у північних, східних та південних регіонах України.

У дослідженні зазначено, що інтеграція технологій Індустрії 4.0 – це не просто шанс, а критично важлива умова для відновлення української промисловості та підвищення її конкурентоспроможності на міжнародному рівні. Проведено SWOT-аналіз, що охоплює внутрішні сильні сторони (наявність кваліфікованих кадрів, інтеграція з глобальним IT-сектором), слабкі сторони (нестача фінансів, застаріла інфраструктура), можливості (доступ до європейських програм, експортний потенціал у сфері двофункціональних технологій) та загрози (руйнування інфраструктури, інвестиційна непривабливість, еміграція інженерів).

Автори наголошують на необхідності державної підтримки, цільових інвестицій та активізації співпраці між промисловими підприємствами, науковими установами та міжнародними партнерами. Важливим є також впровадження принципів циркулярної економіки та технологічного форсайту. Успіх України на шляху до Індустрії 4.0 залежить не лише від внутрішніх реформ, але й від перемоги у війні, що забезпечить стабільність і довіру. У разі ефективного використання наявного потенціалу, Україна має всі шанси приєднатися до країн, що лідирують у глобальному технологічному розвитку.

Ключові слова: хімічна інженерія, індустрія 4.0, цифровізація, проектування і управління процесами, модернізація, SWOT аналіз

Introduction. Industry 4.0, or the Fourth Industrial Revolution, is fundamentally reshaping manufacturing processes and business models worldwide. Based on the widespread application of cyber-physical systems, the Internet of Things (IoT), and big data, this concept opens new approaches to automation, optimization, and integration of manufacturing. In the sector of chemical industry enterprises in Ukraine, such changes represent significant opportunities for enhancing competitiveness, but at the same time also bring serious challenges. Under modern market conditions, the implementation of Industry 4.0 technologies is critically important for the survival and development of all industrial sectors, and especially for enterprises of the chemical industry.

This article examines the impact of Industry 4.0 on enterprises of chemical engineering in Ukraine, as well as the advantages and difficulties associated with the adoption of new technologies. The use of tools such as IoT sensors, cloud platforms, and big data analytics enables enterprises to obtain accurate and timely information about equipment status and Production processes, predict possible failures, and optimize production cycles. This can significantly improve production efficiency, reduce costs, and enhance product quality. The aim of the study is to identify existing and potential problems, threats, and opportunities associated with the formation and

development of Industry 4.0 in Ukraine for enterprises of chemical engineering under force majeure circumstances — the war with Russia (2014–2025) and the destruction of entire industrial sectors in the northern, eastern, and southern regions of the country.

The purpose is to investigate existing and potential issues, threats, and opportunities related to the formation and development of Industry 4.0 in Ukraine amidst force majeure

The importance and implementation of industry 4.0 in the global Ukrainian contexts. State programs aimed at implementing digital transformation in national economies have already been adopted by developed countries such as Germany ("Industrie 4.0," 2012), Italy ("La Fabbrica del Futuro," 2013), the United Kingdom ("High Value Manufacturing Catapult," 2014), the United States ("Industrial Internet Consortium," 2015), Japan ("Industrial Value Chain Initiative," 2015), India ("Make in India," 2015), France ("Usine du Futur," 2017), China ("Made in China," 2017), Singapore ("Singapore Manufacturing Consortium," 2017), Spain ("Industria Conectada 4.0," 2018), and many others.

Industry 4.0 enables rapid data collection, accumulation, and analysis, ensuring production processes with minimal costs. Industry 4.0 stimulates the development of new manufacturing technologies (so-called "nanotechnologies") by influencing the formation of global production systems (See Fig 1.). One of the key ideas is the creation of “smart” enterprises through the integration of robotic systems into fully automated digital production.

In Ukraine, numerous problems persist: war, inflation, corruption, political and social instability, high taxation, limited access to financing, and more. The economy must improve investment attractiveness, strengthen the macroeconomic environment, and ensure stable financial conditions. At the same time, Ukraine has strong potential: enterprises of chemical engineering can potentially replicate the success of its IT sector.

