CHAPTER

INDUSTRY 5.0 IN THE POST-WAR RECONSTRUCTION OF UKRAINE'S INDUSTRY: STRATEGIES FOR ENSURING QUALITY AND SAFETY OF PRODUCTION SYSTEMS

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Summary

The monograph is devoted to the study of strategic aspects of Industry 5.0 technologies implementation into the safety and quality management systems of industrial enterprises in Ukraine. The research analyzes the paradigm shift from total automation of Industry 4.0 to human-centricity and resilience of Industry 5.0 within the context of post-war recovery. It addresses the critical issues of physical asset destruction and human capital shortages, proposing a technological «leapfrog» through the deployment of cobots, artificial intelligence, and digital twins. Particular emphasis is placed on the oil and gas industry as a strategic sector for national energy security. The research results include the development of predictive quality management models based on Big Data and blockchain technologies. A strategic roadmap for the creation of innovative clusters and the integration of Ukrainian enterprises into European value chains, considering ESG standards, is proposed. The monograph proves that the synergy between humans and advanced technologies is the only viable path to building a competitive and secure industrial sector in Ukraine.

Introduction

The contemporary global economy is undergoing a stage of fundamental transformation, where technological progress is no longer an end in itself but is becoming subordinate to the principles of social responsibility and environmental sustainability. The transition from Industry 4.0, which focused on pervasive digitalization and the Internet of Things (IoT), to Industry 5.0 marks the return of the "human factor" to the center of the production process. For Ukraine, undergoing unprecedented trials caused by the war, this global transition coincides with a critical necessity for a complete reimagining and physical restoration of its industrial potential. Post-war reconstruction cannot be a mere restoration of destroyed capacities according to old models; it must become a radical leap toward innovative management models where safety and quality are based on the synergy between human intelligence and advanced technologies.

The primary challenge for the national industry is the risk of "preserving" obsolete technologies during rapid reconstruction. There is a real threat that, due to time and resource constraints, recovery will occur on the principle of "patchwork" repairs rather than the creation of something new. The problem lies in the critical depreciation of fixed assets, which even before the full-scale invasion reached 60–70%, and is now exacerbated by the physical destruction of entire clusters (metallurgy in the East, chemical industry). Without the integration of Industry 5.0, Ukraine risks restoring manufacturing facilities that will be energy-intensive and non-competitive in the EU market within 5-10 years due to non-compliance with the European Green Deal.

The relevance of the research topic is driven by several factors. Firstly, the scale of destruction of Ukraine's industrial infrastructure requires the development of new methodological approaches to designing production systems that are resilient to crises. Secondly, the shortage of skilled labor caused by migration processes and mobilization brings Industry 5.0 technologies to the forefront, as they are aimed at supporting workers, improving their labor conditions, and minimizing risks to life and health. Thirdly, Ukraine's European integration requires domestic enterprises to achieve not only technological upgrades but also compliance with strict ESG (Environmental, Social, and Governance) standards, which are an integral part of the fifth industrial paradigm.

The concept of Industry 5.0 expands the boundaries of efficiency by adding value-based orientations to economic indicators. In intra-firm management, this signifies a transition from rigid control to predictive quality and safety management. The use of collaborative robots (cobots), digital twins, artificial intelligence, and big data analytics allows for the creation of a "smart" environment where technology does not replace the human but complements their capabilities, preventing errors before they occur. For Ukraine, in the context of post-war recovery, the implementation of such tools is a matter not only of competitiveness in foreign markets but also of the physical preservation of human capital.

The greatest challenge for Ukraine’s post-war recovery is not a lack of finances, but a deficit of skilled personnel capable of operating within the 5.0 ecosystem. Industry 5.0 changes the very essence of labor: instead of physical endurance, cognitive skills and emotional intelligence come to the forefront [20; 32].

Strategic directions for human capital development:

– The «Lifelong Learning» concept: Intra-firm management must transform into an educational hub. The use of VR simulators for training in new professions allows for reducing the preparation time of a complex equipment operator from 6 months to 2 weeks. This is vital for the rapid return of veterans to the civilian sector of the economy [8; 12].

– Inclusivity through technology: For the first time in history, the Fifth Industrial Revolution allows for the leveling of human physical limitations. The use of lightweight exoskeletons enables individuals with musculoskeletal injuries to perform complex assembly operations, while AI-powered voice control systems make workplaces accessible to people with visual or motor impairments. This is not only a social responsibility but also a method to overcome the labor shortage [11; 23].

– Psychological Safety and Cognitive Ergonomics: In post-war safety management, a new domain emerges – mental health monitoring. PTSD and chronic stress among employees directly correlate with the frequency of errors and industrial accidents. Industry 5.0 systems utilize emotional state analysis algorithms to automatically adjust work schedules, thereby preventing professional burnout and occupational hazards [4; 22].

Consequently, human capital in Ukraine must evolve from a mere «resource for exploitation» into an intellectual partner to technology. It is this transition that will ensure sustainable production quality and the highest safety standards, aligning with European values and the standards of the future.

Thus, the human-centric approach of Industry 5.0 represents a strategic paradigm shift for Ukraine's industrial sector, moving beyond the traditional exploitation of labor toward an intellectual partnership between humans and technology. The integration of advanced assistive systems and rapid re-skilling methodologies serves as a fundamental pillar for economic resilience. By prioritizing the preservation and development of human capital, Ukrainian enterprises will not only bridge the current labor gap but also ensure long-term compliance with global ESG standards, securing a competitive and sustainable position within the European economic space.

The object of the research is the management processes of industrial production in Ukraine within the context of the transition to a new technological paradigm and the necessity to overcome the consequences of military aggression. The subject of the research encompasses the set of theoretical, methodological, and applied aspects of implementing innovative Industry 5.0 technologies into the quality and safety management systems at domestic enterprises.

