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SECTORAL PROSPECTS FOR THE IMPLEMENTATION OF QUANTUM TECHNOLOGIES IN INDUSTRY 4.0

ГАЛУЗЕВІ ПЕРСПЕКТИВИ ВПРОВАДЖЕННЯ КВАНТОВИХ ТЕХНОЛОГІЙ В ІНДУСТРІЇ 4.0

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Abstract. *This article examines the sectoral prospects for the implementation of quantum technologies within the paradigm of Industry 4.0 and the digital transformation of industrial systems. The study addresses the growing problem of technological asymmetry and the limitations of classical computational methods in managing complex industrial processes characterized by high uncertainty, large data volumes, and nonlinear dynamics. The research aims to identify the key sectors of Industry 4.0 where quantum technologies—particularly quantum computing, quantum communication, and quantum sensing—can provide significant competitive advantages. The article analyzes the potential application of quantum algorithms for optimization, risk modeling, predictive analytics, logistics, cybersecurity, and advanced materials engineering. It also evaluates institutional and infrastructural constraints affecting quantum technology adoption, including the lack of skilled human capital, high implementation costs, and regulatory uncertainty. The findings demonstrate that the integration of quantum technologies into industrial ecosystems will be uneven across sectors, with the highest potential in finance, energy, logistics, pharmaceuticals, and advanced manufacturing. The study concludes that the successful deployment of quantum solutions requires a hybrid technological architecture combining classical and quantum systems, as well as coordinated policies in innovation governance, investment, and education.*

Key words: *quantum technologies, Industry 4.0, quantum computing, digital transformation, industrial ecosystems, quantum optimization, cyber-physical systems.*

Анотація. *У статті досліджуються секторальні перспективи впровадження квантових технологій у парадигмі Індустрії 4.0 та цифрової трансформації промислових систем. Розглядається проблема технологічної асиметрії та обмеженості класичних обчислювальних методів у керуванні складними виробничими процесами, які характеризуються високим рівнем невизначеності, великими обсягами даних і нелінійністю динаміки. Метою дослідження є визначення ключових секторів Індустрії 4.0, у яких квантові технології — зокрема квантові обчислення, квантові комунікації та квантові сенсори —*

можуть забезпечити суттєві конкурентні переваги. У статті проаналізовано можливості використання квантових алгоритмів для оптимізації виробничих процесів, моделювання ризиків, прогнозної аналітики, логістики, кібербезпеки та розробки нових матеріалів. Оцінено інституційні та інфраструктурні бар'єри впровадження, зокрема дефіцит людського капіталу, високу вартість технологій і регуляторну невизначеність. Доведено, що впровадження квантових технологій матиме диференційований характер за секторами, з найбільшим потенціалом у фінансах, енергетиці, логістиці, фармацевтиці та високотехнологічному виробництві. Обґрунтовано необхідність формування гібридної технологічної архітектури та інноваційної політики для ефективної інтеграції квантових рішень.

Ключові слова: *квантові технології, Індустрія 4.0, квантові обчислення, цифрова трансформація, промислові екосистеми, квантова оптимізація, кіберфізичні системи.*

Introduction. Modern Industry 4.0 is characterized by the integration of cyber-physical systems, big data, artificial intelligence, and the Internet of Things. However, the growing complexity of industrial systems and the increasing volume of data create limitations for traditional computational approaches, thereby reducing the efficiency of management, forecasting, and optimization processes. The core problem lies in the need to transition to new computational paradigms capable of processing complex multidimensional systems in real time. Quantum technologies represent a potential response to these challenges; however, their implementation remains uneven, insufficiently explored, and requires a systematic sectoral analysis. This issue is directly related to key practical objectives: improving the efficiency of industrial production, ensuring technological sovereignty, developing innovation ecosystems and strengthening cybersecurity and infrastructure resilience.

The purpose of this article is to identify the sectoral prospects for the implementation of quantum technologies within the Industry 4.0 framework and to substantiate the economic feasibility of their application for enhancing the efficiency, security, and innovativeness of industrial ecosystems.

Literature review. The issue of quantum technologies in industry has been actively explored in contemporary research. A significant contribution to the development of quantum financial and industrial applications has been made by R. Orús, S. Mugel, and E. Lizaso, who substantiated the potential of quantum algorithms for optimization and modeling tasks. The development of digital financial and innovation ecosystems has been studied by D. Arner, R. Buckley, and D. Zetzsche, who emphasize the role of regulatory innovation and fintech infrastructure**.** Issues related to quantum machine learning and new computational models are addressed in the works of V. Havlíček and other scholars. At the same time, contemporary literature still lacks sufficient research on the sectoral dimension of quantum technology implementation within Industry 4.0, particularly from the perspective of economic efficiency, implementation risks, and institutional barriers. These aspects constitute the scientific novelty and research focus of the present study.

Main results of the study. The quantum economy (Q-economy) as a new phenomenon of the 21st century generates not only multifaceted impacts on the industrial systems of developed countries, but also creates new opportunities for their further development through the introduction of effective innovative business processes based on quantum computers (QC), quantum computing, quantum technologies, artificial intelligence (AI), and corresponding business models. Owing to quantum technologies, more accurate tools for trading, analytics, and forecasting are emerging in various spheres and sectors of the economy. At present, the most "quantum-oriented" industries that are rapidly shaping the international quantum market and the Q-economy include information technology, the financial sector, medicine, transport and logistics, energy, and geological exploration. The management segment is also highly receptive in the context of using quantum computing for planning and optimization of production and business processes, as well as risk analysis and forecasting.

