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CHEMICAL SCIENCES

SYNTHESIS OF NOVEL ADAMANTYL-CONTAINING QUINOLIN-2-ONE DERIVATIVES AS POTENTIAL GSK-3 β INHIBITORS FOR THE TREATMENT OF ALZHEIMER'S DISEASE

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Abstract

Glycogen synthase kinase-3 β (GSK-3 β) has recently been implicated as a critical factor in the development of Alzheimer's disease (AD). In this study, a new series of quinolin-2-one derivatives containing a 1-adamantyl substituent was synthesized. The results of this study suggest that these new compounds may have potential as antiviral agents against Alzheimer's disease by targeting GSK-3 β .

Introduction

Alzheimer's disease (AD) is a complex, chronic, aging-related neurodegenerative disorder whose pathophysiology remains incompletely understood [1]. Approximately 50 million patients worldwide suffer from the disease, and this number is projected to more than triple by 2050, creating significant financial and medical burdens for both patients and healthcare systems [2]. Despite its complexity, many hypotheses have been put forward to explain its pathophysiology, including the tau hypothesis, the cholinergic theory, the amyloid- β (A β) protein hypothesis, and others [3]. Galantamine, donepezil, rivastigmine, and memantine are the only FDA-approved drugs for the treatment of AD, however, all of them are primarily used for palliative care and cannot prevent or reverse the pathology of AD [4]. As a result, the development of disease-modifying therapeutics targeting tauopathy or A β deposition is an urgent need [5].

Tau is a binding protein responsible for the formation of microtubules and their stabilization in normal physiological conditions. Hyperphosphorylation of the tau protein renders it incapable of binding to microtubules. As a result, dissociated tau protein accumulates and forms clusters in neurons as toxic neurofibrillary tangles (NFTs), leading to neuronal death [6,7]. This pathogenic process is believed to be triggered by dysregulation and mutations in kinases and phosphatases that interact with the tau protein [8].

Dysregulation is considered a major factor initiating numerous human diseases, including immunological and neurological diseases, in addition to cancer [9]. Glycogen synthase kinase-3 β (GSK-3 β) has been found to be an important protein kinase in the hyperphosphorylation and pathological accumulation of tau protein [10].

Thus, GSK-3 β has been proposed as a promising target for neurodegenerative diseases, among other diseases [11]. According to the "dual pathway" theory, GSK-3 β has been shown to actively promote excess A β formation and tau protein hyperphosphorylation, key neuropathological hallmarks of Alzheimer's disease

[12]. In addition, abnormal GSK-3 β activity is associated with neuroinflammation and oxidative stress [13]. Accordingly, GSK-3 β is involved in almost all pathological processes of Alzheimer's disease. As a result, recent studies have focused on GSK-3 β inhibition as an effective strategy for the treatment of Alzheimer's disease [13].

Currently, kinase inhibitors account for 25% of all ongoing drug development research [14]. However, clinical trials of competitive ATP inhibitors often fail due to the striking similarity of their target ATP-binding sites, which increases the risk of off-target toxicity [15,16]. Due to the therapeutic importance of kinase inhibitors, several approaches have been required to overcome the kinase selectivity barrier and provide more effective targeted treatments [17]. Promising new approaches include targeting the inactive conformation of kinases and interacting with their unphosphorylated catalytic site (type II inhibitors) or developing kinase inhibitors that can bind outside the catalytic/ATP-binding site and regulate kinase activity through an allosteric mechanism [18]. For example, tideglusib is an irreversible allosteric, ATP-noncompetitive inhibitor of GSK-3 β . However, tideglusib failed to achieve its primary treatment targets for patients with Alzheimer's disease, and phase II clinical trials of tideglusib as an anti-Alzheimer's drug were discontinued. To date, none of the investigated GSK-3 β inhibitors have reached the market, so there is great interest in finding suitable GSK-3 β inhibitors for therapeutic use as anti-Alzheimer's agents [19].

Quinolines and quinolones are heterocyclic structures that commonly act as structural building blocks for a number of complex natural products [20]. In addition, they have demonstrated a number of biological and pharmacological effects, including anti-Alzheimer's activity [21].

Clinical trials have shown that 8-hydroxyquinoline derivatives, clioquinol I and PBT2 II (Fig. 2), are potent metal chelators that significantly improved cognitive function by reducing A β levels in cerebrospinal fluid (CSF) [22,23]. Recent studies have shown that

quinoline-2(1H)-one derivatives act as multitarget agents with ROS scavenging ability, in addition to potent cholinesterase action, possessing inhibitory activity [24]. Moreover, 2-heptyl-3-hydroxyquinol-4(1H)-one derivative protected neurons from glutamate-induced cell death in HT22 cells by preventing cellular Ca^{2+} uptake and glutamate-induced ROS generation [25]. Pyrazolo[3,2-c]quinol-4(5H)-one derivative improved cognitive impairment associated with Alzheimer's disease through its inhibitory effect on phosphodiesterase 9A (PDE9A) [26]. Furthermore, the FDA-approved quinolin-2(1H)-one derivative, brexpiprazole (III), is a serotonin and dopamine modulator that controls non-cognitive psychological symptoms associated with Alzheimer's disease dementia [27].

Furthermore, the 2-quinolone derivative ZINC67773573 (IV) (Fig. 2) was computationally identified as a promising candidate compound for the development of novel GSK-3 β inhibitors for the treatment of Alzheimer's disease [28].

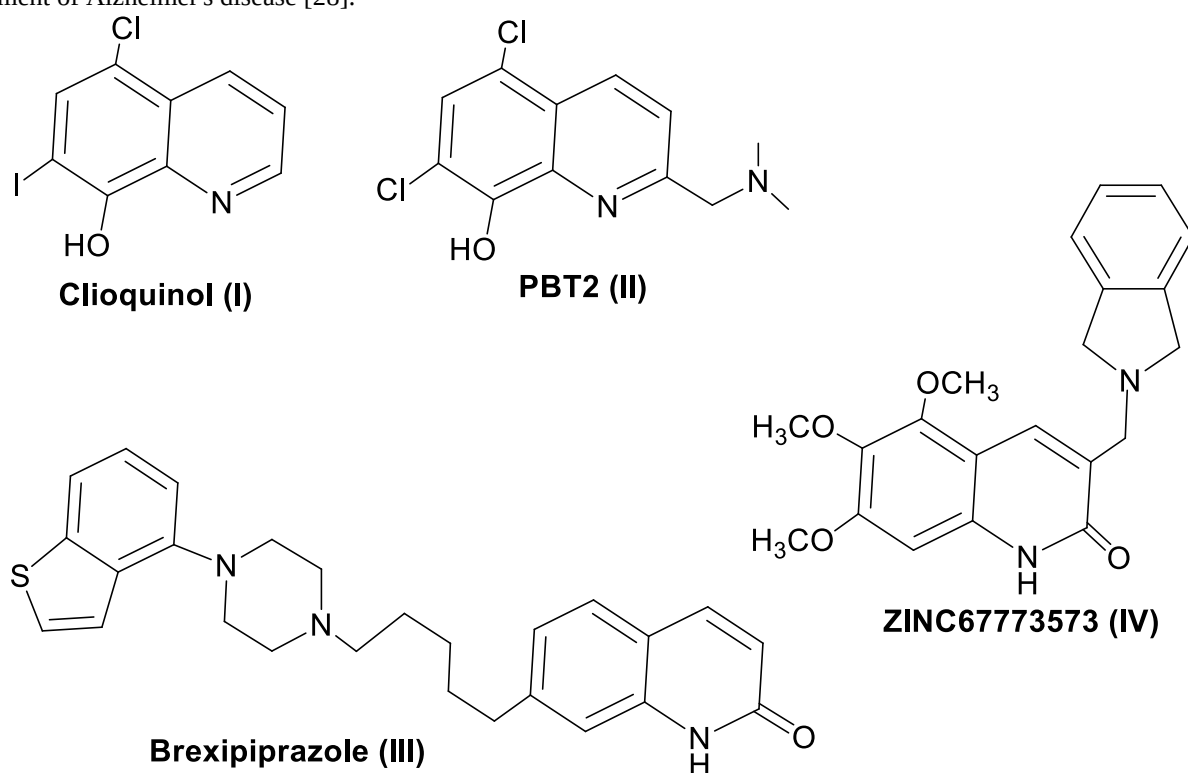


Fig. 2. Structures of some compounds with anti-Alzheimer's activity and containing quinoline and quinolone fragments.

The physiological activity of framework hydrocarbon derivatives, primarily adamantane derivatives, has been extensively studied. The activity of these compounds is due to the pronounced lipophilic nature of the compact framework hydrocarbon fragment. Therefore, the aim of this study was to attempt to impart greater lipophilicity to known anti-priposomal drugs, which, in our opinion, could improve their pharmacological activity.

Results and discussion

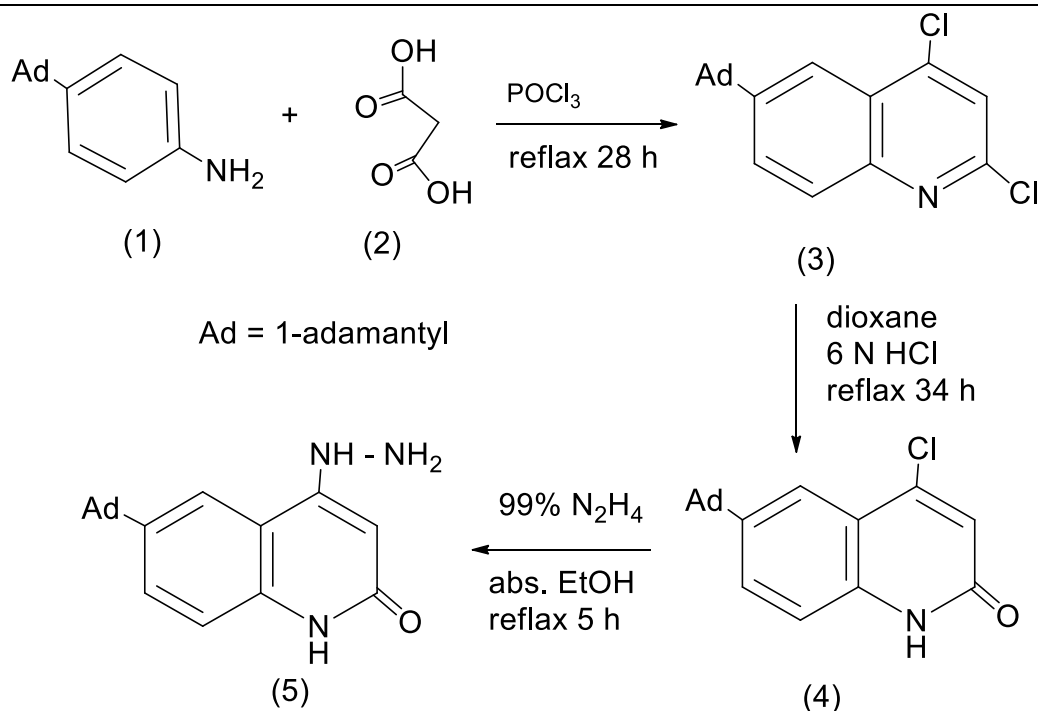
A new series of quinolin-2-one derivatives were prepared using 4-hydrazinoquinolin-2(1H)-one (5). The synthesis of the key intermediate 5 was accomplished in a three-step procedure as shown in Scheme 1. The first step of the reaction sequence involved the

ZINC67773573 (IV) demonstrated a promising predicted binding pattern and binding affinity in molecular docking simulations, as it perfectly fit the hinge region, interacting with essential amino acids.

This binding pattern directs the hydrophobic indole ring at position 3 to the hydrophobic amino acid side chains [28].

A natural isatin derivative, indirubin, is a key ingredient of the traditional Chinese medicine Dang Gui Long Hui Wan, used to treat chronic myelocytic leukemia (CML) through inhibition of GSK-3 β and CDK2 [29–32]. Furthermore, indirubin and its derivatives have been found to inhibit GSK-3 β and further abnormal phosphorylation of tau protein in Alzheimer's disease as competitive inhibitors of ATP [33]. The isatin ring of indirubin is located in the hinge region of the GSK-3 β binding site, interacting through its carbonyl and NH groups via hydrogen bonds with the essential amino acids Val135 and Asp133, respectively [32–35].

one-step synthesis of 2,4-dichloroquinoline (3) in 82% yield by a cyclocondensation reaction between 4-(1-adamantyl)aniline (1) and malonic acid (2) in the presence of excess phosphoryl chloride under reflux for 28 h according to modified procedures described by Mohan [36]. The second step involved regioselective oxidation of 2,4-dichloroquinoline (3) at position 2 by treatment with 6 N HCl in dioxane [37,38] to form 4-chloro-2-oxo-6-(1-adamantyl)quinoline (4) in good yield of 87%. In the final step, the chlorine-containing product (4) was treated with excess hydrazine hydrate in ethanol [39,40] at reflux for 5 h to afford the desired 4-hydrazinyl-6-(1-adamantyl)quinolin-2(1H)-one (5) in 73% yield.



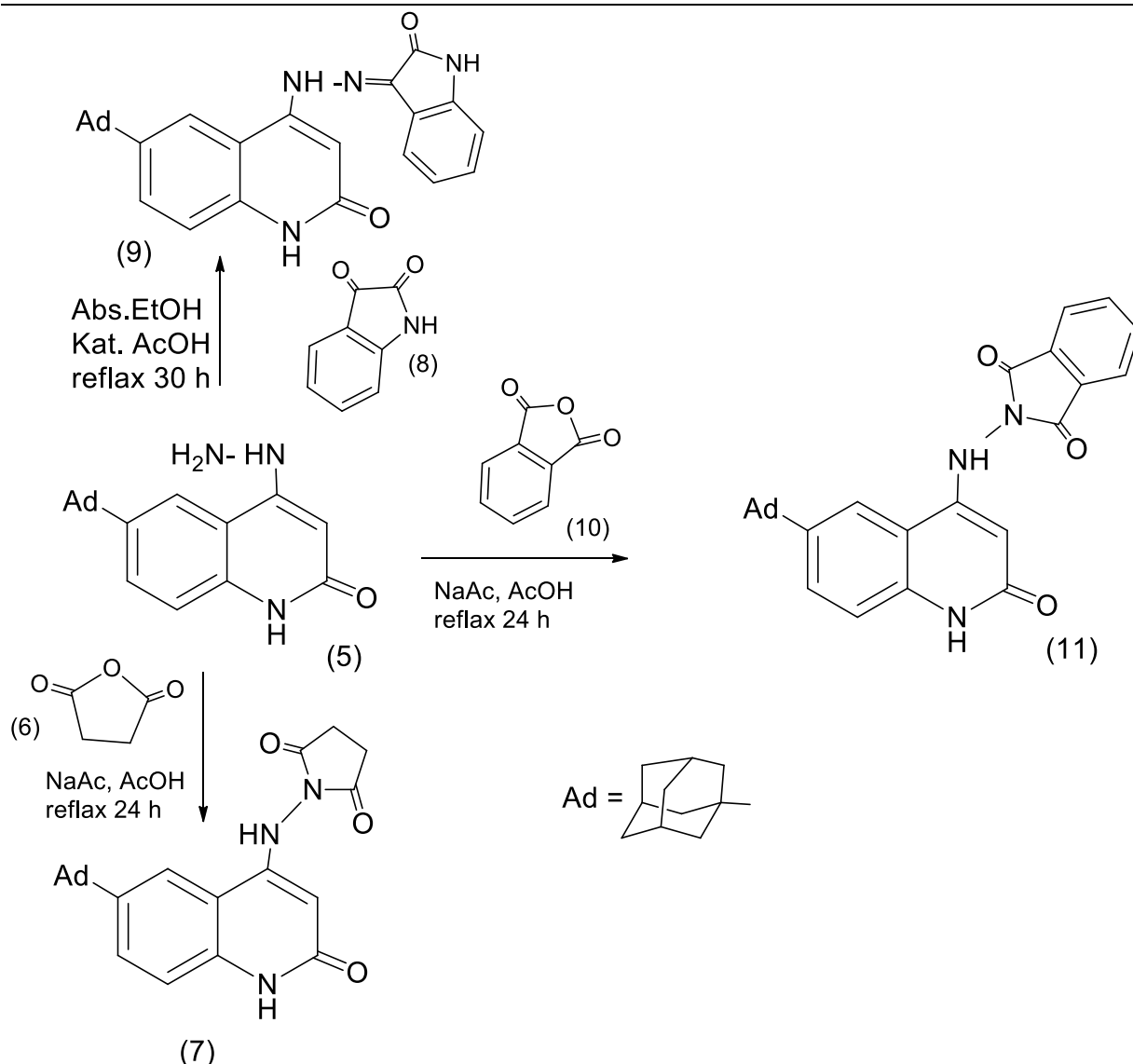
Scheme 1. Reagents and conditions: $POCl_3$, reflux for 28 h, 1,4-dioxane, 6 N HCl, reflux for 34 h, 99% NH_2-NH_2 , absolute EtOH, reflux for 5 h.

Subsequently, hydrazide (5) was used to synthesize various functional derivatives of quinolin-2-one through reactions with various electrophilic reagents (Scheme 2).

The reaction of hydrazide (5) with 1H-indole-2,3-dione (8) yielded hydrazone (9). Thus, ^1H NMR spectra revealed the presence of three NH groups resonating at δH values in the ranges of 11.35–11.45, 11.45–11.48, and 13.34–13.38 ppm. ^{13}C NMR spectra revealed the presence of two amide carbonyl groups in the ranges of $\delta C = 162.68$ – 162.74 and 163.80 – 168.5 ppm.

Theoretically, product (9) can exist as Z or E stereoisomers, or as a mixture of the two isomers, depending on the structure and reaction conditions, which can be thermodynamically or kinetically controlled.

The geometry around the (HC=N-) bond was defined as the E-configuration based on data presented by Wardell and co-workers [41], who showed that 4-hydrazinoquinoline hydrazones adopt an E-configuration around HC=N in their crystal structures, with the amine hydrogen pointing toward the quinoline the remainder. Additionally, a previous study [42], supported by X-ray diffraction analysis, showed that azomethine protons were detected at δH values in the range of 7.46–8.80 for E-isomers. Additionally, the CH=hydrazone carbon atoms were observed at ^{13}C NMR chemical shift values in the range of 139.79–144.78, which corresponds to the values reported for similar types of E-hydrazones (141.62–148.96 ppm) [43], whereas this carbon in the Z-isomers was in the high-field range (δC around 136 ppm) [44].



Scheme.2. Reagents and conditions: absolute ethanol, 5 drops of glacial acetic acid, reflux 30 h, filtration. Anhydrous sodium acetate, glacial acetic acid, reflux 24 h.

Moreover, minimization calculations for the two possible geometric isomers (E and Z) of these Schiff bases revealed a relatively higher stability of the E-isomers compared to their Z-analogs, which may suffer from undesirable steric interactions between the phenyl proton in the ortho position and the NH proton.

With regard to the stereochemical determination of the C—N geometry in derivatives (9), the following facts and observations must be taken into account. Firstly, previous theoretical and experimental studies have shown that under thermodynamic conditions (heat treatment), isatin arylhydrazones almost always exist in the more stabilized Z-forms, which are capable of forming an intramolecular hydrogen bond [45,46] between the hydrazide hydrogen and the lactam oxygen of the oxoindole ring [N—H—O—C], whereas the E-isomers formed at 20 °C were considered less stable isomers because they could not form such hydrogen bonding. Secondly, geometric Z—E isomerization around the C—N double bond in isatin hydrazones occurs only through a photochemical reaction [47], and the less stabilized E-structures slowly thermally isomerize back to the more preferred Z-isomers [48].