The aim of this monograph section is to substantiate strategic directions and develop practical recommendations for the transformation of Ukraine's industrial production based on Industry 5.0 principles. Particular emphasis is placed on the integration of automated quality management systems with industrial safety protocols, which allows for the minimization of occupational injuries and ensures stable product characteristics in an unstable environment.

The scientific novelty of the results lies in the formation of a holistic «Quality and Safety 5.0» concept for post-war recovery. Unlike existing approaches, this concept accounts for specific wartime risks and the requirement for rapid adaptation to EU standards. The practical significance of this section consists in the potential for industrial managers, government agencies, and researchers to utilize the proposed algorithms to develop strategies for the modernization of the Ukrainian economy.

The provisions set forth in this monograph are based on a systemic approach, an analysis of international experience, and the forecasting of technological trends. The authors are convinced that Industry 5.0 will serve as the foundation upon which a new, strong, and innovative industrial Ukraine will emerge.

1. Theoretical and methodological basis and strategic vectors of Industry 5.0 development under global challenges

The evolutionary path of industrial development over the last two centuries has progressed from steam-powered mechanization to complex neural networks managing entire factories. However, the transition from the fourth to the fifth industrial revolution remains the most debated topic in the scientific community. While the first three revolutions focused on increasing productivity through technical improvements, Industry 4.0, which originated in Germany in 2011 as the «High-Tech Strategy 2020» strategic initiative, concentrated on the full digital integration of vertical and horizontal value chains [14; 24].

Nonetheless, a decade of Industry 4.0 implementation has revealed a significant "methodological trap": excessive focus on digitalization, cyber-physical systems (CPS), and autonomous robots led to the gradual displacement of humans from the production circuit. This triggered a series of socio-economic risks, ranging from rising technological unemployment to a decline in the creative potential of manufacturing. As Michael Rada, a key visionary of the fifth paradigm, argues, Industry 5.0 emerged not as a negation of the fourth revolution, but as a necessary humanistic correction of its outcomes [11; 28].

Conceptual Transformation of the Paradigm. At the core of Management 5.0 lies a shift from the «Efficiency First» concept to «Human-Centricity First». The scholarly works of J. Müller and S. Nahavandi emphasize that Industry 5.0 represents a return of the «craftsman's spiri» at a high-tech level [22; 31].

For quality management, this implies a fundamental shift in the object of management. While in Industry 4.0 we managed data from machines, in Industry 5.0 we manage synergy. Collaboration between humans and artificial intelligence allows for achieving what remains inaccessible to algorithms: critical thinking, ethical evaluation, and intuitive problem-solving. In the context of the Ukrainian industry, which requires rapid recovery, this approach allows for more than just copying Western models; it enables the building of production facilities with a high level of adaptability to resource shortages.

In contrast to Industry 4.0, which focused on pervasive automation, Industry 5.0 returns the human to the center of the production process, creating conditions for the synergy of intelligence and technology. A detailed comparative analysis of the transformation of key parameters is presented in Table 1.

Table 1

Comparative analysis of technology transformation: from Industry 4.0 to Industry 5.0 in the oil refining industry

Comparison Parameter	**Industry 4.0 (Digitalization)**	**Industry 5.0 (Human-centricity and Resilience)**	**Impact on Quality and Safety**
Human-Machine Interaction	Full automation. Robots replace humans on the production line/unit	Collaboration. Cobots and exoskeletons enhance human capabilities	Reduction of occupational diseases and industrial injuries
Quality Management	Statistical control based on Big Data (defect detection)	Predictive quality. AI prevents deviations before they occur	Achievement of the "Zero Defect" standard
Maintenance	Preventive maintenance according to schedule/regulations	Predictive Maintenance. Condition-based repair (Digital Twins) [9]	Elimination of sudden accidents and petroleum product leaks
Environmental Aspect	Emission monitoring (violation recording	Circular economy. Carbon Capture (CCUS) and energy recycling	Compliance with European Green Deal and CBAM requirements [13; 18]
Safety	Emergency shutdown systems triggered by critical indicators	Safety 5.0. Monitoring of employee's psychophysical state (biotelemetry) [15]	Prevention of errors caused by stress or fatigue
Cybersecurity	Network perimeter protection (Firewalls)	Zero Trust & AI-Defense. Continuous verification and autonomous attack detection	Protection of strategic facilities against cyber-sabotage

Source: author's development based on [22; 31]

An analytical comparison of Industry 4.0 and 5.0 concepts within the oil refining sector allows for the following conclusions:

1. Unlike Industry 4.0, where safety was ensured through mechanical automation, the 5.0 model introduces a layer of «intelligent support». This enables the delegation of high-risk operations to collaborative robots (cobots),

while maintaining the human's role in strategic oversight. This approach reduces the probability of errors caused by the human factor by 75–80%.

2. It has been established that the transition from “statistical defect detection” (4.0) to «predictive prevention» (5.0) creates a new quality architecture. This is critical for oil refining, where fuel quality depends on micro-parameters of pressure and temperature, which AI can adjust in real-time.

3. Comparative analysis demonstrates that Industry 5.0 makes environmental sustainability an integral part of the technological cycle rather than an additional burden. This ensures that Ukrainian oil refineries automatically comply with European carbon border regulations (CBAM).

For a detailed understanding of management in these new conditions, it is essential to analyze the key vectors that form the core of this monographic study:

1. Human-centric approach. In intra-firm management, this transforms the worker's role from an «operational executor» to a “system curator”. Augmented reality (AR) technologies and exoskeletons do not replace human muscles or vision; instead, they expand them, ensuring labor safety. Safety management here shifts to the level of biotelemetry: the system monitors worker fatigue in real-time and automatically adjusts line speeds or suggests breaks [7; 27].

2. Sustainability.The fifth revolution integrates environmental indicators directly into production management KPIs. This is not merely about “end-of-pipe filters” but involves product design based on the Cradle-to-Cradle principle. For Ukraine, where the environmental damage caused by the war is catastrophic, implementing such closed-loop cycles is the only viable path to securing “green” loans from the EU.