The peculiarities of the development of the ***information technology*** sector in the context of quantum computing are determined by the capabilities of quantum computers and their systems to counter modern cyber threats (methods of breaking classical ciphers bypassing conventional information protection methods), the level of sophistication of digital infrastructures, and the power of quantum AI models. Today, cyber threats are associated with *(PostQuantum, 2024)*:

1) intrusion of malicious actors into corporate computer systems and theft of personal customer data, which causes not only a loss of consumer trust but also significant regulatory fines (for example, in the EU, violations of data protection can result in fines amounting to a percentage of a company's annual turnover);

2) digital fraud schemes capable of halting the operation of entire enterprises or offices, where a cyberattack can completely paralyze company activities;

3) personnel/employees who, sometimes lacking basic cybersecurity knowledge, may inadvertently "open the door" to attackers by clicking on suspicious links or downloading infected files. At the same time, modern IT systems have become so complex that even specialists cannot always quickly identify all vulnerabilities and "holes" in security systems;

4) the activities of international criminal groups operating across different countries and regions, exploiting gaps in international law and complicating the work of law-enforcement agencies, thereby making the fight against cybercrime more difficult.

Modern approaches to post-quantum cryptography (*PQC*) and information protection are also linked to the fact that quantum computers are capable of breaking traditional encryption, posing a threat to the protection of personal, corporate, and state data. Quantum key distribution (*QKD*) uses the property of entanglement to guarantee channel security (any attempt at eavesdropping disturbs the quantum state and is quickly detected). This creates the need to develop legislative regulations governing the use of quantum technologies, ensuring security and addressing ethical aspects of healthcare and personal privacy. Moreover, the development of software for quantum computers separately requires a system for protecting intellectual property rights, clear legal frameworks for license distribution, etc. *(Kosobutsky, 2022)*. In addition, since security is ensured through the creation of cryptographic methods resistant to quantum attacks in order to protect information systems from potential threats, cybersecurity issues are moving into the domain of national security and require coordination at all levels of protection of critical infrastructure.

In the segment of AI and machine learning (*QML*), quantum models accelerate clustering and search in large optimization parameter spaces and cost/loss functions, as well as the processing of large and weakly structured data using algorithms such as *Quantum SVM*, *Quantum PCA*, and *Variational Quantum Classifiers*. Practical applications are still limited by the size of existing quantum computers, but this direction is actively developing. As for the modeling of complex systems, quantum computers have the greatest potential because quantum systems naturally model other quantum systems: chemical reactions, materials (superconductors, catalysts), molecular structures for pharmaceuticals, and physical processes in nanotechnology. This implies the creation of new materials for chips, modeling electronic components, and optimizing their architectural solutions *(Opryshchenko, 2025)*.

The current stage of quantum computer development is referred to as *NISQ* – "noisy intermediate-scale quantum" devices. Quantum networks and telecommunications as structural elements of IT infrastructure include quantum internet networks and hybrid classical-quantum cloud services at the first threshold level. At this level, leading companies such as *IBM Quantum, Google Quantum AI, Microsoft Azure Quantum*, and *Amazon Braket* are testing "quantum *VPNs*" based on *QKD* and providing *Quantum-as-a-Service* solutions that allow the use of quantum algorithms without additional investment in new and expensive equipment. In the medium term, quantum computing in cybersecurity, telecommunications, AI, modeling of new materials for IT, and optimization of logistics and resources will become a significant part of hybrid infrastructure alongside classical supercomputers.

Competition in the field of AI accelerates the development of quantum computing, as the capabilities of hybrid systems that combine "classical AI" algorithms and quantum computing are increasing. In turn, quantum computing technology accelerates the improvement of AI through cloud services, which in the future will be applied in various directions and will influence the development of this segment. For example, this concerns the use of AI in the creation of autonomous vehicles (experts estimate the total value of this direction over the next five years at USD 110–210 billion *(McKinsey & Company, 2024)*), as well as the combination of high-precision quantum sensors and AI in cytology and the creation of new medical equipment for diagnostics and treatment. Materials science is also developing by modeling molecules and chemical reactions with a precision unavailable to classical computers (solving complex mathematical problems based on differential equations).

At present, the development of the IT sector, as well as the emerging industry of quantum AI technologies in general, is associated with an acute shortage of personnel and highly qualified specialists. Therefore, for the practical application of quantum technologies it is critically important to overcome the "talent gap" – to build an effective system for training specialists for the new industry (future quantum innovators whose qualifications combine physics, computer science, mathematics, and engineering). With the development of quantum technologies, various architectures and platforms have emerged, each with its own features (technological, commercial, and software-related) and used for solving different tasks. The main quantum platforms are created by key players in the quantum computing market – *IBM Quantum, Google Quantum, Rigetti Computing, IonQ, D-Wave Systems, and Quantinuum* – and include modular systems and superconducting quantum integrated circuits, cloud services through which quantum algorithms can be executed, and developed ecosystems with clear roadmaps toward fault-tolerant quantum systems. This means that the "quantum future" for the IT sector may be hybrid: classical computers + quantum computers + various types of quantum equipment together with quantum platforms *(Spinquanta, 2025)*.