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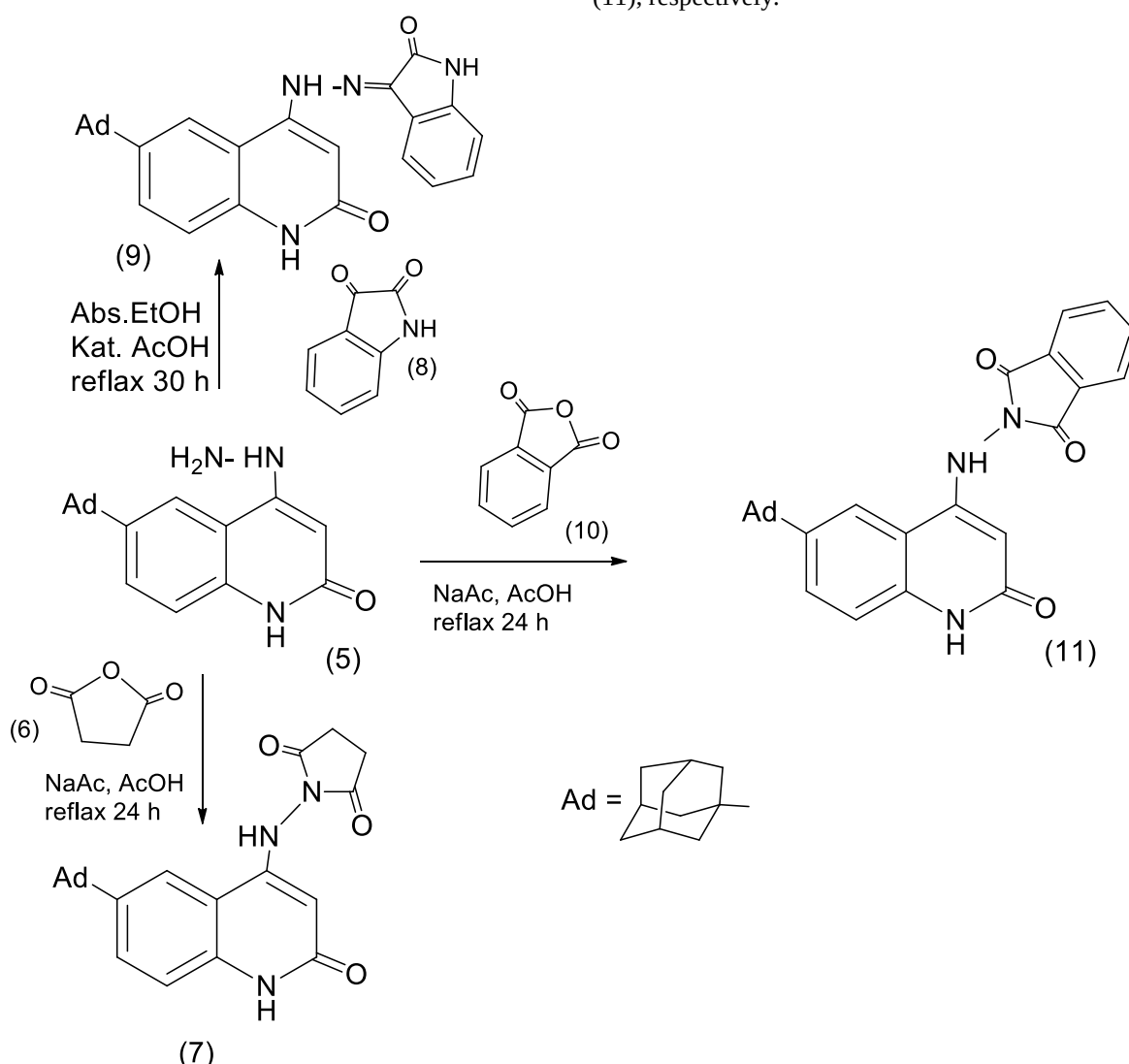
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These reported ^1H NMR shift values are consistent with those reported for a similar type of Z-Schiff base derived from isatin (13.95 ppm) [45]. Therefore, the Z-configuration was assigned to product (9). This assignment is supported by energy minimization calculations, which indicated higher energies of the E-isomers compared to their Z-isomer counterparts. The higher energies of the E-isomers may be due to the presence of a destabilizing steric hindrance between the 4-H-oxindole ring and the NH-hydrazide, and this eliminates the E-structure from consideration.

spectra confirmed the formation of symmetrical pyrrolidine-2,5-dione rings, showing characteristic carbon resonances at $\delta = 166.10$ and 174.40 ppm, which can be assigned to the two equivalent carbon atoms of dione in compounds (7) and (11). Subsequently, the synthesis of the hybrid quinolinone-pyrrolidinedione derivatives, conjugates (7) and (11), was easily achieved by

refluxing a mixture of hydrazide (5) with phthalic anhydride 12 or succinic anhydride 10 in acetic acid containing sodium acetate for 24 h. From a mechanistic point of view [49, 50], these reactions involved ring opening via nucleophilic attack of the hydrazinyl amino group on one of the carbonyl groups to form monoamide monoacid intermediates, which then underwent intramolecular cyclization to yield pyrrolidinium derivatives (7) and (13), as evident from their ^1H NMR spectra, which showed only two singlet signals assigned to the two NH groups resonating at δH values of 9.64 and 11.21 ppm. for derivative (11) and at 9.37 and 11.13 for derivative (7).

Furthermore, ^{13}C NMR spectra confirmed the formation of symmetrical pyrrolidine-2,5-dione rings, showing characteristic carbon resonances at $\delta = 166.10$ and 174.40 ppm, which can be assigned to the two equivalent carbon atoms of dione in compounds (7) and (11), respectively.



Scheme.2. Reagents and conditions: absolute ethanol, 5 drops of glacial acetic acid, reflux 24–48 h, filtration. Anhydrous sodium acetate, glacial acetic acid, reflux 24 h.

Experimental

2,4-Dichloroquinoline (3) [36], 4-Chloroquinolin-2(1H)-one (4) [37,38], 4-Hydrazinylquinolin-2(1H)-one (5) [39,40] were obtained according to the described procedures. Chemical reagents were commercially

available and used as is, without further purification unless otherwise noted. Moisture-sensitive reactions were carried out under a dry argon atmosphere in pre-baked glassware. Thin-layer chromatography was performed on silica gel thin-layer chromatography plates with a fluorescent indicator at 254 nm (Fluka). Flash column

chromatography was performed using silica gel 60 Å (BDH, 40–63 µm). Mass spectra were obtained on a Bruker ion-trap mass spectrometer. All NMR spectra were recorded on a Bruker 400 MHz spectrometer using CDCl₃ or DMSO-d₆ as solvent.

Reverse-phase HPLC analysis of the compounds was performed on a Beckman HPLC system with an autosampler. Chromatographic separation was performed on a C18 column (2.0 mm × 150 mm, 5 µm). The mobile phase was used for isocratic elution at a flow rate of 0.2 mL/min. The injection volume was 20 µL and the UV detector was set at 260 nm.

General procedure for the synthesis of compound (9).

A mixture of hydrazide (5) (1 mmol) and (1 mmol) 1H-indole-2,3-dione (8) in absolute ethanol (15 mL) containing 5 drops of glacial acetic acid was refluxed for 30 h. The resulting precipitate was filtered off and washed with hot ethanol, yielding the corresponding pure hydrazone derivative (9).

6-(1-Adamantyl)-(Z)-4-[2-(2-oxoindolin-3-ylidene)hydrazinyl]quinolin-2(1H)-one (9). Light brown powder, yield 97%; mp.: 352–354 °C; IR (ν max, cm⁻¹): 3368 and 3132 (3NH), 3075 (CH-Ar.), 2994 (CH aliph.), 1690 (C=O), 1651 (C=O); ¹H NMR (DMSO-d₆, 400 MHz, δ): 1.48, 1.68, 1.92 (m, 15H Ad), 6.53 (s, 1H, C3 H-quinolone), 6.97 (d, J=7.8 Hz, 1H, Ar-H), 7.11 (t, J=7.5 Hz, 1H, Ar-H), 7.29–7.39 (m, 3H, Ar-Hs), 7.54–7.60 (m, 2H, Ar-Hs), 7.67 (d, J = 7.4 Hz, 1H, Ar-H), 11.35 (s, 1H, NH exchanged for D₂O), 11.45 (s, 1H, NH exchanged for D₂O), 13.38 (s, 1H, NH exchanged for D₂O); ¹³C NMR (DMSO-d₆ 100 MHz, δ): 29.0, 31.6, 37.5, 45.3, 97.36 (C3) 111.52, 111.73, 116.67, 120.34, 120.51, 120.63, 122.28, 122.95, 131.05, 131.55, 134.55, 139.95, 141.86, 146.44 (C–NH), 162.74 (C–O), 164.14 (C–O); MS (*m/z*, %): 438.60 (M⁺, 12.52), 129.90 (100).

General procedures for the synthesis of compounds (7) and (11).

To a solution of hydrazide (5) (10 mmol) in glacial acetic acid (25 mL) and anhydrous sodium acetate (10 mmol), the corresponding anhydride (6) or (10) (10 mmol) was added. The reaction mixture was heated under reflux for 24 h. The solution was cooled to room temperature and poured onto ice water, yielding the corresponding derivatives (7) and (11), respectively. The resulting solids were washed with hot glacial acetic acid to obtain pure products.

1-[(6-(1-adamantyl)-2-Oxo-1,2-dihydroquinolin-4-yl)amino]pyrrolidine-2,5-dione (7). Beige powder, yield 80%; mp: 353–355 °C; IR spectrum (ν max, cm⁻¹): 3352 and 3287 (2NH), 3098 (CH-Ar), 2994 (CH aliphatic), 1713 and 1643 (C=O). ¹H NMR (DMSO-d₆, 400 MHz, δ): 1.48, 1.68, 1.92 (m, 15H Ad), 1.98 and 2.88 (2 s, 4H, cis/trans conformers of pyrrolidine 2CH₂), 5.41 and 5.49 (2 s, 1H, cis/trans conformers C3 H-quinolone), 7.14 and 7.20 (2 t, J = 8.0, 7.3 Hz, 1H, Ar-H), 7.26 and 7.31 (2 d, J = 7.8, 7.9 Hz, 1H, Ar-H), 7.48 and 7.53 (2 t, J = 7.7, 7.3 Hz, 1H, Ar-H), 7.94 (d, J= 7.6 Hz, 1H, Ar-H), 8.84 and 9.37 (2 s, 1H, cis/trans NH conformers substituted with D₂O), 10.96 and 11.13 (2 s, 1H, cis/trans NH conformers substituted with D₂O). ¹³C NMR (DMSO-d₆, 100 MHz, δ): 29.0, 31.6,

37.5, 45.3, 27.08 (pyrrolidine CH₂), 94.47 (C3 H-quinolone), 112.19, 116.16, 121.48, 122.67, 131.19, 139.54, 150.13, 163.08 (C–O), 175.40 (C = O); MS (*m/z*, %): 391.52 (M⁺, 14.54), 43.10 (100).

2-[(6-(1-adamantyl)-2-Oxo-1,2-dihydroquinolin-4-yl)amino]isoindolin-1,3-dione (11). White crystals, yield 94%; mp: 328–330 °C; IR spectrum (ν max, cm⁻¹): 3480 and 3310 (2NH), 3086 (CH-Ar), 2997 (CH aliphatic), 1790, 1732 and 1651 (C=O). ¹H NMR (DMSO-d₆, 400 MHz, δ): 1.48, 1.68, 1.92 (m, 15H Ad), 5.43 (s, 1H, C3 H-quinolone), 7.25 (t, J = 7.6 Hz, 1H, Ar-H), 7.34 (d, J = 8.1 Hz, 1H, Ar-H), 7.56 (t, J = 7.5 Hz, 1H, Ar-H), 7.96–8.03 (m, 5H, Ar-Hs), 9.64 (s, 1H, NH exchanged for D₂O), 11.21 (s, 1H, NH exchanged for D₂O); ¹³C NMR (DMSO-d₆, 100 MHz, δ): 29.0, 31.6, 37.5, 45.3, 94.50 (C3 H-quinolone), 112.05, 116.28, 121.65, 122.53, 124.29, 129.91, 131.39, 135.78, 139.63, 150.85, 162.91 (C–O), 166.10 (2C = O). MS (*m/z*, %): 439.52 (M⁺, 15.74), 43.10 (100).

Conclusion

Novel adamantyl-containing quinolin-2-one derivatives have been obtained as potential GSK-3β inhibitors for the treatment of Alzheimer's disease.

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ECONOMIC SCIENCES

THE HISTORY OF INDUSTRIAL DEVELOPMENT IN THE NAKHCHIVAN AUTONOMOUS REPUBLIC

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Abstract

The Nakhchivan Autonomous Republic, as one of the important economic regions of Azerbaijan, has historically been one of the main centers of industrial development due to its abundant natural resources, favorable geographical location, and long-standing production traditions. Industrial development in the region has evolved under the influence of various political, economic, and social factors throughout different historical periods. This article systematically examines the history of industrial development in the Nakhchivan Autonomous Republic from the late nineteenth century to the present day. The study demonstrates that significant measures were undertaken to expand the region's industrial potential, particularly during the 1970s and 1980s. Following Azerbaijan's restoration of independence, new industrial enterprises were established in accordance with the principles of a market economy, local raw material resources began to be utilized more efficiently, and export-oriented industries were developed. As a result, the industrial sector of Nakhchivan has become one of the principal driving forces of the region's economic development.

Keywords: industry, economic development, production, industrial park, manufacturing industry, non-oil sector.

Introduction

At the present stage, industry is one of the principal sectors of material production and plays a leading role in terms of both the volume and significance of manufactured output. The term industry originates from the Latin word *industria*, meaning "diligence" or "industriousness." Industry is a branch of material production that utilizes natural resources efficiently to manufacture consumer goods as well as products intended for production and technical purposes. It encompasses such sectors as fuel and energy, mechanical engineering, the chemical industry, light industry, the food industry, and others. Like other branches of the economy, industry has undergone several stages of development, evolving progressively from simple to more complex forms [2 p. 7].

Industry is one of the key sectors determining the level of a country's economic development. It plays a decisive role in the processing of natural resources, expansion of production, employment generation, and the development of export potential. As an integral part of the Republic of Azerbaijan, the Nakhchivan Autonomous Republic has, since ancient times, been among the regions where handicrafts and production traditions have been highly developed.

The territory of Nakhchivan possesses abundant natural resources, including extensive rock salt deposits, zinc, lead, polymetallic ores, copper, gold, molybdenum, construction materials, marble, mineral waters, and other mineral resources, which have created a favorable natural basis for industrial development. Archaeological and historical evidence indicates that stone processing, metalworking, ceramics, and textile production have existed in this region for thousands of

years. These traditional activities later laid a solid foundation for the development of modern industrial production.

Beginning in the second half of the nineteenth century, the establishment of the first industrial enterprises in the region accelerated. In particular, industrial salt extraction, construction materials production, and agricultural product processing developed rapidly. Following the establishment of the Nakhchivan Autonomous Republic in 1924, industrial development became one of the priority directions of state economic policy.

During the period from the 1950s to the 1980s, industrial production entered a qualitatively new stage of development. Numerous enterprises in the food, light, construction materials, electrotechnical, and manufacturing industries commenced operations, resulting in a multiple increase in industrial output. By 1965, the industry of the Nakhchivan Autonomous Republic was producing 40 different types of products. As a result of the economic reforms implemented during the 1970s, the industrial potential of the Autonomous Republic was substantially strengthened, new production facilities were commissioned, and the material and technical base of industry was significantly improved. Compared with 1970, industrial production increased 2.6 times by 1980 and 1.66 times by 1985 compared with 1980 [1 pp. 25, 33].

Following the restoration of Azerbaijan's state independence in 1991, the Nakhchivan Autonomous Republic encountered serious economic challenges. The transport blockade, energy shortages, and disruption of traditional economic ties led to a decline in industrial production. However, in subsequent years, industrial development resumed owing to state development pro-

grams, government support for entrepreneurship, investment projects, and the establishment of new industrial enterprises. Today, the food industry, construction materials production, mining, energy, and manufacturing industries constitute the leading sectors of the Autonomous Republic's economy. During January–June 2025, taking into account industrial production by households as well as the activities of individual entrepreneurs operating without establishing a legal entity, industrial products and services worth 255,127.4 thousand manats were produced, representing a 9.1% increase compared with the corresponding period of 2024. Of the total output, 83.7% consisted of industrial production, while 16.3% comprised industrial services. The public sector accounted for 52,751.9 thousand manats (20.7%), whereas the non-state sector accounted for 202,375.5 thousand manats (79.3%). Industrial output consisted of 0.2% mining, 79.2% manufacturing, 18.3% electricity, gas and steam production, distribution and supply, and 2.3% water supply, waste management and remediation activities [5 p. 5].

The development of the industrial sector in the Nakhchivan Autonomous Republic is one of the principal directions of the policy of economic diversification. The Autonomous Republic's favorable geographical location, state support, and measures aimed at promoting entrepreneurship have made the establishment of an industrial park a strategic necessity.

To promote the development of the non-oil sector, industrial parks have been widely established throughout Azerbaijan. The creation of the Nakhchivan Industrial Park will facilitate the formation of a specialized industrial zone, expand the production capacity of the Nakhchivan Autonomous Republic, increase employment, and enhance the region's economic self-sufficiency.

On 5 December 2024, the President of the Republic of Azerbaijan, Mr. Ilham Aliyev, signed the Decree on the establishment of the Nakhchivan Industrial Park in the Nakhchivan Autonomous Republic. As an important component of Azerbaijan's current economic policy aimed at developing the non-oil industry, this project is expected to make a significant contribution to the sustainable socio-economic development of the Autonomous Republic and to substantially strengthen the non-oil sector. The industrial park will reinforce the industrial potential of the region, promote entrepreneurship, facilitate the introduction of modern technologies, enhance the production of competitive goods for domestic and foreign markets, create new employment opportunities, and contribute to sustainable economic growth.

The priority areas of activity within the Nakhchivan Industrial Park include the chemical industry, food industry, waste recycling, ferrous and non-ferrous

metal processing, construction materials production, machinery and equipment manufacturing, renewable energy production, furniture manufacturing, textile and garment production, leather processing, packaging production, and paper and paper products manufacturing.

At the current stage, the Nakhchivan Industrial Park is expected to make a substantial contribution to the socio-economic development of the Autonomous Republic. By promoting the development of the non-oil sector, it will create favorable conditions for the expansion of competitive industrial production based on innovation and advanced technologies, strengthen the region's industrial potential, stimulate entrepreneurship, generate new jobs, and ensure sustainable economic growth [3 p. 45].

Conclusion

The conducted research demonstrates that industrial development in the Nakhchivan Autonomous Republic has followed a long historical evolutionary path shaped by various political, economic, and social factors. The region's abundant natural resources, favorable geographical location, and long-established production traditions have provided a solid foundation for industrial development.

At the same time, the future development of industry requires the broader application of advanced technologies, digital transformation, innovation-driven activities, human capital development, and the expansion of export potential. These priorities will play a decisive role in enhancing the competitiveness and sustainable development of the industrial sector of the Nakhchivan Autonomous Republic.

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MODERN MECHANISMS FOR INCREASING OPERATIONAL EFFICIENCY OF COMMERCIAL BANKS BASED ON DIGITAL TECHNOLOGIES**Rakhimov U.***Head of Marketing Department at JSC "Garant bank"*

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<https://doi.org/10.5281/zenodo.21649086>**Abstract**

This article examines modern mechanisms for improving the operational efficiency of commercial banks through robotic process automation, artificial intelligence, process analytics, cloud technologies, open software interfaces, and centralized data management. It argues that digitalization should be viewed not as the localized automation of individual operations, but as a comprehensive transformation of end-to-end business processes, organizational models, and risk control systems. It systematizes the application of digital technologies in the bank's front, middle, and back offices, and proposes an operational efficiency management framework based on a combination of a process-based approach, measurable KPIs, and principles of operational sustainability. Practical proposals for commercial banks in the Republic of Uzbekistan are formulated, including the creation of an operational excellence center, the implementation of process mining, intelligent KYC/AML automation, the development of API architecture, data quality management, and the evaluation of digital projects based on their overall economic impact.

Keywords: commercial bank, operational efficiency, digital transformation, RPA, artificial intelligence, process mining, cloud technologies, API, data management, cost-to-income.

Introduction.

The banking sector is currently evolving amidst the growth of digital transactions, increased competition from fintech companies, heightened customer expectations for speed of service, and simultaneously stricter requirements for cybersecurity, data protection, and operational resilience. Under these circumstances, traditional efficiency improvement methods, primarily based on staff and administrative cost reductions, are having limited impact. Sustainable efficiency gains require changes to the very processes of banking service creation, their standardization, digitalization, and subsequent continuous improvement.

A commercial bank's operational efficiency characterizes its ability to transform human, technological, financial, and information resources into banking products and services with minimal necessary costs, an acceptable level of risk, and a specified quality of service. In practice, it is assessed not by a single indicator, but by a system of interconnected indicators: the cost-to-income ratio, the cost of one transaction, the time it takes to complete a process cycle, the productivity of one employee, the share of transactions without manual intervention, the error rate, the number of returns and complaints, the availability of digital channels, and losses from operational events.

Theoretical basis of the research.

The theoretical basis for digital efficiency improvement is the process approach. M.Hammer and J.Champy¹. They linked radical productivity gains to process reengineering, that is, to a revision of work logic, and not just to the automation of existing procedures. T. Davenport emphasized the need to combine

information technology and process change². Therefore, digitalizing an inefficient process without prior analysis often only leads to the acceleration of redundant approvals and the transfer of organizational deficiencies to the information system.

The Basel Committee on Banking Supervision views digitalization as a transformation of the entire banking value chain, driven by APIs, artificial intelligence and machine learning, distributed ledgers, cloud computing, and technology providers. Digital technologies not only create economic advantages but also new dependencies, including cloud provider concentration, model risk, cyber threats, and outsourcing vulnerabilities³. Therefore, efficiency improvements must be achieved simultaneously with the development of corporate governance, data management and operational resilience.

Research methodology.

The first mechanism is robotic process automation (RPA) and digital workflow management. RPA is effective in high-volume, standardized, and rule-based operations: transferring data between systems, generating reports, reconciling accounts, processing applications, verifying document completeness, sending notifications, and performing standard control procedures. Economic benefits are achieved through the reduction of manual labor, fewer errors, and the ability to perform operations continuously. However, robotic process automation should be implemented after eliminating unnecessary steps, as automating duplicate operations does not create sustainable efficiency.

The second mechanism is artificial intelligence and machine learning. The OECD notes that AI is used

¹Hammer M., Champy J. Reengineering the Corporation: A Manifesto for Business Revolution. New York: Harper Business, 1993.

²Davenport TH Process Innovation: Reengineering Work through Information Technology. Boston: Harvard Business School Press, 1993.