Resilience. This refers to the industrial system's ability to maintain functionality during critical failures. In the context of energy terrorism and logistical disruptions, resilience becomes more vital than immediate profitability. Management 5.0 utilizes «digital twins» not only for monitoring but also for real-time stress testing of supply chains [12; 30].

The scientific discussion regarding the implementation of these principles in Ukraine faces the challenge of a “twin transition”. Our enterprises must simultaneously complete the tasks of Industry 3.0 (modernization of core assets), implement elements of Industry 4.0 (automation of accounting and processes), and adapt to the requirements of Industry 5.0 (social responsibility).

A crucial aspect of this research is the analysis of how the digital literacy of management affects the level of occupational injuries. Statistical data indicate that at enterprises where Smart-Safety elements have been implemented, the injury rate decreases by 45–60%, confirming the hypothesis of a direct correlation between innovativeness and a secure safety environment [15; 30]. However, barriers remain: the psychological resistance of personnel ("machines will replace us") and the high capital intensity of initial investments.

In conclusion, the genesis of Industry 5.0 – is not merely another change of digits in the era's name. It is a fundamental paradigm shift in industrial management, where technology serves the human being, ensuring their safety and high quality of life. This shift is critically important for the post-war revival of Ukraine as a modern industrial state.

One of the most complex tasks in developing the "Quality 5.0" model is the creation of a cognitive quality control methodology. Unlike standard Statistical Process Control (SPC), cognitive control is based on the "Edge Computing" concept – processing data directly at the point of origin [12; 15].

In the context of safety management, the 5.0 model proposes the concept of "Zero Risk through Prediction". This is implemented through three levels of integration:

1. IoT sensors on every equipment unit.
2. Neural networks that detect anomalies in the behavior of metals or electrical circuits.
3. Human-operator decision-making based on system recommendations, which allows for avoiding fatal errors during unpredictable circumstances (e.g., during shelling or sudden power outages).

In the Industry 5.0 paradigm, the concepts of quality and safety cease to be separate management functions. Contemporary scientific thought suggests that they form a unified bio-cyber-physical system, where any deviation in the employee's state (fatigue, stress) instantaneously correlates with the probability of a product defect. The "Quality 5.0" concept transforms the classical PDCA (Plan-Do-Check-Act) cycle into a dynamic cycle of intelligent anticipation [11; 20].

Transformation of ISO 9001 and ISO 45001 Standards. Traditional quality management systems (ISO 9001:2015) and occupational health and safety systems (ISO 45001:2018) are based on the principles of risk-based thinking. However, in the context of the fifth industrial revolution, this is no longer sufficient. The transition to «Safety 5.0» requires a shift in focus from reactive mitigation of consequences to real-time preventive management [15; 22].

A defining feature of the integrated Industry 5.0 model is the deployment of Edge Computing technologies. Unlike Industry 4.0, where data are predominantly transmitted to cloud infrastructures for processing, Industry 5.0 enables the real-time processing of critical safety signals directly at the point of operation. This capability is particularly vital for Ukrainian enterprises operating under conditions of unstable connectivity or heightened exposure to cyber threats.

Architecture of an Intelligent Safety and Quality Management System:

1. AI-Driven Predictive Analytics Layer.

Neural networks process real-time video streams from production lines, enabling not only the detection of micro-defects in products but also the identification of unsafe operator behavior, including improper ergonomics or the absence of personal protective equipment.

2. Cognitive Support Layer (AR/VR Interface).

The use of augmented reality (AR) devices provides workers with real-time guidance during complex assembly operations, thereby reducing cognitive load and minimizing the probability of human error. This forms the foundation of the Zero Defect Manufacturing paradigm – production systems aimed at eliminating defects [15; 22; 29].

3. Biotelemetry Layer (Wearable IoT).

Wearable sensors continuously monitor physiological indicators such as heart rate and cortisol levels. Upon reaching critical fatigue thresholds, the system autonomously recommends rest periods or adjusts production intensity to safer levels.

For Ukraine, the integration of such a model in the post-war recovery phase carries not only technological but also profound social significance. The reconstruction of industrial facilities based on the principles of "Safety 5.0" will enable the inclusion of veterans and persons with disabilities in the workforce through the use of exoskeletons and adaptive human-machine interfaces, representing the pinnacle of a human-centric industrial paradigm [11; 30].

Resilience in the context of Industry 5.0 is defined not only by a system's capacity to withstand external shocks, but also by its ability to rapidly self-organize and adapt. In the academic discourse of 2024–2025, the concept of organizational resilience has become a central category in industrial strategic management [30; 32].

For Ukraine's manufacturing sector, resilience can be characterized across three key dimensions:

– Technological resilience: the modular design of production lines, enabling rapid reconfiguration in the event of component failures or changes in logistics.

– Energy resilience: the integration of smart grid technologies and energy storage systems directly into production processes, ensuring operational continuity under blackout conditions.

– Social resilience: the formation of a safety-oriented organizational culture in which each employee acts as an active participant in risk management, rather than merely an object of control.

The methodology for assessing Industry 5.0 resilience includes stress testing of enterprise digital twins. Prior to launching actual production, management simulates thousands of scenarios, ranging from supply chain disruptions to abrupt changes in quality standards. This approach enables the creation of a strategic reserve of adaptability, which constitutes a key competitive advantage in an era of turbulence [9; 12].

An analysis of Ukraine's industrial sector as of early 2025 indicates the presence of profound structural distortions. According to the KSE Institute, the total direct damage to Ukraine's infrastructure caused by the war has exceeded USD 170 billion, with losses of industrial assets accounting for a critical share of this amount [10; 19].

Destruction Challenges in Quantitative and Structural Dimensions:

1. Physical destruction of assets:

The most severely affected sectors are those with a high concentration of capital, particularly metallurgy and the chemical industry in Eastern Ukraine. This has created a tabula rasa situation, in which traditional modernization approaches are no longer feasible, making a radical transition to Industry 5.0 the only viable pathway.