In the modern ***financial sector*** of developed economies, quantum technologies (quantum computing and quantum algorithms), on the one hand, significantly accelerate the calculation of the value of derivative financial instruments and services, revolutionize algorithmic trading management, and improve traditional methods of risk control and management. On the other hand, they rapidly process and analyze large volumes of data from complex financial operations and optimize investment portfolios in accordance with current market pricing. Leading banks in developed countries are intensively introducing experimental testing systems aimed at minimizing financial risks (this is especially important for two types of portfolios: mortgage loans and treasury bills). It has been proven that quantum-AI-based computing technologies allow only a few dozen required simulations instead of thousands or millions in the case of classical computing *(Orson, 2025)*. This makes it possible to more effectively prevent fraud in any form and detect anomalies such as unexpected changes in stock prices.

Leading financial institutions that are currently actively investing in the development of quantum solutions (portfolio optimization, risk modeling, the integration of quantum computing and AI) as of 2025 include *JPMorgan Chase, Goldman Sachs, HSBC*, and *Barclays*. For example, *JPMorgan Chase* has its own department and team of specialists in quantum research and cooperates with QC Ware in the segment of developing "deep hedging" – a quantum-classical approach for hedging derivatives, structuring into a single system quantum methods for risk modeling, option valuation, and machine learning. *Goldman Sachs*, cooperating with quantum startups and providers, invests in research into quantum algorithms for building pricing models of complex financial instruments – options and derivatives *(Entangled Future, n.d.)*.

HSBC, as one of the recognized leaders in the financial sphere in terms of implementing quantum technologies, is actively investing in quantum-secure communications (*QKD*) and asset tokenization. In 2025, together with *IBM*, it implemented a pilot project, the results of which showed that a hybrid quantum-classical algorithm improved the accuracy of forecasting bond order-fill conditions by approximately 34% *(Elizadeh et al., 2024)*. As for *Barclays*, the bank, also in partnership with *IBM*, created a "brain trust" consisting of physicists, mathematicians, and programmers to study quantum algorithms for optimizing settlement calculations.

Currently, for banks, the key areas in which quantum approaches are actively researched, adapted to business processes, and implemented as pilot projects are the following:

1. ***Portfolio optimization and trading strategies.*** Quantum optimization algorithms (for example, QAOA), which significantly accelerate the solution of problems with a large number of variables, are used for: optimizing portfolio structure taking into account risk; selecting the most effective assets; forming rebalancing strategies; routing and optimizing trade execution.
2. ***Risk management.*** Quantum methods enable accelerated calculation of VaR, CVaR, and stress-testing scenarios, while quantum computing accelerates the modeling of complex dependencies between assets.
3. ***Modeling and valuation of derivatives.*** Quantum algorithms accelerate Monte-Carlo

simulations used for option pricing, evaluation of complex structured products, and quantitative analytics.

4. ***Cryptography and cybersecurity.*** Quantum-secure communications (QKD) for banking transactions and internal communications, and preparation for the PQC era to ensure protection against future quantum attacks.

5. ***Fraud detection and anomaly detection.*** Quantum machine learning models (QML) improve anomaly classification, recognize patterns in transaction data, and contribute to combating money laundering (AML).

6. ***Algorithmic trading and market forecasting.*** Quantum ML models improve time-series forecasting, increase signal accuracy, and accelerate models with high-dimensional data.

7. ***Portfolio insurance and actuarial calculations.*** Quantum models optimize not only forecasting of insurance risks, but also insurance reserves and actuarial scenarios.

From these seven key areas, four main directions of the use of quantum technologies by banks in modern conditions should be highlighted *(Byrum, 2025)*. First, quantum cryptography (*QKD*) for protecting channels for transmitting financial information from unauthorized interception based on quantum mechanics principles. A number of well-known banks – *Bank of China, BBVA, HSBC, JPMorgan Chase* – have already carried out pilot projects related to quantum cryptography in cooperation with *ID Quantique, Toshiba Quantum*, and *ZTE Quantum Lab*.

Second, quantum machine learning (*Quantum ML*) for processing large volumes of financial data to detect fraud, calculate risks, credit scoring, dynamic pricing, and algorithmic trading. *Goldman Sachs* together with *IBM Quantum* studied the use of quantum computing for pricing complex derivatives, while *Barclays* already applies quantum algorithms to portfolio optimization tasks.

Third, quantum optimization for finding the best financial strategies, investment decisions, logistics, and resource allocation. Classical optimization methods require large computational power, whereas quantum algorithms (such as *QAOA* or *Grover's search*) significantly accelerate such calculations. *JPMorgan Chase* together with *D-Wave* is actively researching portfolio optimization, while *BBVA* tests quantum optimization in corporate banking.

Fourth, *PQC* algorithms resistant to quantum attacks, used to upgrade the entire digital security infrastructure of banks before quantum computers become a threat. *HSBC* and *Deutsche Bank* are already testing post-quantum algorithms as replacements for *RSA* and *ECC* (together with *NIST, Microsoft*, and *IBM*).