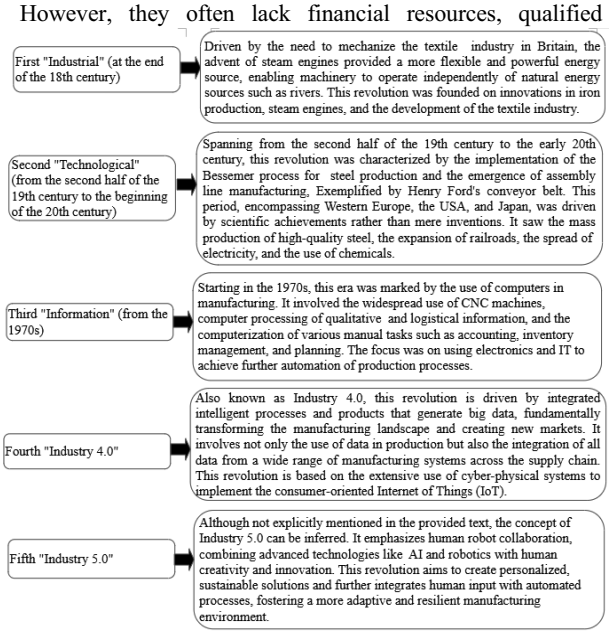
The main challenge for domestic enterprises in the transition to Industry 4.0 is the almost complete absence of priorities at the level of technical policy. Clear transformation plans, specific budgets, and investments are required. This demands state funding of the IT sector and a motivation system for specialists (especially IT experts) to work at domestic enterprises. Deeper integration with the European Union is also crucial. Reforms in legislation, taxation, education, science, and infrastructure play a key role.

Evolution of Industrial Revolutions: Components of Industry 4.0. Industry 4.0, or the Fourth Industrial Revolution, marks the era of digital transformation in production, uniting cyber-physical systems, the Internet of Things, big data, artificial intelligence, and other advanced technologies. This revolution fundamentally changes approaches to manufacturing, management, and business models, providing new levels of efficiency, productivity, and flexibility.

For businesses in Ukraine, particularly in the chemical engineering sector, the implementation of Industry 4.0 presents vast opportunities for development and enhancing competitiveness.

For Ukrainian enterprises, especially in the electrotechnical sector, the introduction of Industry 4.0 opens enormous prospects. Chemical industry enterprises play a key role in the Ukrainian economy, providing jobs, innovation, and stability. According to the Ukrainian Chamber of Commerce and Industry, such enterprises account for about 60% of employment.

However, they often lack financial resources, qualified specialists, and modern technologies [1].



And it offers solutions to many of these issues by providing tools for automation, optimization, and increased productivity of manufacturing processes. Implementing IoT, cyber-physical systems, big data analytics, and artificial intelligence can help small and medium-sized enterprises enhance efficiency, reduce costs, and improve product quality. Moreover,

Fig. 1.General characteristics of industrial revolutions

Industry 4.0 technologies foster greater flexibility and adaptability to market changes, which is especially crucial in today's dynamic economic environment.

Using examples of successful implementations, analyzing the current market state,
and proposing recommendations for Industry 4.0 is built upon a range of advanced technologies that interact to create smart factories, where machines, humans, and systems exchange information in real time. Below, we discuss the key components of Industry 4.0 and their impact on enterprises in the chemical engineering sector.

Internet of Things (IoT) is a network of physical devices connected to the Internet that can collect and exchange data. In the context of manufacturing, IoT enables the creation of smart factories where machines and equipment can be automatically monitored and optimized. Implementing IoT can significantly enhance production efficiency, reduce equipment maintenance costs, and improve product quality through continuous real-time data monitoring and analysis [2].