2. Indirect losses and value-added deficit:

Estimates of indirect economic losses by the end of 2026 exceed USD 1.7 trillion. This reflects a profound disruption of value chains, which now need to be rebuilt on fundamentally new, digitally driven foundations.

3. Crisis of the security environment:

More than 30% of Ukraine's territory is potentially contaminated with landmines, creating unprecedented risks for the agro-industrial and extractive sectors. Under such conditions, safety management requires the deployment of unmanned technologies and robotic systems for remote demining operations [29; 31].

A critical dimension of the problem is the labor force shortage. According to various estimates, Ukraine has lost approximately 5–7 million working-age individuals due to migration and mobilization. This has led to a paradoxical situation: on the one hand, unemployment persists; on the other, there is a severe shortage of qualified personnel for emerging industries. In this context, Industry 5.0 – with its emphasis on reskilling–represents a key mechanism for bridging this gap. The application of artificial intelligence for accelerated workforce training, alongside collaborative robots (cobots) to compensate for physical labor shortages, is no longer optional but a necessity for economic survival.

The concept of technological leapfrogging in the context of Ukraine's post-war recovery is based on the idea of bypassing intermediate stages of technological development that have already become obsolete. Rather than reconstructing industrial facilities based on late 20th-century models, Ukraine has a unique window of opportunity to embed Industry 5.0 standards directly into the foundation of newly established enterprises [4; 16].

Mechanisms for Implementing Leapfrogging in the Ukrainian Context:

1. Design Based on Digital Twins:

In traditional management, factory construction begins with a physical foundation. Within the Industry 5.0 paradigm, a complete digital replica of the future production system is created first. This enables the optimization of material flows, simulation of safety zones, and testing of workplace ergonomics prior to the procurement of any physical equipment. For Ukrainian investors, this approach significantly reduces the risks of inefficient capital allocation [9; 12].

2. Modularity and Decentralization:

Post-war reconstruction requires the development of distributed yet networked production nodes. This enhances system resilience to potential military threats. The use of micro-factories equipped with 3D printers and flexible robotic systems allows for the production of high-tech goods in close proximity to consumers, thereby substantially reducing logistics costs and associated risks [21; 27].

3. Energy Independence of the "Smart Factory":

Industry 5.0 presupposes the integration of renewable energy sources directly into enterprise infrastructure. The implementation of industrial energy storage systems (BESS) combined with AI-driven energy consumption management ensures the resilience of Ukrainian factories to fluctuations in the energy system. This is a critical factor for maintaining both safety and quality in continuous production processes [18; 32].

Economic Impact of Leapfrogging Implementation: According to estimates by international consultants, the integration of intelligent management systems at the "greenfield" stage increases energy efficiency by 30–40% and reduces the investment payback period by 2.5–3 years compared to the modernization of existing ("brownfield") facilities. However, the primary advantage lies in the automatic compliance of production with EU environmental standards (CBAM), thereby granting Ukrainian manufacturers access to premium markets [13; 18].

The reconstruction of Ukraine's industrial potential should be grounded in the principles of territorial decentralization and smart specialization. The author proposes a project-based model of a network of innovative clusters designed to ensure a technological breakthrough in the period 2025–2026. The strategic project framework for 2025–2026 outlines the planned zones of technological recovery based on the principles of Industry 5.0:

1. Western Ukrainian Oil and Gas Hub (Lviv and Ivano-Frankivsk regions): Focus on underground gas storage (UGS) and hydrogen technologies; implementation of remote well management systems and digital twins of storage facilities.

2. Poltava-Kharkiv Extraction Cluster (Smart Extraction): Advanced drilling technologies and enhanced recovery from depleted fields; application of “Seismic 5.0”, AI-driven cognitive data interpretation, and drone-based defect detection systems.

3. Dnieper Industrial Polygon (Dnipro, Kremenchuk): Deep oil refining and environmentally oriented mechanical engineering; deployment of cobot-assisted welding lines and intelligent energy management systems.

4. Kyiv Digital Center for Industrial Safety: Development of software solutions for cybersecurity of industrial control systems (ICS) and biotelemetry systems; use of cloud computing for industrial data processing and VR-based training centers for workforce development.

Designing innovative clusters for the period 2025–2026 makes it possible to formulate a strategic vision for recovery:

1. Instead of concentrating industry in large hubs, a network-based cluster structure is proposed. This increases national security (resilience to attacks) and enables the most efficient use of the specific resources of each region (for example, underground gas storage in the West and extraction in the East).

2. The project confirms that the implementation of Industry 5.0 should be differentiated. The Eastern cluster (Smart Extraction) requires a focus on AI for exploration, while the Western cluster should emphasize storage technologies and hydrogen energy. This approach optimizes both public and private investment.

3. The creation of these clusters by 2026 will generate more than 50,000 new high-tech jobs, contributing to the reintegration of veterans and the return of scientific personnel to Ukraine. The clusters will become centers of “leapfrogging,” where education (VR centers) is directly integrated into the production process.

The study of theoretical foundations confirms that Industry 5.0 is an evolutionary response to the shortcomings of the Fourth Industrial Revolution. It reorients industrial systems from pure productivity toward social value, resilience, and sustainability. It has been established that safety and quality management in the new paradigm is based on harmonious collaboration between humans and machines. A methodological foundation for creating human-centered production ecosystems has been developed. The Fifth Industrial Revolution is defined as a foundation for modernizing Ukraine’s industry in line with European standards.

It is substantiated that the transition to Industry 5.0 is an objective necessity for Ukraine, as traditional recovery models do not take into account modern requirements for resilience and social responsibility. It has been determined that the physical destruction of assets creates conditions for radical modernization based on the “Greenfield” principle. It is proven that the success of reforms depends on the transformation of human capital and the implementation of continuous learning strategies (reskilling).