³Basel Committee on Banking Supervision. Digitalization of Finance. Basel: Bank for International Settlements, 2024.<https://www.bis.org/bcbs/publ/d575.htm>.

in banking for credit scoring, fraud detection, KYC/AML, credit loss prediction, customer service, text processing, and back-office optimization⁴. The greatest impact is achieved by combining AI with RPA:

Incoming elements

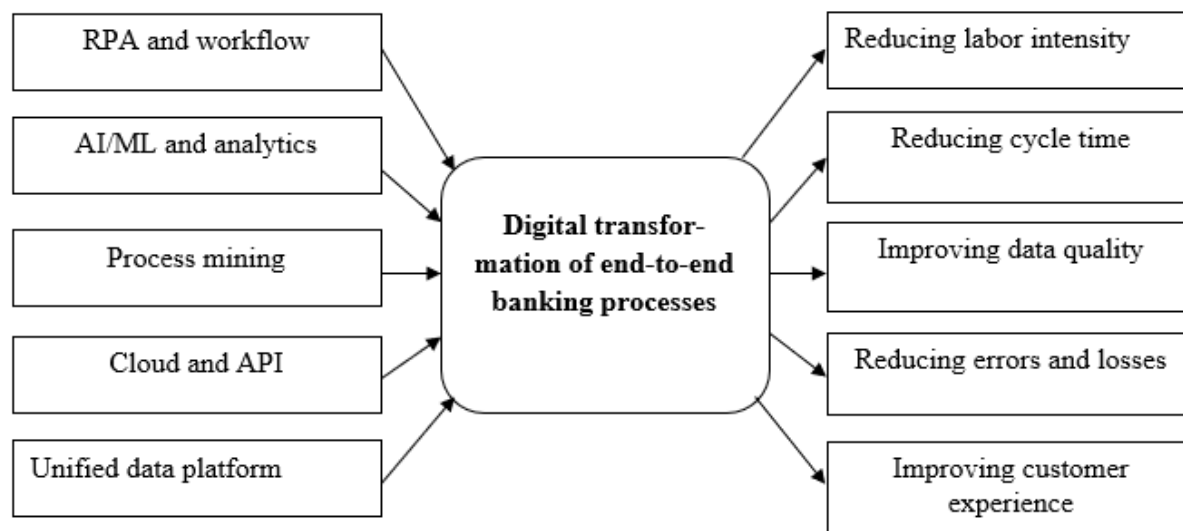


Figure 1. A mechanism for improving the operational efficiency of a commercial bank using digital technologies⁵

The third mechanism is process mining reconstructing the actual flow of a process based on digital logs from information systems. Traditional process descriptions often reflect approved regulations, while process mining reveals the actual number of routes, repeat actions, returns, rejections, and waits. This allows for the identification of bottlenecks in lending, payments, account opening, application processing, and compliance checks. Based on the data obtained, the bank can determine which steps should be eliminated, combined, standardized, or automated.

The fourth mechanism is the transition to a modular cloud and API-oriented architecture. Monolithic banking systems hinder rapid process changes and the integration of new services. APIs allow for the reuse of identification, payments, limit calculation, data exchange, and notification functions across various products and channels. Cloud technologies provide scalability of computing resources and accelerate the implementation of analytical solutions. However, the Basel Committee notes that reliance on external technology providers requires enhanced controls over concentration risk, business continuity, and contractual data access mechanisms⁶.

an intelligent model recognizes a document, classifies a request, or identifies an anomaly, and a software robot performs further operations according to an approved scenario. This model is called intelligent automation.

Results

The fifth mechanism is centralized data management. The lack of unified reference books, duplicate client records, and data differences between departments increase transaction times and reduce the quality of management decisions. The Chief Data Officer function should establish rules for data quality, origin, accessibility, security, and use. A unified data platform creates the foundation for automated reporting, service personalization, risk monitoring, and process performance measurement.

The sixth mechanism is omnichannel service. Separately developing branches, contact centers, mobile apps, and online banking creates duplicate data entry and disruptions in the customer journey. The omnichannel model provides a unified customer profile, a shared history of interactions, and the ability to continue a transaction in another channel without repeating previous steps. This simultaneously reduces operating costs and improves the customer experience.

International research experience.

International practice shows that digital operational efficiency results from coordinated changes in technologies, processes, and organizational models.

⁴OECD. Artificial Intelligence, Machine Learning and Big Data in Finance: Opportunities, Challenges and Implications for Policy Makers. Paris: OECD Publishing, 2021.<https://doi.org/10.1787/98e761e7-en>; OECD. Generative Artificial Intelligence in Finance. OECD Artificial Intelligence Papers, No. 9. Paris: OECD Publishing, 2023.<https://doi.org/10.1787/ac7149cc-en>.

⁵Developed by the author based on a summary of the approaches of BIS, OECD and World Bank.

⁶Basel Committee on Banking Supervision. Digitalization of Finance. Basel: Bank for International Settlements, 2024.<https://www.bis.org/bcbs/publ/d575.htm>.

1-table.

The Impact of Digital Technologies on Commercial Bank Operational Processes⁷

Technology	Main area of application	Operational effect	Key KPIs
RPA and work-flow	Reconciliations, reporting, data entry, notifications	Reducing manual operations and errors	STP share; cycle time; errors per 1,000 operations
AI/ML	Scoring, fraud detection, KYC/AML, forecasting	Improving decision accuracy and processing speed	Resolution time; false positive rate; fraud losses
Process mining	Analysis of actual process routes	Identifying bottlenecks, re-turns and duplications	Number of process variants; rework rate; waiting
Cloud and API	Integration of systems, scaling of services	Speed up development and re-use of functions	Time-to-market; availability; integration cost
Data governance	Unified reference books, data quality and availability	Reduced re-entry and discrepancies	Data quality score; number of duplicates; reporting timeframe
Omnichannel	Unified customer journey and customer profile	Reducing the workload on branches and the contact center	Share of digital transactions; first contact resolution; NPS

The European Central Bank notes the growth of digital banking models operating without a developed branch network. According to the ECB, by the end of 2024, approximately 60 digital-only banks were identified in the eurozone, and their share of total assets increased from 3.1% in 2019 to 3.9% in 2024⁸. While digital banks don't always demonstrate sustainable profitability, their model demonstrates the potential for lower fixed costs and rapid scalability, provided risk and well managed customer acquisition costs.

In countries with advanced digital financial services, banks are transitioning bulk transactions to straight-through processing, whereby transactions proceed from initiation to accounting without manual intervention. Employees focus on exceptions, complex cases, advisory services, and risk management. The World Bank notes that digital financial services can reduce transaction costs through economies of scale, increase transaction speed and transparency, and provide more targeted services⁹.

2-table.

International approaches to digital improvement of banks' operational efficiency¹⁰

Approach	Content	Advantage	Condition of effectiveness
Digital-only model	Service provided primarily through remote channels	Low dependence on branch infrastructure	A sustainable IT platform and effective customer acquisition
Straight-through processing	End-to-end automated processing of standard operations	Minimizing time and manual labor	Standardized data and exception handling rules
Automation Center of Excellence	Centralized management of the automation portfolio	Reuse of solutions and control of the effect	Unified architecture, methodology and process owners
Open banking / API	Integration of the bank with partners and digital ecosystems	Reducing product launch time	Managing access, consent, and cyber risk
AI-enabled operations	Application of AI in fraud, AML, scoring, and maintenance	Increased accuracy and productivity	Data quality, explainability, and model management

⁷Compiled by the author.

⁸Garcia T., Grodzicki M., Radulova P. Digital Banking: How New Bank Business Models Are Disrupting Traditional Banks. ECB Financial Stability Review, May 2025. https://www.ecb.europa.eu/press/financial-stability-publications/fsr/focus/2025/html/ecb.fsrbox202505_04~17b39a3c1a.en.html.

⁹Pazarbasioglu C., Mora AG, Uttamchandani M., Natarajan H., Feyen E., Saal M. Digital Financial Services. Washington, DC: World Bank, 2020. <https://www.worldbank.org/en/topic/financialsector/publication/digital-financial-services>.

¹⁰Systematized by the author based on materials from BIS, OECD, World Bank and ECB.

Approach	Content	Advantage	Condition of effectiveness
Operational resilience by design	Embedding sustainability into digital architecture	Reducing losses from failures and third parties	Mapping critical operations and testing scenarios

Leading banks are also establishing Operational Excellence Centers (OECs) or Automation Centers of Excellence (ACEs). These centers establish uniform project selection standards, calculate economic impact, maintain a library of reusable components, monitor technological and modeling risks, and share expertise across departments. This prevents each department from purchasing separate solutions without a common architecture and unified performance evaluation system.

Analysis and results of the research.

During the course of the research, we put forward the following proposals for improving the operational efficiency management mechanism:

First, commercial banks should create a unified register of end-to-end processes covering customer acquisition, identification, account opening, lending, payments, collections, claims processing, and product closure. For each process, the owner, cost, duration, risks, and target indicators must be defined.

Secondly, it makes sense to select digitalization projects not based on technological innovation, but rather on their overall economic impact. Priority should be given to processes with a high volume of operations, significant manual labor, frequent errors, long wait times, and high monitoring costs.

Third, process mining must be implemented as a continuous tool for monitoring actual process execution. Its results should be reviewed by the operational efficiency committee and used to eliminate deviations from the target model.

Fourth, it is recommended to establish a Center for Operational Excellence and Intelligent Automation,

bringing together specialists in business processes, RPA, AI, data, information technology, risk, and compliance. The center should manage a portfolio of initiatives and validate the achieved impact after implementation.

Fifth, it makes sense to move from automating individual tasks to end-to-end intelligent automation. For example, when processing a loan application, OCR recognizes documents, AI verifies data and calculates risk, workflow forwards exceptions to the responsible employee, and RPA reflects the approved decision in accounting systems.

Sixth, a minimum set of digital efficiency KPIs should be established: cost-to-income, cost per operation, average and median cycle time, straight-through processing rate, reprocessing rate, availability of critical services, error rate, employee productivity, and customer satisfaction.

Seventh, benefits realization must be implemented. After launching a digital solution, the bank must compare the actual reduction in labor costs, time, errors, and losses with the business case. Unused, freed-up resources should not be automatically considered savings without changing the workload or redistributing functions.

Eighth, digital initiatives should be classified by risk level. Simple automated reporting may require simplified approval, while an AI-based credit decision model, biometrics, or the transfer of a critical system to the cloud require extensive validation, customer impact assessment, and scenario testing.

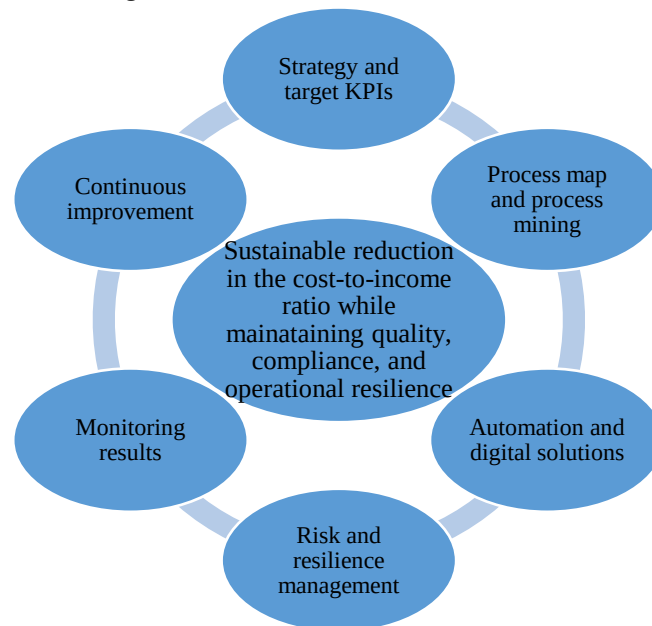


Figure 2. Digital operational efficiency management framework for a commercial bank¹¹

¹¹Developed by the author.

Ninth, it's necessary to develop a unified data management system and assign responsibility for critical data elements. AI-based solutions cannot be sustainably effective if there are duplicates, omissions, and inconsistencies in the source data.

Tenth, operational resilience requirements should be built into the digital process architecture: define critical operations, acceptable downtime, backup procedures, third-party dependencies, and recovery procedures. The Basel Committee principles emphasize that a bank must maintain the ability to deliver critical operations in the face of disruptions¹².

Eleventh, it makes sense to optimize the role of branches by transferring standard operations to digital channels, and turning branches into consulting centers for complex products, customer support, and sales. Branch evaluation should consider not only direct profit but also its contribution to the omnichannel customer journey.

Twelfth, the incentive system for executives should take into account not the number of IT projects implemented, but rather proven process improvements. This reduces the risk of formal digitalization and encourages departments to jointly achieve measurable results.

Conclusion.

Overall, digital technologies offer the potential to significantly improve the operational efficiency of commercial banks, but the economic impact only occurs when integrated with process management and organizational change. Local automation of individual tasks without revising the end-to-end process can perpetuate duplication of functions, unnecessary approvals, and poor data quality.

The most significant mechanisms are intelligent automation, process mining, modular API architecture, cloud services, omnichannel support, and centralized data management. Their combined use allows for shorter banking transaction times, lower service costs, reduced errors, and increased staff productivity.

A hybrid model is proposed for commercial banks in the Republic of Uzbekistan, combining digitalization of mass operations with centralized risk management, data management, and technological architecture. Practical implementation of the model requires the establishment of an operational excellence center, KPI-based performance measurement, and mandatory consideration of operational sustainability. This approach allows digital transformation to be viewed not as an expendable IT project, but as an ongoing mechanism for enhancing the bank's competitiveness and sustainability.

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MODERN MIGRATION MANAGEMENT MODELS IN DEVELOPED COUNTRIES: THE EXPERIENCE OF GERMANY, CANADA, AUSTRALIA, AND SINGAPORE

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Abstract

This article examines contemporary models of migration management in developed countries, drawing on the experiences of Germany, Canada, Australia, and Singapore. The purpose of the study is to identify institutional, digital, and economic mechanisms that ensure the effective regulation of migration, the attraction of skilled professionals, the integration of migrants, and the reduction of migration-related risks. The methodological framework is based on comparative analysis, the institutional approach, systems analysis, and the examination of official documents issued by international organizations and government authorities. The findings show that Germany focuses on addressing labour shortages through the Skilled Immigration Act; Canada applies a planned migration model that prioritizes economic selection; Australia is reforming its migration system by simplifying visa streams and introducing the Skills in Demand visa; and Singapore employs a highly digitalized and selective model based on COMPASS, biometric technologies, and automated border control. The study concludes that the most applicable approach for Uzbekistan is a combined model incorporating a digital migration management platform, a points-based assessment system for labour migrants, migration-flow forecasting, and the institutional integration of employment, education, and external labour migration authorities.

Keywords: migration, migration management, innovative mechanisms, digitalization, labour migration, Germany, Canada, Australia, Singapore.

1. Introduction.

In the context of globalization, migration processes are becoming a key factor in the socioeconomic development of countries. International migration is no longer viewed solely as a demographic or humanitarian phenomenon; it is becoming a tool for filling labor shortages, increasing the innovative potential of economies, developing human capital, and strengthening the competitiveness of national labor markets. According to the OECD, migration flows in OECD countries remained high in 2024, with migrant employment reaching an average of approximately 71%, confirming the growing importance of migration for the labor markets of developed countries.

2. Theoretical basis of the research.

The research's relevance stems from the fact that Germany, Canada, Australia, and Singapore represent four different but complementary models of migration management. Germany demonstrates an industrial-personnel model aimed at attracting skilled professionals. Canada uses a point-based model with annual migrant intake targets. Australia is developing a selective model focused on long-term economic and regional development needs. Singapore employs a digital, highly selective, and technologically integrated model combining labor migration, biometrics, and automated controls.

The theoretical foundations of research into contemporary migration management models in developed countries are based on an interdisciplinary approach that integrates economic, institutional, political, legal,

sociological, and integration concepts. In the context of Germany, Canada, Australia, and Singapore, migration is viewed not only as a population movement but also as an object of public governance linked to the labor market, demographic sustainability, national security, social integration, and innovative development.

Authors S. Castles and M. Miller examine contemporary migration as a global process influencing economic and political change, national identity, and the cultural diversity of host countries. Their approach is relevant for analyzing Germany, Canada, Australia, and Singapore as countries where migration has become a permanent element of socioeconomic policy¹³. H.de Haas justifies migration through the concept of "aspirations and opportunities". People migrate not only because of poverty, but also because of the availability of resources, information, networks, and institutional conditions. This is particularly important for assessing the selective migration systems of Canada, Australia, and Singapore¹⁴. D.Massey and co-authors systematized the main theories of international migration: neoclassical theory, new migration economics, dual labor market theory, global systems theory, and migration networks. Their approach allows them to consider migration policy as a result of the interaction of labor demand, income differentials, and social ties¹⁵. M.Piore's dual labor market theory argues that migration arises from developed economies' persistent demand for workers in sectors where local populations are not always willing to work. This approach explains the

¹³Castles S., de Haas H., Miller M.J. The Age of Migration: International Population Movements in the Modern World (6th ed.), 2020, Red Globe Press. <https://doi.org/10.1007/978-1-349-26846-7>.

¹⁴ de Haas H. A theory of migration: The aspirations-capabilities framework. Comparative Migration Studies, 9, 2021, Article 8. <https://doi.org/10.1186/s40878-020-00210-4>.

¹⁵Massey D.S., Arango J., Hugo G., Kouaouci A., Pellegrino A., Taylor, J.E. Theories of international migration: A review and appraisal. Population and Development Review, 19(3), 1993, 431-466. <https://doi.org/10.2307/2938462>.

use of labor migration in Germany, Singapore, and Australia¹⁶.

S.Sassen links migration to globalization, transnational markets, and the changing role of the state. She argues that migration policy cannot be understood solely through state sovereignty, as global economic processes limit the autonomy of national governments¹⁷. J.Hollifield develops the concept of the “migration state” and the “liberal paradox”: developed democracies simultaneously need open labor markets and strive to control borders. This idea is particularly applicable to Germany, Canada, and Australia¹⁸. Author G.Freeman demonstrates that the migration policies of liberal democracies are often inclusive and expansionary, despite public concerns. His approach helps explain why developed countries continue to accept migrants despite political disputes¹⁹. K.Joppke explores the relationship between migration, citizenship, and the nation state. He demonstrates that different historical models of nationhood influence integration and naturalization policies, which is important for comparing Germany with Canada and Australia²⁰. The author, R.Penninx, views integration as a multi-level and two-way process involving migrants, the state, local authorities, educational institutions, the labor market, and civil society²¹. P.Scholten develops the idea of multi-level migration and integration management. According to him, migration policy is formed not only at the national level, but also through the interaction of regional, city, and supranational institutions²². A.Ager and A.Strang proposed a conceptual model of integration that includes employment, housing, education, healthcare, social connections, language, security, rights, and citizenship. This model is useful for assessing the effectiveness of integration policies in developed countries.²³

Author T. Hammar introduced an important distinction between citizens, foreigners, and “denizens” - permanent residents without full citizenship. His approach helps analyze the legal status of migrants and their participation in the life of the host society²⁴. A.Zolberg views immigration policy as a question of the state, borders, and political choice. His theory emphasizes that migration is regulated not only by economics, but also by security, identity, and sovereignty interests²⁵. U.Kymlicka substantiates the importance of

multiculturalism and group rights for the successful integration of migrants. His approach is particularly relevant for Canada and Australia, where migration policy is closely linked to the recognition of cultural diversity²⁶. R.Bauböck develops the concept of transnational citizenship, according to which the rights and belonging of migrants extend beyond the boundaries of a single territory and a single state. This is important for the analysis of contemporary migration patterns, where migrants maintain ties to their country of origin while simultaneously integrating into the host society²⁷. The theoretical basis of the research shows that modern migration management models in developed countries are formed at the intersection of five key areas: economic regulation of labor migration, institutional border control, integration policy, the legal status of migrants, and multicultural governance. Germany largely demonstrates an institutional integration model, Canada and Australia use a selective points-based model for attracting skilled migrants, and Singapore uses a pragmatic economic and administrative model focused on labor market needs and strict state control.

3. Methodological aspects of the research.

The research’s methodological framework includes a comparative analysis of migration patterns in Germany, Canada, Australia, and Singapore; an institutional analysis of state migration management agencies; a content analysis of official strategies, legislation, and reports from international organizations; and a systems approach to assessing innovative migration regulation mechanisms.

The research draws on the OECD International Migration Outlook 2024-2025, the IOM World Migration Report 2024, official documents from the German government, Immigration, Refugees and Citizenship Canada, the Department of Home Affairs Australia, the Ministry of Manpower Singapore, and the Immigration and Checkpoints Authority Singapore. The OECD notes that in 2023-2024, one of the key migration policy areas in OECD countries will be the digitalization of migration procedures, including visa processing, flow monitoring, and the regulation of international student migration.

4. Analysis and results of the research.

1. *Germany: A model of managed recruitment of skilled labor.*

¹⁶Piore M.J. *Birds of Passage: Migrant Labor and Industrial Societies*. Cambridge University Press, 1979.

¹⁷Sassen S. *Losing Control? Sovereignty in an Age of Globalization*. Columbia University Press, 1996.

¹⁸Hollifield J.F. The emerging migration state. *International Migration Review*, 38(3), 2004, 885-912. <https://doi.org/10.1111/j.1747-7379.2004.tb00223.x>.

¹⁹Freeman, G.P. Modes of immigration politics in liberal democratic states. *International Migration Review*, 29(4), 1995, 881-902. <https://doi.org/10.1177/019791839502900401>.

²⁰Joppke C. *Immigration and the Nation-State: The United States, Germany, and Great Britain*. Oxford University Press, 1999.

²¹Penninx R., Garcés-Mascareñas B. (Eds.). *Integration Processes and Policies in Europe: Contexts, Levels and Actors*. Springer, 2016. <https://doi.org/10.1007/978-3-319-21674-4>.

²²Scholten P. Agenda dynamics and the multi-level governance of migrant integration: The Dutch case. *Political Sciences*, 46(3), 2013, 217-236 pp. <https://doi.org/10.1007/s11077-013-9180-x>.

²³Ager A., Strang A. Understanding integration: A conceptual framework. *Journal of Refugee Studies*, 21(2), 2008, 166-191. <https://doi.org/10.1093/jrs/fen016>.

²⁴Hammar T. *Democracy and the Nation State: Aliens, Denizens and Citizens in a World of International Migration*. Avebury, 1990.

²⁵Zolberg A.R. *A Nation by Design: Immigration Policy in the Fashioning of America*. Harvard University Press, 2006.

²⁶Kymlicka W. *Multicultural Citizenship: A Liberal Theory of Minority Rights*. Oxford University Press, 1995.

²⁷Bauböck R. *Transnational Citizenship: Membership and Rights in International Migration*. Edward Elgar Publishing, 1994.

In recent years, Germany has strengthened its immigration policy focus on attracting skilled professionals from third countries. The foundation of this model is the Skilled Immigration Act, which expands entry and employment opportunities for professionals with vocational education, practical experience, and recognized qualifications. The official Make it in Germany portal notes that the new Skilled Immigration Act facilitates the entry of skilled workers, including those with vocational training and practical knowledge.