Currently, leading banks create simulations of unstable markets that account for nonlinear probabilistic factors (quantum market modeling), use quantum classifiers (*QNN, QSVM*) to detect atypical transactions (fraud), hybrid quantum-classical ML models to analyze customer behavior (AI consulting), and partnerships with leading quantum companies. For example, *JPMorgan Chase* partners with *IBM* and *D-Wave* in quantum optimization and derivatives pricing; *Multiverse Computing* works with *BBVA* on “portfolio optimization on quantum processors”; *HSBC* together with *BT* and *Toshiba* develops QKD projects for secure communications; *IBM Quantum* and *Goldman Sachs* cooperate on QML for financial models; next-generation cryptography is developed jointly by *Standard Chartered* and *ID Quantique (Zhou, 2025).*

Such active cooperation is due to the fact that the banking sector is highly concerned that quantum computers may break *RSA, ECC*, and *TLS* encryption, making critical information vulnerable. The full migration to new ciphers (including quantum-secure protocols) is estimated to take 5–10 years. In general, banks use quantum technologies both for innovation and for self-protection, investing in *QKD, QML*, optimization, and the development of quantum-resistant infrastructures, since the second quantum revolution will transform everything – from encryption to financial decision-making.

The potential advantage of quantum approaches over classical ones in efficiently solving financial problems—such as portfolio optimization and derivatives hedging—lies in the following *(Ko & Lee, 2025)*.

In the classical approach to ***portfolio optimization***, classical quadratic programming is used (for example, minimizing risk at a given return within the mean–variance framework) together with classical algorithms whose computational complexity increases sharply in the presence of nonlinear constraints such as transaction costs, rebalancing, and risk considerations when scaling to many assets. In addition, Monte Carlo simulations (used for risk assessment) typically require a large number of iterations, especially for high-precision estimates, which becomes computationally slow in high-dimensional settings.

Under a quantum approach, the *QAOA* algorithm formulates portfolio optimization as a quadratic unconstrained binary optimization (*QUBO*) problem and searches for the optimum potentially faster and more effectively under complex (including hybrid) constraints. Compared to classical approaches, some hybrid quantum solutions have already demonstrated competitive results even on limited quantum hardware. Thus, the potential advantage of the quantum approach lies in its ability to process more complex constraints with fewer trade-offs in speed, even when combined with classical computing platforms. At the same time, real quantum advantage is not guaranteed in all cases, especially for small or well-structured problems where classical solutions are already highly efficient.

With regard to ***derivatives hedging***, the classical approach relies on stochastic models (e.g., the Black–Scholes model, delta-hedging models, or more complex multifactor models) combined with classical machine learning methods such as reinforcement learning (*RL*). However, classical *RL* faces limitations: training an agent that accounts for transaction costs, nonlinear markets, and liquidity risk is a complex and computationally expensive task. Within a quantum-classical (actor–critic) framework, the search and evaluation of hedging strategies are performed with a quantum component, whose solutions demonstrate significantly higher quality (for example, more accurate hedging with lower error) compared to classical approaches. Even at the current stage of quantum technology development, hybrid quantum-classical models can better capture complex market factors—such as liquidity, nonlinearity, and transaction structures—than simplified classical models. In the medium term, with the development of quantum computing, quantum infrastructure, and cloud-based access via *APIs*, such an approach is expected to provide a real competitive advantage in derivatives hedging.

The use of quantum computing in the context of modern mortgage lending markets is of particular interest to banks and other financial institutions, as it enables the solution of a wide range of tasks: (a) real estate pricing and valuation of mortgage collateral; (b) forecasting changes in real estate markets; and (c) more accurate risk calculations in mortgage lending, including the selection of optimal scoring models and default probability forecasting *(Myronchuk et al., 2024)*. Another potential application of quantum technologies is the development of more efficient project management systems for residential construction.

In addition, several important advantages arise from the use of quantum computing. First, there is a significant increase in the security of mortgage lending operations through the use of advanced encryption methods that ensure the protection of clients' personal data against unauthorized access. Second, quantum approaches enable the creation of individualized lending programs for each borrower, determining the maximum loan amount that can be granted with minimal risk to the bank, thereby reducing errors in risk calculations and improving overall operational efficiency. Third, the optimization of banking systems through nonlinear optimization based on *Grover's algorithm* can accelerate mortgage approval processes, while the use of blockchain technologies enables secure recording of all stages of loan issuance and repayment. This creates a transparent accounting system for transactions between banks and clients and reduces opportunities for borrower fraud.

Quantum technologies are no longer viewed merely as a distant prospect, but rather as an integral component of banking cybersecurity strategies. Although quantum computing has not yet been widely implemented across all banking processes, concrete research initiatives and pilot projects are already underway. This indicates that European banks are preparing for the future active deployment of quantum hardware, quantum computing, and quantum algorithms. Today, the European Union and European financial institutions are taking quantum readiness very seriously, particularly in the field of cybersecurity – through forums, conferences, and cooperation among central banks. Banks are exploring quantum technologies, testing transaction models, and researching quantum key distribution (*QKD*) and post-quantum cryptographic algorithms with strategic investment support from supranational institutions (for example, the *European Investment Bank* promotes the development of quantum companies to build an ecosystem that can positively impact the financial sector). While significant challenges remain, there is a clear understanding that the "quantum era" in finance is not a question of "if," but of "when."