2. Innovative toolkit for safety and quality management: sector-specific features of the oil and gas complex

The transition to Industry 5.0 implies a paradigm shift from "Quality Control" (post-production inspection) to "Quality Prevention" (defect prevention). This process is based on the architecture of Predictive Quality Management (PQM) [15; 22].

Predictive management toolkit:

1. Computer Vision 5.0: Modern computer vision systems are capable of recognizing not only geometric deviations of a component but also structural changes in metal or composite materials at the micro level during processing. This makes it possible to stop the process before a defect becomes irreversible.
2. Big Data Analytics: The system collects thousands of parameters: air temperature in the workshop, humidity, machine vibration, and even power grid indicators. AI identifies correlations between these factors and product output quality, creating a self-learning model of the optimal production cycle [7; 21].
3. Blockchain for quality traceability: Each product receives a "digital passport" based on blockchain technology. This ensures that data on raw material quality, production conditions, and test results cannot be falsified. For Ukrainian exporters, this is key to building trust in the markets of the USA and Japan [15; 25].

In the era of Industry 5.0, occupational safety is transforming from passive compliance with instructions into a dynamic Smart Safety ecosystem. The core idea is to create a barrier-free and safe environment where technology acts as a "guardian angel" for workers, minimizing the risks of injuries even under unstable conditions of post-war production [15; 30].

Technological components of intelligent safety:

1. Wearable devices and biotelemetry: The use of smart vests, helmets, and watches enables real-time monitoring of critical vital signs (heart rate, blood oxygen saturation, body temperature). In the context of Ukraine, where many workers are under chronic stress, the system can automatically block access to hazardous equipment if it detects signs of a panic attack or critical operator fatigue [4; 19].
2. Cognitive Augmented Reality (AR): Visualization of hazardous zones and "invisible" threats (radiation, gas leaks, electrical voltage) through AR interfaces. This allows personnel to navigate damaged facilities during recovery operations, avoiding hidden dangers.
3. Autonomous fire suppression and emergency response systems: Integration of inspection drones that continuously monitor the condition of

structures and automatically localize threats without human involvement. This is critical for enterprises located in areas at risk of repeated attacks.

Post-war recovery of Ukraine is impossible without large-scale foreign investment. However, modern capital has become more selective: investors pay attention not only to profitability but also to compliance with ESG (Environmental, Social, and Governance) criteria. Industry 5.0 is the most effective tool for the rapid adaptation of Ukrainian businesses to these requirements [13; 31].

Roadmap stages:

– Digital maturity (2025-2026): Implementation of end-to-end monitoring systems for energy consumption and CO_2 emissions. Creation of “digital passports” for enterprises to ensure transparency of business processes.

– Social modernization (2026–2027): Introduction of inclusive workplaces based on exoskeletons and cobots. Development of in-house psychological rehabilitation programs using VR technologies.

– Global integration (2027+): Full certification in accordance with EU Green Deal standards. Integration of Ukrainian factories into European supply chains as highly technological and socially responsible partners.

The oil and gas industry of Ukraine, in the context of post-war recovery, requires not just repair but full intellectualization of extraction assets. The concept of “Smart Fields” (digital oilfields) within Industry 5.0 goes beyond simple automation of data collection. It involves the creation of a self-regulating system where artificial intelligence, in collaboration with a geological engineer, ensures maximum reservoir recovery with zero risk to the environment and personnel [7; 21].

The implementation of Industry 5.0 technologies at the extraction stage makes it possible to address a key problem of Ukrainian fields-their high depletion rate (over 70–80%). The use of fiber-optic sensors inside wells enables real-time monitoring of fluid inflow, water cut, and pressure. Within the Industry 5.0 paradigm, this data is transmitted not just to an operator’s console but to a “digital twin of the field,” which models extraction scenarios 5–10 years ahead, taking into account even micro-changes in rock structure [9; 14].

Special attention is given to safety. A Smart Well 5.0 is equipped with autonomous shut-off valves capable of independently stopping extraction when abnormal vibrations are detected (for example, during seismic activity or due to external mechanical damage). This minimizes the risk of oil spills or gas leaks, which is a top priority in environmentally vulnerable regions of Ukraine.

One of the most hazardous processes in the oil and gas industry is the inspection and repair of tanks and pipelines. Traditionally, this requires human presence in confined spaces with high concentrations of explosive and toxic vapors. Industry 5.0 proposes replacing human labor in such areas with specialized robots and inspection drones [12; 26].

In Ukraine, where a significant part of the oil transportation system requires integrity checks after shelling, the use of crawler robots capable of performing ultrasonic diagnostics of pipe walls without opening them is critically important. These devices transmit data to augmented reality (AR) glasses worn by an engineer located in a safe zone. In this way, the quality of weld seams and metal thickness are assessed with micron-level precision, ensuring the reliability of strategic resource transportation.

For oil refineries, the implementation of welding cobots is particularly relevant. These systems can operate in complex geometric conditions of fractionation columns, ensuring perfect joint quality, which directly affects the tightness of installations and the overall safety of the enterprise [15; 22].

In the era of Industry 5.0, Ukraine's oil and gas sector faces stringent requirements under the EU Green Deal. Decarbonization is no longer just an environmental slogan but an economic necessity for exporting products. The use of innovative technologies makes it possible to transform a traditionally "polluting" industry into an environmentally sustainable system.

Case of Saudi Aramco and Shell: Saudi Aramco and Shell have already implemented intelligent methane leak detection systems using satellites and laser scanners mounted on drones. Methane has a greenhouse effect 25 times greater than CO_2, making its capture a priority. For Ukraine's gas transmission systems (GTS), the implementation of similar "Intelligent Leak Detection" systems would not only improve environmental performance but also help retain up to 2–3% of produced gas that was previously lost due to technological micro-leaks [17; 25].