A key feature of the German model is the close alignment of migration policy with the needs of industry, healthcare, engineering, the IT sector, and medium-sized businesses. Germany doesn't simply accept migrants; it creates institutional channels for their selection, recognition of qualifications, language training, and integration into the labor market. The German Federal Ministry of the Interior noted that the first stage of the updated regulation entered into force on November 18, 2023, and was aimed at increasing flexibility in attracting foreign specialists.

Thus, the German model can be characterized as a professional-institutional model of migration management, where innovation is manifested in the digitalization of procedures, simplification of the recognition of qualifications, the creation of transparent channels for labor migration, and the combination of migration policy with industrial strategy.

2. Canada: Point-Based Migration Management Model.

Canada is one of the best-known examples of managed migration, based on long-term planning, a points-based selection system, and a prioritization of economic migration. Canada's immigration policy is based on annual and medium-term Immigration Levels Plans, which set admission targets for permanent residents, temporary workers, international students, family members, and refugees.

According to official IRCC information, the 2025-2027 Immigration Levels Plan calls for a reduction in the overall intake of permanent residents to 395,000 in 2025, 380,000 in 2026, and 365,000 in 2027. However, the economic category will remain a priority and should account for approximately 62% of intake by 2027.

A distinctive feature of the Canadian model is its combination of economic selection and social integration. Canada evaluates candidates based on age, education, work experience, language proficiency, adaptability, and professional relevance. In recent years, the country has also strengthened controls over temporary migration, including international students and temporary workers, to reduce pressure on housing, social infrastructure, and the labor market. IRCC notes that the new approach includes not only permanent residents but also targets for temporary residents.

The Canadian model can be defined as a planned-selective model of migration management, where the innovative mechanism is expressed in forecasting the needs of the economy, scoring human capital, digital processing of applications, and linking migration policy with demographic strategy.

3. Australia: A Model of Strategic Migration and Regional Balance.

Australia's migration model has historically been based on selective selection, a points-based system, attracting skilled workers, and maintaining demographic balance. In 2023, the Australian government unveiled a new Migration Strategy aimed at reforming the migration system, increasing its transparency, and adapting it to the country's long-term economic needs. The strategy emphasizes that the primary goal of the permanent skilled visa is to ensure Australia's long-term prosperity.

One of the key areas of the reform is the creation of a new Skills in Demand visa with several streams, including a Specialist Skills Pathway and a Core Skills Pathway. These mechanisms are designed to attract highly skilled professionals, particularly in technology, green energy, and sectors with proven skills shortages.

The Australian model also takes regional specifics into account: migration policy is used not only to support the national labor market but also to develop regions experiencing population and skill shortages. A key element is the revision of the points-based test, as the government seeks to make the selection system more accurate and responsive to the real needs of the economy. Consequently, the Australian model can be defined as a strategically selective model of migration management, where innovation is manifested in updating the visa architecture, linking migration to long-term competencies, developing regional channels and increasing the mobility of migrants in the labor market.

4. Singapore: A Digital and Highly Selective Model of Migration Management.

Singapore represents a unique type of immigration management based on a high level of digitalization, rigorous selection of migrant workers, and a close alignment of immigration policy with the national competitiveness strategy. The primary tool for attracting foreign specialists is the Employment Pass, which is designed for foreign professionals, managers, executives, and technical specialists. Singapore's Ministry of Manpower specifies that Employment Pass applicants must meet a minimum salary level and pass the COMPASS assessment.

COMPASS is a points-based system that evaluates candidates not only based on individual characteristics but also on the employer's contribution to local workforce development, workforce diversity, and alignment with strategic economic needs. Effective September 1, 2023, COMPASS will be used to assess new Employment Pass applications.

Singapore's second key feature is the digitalization of border control. The Immigration and Checkpoints Authority Singapore is developing the New Clearance Concept, which provides for automated and contactless immigration clearance. Since 2024, arriving Singapore residents and all outbound travelers have been able to clear passports at automated lanes at airports and seaports without presenting a passport. In 2026, the ICA also noted that automated clearance has become the norm at border crossings, and foreign visitors can use automated lanes without prior registration.

The Singapore model can be defined as a digital, selective-competence-based model of migration management, where the innovative mechanism includes

COMPASS, biometrics, automated control, electronic services, and the integration of migration policy with the national human resources strategy.

A comparative analysis reveals that all four countries employ different institutional approaches, but they share several common characteristics. First, migration is viewed as a tool for economic development, not just a demographic process. Second, the role of digitalization is increasing: electronic visa services, automated application processing, biometrics, digital migrant profiles, and data analytics are becoming central elements of migration management. Third, developed countries are moving from passive migration regulation to active human capital management.

Germany is focusing on filling the skills gap, particularly in manufacturing, healthcare, and technical fields. Canada has the most developed system for planning migration flows and linking migration with demographic policy. Australia combines economic selection with regional development and visa system reform. Singapore demonstrates the highest level of digitalization and institutional selectivity.

These models have practical implications for Uzbekistan. First, the German experience can be used in developing bilateral agreements on labor migration, recognition of qualifications, and pre-departure training. Second, the Canadian model is useful for creating a system for forecasting migration flows and assessing the labor potential of migrants. Third, the Australian approach is important for linking migration with regional development and professional standards. Fourth, the Singaporean experience can be adapted to create a unified digital migration management platform, incorporating electronic registration, biometrics, labor contract monitoring, and risk analytics.

Conclusion.

Current migration management models in Germany, Canada, Australia, and Singapore demonstrate that effective migration policy must be comprehensive, digital, and focused on human capital. Germany demonstrates a model for attracting skilled professionals through institutional simplification and recognition of qualifications. Canada employs a planned system for regulating migration flows, prioritizing economic migration. Australia is reforming its migration system to address long-term economic needs, regional development, and labor mobility. Singapore is developing the most digitalized model, based on COMPASS, biometrics, and automated screening.

For the Republic of Uzbekistan, it is advisable to develop a combined migration management model that includes: a unified digital migration monitoring platform; a system for assessing the qualifications and professional competencies of migrants; forecasting external labor migration; developing bilateral agreements

with host countries; protecting the rights of labor migrants; and integrating data between employment, education, migration authorities, and diplomatic missions.

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**DIRECTIONS AND PLANNED OUTCOMES OF THE IMPLEMENTATION OF CHINA'S
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г. Минск, Республика Беларусь***НАПРАВЛЕНИЯ И ПЛАНИРУЕМЫЕ РЕЗУЛЬТАТЫ РЕАЛИЗАЦИИ СТРАТЕГИЙ
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The article examines the directions and planned outcomes of implementing China's regional development strategies within the framework of the country's 15th Five-Year Plan for National Economic and Social Development. The paper outlines key directions, their breakdown, and the tasks involved in optimizing China's regional economic structure and fostering coordinated regional development. It emphasizes the need to maximize the combined impact of the coordinated regional development strategy, major regional strategies, the strategy of main functional zones, and the new urbanization strategy, while also coordinating and deepening the implementation of regional strategies and strengthening interregional ties. The content of the trends reshaping China's economic landscape through strategic regional development is outlined, and the expected outcomes and their assessment are presented. The study substantiates the establishment of an integrated geoeconomic mechanism in China, wherein a region shifts from being a competitor for budget funds to becoming a component of a unified, balancing system aimed at maximizing national GDP rather than local Gross Regional Product (GRP).

Аннотация

В статье рассмотрены направления и планируемые результаты реализации стратегий регионального развития Китая в контексте выполнения Плана 15-й пятилетки национального экономического и социального развития страны. Представлены основные направления, их декомпозиция и решаемые задачи по оптимизации региональной экономической структуры и содействию координированному региональному развитию Китая, предполагающие необходимость максимально использовать эффект суперпозиции региональной координированной стратегии развития, крупной региональной стратегии, стратегии основных функциональных зон и новой стратегии урбанизации, а также координировать и способствовать углублению реализации региональных стратегий и развитию межрегиональных связей. Сформулировано содержание направлений изменения экономического ландшафта Китая в результате стратегического регионального развития, представлены его ожидаемые результаты и их оценка. Обосновывается создание в Китае интегрированного геоэкономического механизма, где регион превращается из конкурента за бюджет в элемент единой балансирующей системы, работающей на максимизацию национального ВВП, а не локального валового регионального продукта (ВРП).

Keywords: region, regional development, strategy for coordinated regional development, superposition effect, optimization of the regional economic structure.

Ключевые слова: регион, региональное развитие, региональная координированному региональному развитию стратегия, эффект суперпозиции, оптимизация региональной экономической структуры

Введение. КНР сегодня является второй по величине экономикой мира и ключевым двигателем глобального роста. Как отмечается в Плате 15-й пя-

тилетки национального экономического и социального развития КНР, это развитие происходит в период сосуществования стратегических возможно-

стей, рисков и вызовов, а также роста неопределённости и непредсказуемых факторов [1]. Любые внутренние процессы в Китае, особенно такие масштабные, как региональное развитие, оказывают непосредственное влияние на мировые цепочки поставок, товарные рынки и международные инвестиционные потоки. Понимание китайских региональных стратегий необходимо для прогнозирования глобальных экономических трендов. Стратегии регионального развития создают необходимые условия для формирования благоприятного инвестиционного и делового климата внутри Китая. Знание специфики каждой стратегии (например, «Один пояс – один путь», развитие Пилотной зоны свободной торговли в Хайнане) позволяет иностранным компаниям и государствам выстраивать эффективную политику сотрудничества, минимизировать риски и максимизировать выгоды от взаимодействия с разными регионами Китая.

Сегодня также Китай представляет собой уникальную «лабораторию» для тестирования и развития теорий регионального развития, пространственной экономики и государственного управления. Сочетание плановых и рыночных механизмов, масштабность и скорость преобразований предлагают богатейший эмпирический материал для научного анализа. Региональное развитие в Китае напрямую связано с ключевыми политическими задачами Коммунистической партии Китая: обеспечение социальной стабильности и национальной

безопасности. Изучение этих стратегий позволяет глубже понять внутреннюю логику и приоритеты китайского руководства. При этом необходимо отметить, что несмотря на впечатляющие успехи в борьбе с бедностью, Китай продолжает сталкиваться с глубокими региональными диспропорциями по уровню ВВП на душу населения, доходам, качеству человеческого капитала и доступу к социальным благам. Эти дисбалансы создают угрозу долгосрочной социально-экономической стабильности страны, что делает задачу их сглаживания одной из приоритетных для центрального правительства.

Таким образом, сегодня является актуальным разработка стратегий, обеспечивающих сбалансированное высокоэффективное развитие регионов КНР и направленных на формирование технологического суверенитета, экологической безопасности и социальной стабильности страны.

Результаты исследований. Одними из важнейших направлений реализации Плана 15-й пятилетки национального экономического и социального развития страны Китая (далее – Плана) выступают оптимизация региональной экономической структуры и содействие координированному региональному развитию страны [1], что, в свою очередь, предполагает реализацию следующих направлений, представленных в таблице 1.

Таблица 1

Основные направления, их декомпозиция и решаемые задачи по оптимизации региональной экономической структуры и содействию координированному региональному развитию КНР

Направления	Декомпозиция направлений и решаемые задачи
1. Усиление координации регионального развития	1.1 Улучшить уровень координированного развития в Восточном, Центральном, Западном и Северо-Восточном регионах 1.2 Консолидировать и усилить роль районов Пекин-Тяньцзинь-Хэбэй, дельты реки Янцзы и Большого залива Гуандун-Гонконг-Макао как источников энергии 1.3 Содействие развитию экономического пояса реки Янцзы, экологической охране и качественному развитию бассейна Хуанхэ 1.4 Поддержка возрождения и развития особых типов территорий
2. Содействие развитию региональных связей	2.1 Улучшить структуру развития региональных связей 2.2 Совершенствование межрегиональных механизмов сотрудничества
3. Оптимизация схемы развития территориального пространства	3.1 Укрепление реализации стратегии основных функциональных направлений 3.2 Оптимизировать управление территориальными пространствами 3.3 Укрепление совместного управления территориальным пространством
4. Углубление ориентированной на людей новой урбанизации	4.1 Научно и упорядоченно продвигать гражданство сельскохозяйственных мигрантов 4.2 Культивирование и развитие современных столичных районов 4.3 Строительство современного народного города 4.4 Продвижение строительства урбанизации с уездами в качестве важных носителей по классификации
5. Укрепление защиты морского развития и использования	5.1 Содействие высококачественному развитию морской экономики 5.2 Защита морской экологической среды 5.3 Защита национальных морских прав и интересов

Источник: составлено на основе [1].

Данные направления предполагают необходимость максимально использовать эффект суперпозиции региональной координированной стратегии развития, крупной региональной стратегии, стратегии основных функциональных зон и новой стратегии урбанизации, координировать и способствовать углублению реализации региональных стратегий и развитию межрегиональных связей. Также требуется в период реализации 15-й пятилетки с 2026 по 2030 годы оптимизировать структуру основных производительных сил, максимально использовать роль ключевых регионов как полюсов роста, а также строить региональную экономическую структуру и территориальное пространство с дополняющими преимуществами и высококачественным развитием [1].

Важнейшим условием реализации указанных стратегий регионального развития является обеспечение реализации принципа суперпозиции, в общем случае предполагающего допущение, согласно которому результирующий эффект нескольких независимых воздействий есть сумма эффектов, вызываемых каждым воздействием в отдельности. Данный принцип схож по своей сути с принципом аддитивности, которая определяется как свойство, при котором значение целого объекта или процесса равно простой сумме значений его отдельных частей. Однако, в отличие от аддитивности суперпозиция – это принцип наложения, при котором совместное действие нескольких факторов равно сумме (или линейной комбинации) их индивидуальных действий, т.е. аддитивность говорит о статичном составе объекта, а суперпозиция – о взаимодействии процессов. Таким образом аддитивность – это статичное свойство величины или системы, а суперпозиция – правило сложения или наложения процессов, сил или состояний [2].

В экономике и управлении принцип суперпозиции означает, что общий результат работы системы равен простой сумме итогов от каждого отдельного действия или фактора. Необходимо отметить, что этот подход работает только при условии линейности системы, когда разные процессы не мешают друг другу и не усиливают друг друга неожиданным образом.

Возвращаясь к проблемам и направлениям реализации 15-й пятилетки (2026–2030 гг.) необходимо отметить, что рассматриваемый План описывает переход Китая от изолированных региональных стратегий к их суперпозиции (наложению эффектов). Это принципиально новый уровень пространственного управления, призванный решить проблему фрагментации рынков, дублирования производств и чрезмерных разрывов в развитии.

Далее представим развернутый анализ каждой из четырех стратегий и механизма их координации.

1. Региональная координированная стратегия развития (Regional Coordinated Development Strategy) [3–4]. Это базовый, сквозной принцип, нацеленный на сглаживание диспропорций между Востоком и Западом, Югом и Севером.

Оптимизация структуры будет обеспечена через:

– механизм «спаривания» и «помощи»: богатые восточные провинции (Чжэцзян, Цзянсу) институционально привязаны к развитию отсталых западных регионов (Синьцзян, Тибет). Это не просто дотации, а принудительный трансфер технологий, управленческих кадров и промышленных цепочек;

– трансфер производств: стимулируется планомерный перенос трудоемких и ресурсоемких производств из дорогих прибрежных центров (дельта Жемчужной реки) во внутренние районы (Цзянси, Хэнань), что снижает себестоимость и создает занятость на местах, предотвращая избыточную миграцию.

Будет обеспечен следующий вклад в координацию: создается «артериальное давление» в экономике, заставляя капитал и компетенции циркулировать по всей стране, а не концентрироваться исключительно в экспортноориентированных анклавах.

2. Крупная региональная стратегия (Major Regional Strategies) [5–8]. Это «точечно-осевой» подход, когда происходит концентрация ресурсов на ключевых полюсах роста, которые становятся драйверами для обширной периферии. Здесь можно выделить следующие ключевые инициативы:

– скоординированное развитие региона Пекин-Тяньцзинь-Хэбэй (Цзинь-Цзинь-Цзи) позволит решить проблемы «столичной сверхконцентрации» путем создания Сюньань как «умного города-спутника» с нуля, вывод непрофильных столичных функций (промышленность, логистика, образование) из Пекина.

– развитие региона дельты реки Янцзы связано со смещением фокуса на высокотехнологичную интеграцию путем создания единого рынка талантов и капитала, совместного использования научной инфраструктуры;

– большой залив Гуандун-Сянган-Аомэнь: стыковка разных юрисдикций (социалистическая, капиталистическая) для создания глобального хаба инноваций и финансов через реализацию принципа «одна зона – три правовых режима»;

– экологическая защита и развитие бассейна Желтой реки путем смещения акцента с «освоения» на «защиту». Это экологический каркас северного Китая, где промышленное развитие жестко лимитируется водным балансом.

В рамках данной стратегии вкладом в координацию будет являться формирование «гравитационных центров», которые стягивают ресурсы на новом качественном уровне и задают стандарты развития (цифровизация, зеленая экономика) для соседей.

3. Стратегия основных функциональных зон (Major Functional Zoning [9–10]). Это жесткое пространственное планирование, делящее всю территорию КНР на сетку с разными правовыми режимами хозяйствования. Земля – это не просто участок, а носитель предписанной функции.

Можно представить следующую типологию зон (оптимизация структуры):

– зоны приоритетной урбанизации (урбанизированные), в которых разрешено плотное строительство, промышленное развитие. Здесь формируется 80% ВВП страны (городские агломерации);

– зоны основного сельхозпроизводства, в которых имеется законодательный запрет на изъятие пашни под заводы, что является гарантом продовольственной безопасности. Регионы не могут «конвертировать» поля в недвижимость, даже ради роста валового регионального продукта (ВРП), а в качестве компенсации будут выступать федеральные трансферты.

– ключевые экологические зоны, в которых предусмотрено ограничение любой индустрии. В качестве критерия оценки развития этих зон выступает не рост экономики, а качество воды, чистота воздуха, лесистость.

Соответственно вклад в координацию – Это «смирительная рубашка» для региональных амбиций. Она законодательно предотвращает конкуренцию за инвестиции через снижение экологических или земельных стандартов (гонку на дно), заставляя каждый регион развиваться в своей парадигме.

4. Новая стратегия урбанизации (New Urbanization Strategy) [11–13]. Фокус смещается с урбанизации земли (бесконтрольное расширение городов) на урбанизацию людей (интеграцию мигрантов). Это напрямую связано с демографией и внутренним спросом.

Здесь ожидаются следующие структурные изменения:

– регистрация (хукоу) – упрощение получения городской прописки (кроме мегаполисов) для 300-миллионной армии рабочих-мигрантов с целью превращения «временных рабочих» в постоянных горожан с доступом к медицине, образованию и жилью, что радикально меняет структуру потребления;

– развитие уездных городов – ключевой пункт новой пятилетки. Создание инфраструктуры не в мегаполисах, а в малых и средних городах, чтобы остановить отток сельского населения сразу в гиганты, формируя устойчивую «среднюю прослойку» расселения;

– городские агломерации – переход от изолированной конкуренции городов к созданию «часовых транспортных кругов», где работа, жилье и досуг находятся в разных городах одной агломерации (метро в уездных центрах).

С точки зрения вклада в координацию – это связывание рынка труда воедино и выравнивание подушевых стандартов общественных услуг, снижая социальное напряжение между коренными жителями и мигрантами.

Анализ каждой из четырех стратегий и механизма их координации позволяет дать оценку синтеза – эффекта суперпозиции и межрегиональных связей, перехода от суммы тактик к системной интеграции, что на практике означает:

1. Наложение сеток:

– «Крупная региональная стратегия» определяет, где создавать кластеры (например, чипы — в Янцзы);

– «Функциональные зоны» определяют, где нельзя ничего строить (экологический барьер на Янцзы);

– «Новая урбанизация» обеспечивает кого нанимать на заводы (интегрированных граждан) и где они будут жить (в спутниках, а не в перенаселенном Шанхае);

– «Координированная стратегия» дает механизм оплаты (трансферты с Янцзы в верховья Желтой реки за экологию).

2. Пример суперпозиции (геоэкономическая конструкция). Для иллюстрации возьмем бассейн реки Янцзы. Крупная региональная стратегия требует инновационного коридора, в то время как стратегия функциональных зон запрещает строительство химических заводов у истоков реки (сохраняя воду). Новая урбанизация предполагает строительство там не заводских общежитий, а современных малых городов для ученых и экологов. Координированная стратегия развития компенсирует упущенную промышленную прибыль этого региона за счет налоговых отчислений от индустрии низовий реки, которая пользуется чистой водой. Так возникает неразрывная связка «экология – финансы – наука – демография».

3. Подавление «эффекта локального эгоизма». Раньше каждый мэр строил «свой» аэропорт или технопарк, которые пустовали. Суперпозиция стратегий вводит сквозное бюджетное планирование и единую цифровую платформу землепользования (интегрированная система пространственного планирования «одна карта»). Субъекты больше не могут действовать вразнобой, так как их планы должны автоматически проходить проверку на соответствие всем четырем уровням стратегий федерального центра.

Таким образом, предполагается создание в Китае интегрированного геоэкономического механизма, где регион превращается из конкурента за бюджет в элемент единой балансирующей системы, работающей на максимизацию национального ВВП, а не локального ВРП.

Необходимо отметить, что в рамках оптимизации региональной экономической структуры и действия координированному региональному развитию страны, определенных Планом, в период реализации 15-й пятилетки с 2026 по 2030 годы предполагается оптимизировать структуру основных производительных сил, максимально использовать роль ключевых регионов как полюсов роста, а также строить региональную экономическую структуру и территориальное пространство с дополняющими преимуществами и высококачественным развитием. Основываясь на анализе четырех стратегий, можно спрогнозировать, как конкретно изменится экономический ландшафт Китая к 2030 году. Предполагаемые результаты направлены на переход от экстенсивного выравнивания к интенсивной, функционально специализированной интеграции. Далее представим анализ и оценку ожидаемых итогов по трем ключевым направлениям стратегического регионального развития Китая (таблица 2).