Big Data refers to the processing and analysis of vast amounts of data generated from various sources such as sensors, machines, and manufacturing systems. Analyzing big data enables businesses to derive valuable insights for making more informed decisions, optimizing production, and predicting potential failures.This allows small and medium-sized enterprises to automate and optimize manufacturing processes, increasing productivity and reducing human errors [3].

Cloud technologies enable storing and processing data on remote servers, providing access to information and computational resources over the Internet. Using cloud technologies allows small businesses to access powerful computing resources without significant investments in their own infrastructure, enhancing business flexibility and scalability[4].

Ukrainian SMEs in the electrical engineering sector exhibit significant potential for development owing to their high product quality and experienced personnel. However, successful adoption of Industry 4.0 hinges on overcoming challenges such as limited financial resources and a shortage of skilled professionals. Leveraging advanced technologies can yield substantial benefits by enhancing efficiency, cutting costs, improving product quality, and bolstering international competitiveness. Simultaneously, it is crucial to address potential threats linked to economic instability and cybersecurity through strategic mitigation strategies. This approach is essential for ensuring sustainable growth and resilience in the global market landscape.

I. SWOT ANALYSIS

The methodology for conducting the SWOT analysis was based on official statistical reports from industry enterprises as well as research conducted by scholars in chemical engineering. Additionally, it incorporated assessments by leading authors regarding the positive and negative aspects present in the industry during wartime. This comprehensive

approach provided a solid foundation for understanding the current state and challenges of the industry, ensuring an in-depth analysis of its strengths, weaknesses, opportunities, and threats in the context of the ongoing conflict.

Regarding the **Strengths** of Ukraine's industrial landscape is marked by a rapidly growing IT sector, well-integrated into the global IT industry. The government's awareness of Industry 4.0 challenges, alongside ongoing decentralization reforms, highlights the country's commitment to digital transformation. Ukraine boasts significant potential in key industries like chemical and mechanical engineering for building. Universities, IT professionals, and institutions under the National Academy of Sciences provide a robust scientific foundation [5]. Additionally, over 100 organizations are actively offering Engineering 4.0 solutions, underscoring the country's innovative capacity.

An example of Ukraine's strengths in this context is the burgeoning drone manufacturing sector, which demonstrates the nation's ability to leverage advanced technologies for military and civilian purposes. Ukrainian-made drones, developed in response to wartime needs, have gained recognition for their efficiency and innovation, contributing to the defense sector and showcasing Ukraine's engineering prowess on the global stage. This not only strengthens national security but also positions Ukraine as a competitive player in the global drone market. The SWOT analysis - in Table 1. Concerning the **Weaknesses.** Despite these strengths, Ukraine faces challenges in its pursuit of Industry 4.0. Government efficiency remains insufficient, with limited regulatory influence over industrial sectors. The government's capacity to engage with experts, the Academy of Sciences, universities, and IT professionals is also constrained, hampering collaborative efforts in Industry 4.0. The absence of active national, regional, and sectoral strategies further exacerbates these issues. The destruction of Industry 4.0 ecosystems due to ongoing conflict has weakened support for developers and hindered the creation of an effective export strategy.

A major weakness is the lack of a robust legal and regulatory framework to support the digital transformation of industries. This is compounded by insufficient incentives for businesses to adopt Industry 4.0 technologies, which leads to a slow uptake and hinders progress [6]. The war has also disrupted supply chains, making it difficult for industries to source the necessary materials and components for modernization efforts.

Desired results that can be obtained. Despite the bloody war and the catastrophic destruction of the economy, Ukraine has great opportunities due to the fact that, thanks to Western partners, it gained access to European Industrialization 4.0 programs in the field of electrical engineering during the war. It is still unknown how Ukrainian specialists will take advantage of these unexpected opportunities, but if they follow the "road maps", including those embedded in them, this can ensure that the state of the domestic chemical engineering industry is aligned with the world level of development of the industry.