CCUS Technology (Carbon Capture, Utilization, and Storage): Industry 5.0 proposes integrating carbon capture systems directly into oil refining cycles. Captured CO_2 can be injected back into depleted reservoirs to enhance oil recovery (EOR method). For facilities such as Kremenchuk Oil Refinery or Shebelinka Gas Processing Plant, during their post-war modernization, the implementation of such cycles would enable them to achieve "Low-Carbon Fuel" status, significantly increasing asset capitalization [17; 32].

In the context of Industry 5.0, Ukraine's oil and gas sector should transform into an energy hub where traditional hydrocarbons coexist with renewable energy sources. A key element of this transformation is Green Hydrogen.

Strategic importance for Ukraine:

Ukraine possesses one of the most powerful gas transmission systems (GTS) in the world, which, under conditions of reduced transit of Russian gas, can be adapted for transporting a mixture of natural gas and hydrogen (H_2NG) to Europe.

Industry 5.0 technologies enable precise monitoring of pipeline integrity, as hydrogen molecules are significantly smaller than methane and prone to diffusion through metal [6; 18; 32].

Industry 5.0 toolkit in hydrogen energy:

1. AI-controlled electrolyzers: The use of surplus energy from nuclear power plants and renewable energy sources for hydrogen production requires instantaneous system response to fluctuations in grid frequency. Artificial intelligence predicts generation peaks and automatically adjusts the capacity of electrolysis units.

2. Nanotechnology-based hydrogen leak sensors: Since hydrogen is odorless and colorless, safety management relies on quantum sensors integrated into a unified IIoT network.

Case of Linde and Ukrgazvydobuvannya: A potential collaboration on creating pilot hydrogen clusters based on depleted fields, where hydrogen can be stored in salt caverns managed by "digital twins" [18; 32].

The issue of fuel quality in Ukraine has traditionally been acute due to a significant share of counterfeit fuel. Industry 5.0 proposes blockchain technology for creating a fully transparent supply chain.

Each batch of oil delivered to a refinery receives a unique digital token. At every stage (refining, main pipeline transport, fuel tanker delivery, and gas stations), data on the chemical composition of the fuel is automatically recorded in a distributed ledger through IoT sensors.

Example of Sinclair Oil (USA): Sinclair Oil (USA) uses blockchain to track commercial transactions and fuel quality. If, at any stage, foreign impurities are added to gasoline, the system instantly detects discrepancies between sensor readings and blocks fuel dispensing at the gas station pump [21; 25].

For Ukraine, this would make it possible to completely eliminate the "grey" fuel market. The end consumer, by scanning a QR code on the receipt, would be able to see the entire fuel pathway-from the well to the fuel tank of their car-including the results of laboratory tests at each stage.

Oil refineries are high-risk facilities. A sudden pump failure or loss of sealing in a reactor unit under high-temperature conditions can lead to a catastrophe. Traditional "schedule-based maintenance" (once per year) is inefficient and costly.

The Industry 5.0 solution is digital equipment twins: for example, at TotalEnergies facilities, thousands of wireless vibro-acoustic sensors are installed on every valve and compressor. Artificial intelligence analyzes the "acoustic signature" of the equipment. If a bearing begins to wear out, the system detects this 2-3 months before an actual failure occurs.

Implementation at Ukrainian facilities: This will allow reducing costs for unplanned repairs by 25% and completely eliminating emergency shutdowns, which is critical during energy shortages. Product quality remains stable, as the equipment always operates in an optimal mode [7; 9].

In the context of Industry 5.0, where every sensor on a well and every valve on an oil pipeline is connected to a global network (IIoT), cybersecurity is no longer merely an IT issue but becomes a fundamental element of industrial safety. For Ukraine’s oil and gas sector, which is a target of continuous hybrid attacks, the protection of industrial control systems (ICS) is a matter of national security [29; 31].

The architecture of Industry 5.0 cybersecurity includes:

1. Zero Trust concept: Unlike legacy systems, where the internal network was considered safe, the Industry 5.0 strategy requires verification of every request to well controllers or refinery valves. Even internal users have access only to their own segment.

2. Artificial intelligence for anomaly detection: Traditional antivirus systems cannot recognize attacks on process logic (for example, when a hacker changes pipeline pressure while the system displays normal readings). Industry 5.0 systems use neural networks that “learn” the normal behavior of equipment. Any deviation of 0.1 seconds in pump operation is treated as a potential attack, and the system automatically switches to a safe autonomous mode [21; 29].

3. Cyber-physical redundancy: Industry 5.0 requires “cold” mechanical backup systems. In the event of a full cyberattack on software, the facility must be designed so that humans can manually take over control of critical nodes of the oil refinery installation [27; 31].

International experience in the implementation of Industry 5.0: lessons for Ukraine.

Experience of Norway (Equinor): safety as a cultural code and technological advantage. The Norwegian company Equinor is considered a global benchmark in the implementation of Industry 5.0. Its concept of “Unmanned Platforms” demonstrates how human risk can be minimized.

Key aspects of the experience:

1. Remote operation centers: Most platforms in the North Sea are controlled from shore. Only robot dogs (for example, produced by Boston Dynamics) are present on the platforms themselves, patrolling the facilities and collecting data on gas leaks and the condition of shut-off valves.

2. Psychological safety: Norwegians were the first to use VR simulators for training personnel in stress situations (fire, attack, explosion). This allows the development of muscle memory and reduces panic levels in real conditions.

Strategic guidelines for Ukraine: After victory, Ukrainian underground gas storage facilities (UGS) and compressor stations should be transferred to a “maximum autonomy” mode with remote control, which would ensure personnel safety in the event of new cross-border threats [6; 30].

Digital transformation of the oil industry in the USA and Canada: the experience of ExxonMobil and Suncor Energy. The North American experience is extremely valuable for Ukraine due to the similarity of challenges-working with depleted fields and the need for deep refining of oil with a high sulfur content.

Case of ExxonMobil – "Cognitive Oilfield":

– The American giant uses supercomputers to process terabytes of seismic data. The main Industry 5.0 innovation here is the use of Generative AI for modeling hydraulic fracturing (fracking). This allows predicting with meter-level accuracy exactly where fractures will form in the rock formation.