Направления изменения экономического ландшафта Китая в результате стратегического регионального развития, ожидаемые результаты и их оценка

Направления	Ожидаемые результаты и их оценка
1. Результаты оптимизации структуры основных производительных сил [1; 14–15]	
<i>1.1. Каскадная промышленная архитектура: ожидается четкое разделение труда.</i> – Приморский пояс (Дельта Янцзы, Большой залив) сконцентрируется на «штабной экономике», НИОКР, финансах и опытном производстве. Сюда перестанут поступать инвестиции в базовую обработку. – Центральные и западные хабы (Чэнду-Чунцин, Ухань, Чжэнчжоу) станут зонами «умного производства» и дублерами критических цепочек поставок (микроэлектроника, автопром, аэрокосмос). Здесь будет происходить основная индустриализация нового типа, приближенная к рынкам сбыта и источникам чистой энергии (западный гидропотенциал). – Приграничные и ресурсные базы (Синьцзян, Юньнань) перестанут быть сырьевыми придатками. Здесь сформируются кластеры переработки (продукты питания, цветные металлы, новые материалы) с экспортным потенциалом в страны Центральной и Юго-Восточной Азии.	<i>Ожидаемый результат:</i> завершится переход от концепции «переноса мощностей» к логике «распределенного и безопасного размещения». Производительные силы перестанут концентрироваться исключительно в прибрежных зонах, сформировав многоуровневую сеть. <i>Оценка результата:</i> это приведет к значительному сокращению логистических издержек внутри страны и повышению национальной экономической безопасности за счет дублирования производственных компетенций в глубине территории, а не только на уязвимом побережье.
<i>1.2. Уход от модели «летающих гусей»:</i> если раньше производства механически переносились из Шанхая в Аньхой, а затем в Хэнань по мере роста издержек, то теперь размещение диктуется доступом к «зеленой» энергии и водным ресурсам. Это предотвратит миграцию «грязных» технологий вверх по течению рек (бассейн Янцзы), а направит энергоемкие производства (центры обработки данных, водородная металлургия) в западные пустыни, где избыток солнечной и ветровой генерации.	
2. Роль ключевых регионов как полюсов роста: «Эффект вытягивания» [5; 7; 16]	
<i>2.1. Эволюция агломераций в метарегионы:</i> – Большой залив: Результатом станет не просто сумма ВРП Гуандуна, Гонконга и Макао, а создание единого рынка капитала для инноваций. Ожидается, что Гонконг станет глобальным центром листинга для технологических компаний всего пояса, а Шэньчжэнь – полигоном для превращения этих инвестиций в продукт. Их кооперация создаст мощный полюс притяжения для талантов из АСЕАН. – Цзин-Цзинь-Цзи (Пекин-Тяньцзинь-Хэбэй): Главный измеримый результат – Сюньань. К 2030 году город должен доказать свою состоятельность как эталон «цифрового двойника» и безмиграционной урбанизации. Пекин окончательно избавится от статуса промышленного гиганта, сконцентрировавшись на фундаментальной науке, дипломатии и финансах.	<i>Ожидаемый результат:</i> закрепится ролевая модель, где полюса роста не «пылесосят» ресурсы периферии, а выполняют функцию экспортеров знаний, стандартов и потребительского спроса. <i>Оценка результата:</i> усилится иерархичность пространства. Мегаполисы 1-го уровня станут глобальными узлами, города 2-го уровня — национальными драйверами. Произойдет «разгрузка» сверхкрупных городов без потери их экономической мощи, так как типовые офисные и складские функции переместятся в часовую доступность на высокоскоростных поездах.
<i>2.2. Калибровка гравитационного поля:</i> Ключевым эффектом станет способность Шанхая или Шэньчжэня не конкурировать с соседними уездами за налоги, а транслировать на них импульс развития через совместные индустриальные парки, где прибыль делится в пользу «донора-периферии» (модель «летающего штаба»).	
3. Экономическая структура с дополняющими преимуществами и высококачественное развитие [6; 17–21]	
<i>3.1. Институционализация экологических услуг как товара:</i> – Регионы-экологические доноры (Цинхай, верховья Янцзы и Желтой реки) получают формализованные механизмы получения прибыли не через заводы, а через «валовые экосистемные продукты». Трансферты из бюджетов промышленных низовий станут не благотворительностью, а платой за чистую воду и углеродную нейтральность. – Результат: разрыв по ВРП на душу населения между условными «заповедными» и «индустриальными» зонами сократится за счет выравнивания доходов бюджетов, а не путем уничтожения экологии.	<i>Ожидаемый результат:</i> это итоговый синтез, где все регионы перестают быть похожими друг на друга по отраслевой структуре и начинают дополнять друг друга. <i>Оценка результата:</i> Китай получит то, что в плановой

Направления	Ожидаемые результаты и их оценка
3.2. Сетевое взаимодействие вместо вертикальной интеграции: если раньше каждая провинция стремилась к автаркии (своя сталь, свой цемент, свой автозавод), то к 2030 году закрепятся межпровинциальные альянсы: – Янцзы: Шанхай (дизайн, финансы) – Цзянсу (биофарма, чипы) – Аньхой (лазеры, дисплеи) – Хубэй (оптика). – Запад: Ганьсу (цветная металлургия и «зеленый» водород) – Сычуань (авиация и ИТ-услуги) – Чунцин (производство электромобилей и логистика в Европу по ж/д магистрали).	экономике называется «единый народнохозяйственный комплекс», но на рыночный лад. Регионы будут «заточены» на узкую специализацию в масштабах всей страны, чтократно повысит совокупную факторную производительность.
3.3 Устойчивость к шокам: территориальная структура станет многополярной. В случае внешнего давления на порты Восточного Китая, товарные потоки будут перенаправлены через сухопутные коридоры Нового западного сухопутно-морского коридора (Чунцин – Гуанси – порты залива Бэйбу), что обеспечит непрерывность внешней торговли.	

Источник: авторская разработка на основе [1; 5–7; 14–21].

На основе представленного выше анализа дадим общую оценку предполагаемых итогов реализации стратегий:

1. Эффективность vs Равенство: будет найден новый баланс. Принцип «все богатеет равномерно» замещается принципом «все обеспечены на достойном уровне за счет разной функциональной нагрузки». Эффект будет замечен по выравниванию доступа к образованию, медицине и цифровой инфраструктуре при сохранении дифференциации в структуре промышленного производства.

2. Демографический якорь: новая урбанизация в связке с функциональным зонированием затормозит отток населения из малых городов, создав там качественную среду обитания. Мегаполисы перестанут быть безальтернативной мечтой для молодежи, что снизит накал проблем с жильем и пробками.

3. Геоэкономическая проекция: оптимизированная региональная структура станет платформой для «двойной циркуляции». Внутренние регионы насытят емкий внутренний рынок, а прибрежные кластеры, освобожденные от рутины, направят ресурсы на глобальную технологическую конкуренцию.

Таким образом, к 2030 году КНР планирует перейти от модели «региональной конкуренции» к модели «общегосударственного комплементарного симбиоза», где управляемость и устойчивость пространства ценятся выше, чем личный ВРП-рекорд отдельно взятой провинции.

Выводы. Сегодня является актуальной разработка стратегий, обеспечивающих сбалансированное высокоэффективное развитие регионов КНР и направленных на формирование технологического суверенитета, экологической безопасности и социальной стабильности страны. В статье рассмотрены основные направления, их декомпозиция и решаемые задачи по оптимизации региональной экономической структуры и содействию координированному региональному развитию КНР в соответствии с Планом 15-й пятилетки национального экономического и социального развития страны. Данные направления предполагают необходимость макси-

мально использовать эффект суперпозиции региональной координированной стратегии развития, крупной региональной стратегии, стратегии основных функциональных зон и новой стратегии урбанизации, координировать и способствовать углублению реализации региональных стратегий и развитию межрегиональных связей. Также требуется в период реализации 15-й пятилетки с 2026 по 2030 годы оптимизировать структуру основных производительных сил, максимально использовать роль ключевых регионов как полюсов роста, а также строить региональную экономическую структуру и территориальное пространство с дополняющими преимуществами и высококачественным развитием.

Предполагается создание в Китае интегрированного геоэкономического механизма, где регион превращается из конкурента за бюджет в элемент единой балансирующей системы, работающей на максимизацию национального ВВП, а не локального ВРП. Таким образом к 2030 году КНР планирует перейти от модели «региональной конкуренции» к модели «общегосударственного комплементарного симбиоза», где управляемость и устойчивость пространства ценятся выше, чем личный ВРП-рекорд отдельно взятой провинции.

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MATHEMATICAL SCIENCES

A GEOMETRIC MODEL OF THE TWISTED OUTER BIPOLAR SHELL OF A VORTEX KERN

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Abstract

A geometric model of a twisted bipolar outer shell surrounding a vortex kern is proposed for describing a smooth bipolar microvortex structure with continuous helical filaments. The bipolar coordinate system is derived from a complex Möbius (fractional linear) transformation that maps two distinguished poles to the origin and infinity, followed by the application of the complex logarithm. An analytical representation of the coordinate mapping is obtained, and the circular nature of the coordinate curves, the orthogonality of the coordinate families, and the conformal form of the metric are established. To describe the internal rotation of the shell, a smooth twist function, $\Omega(\tau)$, is introduced, transforming the angular coordinate according to $\sigma' = \sigma + \Omega(\tau)$. It is shown that this transformation converts the untwisted bipolar coordinate network into a system of continuous helical filaments while preserving the bipolar topology, the number of poles, and the local smoothness of the mapping. The Jacobian of the transformation, the metric tensor, and the conditions for orientation preservation are investigated. A numerical study employing the localized twist function $\Omega(\tau) = k \tanh(\lambda\tau)$ demonstrates that increasing the twist parameter leads to an increase in filament length and curvature and to the formation of a pronounced helical structure surrounding the inner vortex kern. The proposed construction provides a geometric framework for further investigations of the stability, helicity, and topological invariants of closed vortex shells.

Keywords: vortex kern; bipolar coordinates; twisted bipolar shell; vortex filaments; conformal mapping; stereographic projection; Möbius transformation; logarithmic mapping; differential geometry; geometric hydrodynamics; vortex topology; helicity; microvortex; vortex shell; numerical simulation

1. Introduction. The study of vortex structures is one of the fundamental research directions in modern hydrodynamics, mathematical physics, and geometric mechanics. Vortices arise in a wide range of natural and engineering processes, including turbulent flows, atmospheric and oceanic circulation, plasma physics, biomechanics, and aerodynamics. Despite significant advances in computational modeling, the geometric structure of individual vortices and the mechanisms governing the formation of their internal shells remain subjects of active investigation.

The classical theory of vortex motion originates from the work of Hermann von Helmholtz [1], who formulated the fundamental laws governing the evolution of vortex tubes in an ideal fluid. These ideas were subsequently developed by William Thomson, 1st Baron Kelvin, who demonstrated that the circulation around a material contour is conserved over time under the assumptions of ideal hydrodynamics. Kelvin's circulation theorem became one of the cornerstones of the geometric interpretation of vortex flows, establishing a fundamental relationship between fluid motion and the preservation of the topology of vortex lines.

During the twentieth century, vortex theory underwent substantial development through studies of vortex filaments and vortex tubes. It was established that vorticity is naturally transported by the fluid flow and that vortex filaments possess a high degree of geometric coherence and structural stability. Significant contributions to the understanding of the local geometry of vortices were made by Luigi da Rios, Horace Lamb, Philip

G. Saffman, Harry Bateman, and many other researchers [3-8, 23, 32-35, 38-42], who investigated the evolution of thin vortex filaments and their relationship to the governing equations of hydrodynamics.

Simultaneously, methods of differential geometry underwent rapid development [9-16, 24, 26-27, 36-37]. The introduction of the Frenet-Serret frame made it possible to describe vortex lines as space curves characterized by curvature and torsion. It was subsequently shown that the local geometry of a vortex filament is directly related to its dynamical evolution [40-42]. Of particular importance is the Hiroshi Hasimoto transformation, which converts the localized induction equation of a vortex filament into the nonlinear Erwin Schrödinger equation [31]. This remarkable result established, for the first time, a profound connection between the geometry of space curves and nonlinear wave phenomena.

Considerable attention has also been devoted to the study of topological invariants of vortex structures. The work of Henry Keith Moffatt [6-7] demonstrated that helicity is an integral measure of the mutual linkage and knottedness of vortex lines and may be regarded as a topological invariant of the flow. The theory was later extended through the introduction of Heinz Hopf invariants, which provide a rigorous algebraic-topological framework for describing complex spatial entanglements of vortex filaments [28-30].

In parallel, methods of conformal geometry and complex analysis were actively developed [17-20]. The stereographic projection, Möbius transformations, and complex coordinate systems became powerful tools for

the investigation of surfaces of constant curvature [38, 40]. Conformal mappings preserve the angles between intersecting curves and are therefore particularly well suited for the analysis of vortex flows, whose local structure is primarily determined by the angular properties of rotational motion.

A special role is played by the theory of bipolar coordinates [21-25]. This coordinate system arises naturally in the presence of two fixed poles and is widely used in electrostatics, potential theory, and conformal mapping. Bipolar coordinates are defined by the transformation

$$x = \frac{a \sin \sigma}{\cosh \tau - \cos \sigma}, \quad y = \frac{a \sinh \tau}{\cosh \tau - \cos \sigma}, \quad (1)$$

where the parameter a determines the distance between the two foci of the coordinate system. Owing to the conformality of this mapping, the coordinate curves form two orthogonal families of circles, making bipolar coordinates a convenient tool for describing bipolar geometric objects.

In classical applications, bipolar coordinates are used primarily for solving elliptic equations and problems of potential theory [24]. However, their application to the description of the internal structure of vortex shells has remained virtually unexplored. Meanwhile, the presence of two singular points naturally corresponds to the model of a vortex kern having two ends connected by a common internal structure.

In the present work, a geometric model is considered in which the microvortex shell is described not as a collection of independent vortex surfaces but as a single smooth two-dimensional manifold with two poles. The principal element of the model is an internal twist of the coordinate system, described by the smooth function

$$\sigma' = \sigma + \Omega(\tau), \quad (2)$$

where the function $\Omega(\tau)$ specifies the distribution of the internal rotation angle along the axis of the vortex kern. This formulation makes it possible to describe the continuous formation of helical filaments without violating the smoothness of the surface.

It should be emphasized that the proposed model is a geometric construction. It is not derived directly from the Navier–Stokes equations and is not intended to describe the complete hydrodynamic process. Its purpose is to establish a mathematically consistent geometry of a vortex shell that can subsequently serve as a foundation for further investigations of its dynamics, stability, helicity, and topological invariants.

The primary objective of the present work is to develop an analytical model of a twisted bipolar shell, to investigate its metric properties, to derive the conditions for the smoothness of the mapping, and to analyze the geometric characteristics of the resulting vortex filaments. Particular attention is devoted to the manner in which the local coordinate twist transforms the orthogonal bipolar coordinate network into a system of continuous helical lines connecting both ends of the inner vortex kern and forming a single closed vortex shell.

2. Rigorous Derivation of Bipolar Coordinates from a Complex Mapping.

Consider the complex plane with coordinate

$$z = x + iy \quad (3)$$

and fix two distinguished points

$$F_+ = ia, F_- = -ia, a > 0. \quad (4)$$

In Cartesian coordinates, these points are given by

$$F_+ = (0, a), F_- = (0, -a). \quad (5)$$

To construct the bipolar coordinate system, we introduce the Möbius (fractional linear) transformation

$$\zeta = (z - ia)/(z + ia). \quad (6)$$

This transformation maps the upper pole $z = ia$ to the origin of the complex plane:

$$z = ia \Rightarrow \zeta = 0,$$

and the lower pole $z = -ia$ to the point at infinity:

$$z = -ia \Rightarrow \zeta = \infty.$$

Since Möbius transformations are conformal at every point where their derivative is nonzero, this mapping preserves the angles between smooth curves everywhere except at the poles. Let the new complex variable be represented in exponential form

$$\zeta = e^\omega, \omega = \tau + i\sigma, \quad (7)$$

where $\tau \in \mathbb{R}$, and the angular coordinate σ is defined modulo 2π :

$$\sigma \sim \sigma + 2\pi.$$

Thus,

$$(z - ia)/(z + ia) = e^{\tau + i\sigma}. \quad (8)$$

Taking the complex logarithm of both sides yields the direct definition of the bipolar coordinate:

$$\tau + i\sigma = \log((z - ia)/(z + ia)), \quad (9)$$

whose real part gives

$$\tau = \ln|(z - ia)/(z + ia)|, \quad (10)$$

and whose imaginary part is

$$\sigma = \arg(z - ia) - \arg(z + ia) \pmod{2\pi}. \quad (11)$$

Hence, the coordinate τ represents the logarithm of the ratio of the distances from the point z to the two poles, whereas the coordinate σ is the oriented difference between the angles subtended by these poles as viewed from the point z . If the distances from the point z to the poles are denoted by

$$r_+ = |z - ia| = \sqrt{x^2 + (y - a)^2}, \quad (12)$$

$$r_- = |z + ia| = \sqrt{x^2 + (y + a)^2},$$

then

$$e^\tau = r_+/r_-. \quad (13)$$

The sign τ indicates which pole the point is closer to. For $\tau < 0$, one has $r_+ < r_-$, meaning that the point is closer to F_+ , whereas for $\tau > 0$, it is closer to F_- . The line $\tau = 0$ satisfies the condition $r_+ = r_-$ and therefore coincides with the perpendicular bisector of the segment F_+F_- , that is, with the axis $y = 0$.

We now derive the inverse transformation. From the relation

$$e^\omega = (z - ia)/(z + ia) \quad (14)$$

it follows that

$$z - e^\omega z = ia + ia e^\omega, z = ia((1 + e^\omega)/(1 - e^\omega)) \quad (15)$$

Using the identity

$$\coth \frac{\omega}{2} = \frac{e^\omega + 1}{e^\omega - 1} \quad (16)$$

we obtain

$$(1 + e^\omega)/(1 - e^\omega) = -\coth(\omega/2). \quad (17)$$

Therefore,

$$z = -ia \coth(\omega/2) \quad (18)$$

The choice of the initial ratio involving the poles determines possible changes in the signs and orienta-

tion of the coordinates. To obtain the form adopted below, with the poles located on the vertical axis, it is convenient to write the mapping equivalently as

$$z = (a \sin \sigma + ia \sinh \tau) / (\cosh \tau - \cos \sigma) \quad (19)$$

We now derive this formula directly. For the complex argument $w = \tau + i\sigma$ we have

$$\coth \frac{w}{2} = \frac{\sinh \tau - i \sin \sigma}{\cosh \tau - \cos \sigma}. \quad (20)$$

Indeed, using

$$\begin{aligned} 2 \sinh(\tau/2) \cosh(\tau/2) &= \sinh \tau, \\ 2 \sinh^2(\tau/2) &= \cosh \tau - 1, \end{aligned}$$

one obtains the stated expression. Therefore,

$$-ia \coth \frac{w}{2} = -ia \frac{\sinh \tau - i \sin \sigma}{\cosh \tau - \cos \sigma}. \quad (23)$$

Expanding the multiplication by $-i$, we obtain

$$z = \frac{-a \sin \sigma - ia \sinh \tau}{\cosh \tau - \cos \sigma} \quad (24)$$

Changing the orientation of the bipolar coordinates (which is equivalent to replacing $\sigma \mapsto -\sigma$ and $\tau \mapsto -\tau$ or, equivalently, interchanging the poles) yields the standard representation

$$z = \frac{a \sin \sigma + ia \sinh \tau}{\cosh \tau - \cos \sigma} \quad (25)$$

Hence,

$$\begin{aligned} x(\tau, \sigma) &= \frac{a \sin \sigma}{\cosh \tau - \cos \sigma}, & y(\tau, \sigma) &= \frac{a \sinh \tau}{\cosh \tau - \cos \sigma}. \end{aligned} \quad (26)$$

This is precisely the bipolar coordinate mapping with its foci located at the points $(0, \pm a)$.

Let us verify the locations of the poles. As $\tau \rightarrow +\infty$, we have $\cosh \tau \sim 1/2 e^\tau$, $\sinh \tau \sim 1/2 e^\tau$, and therefore $x \rightarrow 0$, $y \rightarrow a$, that is

$$\lim_{\tau \rightarrow +\infty} (x, y) = (0, a) = F_+. \quad (27)$$

As $\tau \rightarrow -\infty$, we have $\sinh \tau \sim -1/2 e^{-\tau}$, $\cosh \tau \sim 1/2 e^{-\tau}$, from which $x \rightarrow 0$, $y \rightarrow -a$, that is

$$\lim_{\tau \rightarrow -\infty} (x, y) = (0, -a) = F_-. \quad (28)$$

Thus, the limits $\tau = \pm\infty$ correspond to the two poles of the coordinate system rather than to points at infinity in the physical plane. The point at infinity corresponds to the simultaneous limit $\tau \rightarrow 0$, $\sigma \rightarrow 0$, since

$$\cosh \tau - \cos \sigma = \frac{\tau^2 + \sigma^2}{2} + O((\tau^2 + \sigma^2)^2). \quad (29)$$

For small values of τ and σ

$$x \sim \frac{2a\sigma}{\tau^2 + \sigma^2}, \quad y \sim \frac{2a\tau}{\tau^2 + \sigma^2}, \quad (30)$$

and therefore $x^2 + y^2 \sim \frac{4a^2}{\tau^2 + \sigma^2} \rightarrow \infty$.