According to an optimistic forecast scenario for the development of the banking sector for 2035–2040, the 2Q revolution will achieve the following *(PostQuantum, 2024)*:

- ***Absolute communication security*** – through quantum cryptography: all major banks will transition to *QKD* connections between headquarters, data centers, and exchanges. Client transactions will be encrypted using post-quantum algorithms approved by the *NIST standard* (e.g., *CRYSTALS-Kyber, Dilithium*). Information breaches will become physically impossible—any eavesdropping attempt alters the quantum state of the key, and the system signals an attack.
- ***Quantum asset management optimization***: banks will utilize quantum optimization algorithms (*QAOA, VQE*) for portfolio and risk management, dynamic hedging, and real-time liquidity analysis. Calculations that previously took hours or days on supercomputers will be performed in seconds on a quantum chip. For example, banks will be able to calculate an optimal portfolio of 1,000 assets in real time, taking into account macroeconomic shocks and client constraints.
- ***Quantum machine learning (QML) → personalized banking AI***: client analytics will operate on hybrid quantum-classical neural networks capable of understanding behavioral patterns, emotions, and client preferences. AI assistants in banks will recommend investment products that align not only with income but also with the client's values, forecast future solvency using quantum probabilistic models, and detect fraudulent actions before they become visible.
- ***Quantum-resilient banking infrastructure***: all internal bank protocols will be built on post-quantum cryptographic algorithms; smart contracts, blockchain, and tokens will account for quantum threats, and networks will self-assess for quantum influence (e.g., via random fluctuations linked to quantum noise).
- ***Quantum-accelerated trading***: algorithmic trading will run on specialized quantum processors. Arbitrage strategies will be implemented faster than classical algorithms, leveraging the parallel superposition of possible market scenarios. Banks without a quantum processor will lose revenue due to slower algorithmic execution.
- ***Financial forecasting = quantum simulation***: economic scenarios will no longer be constructed manually; quantum simulations will model market collapses, the impact of climate change on global finance, cryptocurrency instability, and the effects of wars, migration, and pandemics within a complex nonlinear environment.

New banking professions will emerge, such as quantum financial analysts (designing quantum risk and return models), quantum crypto-architects (ensuring quantum-resilient bank security), *QML*-engineers (developing hybrid quantum-classical AI for banking services), quantum simulator operators (creating future financial simulations), and quantum asset trust managers (managing assets built on quantum cryptography). Overall, the banks of the future will be a hybrid of quantum physics, AI, and financial ethics, with the most successful financial institutions being those that begin preparing for the quantum transition today.

Quantum technologies also have the potential to radically transform the ***medical sector*** – from drug development at the atomic level with specified properties to diagnostics and data protection. Quantum computing creates new opportunities, first, for discovering novel treatments, including personalized therapies aligned with a patient's genetic profile; second, for rapid diagnostics and chemical reaction modeling in the near future with initial practical applications; third, for developing measures against viruses, oncological and autoimmune diseases, protein folding simulations, and advancing therapies for neurodegenerative disorders such as Parkinson's and Alzheimer's, currently considered incurable. The prospects for quantum technologies in medicine are substantial, although most remain in active research and prototype stages. Key breakthrough directions in applying quantum approaches to medicine include *(Alrashed, 2025)*:

a) ***Quantum computing for drug discovery*** – QC is already capable of modeling molecules and chemical reactions at levels unreachable by classical supercomputers. Potential benefits include accelerated discovery of new drugs (precise modeling of proteins, enzymes, and drug interactions), optimization of drug structures, and prediction of side effects and interactions. This could reduce drug development time and cost from 10–15 years to 2–3 years.

b) ***Quantum sensors for diagnostics*** – highly sensitive to magnetic and electric fields, temperature, or gravitational changes, enabling next-generation ultra-precise *MRI* (quantum magnetometers based on *NV* centers in diamonds) and early detection of oncology or neurodegenerative diseases through nanoscale biomarkers. In the future, quantum sensors may detect neuronal electrical activity at the single-cell level without invasive implants. Although still experimental, mass adoption is expected within 5–7 years.

c) ***Quantum biology*** – a young field studying quantum effects in biological systems, enabling the use of quantum technologies to understand photosynthesis mechanisms, bird migration, new therapeutic methods (e.g., through effects on quantum processes in proteins), and ultra-precise models of cellular processes, including *DNA* mutations. Significant progress in quantum molecular modeling is expected over the next 8–10 years.

d) ***Quantum cryptography for medical data*** – ensuring fully secure communication channels (*QKD*) between hospitals, safe telemedicine, secure medical cloud systems, and protection of large medical AI systems from cyber threats.

e) ***Quantum modeling of the human body using QC*** – enabling more accurate protein folding simulations than AlphaFold, real-time cellular reaction modeling, and personalized predictions of patient responses for diagnosis and treatment (next-level personalized medicine).

Today, medical information (electronic patient records, examination results, telemedicine data, and personalized therapy data) is among the most valuable assets for hackers—on the "black" market, it sells for higher prices than banking data. According to research, within 5–10 years, powerful quantum computers will be capable of breaking classical ciphers (*RSA, ECC*), making it essential to update medical systems with quantum-resistant measures today. Commercial *QKD* systems are beginning to be integrated into medical data centers. *QKD* makes communication channels between hospitals virtually unbreakable, enabling secure transmission of diagnostic images, protecting AI models from theft, and preventing falsification of medical data *(Chow, 2024).* Currently, large hospitals and research centers in the *PRC* are transitioning to cloud platforms with AI modules, while video consultations, test result transfers, and remote surgery rely on quantum-protected channels to prevent information leaks.