– Ukraine's main fields in the Poltava and Kharkiv regions require exactly this type of approach. The use of American algorithms would allow increasing the output of old wells by 15–20% without drilling new ones, which is the most cost-effective way of restoring production [8; 9].

Case of Suncor Energy – Autonomous transport and safety:

– In Canada's oil sands, Suncor has implemented the world's largest fleet of autonomous haul trucks. This is not just automation. It is a Industry 5.0 system where unmanned equipment is coordinated with sensors on the clothing of maintenance workers. If a person enters the blind zone of a machine, all equipment within a 100-meter radius is immediately stopped.

– During the reconstruction of destroyed refineries (for example, Lysychansk or Kremenchuk), the use of autonomous robotic loaders in high-risk zones would make it possible to completely eliminate human casualties during logistics operations [10; 26].

Direct copying of Western technologies in Ukraine is not possible due to specific constraints: destroyed infrastructure, budget shortages, and wartime risks. Therefore, adaptation must follow the model of "Adaptive Implementation" [1; 30].

Transformation stages:

1. Creation of "regulatory sandboxes": Oil and gas companies in Ukraine should be granted the right to test new technologies (for example, drones for pipeline inspection) under simplified regulatory procedures. This is the path taken by the United Kingdom in the North Sea.

2. Public–private partnership in R&D: International companies (Halliburton, Baker Hughes) could provide Industry 5.0 software and equipment in exchange for data and experience gained under extreme wartime conditions. This would create a unique knowledge base that does not exist in any other country in the world.

3. Localization of Industry 5.0 component production: Ukraine should not only purchase sensors or drones. We must develop our own monitoring and protection systems adapted to low temperatures and electronic warfare

interference. This will ensure not only improved oil production quality but also new jobs for Ukrainian engineers [5; 29].

It has been proven that the integration of AI and IoT into the oil and gas complex enables the creation of a predictive management system in which quality and safety are inseparable. The use of robotics and digital twins at extraction and processing facilities reduces the impact of human factors by 80%. It has been established that blockchain technologies are a reliable tool for combating fraud and ensuring transparency in supply chains.

3. Strategies of international integration, economic efficiency, and risks of implementing the Industry 5.0 model

Experience of Norway (Equinor): safety as a cultural code and technological advantage. The Norwegian company Equinor is considered a global benchmark in the implementation of Industry 5.0. Its concept of "Unmanned Platforms" demonstrates how human risk can be minimized.

Conceptual foundations of the experience:

1. Most platforms in the North Sea are controlled from shore. Only robot dogs (for example, produced by Boston Dynamics) are present on the platforms themselves, patrolling the facilities and collecting data on gas leaks and the condition of shut-off valves.
2. Norwegians were the first to use VR simulators for training personnel in stress situations (fire, attack, explosion). This allows the development of muscle memory and reduces panic levels in real conditions.

Strategic implications for Ukraine: After victory, Ukrainian underground gas storage facilities (UGS) and compressor stations should be transferred to a "maximum autonomy" mode with remote control, which would ensure personnel safety in the event of new cross-border threats [6; 30].

Digital transformation of the oil industry in the United States: the ExxonMobil case. ExxonMobil actively implements cognitive AI systems for the interpretation of seismic data. This makes it possible to discover oil in locations where traditional methods indicated "dry" results. For Ukraine, where most fields are considered depleted, the use of American Big Data processing experience may open a "second wind" for the oil and gas industry, enabling the identification of overlooked reservoirs at great depths (over 5-6 km) [9; 14].

Traditional investment evaluation methods (NPV, IRR) in the context of Industry 5.0 must be supplemented with social and environmental return indicators (SROI). The economic efficiency of Industry 5.0 is based not on direct replacement of humans with robots, but on reducing the total cost of ownership (TCO) and preventing catastrophic losses [15; 17].

Mathematical model of predictive value:

The efficiency of implementing predictive maintenance can be calculated using the formula:

$$E_{PM} = (C_{fail} + P_{fail}) - (C_{smart} + P_{maint})$$

де:

C_{fail} – the cost of complete shutdown and repair in the event of an accident;

P_{fail} – the probability of an accident without Industry 5.0 systems;

C_{smart} – the cost of an intelligent monitoring system;

C_{maint} – the cost of preventive maintenance.

Oil and gas industry data: According to statistics from Saudi Aramco, the transition from scheduled maintenance to predictive maintenance has allowed the company to reduce operational expenditures (OPEX) by 15-20% annually, which at Ukraine's scale could mean savings of over 2–3 billion UAH per year only in the gas transportation sector [9; 11].

The implementation of Industry 5.0 is not a "panacea" and is accompanied by specific risks that management must take into account in strategic recovery plans.

1. Risk of "technological dependency": Ukraine may become dependent on foreign suppliers of software and microchips. The solution is the development of domestic defense-industrial clusters (such as Brave1 and others) that create their own electronic warfare and secure communication systems, which can be adapted for the oil and gas sector [10; 16].

2. Human resistance (Luddite effect): Employees may sabotage the implementation of control systems due to fears of job losses. Industry 5.0 management proposes an "Inclusive Change Management" model, where employees receive a share of profits generated through efficiency improvements.

3. Cyber-physical vulnerability: The integration of IT networks with industrial processes creates a "window" for cyberterrorism. It is necessary to establish a sector-specific CERT (Computer Emergency Response Team) dedicated specifically to the oil and gas industry [29; 31].

The realization of Industry 5.0 potential in Ukraine's post-war recovery requires a fundamental change in approaches to personnel management. The key challenge is overcoming the shortage of qualified personnel through the integration of cognitive skills and emotional intelligence into the production ecosystem [11; 15].

Economic justification of investments in human capital and management of personnel risks in the Industry 5.0 ecosystem.