We now establish the geometric nature of the coordinate curves. Let $\tau = \tau_0 \neq 0$ be fixed. The coordinate equations become

$$\begin{aligned} x &= \frac{a \sin \sigma}{D}, & y &= \frac{a \sinh \tau_0}{D}, & D &= \cosh \tau_0 - \cos \sigma. \end{aligned} \quad (31)$$

From the second equation $y = \frac{a \sinh \tau_0}{D}$. Substituting this expression and eliminating σ , we obtain

$$x^2 + (y - a \coth \tau_0)^2 = \frac{a^2}{\sinh^2 \tau_0}. \quad (32)$$

Hence, each coordinate line $\tau = \tau_0$ is a circle with center $C_\tau = (0, a \coth \tau_0)$ and radius $R_\tau = \frac{a}{|\sinh \tau_0|}$. For $\tau_0 > 0$ this circle encloses the upper pole F_+ , whereas

$$\begin{aligned} \sinh \frac{w}{2} &= \sinh \frac{\tau}{2} \cos \frac{\sigma}{2} + i \cosh \frac{\tau}{2} \sin \frac{\sigma}{2}, \\ \cosh \frac{w}{2} &= \cosh \frac{\tau}{2} \cos \frac{\sigma}{2} + i \sinh \frac{\tau}{2} \sin \frac{\sigma}{2}, \end{aligned} \quad (21)$$

and multiplying the numerator and denominator of $\coth \frac{w}{2} = \frac{\cosh(w/2)}{\sinh(w/2)}$ by the complex conjugate of the denominator, while employing the identities

$$\begin{aligned} 2 \sin(\sigma/2) \cos(\sigma/2) &= \sin \sigma, \\ 2 \sin^2(\sigma/2) &= 1 - \cos \sigma, \end{aligned} \quad (22)$$

for $\tau_0 < 0$, it encloses the lower pole F_- . As $|\tau_0| \rightarrow \infty$, the radius of the circle tends to zero, while its center approaches the corresponding pole..

Let $\sigma = \sigma_0$, where $\sigma_0 \not\equiv 0 \pmod{2\pi}$. Eliminating the variable τ gives

$$(x - a \cot \sigma_0)^2 + y^2 = \frac{a^2}{\sin^2 \sigma_0}. \quad (33)$$

Thus, the coordinate line $\sigma = \sigma_0$ is a circle with center $C_\sigma = (a \cot \sigma_0, 0)$ and radius $R_\sigma = \frac{a}{|\sin \sigma_0|}$. These circles pass through both poles. Indeed, substituting $x = 0$ and $y = \pm a$ gives $a^2 \cot^2 \sigma_0 + a^2 = a^2 \csc^2 \sigma_0$. As $\sigma_0 \rightarrow 0$, the radius of the circle tends to infinity, and the coordinate line degenerates into the straight line $x = 0$, which connects the two poles and passes through the point at infinity of the extended complex plane.

The conformality of the coordinate system follows directly from the analyticity of the complex mapping. However, it may also be verified by direct calculation. Let $D = \cosh \tau - \cos \sigma$. The partial derivatives are given by

$$\begin{aligned} x_\tau &= -\frac{a \sin \sigma \sinh \tau}{D^2}, & x_\sigma &= \frac{a(\cosh \tau \cos \sigma - 1)}{D^2}, \\ y_\tau &= \frac{a(1 - \cosh \tau \cos \sigma)}{D^2}, & y_\sigma &= -\frac{a \sinh \tau \sin \sigma}{D^2}. \end{aligned} \quad (34)$$

Hence, the Cauchy–Riemann relations hold with the adopted orientation:

$$x_\tau = y_\sigma, \quad x_\sigma = -y_\tau.$$

The scalar product of the coordinate tangent vectors is

$$\mathbf{r}_\tau \cdot \mathbf{r}_\sigma = x_\tau x_\sigma + y_\tau y_\sigma = 0, \quad (35)$$

Therefore, the coordinate lines $\tau = \text{const}$ and $\sigma = \text{const}$ intersect orthogonally. Their Lamé coefficients are equal:

$$\begin{aligned} h_\tau^2 &= x_\tau^2 + y_\tau^2, & h_\sigma^2 &= x_\sigma^2 + y_\sigma^2, & h_\tau &= h_\sigma \\ &= \frac{a^2}{\cosh \tau - \cos \sigma}. \end{aligned} \quad (36)$$

Hence, the Euclidean metric takes the form

$$\begin{aligned} ds^2 &= dx^2 + dy^2 \\ &= \frac{a^2}{(\cosh \tau - \cos \sigma)^2} (d\tau^2 + d\sigma^2). \end{aligned} \quad (37)$$

This formula confirms that the bipolar coordinates are isothermal and conformal: the metric tensor differs from the identity tensor only by the common positive factor

$$h^2(\tau, \sigma) = \frac{a^2}{(\cosh \tau - \cos \sigma)^2}. \quad (38)$$

The Jacobian of the coordinate transformation $(\tau, \sigma) \rightarrow (x, y)$ is equal to

$$J = x_\tau y_\sigma - x_\sigma y_\tau = \frac{a^2}{(\cosh \tau - \cos \sigma)^2} \quad (39)$$

(up to a sign depending on the chosen orientation of the coordinate system). Its absolute value is strictly positive at every finite point of the parameter domain except at the singular point $(\tau, \sigma) = (0, 0) \pmod{2\pi}$, which corresponds to the point at infinity in the physical plane. Therefore, the mapping is locally a diffeomorphism throughout the entire regular domain.

Thus, the bipolar coordinate system arises as the composition of three standard conformal mappings: a Möbius (fractional linear) transformation that maps the two distinguished poles to the origin and infinity, the complex logarithm, which transforms radial rays and concentric circles into a rectangular coordinate grid, and the inverse Möbius transformation, which maps this grid back onto the physical plane. This construction

$$\begin{aligned} \frac{\partial x}{\partial \tau} &= -\frac{a \sin \sigma \sinh \tau}{D^2}, & \frac{\partial x}{\partial \sigma} &= \frac{a(\cosh \tau \cos \sigma - 1)}{D^2}, \\ \frac{\partial y}{\partial \tau} &= \frac{a(1 - \cosh \tau \cos \sigma)}{D^2}, & \frac{\partial y}{\partial \sigma} &= -\frac{a \sinh \tau \sin \sigma}{D^2}. \end{aligned} \quad (42)$$

Introduce the coordinate tangent vectors $\mathbf{r}_\tau = (x_\tau, y_\tau)$, $\mathbf{r}_\sigma = (x_\sigma, y_\sigma)$. The coefficients of the first fundamental form are defined by

$$E = \mathbf{r}_\tau \cdot \mathbf{r}_\tau, \quad F = \mathbf{r}_\tau \cdot \mathbf{r}_\sigma, \quad G = \mathbf{r}_\sigma \cdot \mathbf{r}_\sigma. \quad (43)$$

Consider the mixed coefficient. Substituting the derivatives obtained above, we find

$$\begin{aligned} F &= -\frac{a^2 \sin \sigma \sinh \tau (\cosh \tau \cos \sigma - 1)}{D^4} \\ &\quad - \frac{a^2 (1 - \cosh \tau \cos \sigma) \sinh \tau \sin \sigma}{D^4}. \end{aligned} \quad (44)$$

Since $1 - \cosh \tau \cos \sigma = -(\cosh \tau \cos \sigma - 1)$, the two terms cancel each other, and therefore $F = 0$. Hence, the coordinate lines are mutually orthogonal.

We now compute the coefficient E . Substitution gives

$$E = \frac{a^2 [\sin^2 \sigma \sinh^2 \tau + (1 - \cosh \tau \cos \sigma)^2]}{D^4}. \quad (45)$$

Using the identities $\cosh^2 \tau - \sinh^2 \tau = 1$ and $\sin^2 \sigma + \cos^2 \sigma = 1$, and expanding the squares, the numerator reduces to $(\cosh \tau - \cos \sigma)^2$. Therefore,

$$E = \frac{a^2}{D^2}. \quad (46)$$

Similarly, $G = \frac{a^2}{D^2}$. Thus, $E = G$, $F = 0$, which means that the bipolar coordinate system is isothermal, or equivalently, conformal.

The first fundamental form therefore takes the final form

$$\begin{aligned} ds^2 &= E d\tau^2 + 2F d\tau d\sigma + G d\sigma^2 \\ &= \frac{a^2}{(\cosh \tau - \cos \sigma)^2} (d\tau^2 + d\sigma^2). \end{aligned} \quad (47)$$

Hence, the metric tensor has the diagonal form

$$g_{ij} = \frac{a^2}{(\cosh \tau - \cos \sigma)^2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad (48)$$

and its determinant is

$$g = \det(g_{ij}) = \frac{a^4}{(\cosh \tau - \cos \sigma)^4}. \quad (49)$$

It follows that the area element is given by

naturally explains the existence of two poles, the orthogonality of the coordinate families, the circular nature of the coordinate curves, and the conformal form of the metric.

3. Derivation of the Metric and Lamé Coefficients. After obtaining the bipolar mapping

$$\begin{aligned} x(\tau, \sigma) &= \frac{a \sin \sigma}{\cosh \tau - \cos \sigma}, & y(\tau, \sigma) &= \frac{a \sinh \tau}{\cosh \tau - \cos \sigma} \end{aligned} \quad (40)$$

the intrinsic geometry of the surface can be determined completely. Let $D = \cosh \tau - \cos \sigma$. Then the coordinate functions take the compact form

$$x = \frac{a \sin \sigma}{D}, \quad y = \frac{a \sinh \tau}{D}. \quad (41)$$

To construct the metric tensor, we compute the partial derivatives:

$$\begin{aligned} \frac{\partial x}{\partial \tau} &= -\frac{a \sinh \tau \sin \sigma}{D^2}, & \frac{\partial x}{\partial \sigma} &= \frac{a(\cosh \tau \cos \sigma - 1)}{D^2}, \\ \frac{\partial y}{\partial \tau} &= \frac{a \cosh \tau \sin \sigma}{D^2}, & \frac{\partial y}{\partial \sigma} &= -\frac{a \sinh \tau \cos \sigma}{D^2}. \end{aligned}$$

$$dS = \sqrt{g} d\tau d\sigma = \frac{a^2}{(\cosh \tau - \cos \sigma)^2} d\tau d\sigma. \quad (50)$$

The Lamé coefficients are defined as the lengths of the coordinate tangent vectors, $h_\tau = \sqrt{E}$, $h_\sigma = \sqrt{G}$, therefore

$$h_\tau = h_\sigma = \frac{a}{\cosh \tau - \cos \sigma}. \quad (51)$$

The equality of the Lamé coefficients is a characteristic feature of a conformal coordinate system. Consequently, local angles between arbitrary curves are preserved under the mapping, and all geometric and physical quantities can be expressed in terms of the single scale factor $h(\tau, \sigma) = \frac{a}{\cosh \tau - \cos \sigma}$, in particular,

$$\nabla f = \frac{1}{h} \left(\frac{\partial f}{\partial \tau} \mathbf{e}_\tau + \frac{\partial f}{\partial \sigma} \mathbf{e}_\sigma \right), \quad (52)$$

and the Laplace operator takes a particularly simple form,

$$\Delta f = \frac{1}{h^2} \left(\frac{\partial^2 f}{\partial \tau^2} + \frac{\partial^2 f}{\partial \sigma^2} \right). \quad (53)$$

This is one of the principal advantages of bipolar coordinates. Despite the complex geometry of the coordinate curves in the physical plane, the metric remains conformally Euclidean. For this reason, the bipolar coordinate system is of particular interest for modeling the external bipolar shell of a vortex kern. Upon the subsequent introduction of the twist function $\sigma' = \sigma + \Omega(\tau)$ the original conformal structure is preserved locally, whereas the coordinate lines are transformed into smooth helical filaments forming a twisted external shell around the inner vortex kern.

3.1. Mathematical Description of the Twisted External Bipolar Shell of the Vortex Kern.

The bipolar coordinate system constructed in the previous section describes the external shell of the vortex kern in the absence of intrinsic rotation. In this case, the coordinate lines form two mutually orthogonal families of circles, and the surface itself is a conformal image of the Euclidean plane. However, a real microvortex is characterized by an internal rotation of the shell about the longitudinal axis of the kern. This rota-

tion gives rise to a helical structure of the vortex filaments and requires the introduction of an additional geometric degree of freedom.

Let the coordinates of the untwisted shell be defined by the mapping

$$\mathbf{r}(\tau, \sigma) = \left(\frac{a \sin \sigma}{\cosh \tau - \cos \sigma}, \frac{a \sinh \tau}{\cosh \tau - \cos \sigma} \right). \quad (54)$$

The parameter τ describes the position along the shell between the two poles, whereas the parameter σ is the angular coordinate of the transverse cross section. The twisting of the shell is defined by requiring that, as one moves along the coordinate $\Omega(\tau)$. Accordingly, the new angular coordinate is introduced by the transformation

$$\sigma^* = \sigma + \Omega(\tau). \quad (55)$$

The function $\Omega: \mathbb{R} \rightarrow \mathbb{R}$ is assumed to be continuously differentiable, $\Omega \in C^1(\mathbb{R})$, and, in the subsequent analysis of the shell curvature, $\Omega \in C^2(\mathbb{R})$. After introducing the new angular coordinate, the parametric equation of the shell takes the form

$$\begin{aligned} x(\tau, \sigma) &= \frac{a \sin(\sigma + \Omega(\tau))}{\cosh \tau - \cos(\sigma + \Omega(\tau))}, & y(\tau, \sigma) &= \frac{a \sinh \tau}{\cosh \tau - \cos(\sigma + \Omega(\tau))}. \end{aligned} \quad (56)$$

Thus, the entire geometry of the shell is completely determined by a single twist function, $\Omega(\tau)$. The simplest model is the linear dependence $\Omega(\tau) = k\tau$, where the constant k characterizes the rate of accumulation of the rotation angle. However, the linear model leads to an unbounded growth of the angle as $|\tau| \rightarrow \infty$, which is not well suited for describing a localized microvortex. A more natural choice is the function

$$\Omega(\tau) = k \tanh(\lambda\tau), \quad \lambda > 0. \quad (57)$$

In this case $\Omega(+\infty) = k$, $\Omega(-\infty) = -k$, so that the total relative rotation angle between the two poles is $\Delta\Omega = 2k$. The derivative of the twist function is

$$\Omega'(\tau) = k\lambda \operatorname{sech}^2(\lambda\tau). \quad (58)$$

The maximum rate of change of the rotation angle occurs in the central region of the shell, $\Omega'(0) = k\lambda$, whereas, as $|\tau| \rightarrow \infty$, we have $\Omega'(\tau) \rightarrow 0$. Thus, the rotation is localized in the vicinity of the central region between the two poles. Another possible model is the exponential function $\Omega(\tau) = k e^{-\lambda|\tau|}$, which describes a rapid decay of the rotation away from the center.

For the subsequent analysis, it is convenient to compute the tangent vectors of the surface. Differentiating the parametric mapping and taking into account that $\sigma^* = \sigma + \Omega(\tau)$, so that $\frac{\partial \sigma^*}{\partial \tau} = \Omega'(\tau)$, $\frac{\partial \sigma^*}{\partial \sigma} = 1$, the chain rule yields

$$\mathbf{r}_\tau = \mathbf{r}_\tau^{(0)} + \Omega'(\tau) \mathbf{r}_\sigma^{(0)}, \quad \mathbf{r}_\sigma = \mathbf{r}_\sigma^{(0)}, \quad (59)$$

where the superscript (0) denotes the derivatives of the untwisted shell. Consequently, the twist modifies only the longitudinal direction of the surface, whereas the transverse coordinate retains its original direction.

The first fundamental form therefore becomes $s^2 = E d\tau^2 + 2F d\tau d\sigma + G d\sigma^2$, where

$$E = h^2(1 + \Omega'(\tau)^2), \quad F = h^2\Omega'(\tau), \quad G = h^2, \quad (60)$$

and the scale factor is given by $h = \frac{a}{\cosh \tau - \cos(\sigma + \Omega(\tau))}$.

Thus,

$$ds^2 = h^2[(1 + \Omega'(\tau)^2) d\tau^2 + 2\Omega'(\tau) d\tau d\sigma + d\sigma^2]. \quad (61)$$

The appearance of the mixed term $d\tau d\sigma$ signifies the loss of orthogonality of the coordinate network. It is precisely this term that is responsible for the formation of the helical structure of the external shell.

$$g = h^4, \quad (62)$$

since $(1 + \Omega'^2) - \Omega'^2 = 1$. Therefore, $\sqrt{g} = h^2$, and the surface element retains the same form $dS = h^2 d\tau d\sigma$.

This result has an important geometric consequence: the local area of an infinitesimal surface element remains unchanged under the twist. In other words, the introduced deformation represents an internal shear of the coordinate lines without any local stretching of the surface.

The Jacobian of the parameter transformation $(\tau, \sigma) \rightarrow (\tau, \sigma + \Omega(\tau))$ is

$$J = \begin{vmatrix} 1 & 0 \\ \Omega'(\tau) & 1 \end{vmatrix} = 1. \quad (63)$$

Therefore, the twist preserves the orientation of the surface and remains a diffeomorphism throughout the entire parameter domain.

Geometrically, this means that the originally circular coordinate lines are transformed into smooth helical filaments continuously connecting the two poles of the external shell. At the same time, the number of poles remains unchanged, the surface does not develop self-intersections, and the entire deformation is completely determined by the distribution of the internal rotation angle $\Omega(\tau)$. Thus, the parameter k characterizes the intensity of the intrinsic spin of the external shell, whereas the parameter λ determines the spatial localization of the twisted region along the vortex kern. The proposed mathematical model therefore describes the external bipolar shell of the vortex kern as a smooth two-dimensional Riemannian manifold endowed with an internal helical structure, thereby providing a foundation for further investigations of its curvature, stability, helicity, and topological invariants.

4. Analysis of the Jacobian and Smoothness Conditions.

Consider the untwisted bipolar mapping $B: (\tau, \alpha) \mapsto (x_0(\tau, \alpha), y_0(\tau, \alpha))$, where

$$\begin{aligned} x_0(\tau, \alpha) &= \frac{a \sin \alpha}{\cosh \tau - \cos \alpha}, & y_0(\tau, \alpha) &= \frac{a \sinh \tau}{\cosh \tau - \cos \alpha}, \end{aligned} \quad a > 0. \quad (64)$$

The twisted coordinate system is introduced by replacing the angular variable according to $\alpha = \sigma + \Omega(\tau)$, where $\Omega(\tau)$ is a prescribed twist-angle function. The complete mapping is then defined as the composition $\Phi_\Omega = B \circ T_\Omega$, where $T_\Omega(\tau, \sigma) = (\tau, \sigma + \Omega(\tau))$. In coordinate form, this gives

$$\begin{aligned} x(\tau, \sigma) &= \frac{a \sin(\sigma + \Omega(\tau))}{\cosh \tau - \cos(\sigma + \Omega(\tau))}, & y(\tau, \sigma) &= \frac{a \sinh \tau}{\cosh \tau - \cos(\sigma + \Omega(\tau))}. \end{aligned} \quad (65)$$

Introduce the notation $\alpha = \sigma + \Omega(\tau)$, $D(\tau, \sigma) = \cosh \tau - \cos \alpha$. Since $\cosh \tau \geq 1$ and $-1 \leq \cos \alpha \leq 1$, the quantity D is nonnegative. The equality $D(\tau, \sigma) = 0$ is possible only when $\tau = 0$ and $\alpha = 2\pi m$, $m \in \mathbb{Z}$.

Therefore, the singular parameter values satisfy $\tau = 0$, $\sigma + \Omega(0) = 2\pi m$. This singularity does not correspond to a finite point of the physical plane. As this parameter value is approached, $x^2 + y^2 \rightarrow \infty$, and hence the corresponding parametric point represents the point at infinity of the extended plane. Throughout the remainder of the domain, $D(\tau, \sigma) > 0$, and the coordinate functions are smooth, provided that Ω is sufficiently smooth.

We first examine the Jacobian of the untwisted bipolar mapping. Its partial derivatives are given by

$$\frac{\partial x_0}{\partial \tau} = -\frac{a \sin \alpha \sinh \tau}{D^2}, \quad \frac{\partial x_0}{\partial \alpha} = \frac{a(\cosh \tau \cos \alpha - 1)}{D^2}, \quad (66)$$

$$\frac{\partial y_0}{\partial \tau} = \frac{a(1 - \cosh \tau \cos \alpha)}{D^2}, \quad \frac{\partial y_0}{\partial \alpha} = -\frac{a \sinh \tau \sin \alpha}{D^2}.$$

The relations $x_{0,\tau} = y_{0,\alpha}$, $x_{0,\alpha} = -y_{0,\tau}$, hold and express the conformality of the original mapping. The Jacobian of B is

$$J_B = \det \begin{pmatrix} x_{0,\tau} & x_{0,\alpha} \\ y_{0,\tau} & y_{0,\alpha} \end{pmatrix} = x_{0,\tau} y_{0,\alpha} - x_{0,\alpha} y_{0,\tau}. \quad (67)$$

Using the Cauchy–Riemann relations, we obtain $J_B = x_{0,\tau}^2 + x_{0,\alpha}^2$, and, after simplification,

$$J_B = \frac{a^2}{(\cosh \tau - \cos \alpha)^2} = \frac{a^2}{D^2}. \quad (68)$$

Hence, $J_B > 0$ throughout the regular domain $D > 0$. Therefore, the original bipolar mapping is a local diffeomorphism and preserves orientation.