Ukraine has significant **Opportunities** for growth, in the global and EU markets. The potential to leverage international programs for funding scientific and technological advancements is substantial. Ukrainian innovations, especially in military and dual technologies, industrial automation and robotics, have strong export potential, with the possibility of full integration into global markets. The reduced workforce has increased demand for automation and robotics in Ukrainian enterprises, driving modernization efforts. The country's labor market, rich in highly educated engineers and youth, is well-positioned to meet the demands of Industry 4.0. Additionally, the popularity of advanced technologies among the population and the growing trust in national manufacturers provide a favorable environment for the development of Industry 4.0. Ukraine's enhanced international prestige and the potential for large-scale reconstruction after the war present further opportunities for growth and innovation. It should be noted that there are large potential customers for both the latest military technologies developed by Ukrainians in the field of chemical engineering and dual technologies, both among European countries and among the states of the Eastern region and the Arab world. Entering these markets will contribute to increasing the reputation, trust and authority of national manufacturers and the entire chemical engineering industry not only among the population of Ukraine, but also throughout the world. And this can become the foundation of the global transformation and restoration of Ukraine, its economy and the entire chemical engineering industry after the victory in the long-lasting and very bloody war of national liberation with Russia in 2014–2025.

The production of drones in Ukraine is a prime example of capitalizing on these opportunities. The high demand for drones, both domestically and internationally, opens avenues for Ukraine to establish itself as a leader in this niche market. Collaborating with global partners, securing international funding, and exporting drone technology can significantly boost Ukraine's standing in the global Industry 4.0 landscape.

Furthermore, the reconstruction efforts post-war offer a unique opportunity to rebuild with Industry 4.0 principles at the forefront. This includes modernizing infrastructure, adopting smart technologies, and ensuring that new developments are sustainable and future-proof. By positioning itself as a hub for innovation and technology, 1

Ukraine can attract foreign investment and expertise, further accelerating its industrial transformation.

However, Ukraine's path to Industry 4.0 is fraught with **Threats**. The ongoing war with Russia poses a significant risk, leading to social instability and creating unattractive conditions for investors. The country's dependency on debt and the destruction of entire industrial sectors by the enemy further exacerbate the situation.

The rapid brain drain of education engineers, compounded processing industry, risks turning Ukraine's economy into a raw material-based one. The degradation of industrial innovation ecosystems, coupled with insufficient penalties for environmental violations, threatens the sustainability of Ukraine's industrial development. The widespread violations of legislation due to the war and inadequate enforcement measures further undermine the country's progress toward Industry 4.0.

In conclusion, while Ukraine's strengths and opportunities in Industry 4.0 are considerable, the weaknesses and threats it faces are significant. The production of drones exemplifies how Ukraine can leverage its strengths and opportunities, but the challenges ahead require strategic and concerted efforts to overcome [7]. The war has undeniably complicated Ukraine's journey toward Industry 4,0, but with resilience and innovation, the country can navigate these challenges and emerge as a strong contender in the global industrial landscape.

Integration of technological foresight and circular economy. In the face of ongoing war, the development of Industry 4.0 in Ukraine faces both unique challenges and opportunities. Technological foresight plays a critical role in this context, as demonstrated by leading multinational corporations like Siemens and General Electric [8]. These entities employ foresight not only to adapt to rapid

technological changes but also to guide the broader professional community. For Ukraine, the strategic application of such foresight is essential to navigating the complexities of Industry 4.0, especially in sectors like chemical engineering, where resilience and innovation are paramount [9].

Moreover, the concept of the circular economy offers additional prospects for sustainable development within Industry 4.0. The integration of recycling innovations, as seen in European circular networks, can significantly contribute to Ukraine's industrial resilience.

Multinational electrical manufacturing companies (MNEMCs) have shown that active participation in circular ecosystems leads to enhanced resource efficiency, knowledge sharing, and collaborative innovation. For Ukraine, embracing circular economy principles within Industry 4.0 could mitigate some of the war's detrimental effects, offering a pathway to sustainable industrial growth Qq [10–12].