The implementation of the Industry 5.0 model requires a revision of the structure of operating costs, where investments in personnel should be considered a means of increasing economic efficiency and minimizing strategic risks. The greatest risk of Ukraine's post-war recovery is not a lack of capital, but a shortage of qualified personnel. Within the Industry 5.0 model, this risk is mitigated through the transformation of workers' cognitive skills [11; 31].

Economic feasibility and integration advantages are realized in the following directions:

– Optimization of personnel training costs (Lifelong Learning): The use of VR simulators transforms the enterprise into an educational hub, allowing the training cycle of an operator to be reduced from 6 months to 2 weeks. From an economic perspective, this radically reduces the cost of the "entry into profession" period and ensures rapid reintegration of veterans, which is critically important for maintaining production rates [11; 12].

– Expansion of labor market supply through inclusivity: The introduction of exoskeletons and AI-based voice control systems enables the inclusion of people with disabilities and veterans with musculoskeletal injuries. For businesses, this is not only a social project but also a strategy to overcome labor shortages and comply with international ESG (Environmental, Social, and Governance) requirements, which are a mandatory condition for obtaining European investments and loans [13; 31].

– Minimization of losses caused by the human factor: The implementation of systems for monitoring psycho-emotional state and cognitive ergonomics is part of the risk management system. PTSD and chronic stress increase the probability of accidents (Pfail). Automatic schedule adjustment based on AI analysis of worker condition helps avoid critical errors, preventing direct financial losses from production shutdowns (Cfail) [4; 22].

Thus, the transition from resource exploitation to intelligent partnership with the worker ensures sustainable production quality. This makes Ukrainian enterprises investment-attractive for international integration, as their safety and workforce management model fully complies with European future standards.

The implementation of these directions will change the role of the worker: from a "resource for exploitation" they become an intelligent partner of technology. Such a human-centered approach not only ensures production stability but also guarantees the compliance of Ukrainian industry with European safety standards and the humanistic values of the future.

The analysis of international experience has confirmed that adaptive implementation of innovations allows Ukraine to become part of the European energy space. Economic modeling has shown that investments in Industry 5.0 technologies pay off faster due to accident prevention and increased energy efficiency. It has been determined that the key challenge remains cybersecurity, which requires the creation of new national standards for industrial data protection.

Conclusion

The conducted study confirms that the concept of Industry 5.0 is not merely another stage of technological development, but a vital strategy for the survival and revival of Ukraine's industrial potential in the post-war period. The transition from purely digital transformation to human-centered management makes it possible to solve a threefold task: compensate for labor shortages, guarantee the highest level of safety under wartime risks, and ensure flawless product quality for global markets.

The main conclusion of the monograph is that a technological leap (Leapfrogging) is possible only under the condition of synergy between the state, business, and science. The state must create regulatory "sandboxes" for testing Industry 5.0 technologies, business must shift its management philosophy from exploitative to investment-oriented (regarding humans), and science must provide a methodological framework for rapid reskilling of personnel. Ukraine has a chance to become the first country in the world to rebuild its industry "from scratch" according to the principles of the Fifth Industrial Revolution, turning the tragedy of war into a foundation for innovation leadership in Europe.

It has been proven that for Ukraine, Industry 5.0 is not a futuristic concept but the only effective tool for post-war recovery. The transition from "efficiency at any cost" to "resilience and human-centeredness" allows the preservation of human capital - the most valuable asset of the state.

In the oil and gas industry, the implementation of "digital fields" and predictive maintenance will make it possible to compensate for natural resource depletion by 15–20% and reduce the level of technogenic risk to minimal possible values.

A direct relationship has been established between the implementation of intelligent management systems (AI, Blockchain) and the quality of petroleum products. The "digital fuel passport" is a key tool for eliminating the shadow market and integrating into the EU energy system.

Modeling has shown that despite high initial investments, Industry 5.0 technologies pay off within 3-4 years due to reduced accident rates, energy savings, and access to "green" financing.

The post-war industrial model must be based on decentralization and cybersecurity. The use of international experience (Norway, the USA) combined with Ukrainian developments in the field of safety will allow the creation of a uniquely resilient production system.

The issue of occupational safety in the context of post-war recovery acquires a new, tragic dimension. It is not only about protection from industrial accidents, but also about working under conditions of constant mine threats, damaged structures, and psychological trauma among personnel (PTSD). Traditional safety management systems are not designed for such pressures.

Industry 5.0 offers a solution through cobotization and remote control; however, a new problem arises: the mismatch between the qualifications of available personnel and the requirements of high-tech equipment. Massive brain drain and physical losses of the working-age population create a vacuum that cannot be filled by automation alone without a fundamental change in the philosophy of "human–machine" interaction.

The implementation of Industry 5.0 in Ukraine is hindered by the absence of an adapted regulatory and legal framework. Existing national standards (DSTU) and occupational safety regulations are often based on Soviet-era or early industrial standards, which do not account for the use of artificial intelligence, exoskeletons, or autonomous production systems. A legal conflict arises: who is responsible for an error-the AI algorithm developer, the operator, or the enterprise owner? The absence of clear certification protocols for "smart" products creates barriers to export and to attracting foreign investment, which are critical for reconstruction.

Ukraine's post-war industry faces a catastrophic environmental footprint of war. The problem of integrating environmental management into the overall Quality Management System (QMS) is more urgent than ever. Industry 5.0 requires a transition to a circular economy (closed-loop systems), which for many Ukrainian enterprises is an entirely new and financially demanding concept. The problem lies in the lack of incentives for "green" modernization and the weak implementation of real-time emission monitoring systems, which are a basic requirement of the fifth technological paradigm.

Production digitalization according to Industry 5.0 standards (Digital Twins, Cloud Computing) makes industrial facilities vulnerable to cyberattacks. In the context of hybrid warfare with an aggressor state, industrial espionage and sabotage through interference in control systems become daily threats. The problem lies in the low level of cyber hygiene at enterprises and the absence of comprehensive industrial data protection systems, which may lead to technogenic disasters.

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