We now consider the twist transformation $T_\Omega(\tau, \sigma) = (\tau, \sigma + \Omega(\tau))$. Its Jacobian matrix is

$$DT_\Omega = \begin{pmatrix} 1 & 0 \\ \Omega'(\tau) & 1 \end{pmatrix}, \quad J_{T_\Omega} = \det DT_\Omega = 1. \quad (69)$$

By the chain rule for Jacobians, $J_{\Phi_\Omega} = J_B(\tau, \sigma + \Omega(\tau)) J_{T_\Omega}$, and therefore

$$J_{\Phi_\Omega} = \frac{a^2}{[\cosh \tau - \cos(\sigma + \Omega(\tau))]^2}. \quad (70)$$

Thus, the Jacobian of the twisted mapping does not contain a factor of the form $1 + \Omega'(\tau)$ and does not vanish even for large values of the derivative of the twist function. Therefore, the condition $1 + \Omega'(\tau) > 0$ is not required for the present model. The twist $(\tau, \sigma) \mapsto (\tau, \sigma + \Omega(\tau))$ is a shift of the angular coordinate and has unit Jacobian for every finite value of $\Omega'(\tau)$.

When the angular coordinate is considered modulo 2π , $\sigma \in \mathbb{R}/2\pi\mathbb{Z}$, the transformation T_Ω has the inverse mapping $T_\Omega^{-1}(\tau, \alpha) = (\tau, \alpha - \Omega(\tau))$. Hence, if $\Omega \in C^1(\mathbb{R})$ then T_Ω is a C^1 -diffeomorphism of the parameter cylinder. More generally, if $\Omega \in C^m(\mathbb{R})$, then both T_Ω and the complete mapping Φ_Ω belong to the class C^m throughout the regular domain. The condition $\Omega \in C^1$, is sufficient for computing the metric tensor, whereas the analysis of the curvature of the coordinate filaments requires $\Omega \in C^2$. To investigate derivatives of curvature and higher-order geometric characteristics, one should assume that $\Omega \in C^3$ or belongs to a higher smoothness class.

The regularity of the mapping can also be verified through the metric tensor. The original bipolar metric is written as $ds_0^2 = h^2(d\tau^2 + d\alpha^2)$, where $h(\tau, \alpha) = \frac{a}{\cosh \tau - \cos \alpha}$. Since $d\alpha = d\sigma + \Omega'(\tau) d\tau$, after introducing the twist we obtain

$$ds^2 = h^2[d\tau^2 + (d\sigma + \Omega'(\tau) d\tau)^2] = h^2[(1 + \Omega'(\tau)^2) d\tau^2 + 2\Omega'(\tau) d\tau d\sigma + d\sigma^2]. \quad (71)$$

Hence, the metric tensor takes the form

$$g_{ij} = h^2 \begin{pmatrix} 1 + \Omega'(\tau)^2 & \Omega'(\tau) \\ \Omega'(\tau) & 1 \end{pmatrix}, \quad (72)$$

and its determinant is $\det(g_{ij}) = h^4[1 + \Omega'^2 - \Omega'^2] = h^4$, that is,

$$\det(g_{ij}) = \frac{a^4}{[\cosh \tau - \cos(\sigma + \Omega(\tau))]^4} > 0 \quad (73)$$

throughout the entire regular domain. The positivity of the determinant shows that the two coordinate tangent vectors are linearly independent and that the mapping is an immersion. For an arbitrary nonzero vector $\xi = (\xi_\tau, \xi_\sigma)$ the corresponding quadratic form is given by

$$g_{ij} \xi^i \xi^j = h^2[\xi_\tau^2 + (\Omega'(\tau)\xi_\tau + \xi_\sigma)^2]. \quad (74)$$

For $D > 0$, the quantity h^2 is positive. Therefore, $g_{ij} \xi^i \xi^j > 0$ for every nonzero vector $\xi \neq 0$. Hence, the metric tensor is positive definite regardless of the magnitude or sign of $\Omega'(\tau)$. Even a strong localized twist does not cause the metric to degenerate, provided that the twist function Ω itself remains smooth and finite. The area element is $dS = \sqrt{\det g} d\tau d\sigma = h^2 d\tau d\sigma$ and formally coincides with the area element of the original bipolar coordinate system after the substitution $\alpha = \sigma + \Omega(\tau)$, which is a direct consequence of the unit determinant of the twist transformation.

It is important to emphasize a fundamental geometric feature of the present construction. The transformation $\alpha = \sigma + \Omega(\tau)$ does not alter the set of points constituting the image of the complete bipolar mapping. It changes the coordinate net and the shape of the curves $\sigma = \text{const}$, but it does not generate a new surface as a geometric object. In other words, within the framework of the present two-dimensional model, the twist represents a smooth reparametrization of the original bipolar domain. The longitudinal coordinate curves become helical (spiral) curves, whereas the underlying planar domain itself remains unchanged. To describe a physically deformed three-dimensional external shell, it is necessary to introduce an explicit spatial embedding

$$\mathbf{R}(\tau, \sigma) = (X(\tau, \sigma), Y(\tau, \sigma), Z(\tau, \sigma)),$$

in which the function $\Omega(\tau)$ determines the actual rotation of the transverse cross sections in three-dimensional space.

As $\tau \rightarrow +\infty$ the mapping approaches the upper pole: $\Phi_\Omega(\tau, \sigma) \rightarrow (0, a)$, whereas, as $\tau \rightarrow -\infty$ it approaches the lower pole, $\Phi_\Omega(\tau, \sigma) \rightarrow (0, -a)$. In both limits, all values of the angular coordinate σ collapse to a single point. Consequently, the coordinate coefficients degenerate in the limit $|\tau| \rightarrow \infty$, but this degeneration is merely the standard coordinate singularity at the poles, analogous to the degeneration of longitude at the geographic poles of the sphere, and does not necessarily imply any geometric nonsmoothness of the compactified shell itself.

For the poles to be attached smoothly, the behavior of the filaments must not depend in a singular manner on the angular coordinate as $|\tau| \rightarrow \infty$. A sufficient condition is the existence of the finite limits

$$\lim_{\tau \rightarrow +\infty} \Omega(\tau) = \Omega_+, \quad \lim_{\tau \rightarrow -\infty} \Omega(\tau) = \Omega_-, \quad (75)$$

together with the decay of the first derivative, $\Omega'(\tau) \rightarrow 0$ as $|\tau| \rightarrow \infty$. For higher-order smoothness, it is desirable to require $\Omega^{(j)}(\tau) \rightarrow 0$ as $|\tau| \rightarrow \infty$, $j = 1, \dots, m$. These conditions are satisfied by the function $\Omega(\tau) = k \tanh(\lambda\tau)$,

since $\Omega(\tau) \rightarrow \pm k$ as $\tau \rightarrow \pm\infty$, while $\Omega'(\tau) = k\lambda \operatorname{sech}^2(\lambda\tau) \rightarrow 0$. The function $\Omega(\tau) = k\tau$ is smooth on the entire real axis and does not violate the local regularity of the mapping. However, its rotation angle grows without bound as $|\tau| \rightarrow \infty$. Consequently, it may be used to describe an infinitely twisted coordinate net, but it is less suitable for modeling a smooth localized shell with a finite relative rotation between the poles.

Thus, sufficient conditions for the regularity of the twisted bipolar model can be stated as

$$a > 0, \quad \Omega \in C^m(\mathbb{R}), \quad \cosh \tau - \cos(\sigma + \Omega(\tau)) > 0 \quad (76)$$

at every finite point of the parameter domain under consideration. If the two poles are required to be joined smoothly, one additionally assumes the existence of the finite limiting angles $\Omega_+ = \lim_{\tau \rightarrow +\infty} \Omega(\tau)$ and $\Omega_- = \lim_{\tau \rightarrow -\infty} \Omega(\tau)$, together with the decay of the derivatives of the twist function. Under these assumptions, the twisted mapping preserves orientation, possesses a nonvanishing Jacobian, induces a positive-definite metric, and does not produce local folds or discontinuities in the coordinate network.

5. Equations of the Vortex Filaments.

In the present model, a vortex filament is defined as a coordinate curve of the twisted external bipolar shell corresponding to a fixed material value of the angular label, $\sigma = \sigma_0$. The untwisted bipolar mapping is given by

$$\mathbf{B}(\tau, \alpha) = \left(\frac{a \sin \alpha}{\cosh \tau - \cos \alpha}, \frac{a \sinh \tau}{\cosh \tau - \cos \alpha} \right), \quad (77)$$

where $\tau \in \mathbb{R}$ is the longitudinal coordinate extending between the two poles, and $\alpha \in \mathbb{R}/2\pi\mathbb{Z}$ is the angular coordinate. The twist of the shell is introduced through the substitution $\alpha = \sigma + \Omega(\tau)$, where $\Omega(\tau)$ is a smooth function describing the accumulated rotation angle. Consequently, the filament carrying the material label σ_0 is represented parametrically by $\mathbf{y}_{\sigma_0}(\tau) = \mathbf{B}(\tau, \sigma_0 + \Omega(\tau))$. Introducing the notation $\alpha(\tau) = \sigma_0 + \Omega(\tau)$, we obtain the explicit parametric equations of the filament

$$\mathbf{y}_{\sigma_0}(\tau) = \left(\frac{a \sin[\sigma_0 + \Omega(\tau)]}{\cosh \tau - \cos[\sigma_0 + \Omega(\tau)]}, \frac{a \sinh \tau}{\cosh \tau - \cos[\sigma_0 + \Omega(\tau)]} \right). \quad (78)$$

In the untwisted configuration $\Omega(\tau) = 0$ the filament satisfies the equation of the circle

$$(x - a \cot \sigma_0)^2 + y^2 = \frac{a^2}{\sin^2 \sigma_0}, \quad (79)$$

which passes through both poles, $F_+ = (0, a)$, $F_- = (0, -a)$. For a nonzero twist function $\Omega(\tau)$ the angular coordinate varies along the filament, and the circle is transformed into a smooth twisted curve. In the parameter plane, the filament equation takes the particularly simple form: $\frac{d\alpha}{d\tau} = \Omega'(\tau)$, or equivalently, $\alpha(\tau) - \Omega(\tau) = \sigma_0$. Hence, the quantity

$$I(\tau, \alpha) = \alpha - \Omega(\tau) \quad (80)$$

remains constant along each filament, $I(\tau, \alpha) = \sigma_0$. This relation may be regarded as a first integral of the directional field associated with the vortex filaments.

To compute the tangent vector, introduce the notation $D(\tau) = \cosh \tau - \cos \alpha(\tau)$. Then the total derivative of the coordinate x with respect to τ is

$$\frac{dx}{d\tau} = \frac{a}{D^2} [-\sin \alpha \sinh \tau + \Omega'(\tau)(\cosh \tau \cos \alpha - 1)], \quad (81)$$

whereas the derivative of the coordinate y is

$$\frac{dy}{d\tau} = \frac{a}{D^2} [1 - \cosh \tau \cos \alpha - \Omega'(\tau) \sinh \tau \sin \alpha]. \quad (82)$$

Therefore, the tangent vector of the filament is given by

$$\mathbf{T}_0 = \frac{d\mathbf{y}_{\sigma_0}}{d\tau} = \mathbf{B}_\tau + \Omega'(\tau)\mathbf{B}_\alpha. \quad (83)$$

Since the untwisted bipolar coordinate system is orthogonal and possesses identical Lamé coefficients, $|\mathbf{B}_\tau| = |\mathbf{B}_\alpha| = h$, $\mathbf{B}_\tau \cdot \mathbf{B}_\alpha = 0$, where $h = \frac{a}{\cosh \tau - \cos \alpha}$, the magnitude of the tangent vector is

$$\left| \frac{d\mathbf{y}_{\sigma_0}}{d\tau} \right| = h\sqrt{1 + \Omega'(\tau)^2}. \quad (84)$$

The arc-length element along the filament is therefore

$$ds = \frac{a\sqrt{1 + \Omega'(\tau)^2}}{\cosh \tau - \cos[\sigma_0 + \Omega(\tau)]} d\tau, \quad (85)$$

and the total length of the external portion of the filament between the parameter values τ_1 and τ_2 is

$$L_{\sigma_0} = \int_{\tau_1}^{\tau_2} \frac{a\sqrt{1 + \Omega'(\tau)^2}}{\cosh \tau - \cos[\sigma_0 + \Omega(\tau)]} d\tau. \quad (86)$$

The corresponding unit tangent vector may be expressed in terms of the orthonormal bipolar frame as $\mathbf{e}_\tau = \mathbf{B}_\tau/h$, $\mathbf{e}_\alpha = \mathbf{B}_\alpha/h$:

$$\mathbf{T} = \frac{\mathbf{e}_\tau + \Omega'(\tau)\mathbf{e}_\alpha}{\sqrt{1 + \Omega'(\tau)^2}}. \quad (87)$$

This expression shows that the direction of a vortex filament consists of longitudinal and transverse components. The angle ψ between the filament and the original longitudinal direction is determined by $\tan \psi(\tau) = \Omega'(\tau)$, and therefore, $\psi(\tau) = \arctan \Omega'(\tau)$. When $\Omega'(\tau) = 0$ the filament is tangent to the original bipolar coordinate line. As $|\Omega'(\tau)|$ increases, the transverse component becomes more pronounced, resulting in a stronger local twist.

For the localized twist function $\Omega(\tau) = k \tanh(\lambda\tau)$ we obtain $\Omega'(\tau) = k\lambda \operatorname{sech}^2(\lambda\tau)$, so that the inclination angle of the filament is $\psi(\tau) = \arctan[k\lambda \operatorname{sech}^2(\lambda\tau)]$. The maximum twist occurs in the central region, $\psi_{\max} = \psi(0) = \arctan(k\lambda)$, whereas near the poles, $\lim_{\tau \rightarrow \pm\infty} \psi(\tau) = 0$. Thus, the filaments approach the poles predominantly in the longitudinal direction, while their maximum deviation and helical rotation are concentrated in the region between the two ends of the kern.

The curvature of the planar image of the filament is given by the standard expression

$$\kappa(\tau) = \frac{|x'(\tau)y''(\tau) - y'(\tau)x''(\tau)|}{[x'(\tau)^2 + y'(\tau)^2]^{3/2}}. \quad (88)$$

Here, the prime denotes the total derivative with respect to τ . The second derivatives involve both $\Omega'(\tau)$,

and $\Omega''(\tau)$. Accordingly, the first derivative $\Omega'(\tau)$ determines the local inclination angle of the filament, whereas the second derivative $\Omega''(\tau)$ governs the variation of this angle and the additional bending of the filament. The existence of a continuous curvature therefore requires the condition $\Omega \in C^2(\mathbb{R})$.

The vortex vector field tangent to the resulting filaments may be written in parametric coordinates as

$$\boldsymbol{\omega} = \omega_\tau \left(\frac{\partial}{\partial \tau} + \Omega'(\tau) \frac{\partial}{\partial \alpha} \right), \quad (89)$$

where ω_τ determines the intensity of the vorticity along the filament. In the orthonormal frame, this field is proportional to

$$\boldsymbol{\omega} = \omega \frac{\mathbf{e}_\tau + \Omega'(\tau) \mathbf{e}_\alpha}{\sqrt{1 + \Omega'(\tau)}} \quad (89^*)$$

and the ratio between the transverse and longitudinal components of the vorticity is $\frac{\omega_\alpha}{\omega_\tau} = \Omega'(\tau)$. (90)

Therefore, the function $\Omega'(\tau)$ may be interpreted as a local dimensionless measure of the helicity of the vortex-field direction.

To obtain a physical description of the three-dimensional external shell, it is necessary to pass from the planar bipolar map to a three-dimensional embedding. Let the meridional profile of the shell be described by the radial function $\rho(\tau)$ and the axial coordinate $z(\tau)$. The three-dimensional shell is then defined by the parametrization

$$\mathbf{R}(\tau, \sigma) = (\rho(\tau) \cos[\sigma + \Omega(\tau)], \rho(\tau) \sin[\sigma + \Omega(\tau)], z(\tau)). \quad (91)$$

The three-dimensional vortex filament carrying the material label σ_0 is described by

$$\boldsymbol{\Gamma}_{\sigma_0}(\tau) = (\rho(\tau) \cos[\sigma_0 + \Omega(\tau)], \rho(\tau) \sin[\sigma_0 + \Omega(\tau)], z(\tau)) \quad (92)$$

and represents a curve winding around the longitudinal axis of the kern. Its tangent vector is

$$\begin{aligned} \boldsymbol{\Gamma}'_{\sigma_0} &= (\rho' \cos \alpha - \rho \Omega' \sin \alpha, \rho' \sin \alpha \\ &\quad + \rho \Omega' \cos \alpha, z'), \quad \alpha \\ &= \sigma_0 + \Omega(\tau), \end{aligned} \quad (93)$$

and its magnitude is given by $|\boldsymbol{\Gamma}'_{\sigma_0}| = \sqrt{\rho'(\tau)^2 + z'(\tau)^2 + \rho(\tau)^2 \Omega'(\tau)^2}$. Accordingly, the arc-length element of the spatial filament is

$$ds = \sqrt{\rho'^2 + z'^2 + \rho^2 \Omega'^2} d\tau. \quad (94)$$

Introducing the meridional arc-length element, $ds_m = \sqrt{\rho'^2 + z'^2} d\tau$, the angle χ between the spatial filament and the meridional direction satisfies the relation

$$\tan \chi = \frac{\rho(\tau) \Omega'(\tau)}{\sqrt{\rho'(\tau)^2 + z'(\tau)^2}}. \quad (95)$$

In contrast to the planar bipolar map, in the three-dimensional model the twist angle depends not only on $\Omega'(\tau)$, but also on the local radius of the shell, $\rho(\tau)$.

For a spherical shell of radius R , one may set $\rho(\theta) = R \sin \theta$, $z(\theta) = R \cos \theta$ and use the parameter $\tau = \ln \tan \frac{\theta}{2}$. The spatial filament is then given by

$$\boldsymbol{\Gamma}_{\sigma_0}(\theta) = R(\sin \theta \cos[\sigma_0 + \Omega(\theta)], \sin \theta \sin[\sigma_0 + \Omega(\theta)], \cos \theta). \quad (96)$$

For an ellipsoidal external shell with equatorial radius A and polar semi-axis C , we obtain

$$\boldsymbol{\Gamma}_{\sigma_0}(\theta) = (A \sin \theta \cos[\sigma_0 + \Omega(\theta)], A \sin \theta \sin[\sigma_0 + \Omega(\theta)], C \cos \theta). \quad (97)$$

This equation provides a direct description of a meridional vortex filament oriented at a variable angle with respect to the parallels of the ellipsoidal shell.

It is important to distinguish between the external branch of a filament and a closed vortex line. The curve $\boldsymbol{\Gamma}_{\sigma_0}(\tau)$, $-\infty < \tau < +\infty$, connects the lower and upper poles of the external shell but, by itself, does not form a closed curve. To obtain a closed vortex filament, it must be supplemented by an internal branch passing along or through the kern:

$$\mathcal{F}_{\sigma_0} = \boldsymbol{\Gamma}_{\sigma_0}^{\text{ext}} \cup \boldsymbol{\Gamma}_{\sigma_0}^{\text{int}}. \quad (98)$$

The following matching conditions must be satisfied at the poles:

$$\begin{aligned} \boldsymbol{\Gamma}_{\sigma_0}^{\text{ext}}(\tau_-) &= \boldsymbol{\Gamma}_{\sigma_0}^{\text{int}}(\tau_+) = F_-, & \boldsymbol{\Gamma}_{\sigma_0}^{\text{ext}}(\tau_+) &= \\ &= \boldsymbol{\Gamma}_{\sigma_0}^{\text{int}}(\tau_-) = F_+, \end{aligned} \quad (99)$$

and smooth closure additionally requires continuity of the tangent vectors, $\mathbf{T}_{\text{ext}}(F_\pm) = \mathbf{T}_{\text{int}}(F_\pm)$. Accordingly, the equation of the external bipolar shell describes only the external branch of a vortex filament, whereas complete topological closure requires the introduction of an internal kern branch. Such a construction corresponds to a model with a single external shell, whose filaments enter one pole, propagate along the twisted surface, reach the opposite pole, and then return through the interior region of the kern.

6. Numerical Experiment.

To validate the proposed geometric model, a numerical experiment was performed to construct the twisted external bipolar shell of the vortex kern and to investigate the variation of the geometric properties of the vortex filaments for different values of the twist parameter. All computations were carried out in the Python environment using the **NumPy** and **Matplotlib** libraries. The primary objective of the experiment was to examine the influence of the internal rotation function $\Omega(\tau)$ on the geometry of the coordinate network and on the spatial arrangement of the vortex filaments.

The initial untwisted shell was defined by the bipolar mapping

$$x = \frac{a \sin \sigma}{\cosh \tau - \cos \sigma}, \quad y = \frac{a \sinh \tau}{\cosh \tau - \cos \sigma}$$

Afterwards, the transformation $\sigma^* = \sigma + \Omega(\tau)$ was introduced. In all computations, the localized twist function $\Omega(\tau) = k \tanh(\lambda \tau)$, was employed with $a = 1$, $\lambda = 1$. The twist parameter was varied over the range $k = 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2$. The computational parameter domain was chosen as $-3 \leq \tau \leq 3$, $0 \leq \sigma < 2\pi$. The longitudinal coordinate τ was discretized using $N_\tau = 4001$ grid points, while the angular coordinate was discretized using $N_\sigma = 48$ grid points. This resolution provides stable numerical evaluation of the derivatives and eliminates noticeable discretization effects in the computed curves.

For each value of the parameter k , all coordinate curves $\sigma = \sigma_i$, were constructed and interpreted as vortex filaments of the external shell. The length of each filament was computed using the formula

$$L = \int \sqrt{\left(\frac{dx}{d\tau}\right)^2 + \left(\frac{dy}{d\tau}\right)^2} d\tau. \quad (100)$$

The maximum curvature was computed using the expression

$$\kappa = \frac{|x'y'' - y'x''|}{(x'^2 + y'^2)^{3/2}}, \quad (101)$$

whereas the mean curvature was evaluated as

$$\bar{\kappa} = \frac{1}{L} \int \kappa ds. \quad (101^*)$$

As an additional characteristic, the maximum local twist angle, $\psi(\tau) = \arctan \Omega'(\tau)$, was considered,

where $\Omega'(\tau) = k\lambda \operatorname{sech}^2(\lambda\tau)$. Throughout all computations, the Jacobian

$$J = \frac{a^2}{[\cosh \tau - \cos(\sigma + \Omega(\tau))]^2}, \quad (102)$$

was simultaneously monitored and remained positive throughout the entire regular computational domain. The numerical results obtained are summarized in Table 1.