At present, QC can model complex molecular processes involved in cancer diagnostics, such as drug interactions with oncogenic proteins (e.g., *p53, KRAS*), enabling the discovery of new compounds that block mutational pathways and accurately predict toxicity. This is achieved through accelerated testing of thousands of molecular variants (with higher precision than classical simulations) and personalized drug selection for specific tumor genotypes. Companies such as *Roche, Amgen*, and *Pfizer* are already using quantum simulators to study oncological drugs, and quantum magnetometers (e.g., sensors based on *NV* centers in diamond) capable of detecting: a) single protein markers; b) minimal changes in tissue magnetic properties; c) nanoparticles binding to oncomarkers. This allows preventive detection of tumors at an early stage—when they consist of only a few hundred cells, rather than millions *(Liu, 2025).*

Quantum sensors already play a leading role in magnetoencephalography, measuring magnetic fields generated by the human brain to determine the precise location of magnetic signals in the body. Potentially, this allows early diagnosis of brain tumors and oncology, Alzheimer's syndrome, or epilepsy without tissue sampling, and more accurate disease monitoring at cellular and molecular levels than existing methods. In real time, quantum dots are experimentally used to deliver drugs directly into cancer cells, while controlled nanostructures facilitate photodynamic therapy. Additionally, quantum effects in DNA are being studied for their impact on mutation and repair processes *(Magesh et al., 2024).*

In fact, quantum computers, thanks to their ability to operate on quantum states, have significant potential for modeling proteins (including oncogenic proteins) and the electronic structure of molecules. Quantum algorithms (e.g., *Variational Quantum Eigensolver, VQE*) allow identification of fundamental energy states of molecules (electronic configurations) and more accurately reproduce generative design of new molecules (ligands), assessing their stability, binding energy with proteins, and potential efficacy. In other words, AI and quantum computing are combined: AI generates new molecules (ligands), which are then evaluated by a quantum algorithm for their viability *(Yingngam & Khang, 2024).* Using hybrid quantum computing, startups in medical R&D are developing advanced protein design methods that surpass classical approaches.

Thus, quantum approaches in medicine and microbiology can model protein dynamics –

altering shapes and electron motion—particularly important for “hard-to-target” proteins, such as those with conformational changes or complex microenvironments. Quantum models can also be used for pre-screening large molecular libraries to identify the most promising candidates for further laboratory testing, reducing experimental load and accelerating drug discovery. For example, in 2025, researchers at the University of Toronto and Insilico Medicine generated molecules targeting the *KRAS* oncoprotein, previously considered “undruggable,” using a hybrid AI + quantum computing approach *(University of Toronto, 2025)*.

Although the current stage of quantum technology in medicine is relatively early, its potential is significant. Experts in quantum medicine estimate approximate implementation timelines as follows: a) quantum diagnostic sensors – 3–7 years; b) quantum drug discovery – 5–10 years; c) quantum treatment methods – 10+ years; d) full-scale quantum cellular modeling – approximately 10–20 years *(Market Research Future, 2025)*.

As the healthcare sector rapidly moves toward cloud storage and data transmission, the risk to patient privacy increases. Modern cryptography, from passwords to financial systems, can be broken with sufficiently powerful quantum computers. Consequently, quantum technologies now offer a secure, unauthorized-access-resistant approach (quantum-safe cryptography) to support safe data transmission on electronic healthcare platforms. This method, in the context of a potential shift to quantum computing paradigms, demonstrates a genuine strategy for effective steganography of medical files, providing high resistance to data loss attacks *(Bera et al., 2025)*. The advantages in improved forecasting and speed offered by quantum computing create opportunities for breakthrough discoveries. While quantum computing cannot yet fully secure medical data, the technology already presents clear use cases requiring innovative thinking and enabling competitiveness in a rapidly changing business environment alongside classical medical methods.

In summary, quantum technology and quantum models in medicine: a) revolutionize the development of novel drugs and therapeutic methods; b) accelerate research processes for creating effective drugs; c) reduce diagnostic costs and improve accuracy; d) shorten development time and expenses by modeling molecular interactions at the quantum level; e) enable the design of personalized treatment plans using quantum analysis methods, considering patient-specific biological features based on genetic and biomarker information. Essentially, this represents a technological breakthrough in understanding biological processes at the molecular level, accelerating the development of new drugs.

Quantum technologies are beginning to be actively applied in ***logistics*** and supply chain management, fundamentally transforming this segment of the economy by making it more efficient (reducing costs and improving customer service), more flexible (managing inventory through forecasting), and less expensive (reducing delivery times and costs, optimizing logistics routes in real time). In the context of quantum research, time savings become almost decisive – not only in production but also directly in the execution of logistics business operations. Overall, for modern business, time is the most valuable resource, and when it comes to time management, quantum computing is applied simultaneously across multiple areas, significantly increasing efficiency while ensuring consistent results.

The application of quantum technologies in logistics and supply chain management is still at an early stage, but several promising directions for implementation have already been identified *(Dutta et al., 2025, pp. 110–143)*.

Today, one of the most important areas is solving complex optimization problems, such as optimal allocation of transport vehicles, finding the shortest or most cost-effective routes, and dynamically rerouting in cases of traffic congestion, delays, or accidents. Quantum algorithms (e.g., *QAOA*) can potentially find optimal solutions much faster than classical methods, especially for very large datasets. Additionally, in the optimization of operations at ports and hubs, modeling includes ship and cargo queues, efficient allocation of cranes and personnel, and rational planning of loading and unloading operations, potentially reducing delays and increasing port throughput.

Secondly, inventory management benefits from quantum modeling of vast multidimensional scenarios and optimization of stock levels across complex networks, objectively reducing storage costs and helping to prevent shortages. This is particularly effective for global companies with large SKU counts and unpredictable demand. Quantum simulations can process large models more quickly, including: a) demand forecasting considering economic and social factors; b) real-time modeling of transport flows; c) fleet management for autonomous vehicles and equipment.