Thus, by combining technological foresight with circular economy practices, Ukraine can leverage Industry 4.0 to foster industrial innovation, economic resilience, and long-term sustainability, even amid the ongoing conflict.

Table.1 – SWOT Analysis of Implementing and Developing Industry 4.0 in Ukraine during the war

Strengths	Weaknesses
Rapid growth and globalization (European integration) of the IT industry.	Low operational efficiency of the Ukrainian government (second to last in the rankings, according to WEF evaluations).
Unification of Ukrainian innovators within the framework of "Industry 4.0".	Lack of effective industrial, innovation, export, and digital transformation strategies, among other development strategies for the IT industry in Ukraine.
Initiation of reforms, particularly decentralization.	Absence of effective government support for developers and innovators in Industry 4.0.
High potential of higher education institutions and academies, which involve their representatives in "Industry 4.0".	Low involvement of key stakeholders (IT sector, higher education institutions, industrial engineering, etc.) in Industry 4.0.
Significant potential for creating innovative technologies.	Short-term focus on key customers, lacking strategic orientation.
Positive image of Ukrainian workers employed on outsourcing terms.	Underdevelopment of the national manufacturing sector.
Establishment of cooperation with leading innovative foreign companies.	Inadequate legal framework for the development of Industry 4.0 (e.g., low level of intellectual property protection).
	Weak or non-existent regional and sectoral ecosystems for Industry 4.0.
Opportunities	**Threats**
Collaboration with leading countries in the production sector.	The gradual transformation of our country into a source of labor through cooperation.
EU programs as sources of funding for science, development, and more.	Increasing distrust of domestic businesses towards the state.
Manufacturing cooperation (integration into supply chains) with global markets, including outsourcing, freelancing, and export in the IT sector and the field of innovative developments.	Degradation of innovative ecosystems in the domestic industry.
Large capacity of the domestic market.	Economic imbalance, turning the country into a raw material exporter (reducing the share of the processing industry).
Increased penetration and further development of innovative technologies across all sectors of domestic industry.	Lagging behind industrially developed countries in most strategic aspects of Industry 4.0.
Enhanced reputation of national producers in the eyes of Ukrainians.	Increasing distrust of the state by existing businesses.
Securing expanded funding for scientific and innovative developments within existing programs.	Unstable economic situation and high unemployment rates.
Victory in the war with russia and subsequent national recovery.	High state budget expenditures and the country's debt dependency.

Conclusion In the field of Industry 4.0, Ukraine significantly lags behind developed countries. The situation surrounding Industry 4.0 has been analyzed in the conditions of the national liberation war of 2014-2024. As a result of the conducted SWOT analysis, strengths, weaknesses, opportunities, and threats have been identified for Ukraine in the adoption and utilization of Industry 4.0 tools during the critical situation of the 2014-2025 armed conflict with Russia. The analysis revealed insufficient effectiveness of strengths and opportunities, which do not adequately counterbalance the external threats. And this could become a destructive factor for the state, its economy and for the entire electrical engineering industry. But at the same time, despite the long bloody war and the catastrophic destruction of the economy, great opportunities opened up for Ukraine due to the fact that, thanks to Western partners during the war, it gained access to European programs on Industrialization 4.0 in the field of electrical engineering. And if the Ukrainian Government and Ukrainian specialists take advantage of these unexpectedly opened opportunities, it will ensure the alignment of the state of the domestic electrical engineering industry with the global level of industry development. But this is possible only if the Ukrainian nation can withstand and defeat Russia in this protracted and bloody war.

Thus, the activation of digital transformation, the acceleration and improvement of the efficiency of the implementation of the main tools of Industry 4.0 in the electrical engineering industry of Ukraine, which were actually stimulated, among others, by the war unleashed by Russia, will have phenomenal results under the conditions of such a long-awaited victory. As for future research prospects, they include the development of a systemic approach, promoting integration and cooperation between enterprises, academic circles and educational institutions of Ukraine under the supervision of the Government, aimed at the promotion and implementation of innovative technologies of Industry 4.0 in the electrotechnical industry, including military-oriented and dual.