Thirdly, planning global supply chains—which are extremely complex systems with numerous variables (delivery times, risks, customs clearance, weather conditions) – can be enhanced by quantum models that forecast supply disruptions, simulate alternative routes, and optimize supplier selection and interactions. Moreover, quantum technologies encompass not only computation but also quantum cryptography, providing: 1) secure information exchange between logistics centers; 2) prevention of data interception (*QKD*); 3) enhanced security for drones, autonomous trucks, and "smart" warehouses.

Leading companies in the global quantum logistics market actively experimenting with quantum and quantum-inspired solutions include three avant-garde players: *DHL, Toyota & Fujitsu*, and *Einride & IonQ*. For example, *DHL* collaborates with Terra Quantum on hybrid optimization solutions for routing and reducing terminal idle time, and with Honeywell on quantum algorithms for load optimization, multimodal route planning, and supply chain disruption management. *Toyota & Fujitsu* use the "*Digital Annealer*" (quantum-inspired optimizer) and the *QAmplifyNet* model (hybrid quantum-classical neural network) for optimizing transport routes, forecasting delays and backorders in the supply chain, and production planning *(Quantum Horizon, 2025)*.

Regarding the current state of quantum technologies in logistics, companies such as *FedEx, Volkswagen, BMW, Maersk*, and others are testing logistics solutions within pilot projects—applying quantum algorithms to specific supply chain resilience optimization tasks (route optimization, demand forecasting, and quantum data security). However, the current stage is limited by the development of necessary hardware (quantum processors) for widespread adoption. Today, companies are collaborating on using quantum computing to optimize autonomous vehicle routing and enhance logistics business process efficiency. For instance, within the EU, a quantum-optimized traffic management system is being developed to provide "ultra-fast and environmentally safe routes" for public transport by *Volkswagen* and *D-Wave*. Its features include: first, reducing passenger wait times by minimizing long-distance trips without passengers; second, since transport is currently the largest source of greenhouse gas emissions, the system benefits both passengers and drivers while reducing environmental impact by selecting the most efficient routes.

Currently, most real-world projects in the *PRC* logistics market are pilot projects or research initiatives, with full-scale commercial deployment remaining limited. Significant technological barriers (hardware, integration) and investment in quantum initiatives are treated as conditions for the long-term strategies of major logistics companies. Additionally, not all logistics optimization problems are suitable for quantum algorithms, requiring careful assessment of where to implement quantum solutions. At the same time, due to existing limitations of current quantum computers, many companies employ "quantum-inspired" or hybrid models, which can already provide benefits today – the primary economic effect is realized through reduced costs (fuel, time, idle periods) and increased flexibility (responding to changes).

Meanwhile, implementing and integrating quantum solutions into existing logistics IT systems (*ERP, WMS*) is a complex task. This is not only because current quantum computers are still insufficiently powerful with limited coherence times, but also because quantum computing remains costly (especially for demonstration projects), there is a shortage of specialists knowledgeable in both logistics and quantum algorithms, not all logistics problems are suitable for quantum algorithms, and classical algorithms are already proven and sufficiently effective for "traditional" logistics companies *(Phillipson, 2025)*.

The implementation of quantum technologies in logistics is expected to lead to significant shifts in the labor market, as traditional professions gradually become obsolete, giving way to roles requiring specialized knowledge in physics, programming, and engineering. These include positions such as quantum logistics programmers and engineers specializing in quantum cryptography for logistics, which implies investments in education and professional training. Today, several major international logistics companies are already investing in the development of "quantum qualifications."

Thus, quantum technologies hold significant potential for the logistics sector, particularly in combinatorial optimization, routing, scenario simulation, and security. Currently, they complement rather than replace classical systems, meaning that through hybrid approaches, many companies are already realizing benefits. The most successful cases demonstrate not just improvements but real economic value, including cost reduction, increased efficiency, and enhanced supply chain resilience. Therefore, for modern logistics companies, investing in research and pilot projects now is crucial to be prepared for the moment when quantum technologies mature.

QC provides fundamentally new opportunities for the ***energy sector***, spanning production, storage, system optimization, and security enhancement. A key feature of using quantum technologies in modern energy systems – which are complex networks with numerous variables (demand, generation, prices, losses, balancing) – is the application of quantum computing for system optimization. This involves not only optimizing energy distribution (reducing network losses, identifying the most efficient transmission schemes, dynamic balancing amid demand fluctuations) and the operation of power plants and energy blocks (sequencing unit activation/deactivation, reducing costs, and increasing efficiency) but also managing smart grids: scheduling autonomous sources, forecasting and responding to renewable energy generation fluctuations, and rapidly modeling emergency scenarios.

Monitoring and quantum cryptography for energy networks have become a critical area where quantum computing is gaining priority. This includes quantum sensors, which are far more sensitive than classical sensors and have applications ranging from real-time detection of defects and overloads to precise monitoring of voltage and current. Quantum magnetometers are used to monitor energy infrastructure, detect microcracks in turbines, oversee pipelines, and enhance nuclear power plant safety. Quantum key distribution (*QKD*) protects network management from external attacks, prevents interception of communications between facilities, and ensures secure communication among dispatch centers, substations, and sensor nodes. This is particularly important for smart grids, which involve millions of interconnected devices *(Fazilat & Zioui, 2025)*.

Promising optimization of renewable energy generation (*RES*) is being carried out using quantum algorithms, which in the near term will help: a) model wind flows and solar insolation; b) optimize the placement of solar and wind power stations; c) forecast *RES* output with high accuracy; d) improve stability in networks with a high share of renewable energy. A “top ten” group of companies has already emerged in the global energy market, investing heavily in quantum R&D for the energy sector and conducting pilot projects:

- *Chevron and ExxonMobil* (quantum chemistry research for fuel and hydrogen).
- *BMW* and *BASF* (new materials for batteries and accumulators).
- *Siemens Energy* (quantum simulations and sensors for energy networks).
- *EDF* and *EON* (Smart Grid optimization using quantum algorithms).
- *Honeywell* (quantum cryptography for energy infrastructure).
- *IBM* and *Google Quantum AI* (modeling catalysts and materials for energy applications).

The advantages of quantum technologies for the energy sector include rapid solution of complex multifactor optimization problems that are difficult for classical systems, increasing efficiency in energy transmission and distribution, reducing network losses and operational costs, and enhancing overall infrastructure security. Since not all energy problems have yet achieved “quantum advantage,” the high cost of early-stage quantum technology implementation necessitates a combination of quantum and classical solutions.

Indeed, the near future of the energy sector lies in hybrid quantum-classical systems, which combine the precision of classical systems with the speed of quantum algorithms. While classical methods remain the backbone of energy today, quantum technologies are expected to fundamentally transform optimization models for energy network structures, electricity generation forecasting methods, the development of new materials for the sector, and cybersecurity for critical energy infrastructure.

The most promising area where quantum technologies and quantum computing offer a real advantage is the chemical industry, particularly in ***quantum chemistry for creating advanced materials with unique, pre-defined properties*** (such as weight characteristics, high strength, and durability). This dramatically optimizes manufacturing processes, enhancing efficiency and reducing overall production costs. Quantum simulations help model the behavior of atoms and molecules to develop solid-state batteries, more efficient lithium-sulfur and sodium batteries, as well as supercapacitors with high energy density. Experimental projects are underway for new catalysts required for “green” hydrogen production, improving fuel cell efficiency, and reducing the energy consumption of chemical processes. The ability to model the electronic structures of complex materials offers a tangible prospect for creating cheaper high-temperature superconductors and new low-loss materials for transmission lines *(Korzh, 2023)*.

In ***geophysical exploration***, the demand for high-precision measurements in critical applications is rapidly growing, and this demand is met by quantum sensing—future quantum technologies that provide sensitivity unattainable by classical sensing. Modern geophysical research requires quantum gravimeters and magnetometers to assess underground resources (gas, water, geothermal zones) and enable more accurate modeling of subsurface structures. Today, in geology, quantum gravimeters assist in locating oil and other minerals, identifying water sources, and efficiently detecting crustal faults using a “quantum film”—a next-generation matrix that identifies magnetic and gravitational fields and delivers more reliable and precise measurements, particularly under harsh environmental conditions. With the development of quantum sensing technology, interest in cloud platforms, which provide the necessary computational power for real-time data analysis, is increasing.

Modern quantum atomic clocks enable measurements of gravity and other parameters, elevating the performance of *GPS* systems, autonomous vehicles, and any other devices requiring precise timekeeping. By leveraging quantum sensors, the need for *GPS* satellite signals in shielded environments, underwater, or underground could effectively disappear. Their advantages also include minimal calibration requirements and sensitivity and precision 10–20 times higher than conventional systems. Furthermore, quantum sensors (including magnetometers based on neutral atoms or diamonds) will open new possibilities in navigation systems across a wide range of transportation modes. According to *McKinsey* estimates, the commercial quantum sensing market could reach $1 billion by 2030, growing annually by 10–15%, and by 2040, this technology will not only radically transform industries that rely on sensor technologies but will also revolutionize those that depend directly on measurement precision *(Colobridge, 2024)*.

Conclusions. Currently, the new era of technological quantum development—the Q-economy of the 21st century – offers prospects that are transforming nearly all sectors based on collaboration and partnerships among governments, businesses, and the scientific community. This cooperation is becoming crucial for creating a secure quantum future and a sustainable economy. The evolution of information technologies and breakthroughs in understanding and utilizing the fundamental laws of nature to develop new products, services, and business models define a new direction in science and technology. This involves joint financing of research in the Q-economy, the formation of safety and operational standards, and the establishment of international protocols for data protection and privacy.

Thus, the solid-state quantum mechanics of the 1Q revolution made it possible to create the transistor, which today underpins all electronics (classical computers, smartphones, smart homes, etc.), yet this represents only 1% of the potential of quantum physics. The 2Q revolution accelerates the development of technological potential for scientific breakthroughs, competent management, and risk assessment as criteria of global security. The capabilities of future quantum computers in the Q-economy of the 21st century will be millions of times greater than today’s computing machines, with high-speed data processing and transmission capabilities and strong protection against unauthorized access. Quantum technologies and the creation of smart materials with exclusive properties are enabling ultra-fast information processing systems with built-in data security. They are transforming standards in medicine and energy, rules governing financial systems, and the development of industrial sectors of the economy. The growing digital divide between different market segments creates a unique economic dilemma: the drive for careful market information analysis and strategic planning, accompanied by the need for constant adjustment of national macroeconomic priorities.

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