Reference

1. The official site of State Statistics Service of Ukraine. URL: http://www.ukrstat.gov.ua/ (in Ukrainian).
2. Kagermann, H., Wahlster, W., & Helbig, J. (2013). "Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry." Final report of the Industrie 4.0 Working Group.
3. Lee, J., Bagheri, B., & Kao, H. A. (2015). "A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems." Manufacturing Letters, 3, 18–23.
4. Smith, J. (2018). "Challenges of Equipment Downtime in the Electrical Manufacturing Industry." Manufacturing Today, 25(3), 45–52.
5. Brown, A. (2017). "Reducing Maintenance Costs in the Electrical Equipment Sector." Engineering Management Journal, 12(2), 67–74.
6. Kushnirenko O. M., Gachovych N. G. (2020). Vplyv technologij Industriji 4.0 na strukturni transformaciji v ekonomici. [Impact of Industry 4.0 technologies on structural transformations in the economy]. Ekonomichnyj visnyk. Serija: finansy, oblik, opodatkuvannia. 4. Pp. 64–73 (in Ukrainian).
7. Iliashenko S. M., Iliashenko N. S. (2016). Perspektyvy i zagrozy 4 promyslovoji revolyuciji ta jich urachuvanya pry vybori strategij innovacijnogo zrostanya. [Prospects and threats of the fourth industrial revolution and their consideration when choosing innovative growth strategies]. Marketyng i menedzhment innovacij. Pp. 11–21 (in Ukrainian)
8. T. Danko and N. Shyriaieva, 'Industry 4.0 Technology Foresight in Electrical Engineering Sector', in 2023 IEEE 4th KhPI Week on Advanced Technology (KhPIWeek), Oct. 2023, pp. 1–6. https://doi.org/10.1109/KhPIWeek61412.2023.10312870
9. N. Krasnokutska and T. Danko, 'Corporate Social Responsibility and Countries' Reputation: A Study from a Global Strategic Management Perspective', in Comparative CSR and Sustainability, Routledge, 2022, pp. 364–379.
10. T. Danko, R.Wagner, O.Chaikova. Recycling innovation in European circular networks: the case of multinational electrical manufacturing companies - in 2023 IEEE 4th KhPI Week on Advanced Technology (KhPIWeek), Oct. 2023, pp.1–6. https://doi.org/10.1109/KhPIWeek61412.2023.10311581
11. Beltrami M., Orzes G., Sarkis J., Sartor M. Industry 4.0 and sustainability: Towards conceptualization and theory // Journal of Cleaner Production. 2021. Vol. 312, pp. 127733. https://doi.org/10.1016/j.jclepro.2021.127733
12. Peterson, Luisa; Gosea, Ion Victor; Benner, Peter; Sundmacher, Kai. Digital twins in process engineering: An overview on computational and numerical methods. Computers & Chemical Engineering, Vol. 193 (February 2025), Article 108917. https://doi.org/10.1016/j.compchemeng.2024.108917

Відомості про авторів /About authors

Піддубний Микита Володимирович (Piddubnyi Mykyta) – аспірант кафедри хімічної техніки та промислової екології, Національний технічний університет «Харківський політехнічний інститут», м. Харків, Україна; ORCID: https://orcid.org/0009-0009-0281-0342; e-mail: Mykyta.Piddubnyi@mit.khpi.edu.ua.

Кривільова Світлана Павлівна (Krivileva Svetlana) – кандидат технічних наук, доцент, доцент кафедри хімічної техніки та промислової екології, Національний технічний університет «Харківський політехнічний інститут», м. Харків, Україна; ORCID: https://orcid.org/0000-0001-6502-9486; e-mail: Svitlana.Kryvilova@khpi.edu.ua.