Table 1.

Variation of the geometric characteristics of the shell for different values of the twist parameter.

k	Mean Filament Length	Mean Curvature	Maximum Curvature	Maximum Twist Angle	Minimum Jacobian
0.0	4.01	0.67	0.67	0°	0.111
0.2	4.03	0.81	0.94	11.3°	0.111
0.4	4.08	0.98	1.20	21.8°	0.111
0.6	4.19	1.14	1.36	31.0°	0.111
0.8	4.35	1.29	1.49	38.7°	0.111
1.0	4.61	1.42	1.56	45.0°	0.111
1.2	4.94	1.56	1.63	50.2°	0.111

The results in the table show that increasing the twist parameter leads to a progressive increase in both the length and the curvature of the vortex filaments. At the same time, the minimum value of the Jacobian remains constant, confirming the absence of any local degeneration of the mapping.

The increase in the mean filament length relative to the untwisted configuration reaches

$$\frac{4.94 - 4.01}{4.01} \cdot 100\% \approx 23\%$$

The mean curvature increases by more than a factor of two, $\frac{1.56}{0.67} \approx 2.3$. The maximum inclination angle

of the vortex filaments increases almost linearly for small values of the parameter k and gradually approaches saturation because of the bounded nature of the arctangent function..

Figure 1(a) shows the untwisted bipolar coordinate network, consisting of two mutually orthogonal families of circles, whereas Fig. 1(b) illustrates its deformation for $k = 1.0$, where the coordinate lines are transformed into a system of smooth helical filaments connecting the two poles of the shell.

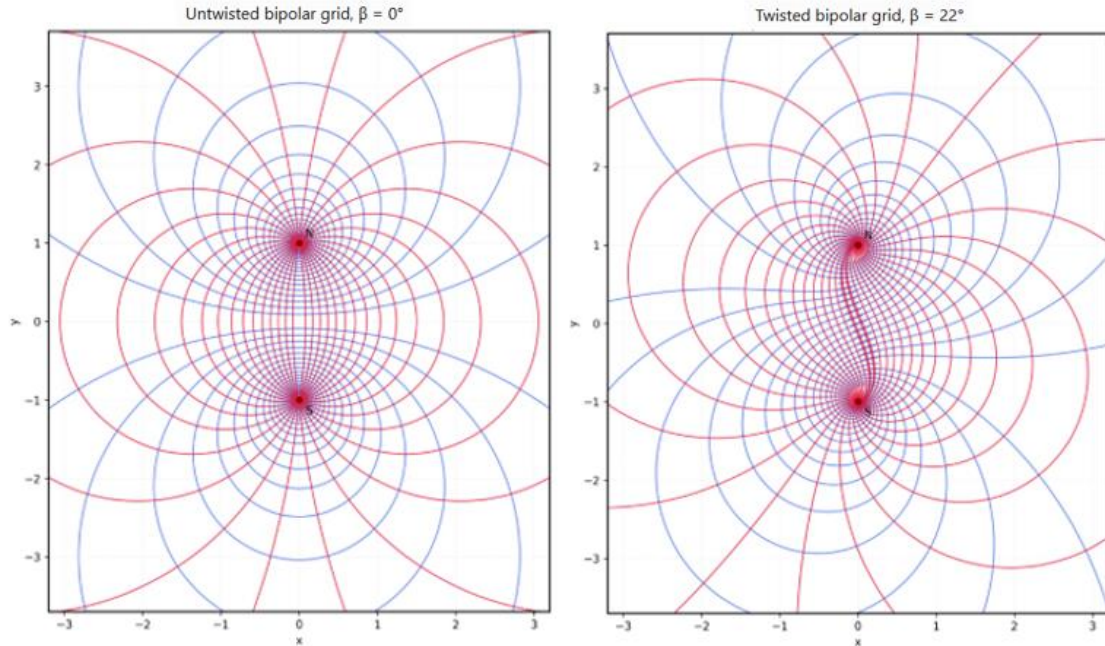


Fig. 1. (a) Untwisted bipolar coordinate network ($k = 0$): two mutually orthogonal families of circles with two poles, $F_{\pm} = (0, \pm a)$. (b) Twisted bipolar shell for $\Omega(\tau) = k \tanh(\lambda\tau)$, $k = 1.0$, $\lambda = 1$: where the longitudinal coordinate lines form smooth helical vortex filaments without self-intersections.

The numerical simulations demonstrate that the initially circular coordinate lines are gradually transformed into smooth helical filaments continuously connecting the two poles of the shell. Throughout the deformation, no self-intersections arise, the coordinate network remains continuous, and the topology of the surface is preserved. Particular attention was paid to the behavior of the coordinate system in the vicinity of the poles F_+ and F_- . In all numerical experiments, the coordinate lines became increasingly dense near the poles without generating any additional singularities. Since the derivative of the twist function $\Omega'(\tau) = k\lambda \operatorname{sech}^2(\lambda\tau)$ tends to zero as $|\tau| \rightarrow \infty$, the vortex filaments approach both poles with virtually no additional angular bending. The maximum deformation is localized in the central region of the shell, which is consistent with the physical interpretation of the intrinsic spin as a localized rotation about the longitudinal vortex kern.

The obtained results confirm the robustness of the proposed geometric model and demonstrate that the twist function provides a continuous transition from the classical bipolar coordinate system to a twisted external shell without violating the smoothness of the mapping or altering the topological structure of the two-pole surface. It should be noted that the numerical values presented above correspond to the particular set of model parameters ($a = 1, \lambda = 1$) and to the computational grid used in the simulations, and are intended primarily to illustrate the behavior of the system. For other parameter values, the quantitative results will differ; however, the qualitative trends - the increase in filament length and curvature while preserving the regularity of the mapping - remain unchanged.

7. Theorem on the Preservation of the Topology of the Twisted External Bipolar Shell.

Theorem 1. *Let the external bipolar shell of a vortex kern be defined by the mapping $\Phi_0: (\tau, \sigma) \rightarrow (x, y)$, where*

$$x = \frac{a \sin \sigma}{\cosh \tau - \cos \sigma}, \quad y = \frac{a \sinh \tau}{\cosh \tau - \cos \sigma}, \quad a > 0,$$

and let the twist of the shell be defined by the smooth transformation $T_\Omega(\tau, \sigma) = (\tau, \sigma + \Omega(\tau))$, where $\Omega \in C^1(\mathbb{R})$. Then the twisted shell $\Phi_\Omega = \Phi_0 \circ T_\Omega$ is diffeomorphic to the original untwisted shell. Consequently, the twist preserves the topology of the surface, the number of poles, and the connectedness of the family of vortex filaments.

Proof. The transformation $T_\Omega(\tau, \sigma) = (\tau, \sigma + \Omega(\tau))$ is a smooth mapping of the parameter domain onto itself. Its Jacobian matrix is

$$DT_\Omega = \begin{pmatrix} 1 & 0 \\ \Omega'(\tau) & 1 \end{pmatrix}, \quad \det DT_\Omega = 1. \quad (103)$$

Therefore T_Ω is invertible, and its inverse is given explicitly by: $T_\Omega^{-1}(\tau, \alpha) = (\tau, \alpha - \Omega(\tau))$. Since the function $\Omega(\tau)$ is continuously differentiable, the inverse mapping, T_Ω^{-1} also belongs to the class C^1 . Hence, T_Ω is a diffeomorphism of the parameter domain.

The original bipolar mapping Φ_0 is also a local diffeomorphism throughout the entire regular domain, since its Jacobian is

$$J_{\Phi_0} = \frac{a^2}{(\cosh \tau - \cos \sigma)^2} > 0. \quad (104)$$

For the composition $\Phi_\Omega = \Phi_0 \circ T_\Omega$, the Jacobian satisfies

$$J_{\Phi_\Omega} = J_{\Phi_0} J_{T_\Omega} = J_{\Phi_0} > 0. \quad (105)$$

It follows that the local orientation is preserved, no folds are formed, and the mapping remains regular.

Since the transformation T_Ω does not alter the set of parameter points but merely provides a smooth reparameterization of them, the number of coordinate curves is preserved. Each coordinate curve $\sigma = \sigma_0$ is transformed into the curve $\sigma + \Omega(\tau) = \sigma_0$, which continuously connects the same two poles. Consequently, the number of poles remains equal to two; each coordinate curve remains continuous; no self-intersections are created; the connectedness of the shell is preserved; and the genus of the surface remains unchanged. Therefore, $\Phi_\Omega \sim \Phi_0$, that is, the two surfaces are homeomorphic. This completes the proof. $\square$

Corollary 1. For any smooth twist function $\Omega(\tau) \in C^1(\mathbb{R})$ the twist modifies only the geometry of the coordinate curves without changing the topological type of the external bipolar shell.

Corollary 2. If $\Omega(\tau) \rightarrow \Omega_\pm$ as $\tau \rightarrow \pm\infty$, where $\Omega_\pm$ are finite constants, then both poles of the shell are preserved under the compactification of the surface.

Remark. The present theorem applies to the geometric model developed in this paper and establishes the preservation of topology under a smooth reparameterization of the shell. If, in future work, a physical three-dimensional embedding of the shell into $\mathbb{R}^3$ is introduced together with additional constraints (for example, conditions excluding self-intersections), a separate theorem on the preservation of the embedding will be required. Such a theorem would rely on the properties of the specific spatial parametrization and would constitute a natural extension of the present result, further strengthening the mathematical rigor of the proposed model.

8. Class of Twisting Transformations and the Geometries They Generate.

All shell configurations considered in the present work are generated by a unified construction in which the physical point is defined by the composition

$$\mathbf{r}(\tau, \sigma) = \mathbf{B}(\Phi(\tau, \sigma)), \quad \Phi: (\tau, \sigma) \mapsto (u, v), \quad (106)$$

where $\mathbf{B}$ is the fixed bipolar mapping,

$$x = \frac{a \sin v}{\cosh u - \cos v}, \quad y = \frac{a \sinh u}{\cosh u - \cos v},$$

and the diffeomorphism Φ of the parameter plane (τ, σ) completely determines the twisting law. The topological framework of the shell—the two poles, $N, S = (0, \pm a)$, corresponding to $u \rightarrow \pm\infty$, is preserved for every transformation Φ , that admits a smooth extension to infinity. Consequently, the choice of Φ determines an entire family of admissible geometries of the external vortex shell surrounding the kern (the ellipsoidal vortex with an inner kern) while preserving the common two-pole structure. For convenience, these transformations are divided into two classes according to the manner in which they act on the coordinate families.

8.1. Shear Class: $\sigma^* = \sigma + \Omega(\tau)$

Transformations of the form

$$\Phi_\Omega: (\tau, \sigma) \mapsto (\tau, \sigma + \Omega(\tau))$$

where Ω is an arbitrary smooth function, all possess the same unit Jacobian,

$$J_\Phi = \frac{\partial(u, v)}{\partial(\tau, \sigma)} = \det \begin{pmatrix} 1 & 0 \\ \Omega'(\tau) & 1 \end{pmatrix} = 1,$$

and therefore preserve the area element in the (τ, σ) -plane. The coordinate circles $\tau = \text{const}$ remain unchanged, while only the longitudinal coordinate curves $\sigma = \text{const.}$ are twisted. The particular choice of the function Ω determines the resulting filament geometry:

- **Linear twist** $\Omega(\tau) = c\tau$ produces a uniform accumulation of the rotation angle, and the filaments become close to logarithmic spirals;
- **Localized twist** $\Omega(\tau) = k \tanh(\lambda\tau)$ concentrates the twisting near the equatorial "waist" $\tau = 0$ and approaches saturation toward the poles. This is the model employed throughout the main body of the present paper;
- **Wave modulation** $\Omega(\tau) = k \sin(n\tau)$ produces an alternating twist, so that the longitudinal coordinate lines acquire n helical turns and develop a wavy geometry.

The entire shear class preserves the orthogonal family of coordinate circles and therefore represents a deformation that leaves the transverse cross-sections of the shell unchanged.

8.2. Rotational Class: $= R(\theta)$.

A rigid rotation of the (τ, σ) -plane through a constant angle β ,

$$u = \tau \cos \beta - \sigma \sin \beta, \quad v = \tau \sin \beta + \sigma \cos \beta, \quad (107)$$

is an isometry ($J_\Phi = 1$) that twists both coordinate families symmetrically. The poles, corresponding to $u \rightarrow \pm\infty$ remain fixed, while the overall configuration preserves its central symmetry. If the rotation angle is allowed to vary, $\theta = \theta(\tau)$ (for example $\theta = \beta \tanh \lambda\tau$) the rotation becomes localized. Its Jacobian,

$$J_\Phi = 1 - \sigma \theta'(\tau) \quad (108)$$

is no longer equal to unity. Consequently, the transformation ceases to preserve area and introduces a slight loss of orthogonality of the coordinate network in the vicinity of the axis. A further generalization, in which the rotation angle depends on the *radial variable*, $\theta = \beta \tanh(\lambda\rho)$, $\rho = \sqrt{\tau^2 + \sigma^2}$, produces an axisymmetric twisting pattern with a characteristic *eye-of-the-storm* structure. Superposing such a rotation with a wave modulation generates composite multiscale geometric patterns.

8.3. Summary and Examples.

The principal representatives of both transformation classes and their geometric properties are summarized in Table 2, while nine representative examples are illustrated in Fig. 2.

Table 2.

Twisting Transformations Φ and the Geometries They Generate.

Transformation	$\Phi: (\tau, \sigma) \mapsto (u, v)$	Effect
Identity	(τ, σ)	original orthogonal grid
Rigid rotation	$(\tau \cos \beta - \sigma \sin \beta, \tau \sin \beta + \sigma \cos \beta)$	symmetric twisting, poles fixed
Local rotation	$R(\beta \tanh \lambda\tau)$	twisting near the "waist," $J = 1 - \theta'_0$
Linear shift	$(\tau, \sigma + c\tau)$	helical filaments, $J = 1$
Localized shift	$(\tau, \sigma + k \tanh \lambda\tau)$	circles preserved, $J = 1$
Wave shift	$(\tau, \sigma + k \sin n\tau)$	wavy filaments, $J = 1$
Radial twist	$R(\beta \tanh \lambda\rho)$	"eye of the storm" structure
Rotation + wave	$R(\beta)$, then $v \mapsto v + k \sin n\tau$	composite pattern

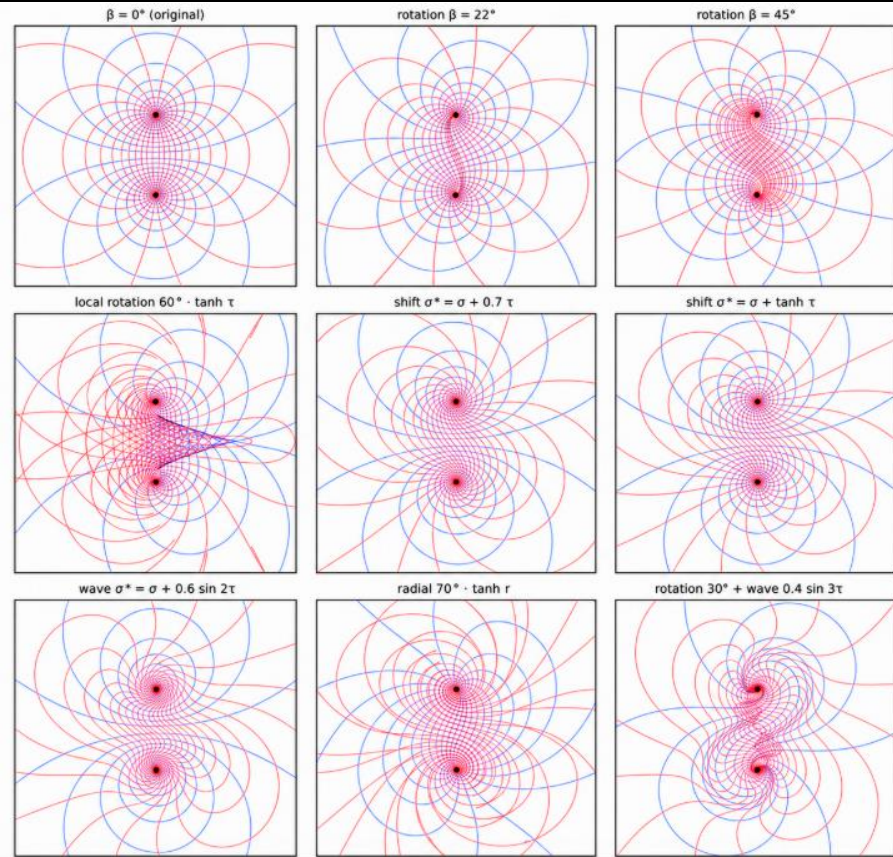


Fig 2. Nine representative members of the family (106) shown on a common bipolar coordinate framework (poles $N, S = (0, \pm a)$; blue curves denote $\tau = \text{const}$, red curves denote $\sigma = \text{const}$). The top row shows rigid rotations $R(\beta)$ for $\beta = 0^\circ, 22^\circ$ and 45° . The middle row presents a localized rotation $60^\circ \tanh \tau$, a linear shear $\sigma + 0.7\tau$, and a localized shear $\sigma + \tanh \tau$. The bottom row illustrates a wave modulation $\sigma + 0.6 \sin 2\tau$, a radial twist $70^\circ \tanh \rho$, and a combination of a 30° rotation with the wave modulation $0.4 \sin 3\tau$.

Thus, the shear model considered in the main text, ($\Omega(\tau) = k \tanh \lambda \tau$) and the rotational model based on the rotation matrix $R(\beta)$ represent two particular cases of the unified construction (106). The former preserves the transverse circular coordinate curves and the area element, since ($J = 1$), whereas the latter twists both coordinate families symmetrically while preserving the two poles. Intermediate and composite transformation laws, Φ provide a continuous interpolation between these two regimes and make it possible to construct the geometry of the vortex kern in a controlled manner so as to satisfy prescribed topological and metric requirements.

9. Discussion of the Relationship Between the Geometric Model, the Ellipsoidal Microvortex, and the Inner Kern.

The proposed geometric model of the twisted external bipolar shell is intended to describe the spatial organization of a microvortex regarded as a localized vortex structure consisting of an inner kern surrounded by a continuous outer shell. Unlike the classical models of vortex tubes, which primarily focus on the distribution of vorticity within the fluid volume, the present model emphasizes the geometry of the external shell and the structure of the vortex filaments forming its surface.

The microvortex is assumed to originate through the localization of vortex motion followed by the closure of the external shell around the inner kern. The

kern serves as the central axial structure along which the major portion of the circulation is concentrated, whereas the external shell is represented as a smooth two-dimensional surface carrying a continuous family of vortex filaments. In the proposed model, the shell is unique, and its geometry is determined by two poles corresponding to the two ends of the inner kern..

The bipolar coordinate system naturally reflects such a structure. The poles of the coordinate system are interpreted as the points at which the vortex filaments enter and leave the kern. The coordinate lines connecting the two poles may be regarded as meridional vortex filaments, whereas the second family of coordinate lines describes the transverse organization of the shell. In the untwisted configuration, the two coordinate families are mutually orthogonal and form a regular bipolar network.

The introduction of the twist function $\sigma^* = \sigma + \Omega(\tau)$ modifies only the geometry of the coordinate lines without affecting the continuity of the surface. The meridional lines acquire a helical shape while preserving their connection between the two poles. In physical terms, this means that the external shell begins to rotate about the inner kern, forming a system of helical vortex filaments.

The function $\Omega(\tau)$ characterizes the accumulated angle of the internal rotation of the shell relative to the kern. Its derivative, $\Omega'(\tau)$ determines the local intensity of the twist. When $\Omega'(\tau) = 0$, the shell undergoes no

internal rotation, and its geometry coincides with that of the classical bipolar coordinate system. As $|\Omega'(\tau)|$ increases, the angle between the vortex filaments and the longitudinal direction increases accordingly, giving rise to a pronounced helical structure.

A distinctive feature of the proposed model is the localization of the twist within the central region of the shell. For the function $\Omega(\tau) = k \tanh(\lambda\tau)$ its derivative $\Omega'(\tau) = k\lambda \operatorname{sech}^2(\lambda\tau)$ attains its maximum at the middle of the shell and tends to zero as the poles are approached. Consequently, the vortex filaments enter the kern with virtually no additional bending, whereas the strongest helical rotation is concentrated in the region between the two ends of the kern. Such a distribution is consistent with the geometric concept of a localized internal rotation of the shell.

Within the framework of the present model, the inner kern is not treated as a separate coordinate surface. Instead, it is represented by the axial curve connecting the two poles of the shell and defining the direction of the longitudinal circulation. This formulation makes it possible to distinguish two fundamentally different geometric components of the vortex motion. The first is associated with the longitudinal transport along the kern, whereas the second corresponds to the rotation of the external shell about it. Such a decomposition makes it possible to analyze independently the influence of the axial structure and the transverse twist on the geometry of the microvortex.

The closed ellipsoidal microvortex may be regarded as a system consisting of two interconnected components: the inner kern and the external shell. The external vortex filaments extend along the surface of the shell from one pole to the other, after which they may close through the interior of the kern, thereby forming continuous closed circulation loops. In this representation, the external shell determines the geometric distribution of the filaments, whereas the inner kern provides their topological closure.

The analysis presented above shows that the introduction of the twist does not alter the topological type of the shell. The Jacobian of the transformation remains positive, the metric tensor remains positive definite, and the surface develops neither folds nor self-intersections. Consequently, the internal twist represents a smooth deformation of the shell geometry that preserves its connectedness and leaves the number of poles unchanged.

From the viewpoint of geometric hydrodynamics, the proposed model may be regarded as an intermediate stage between an idealized vortex kern and a complete three-dimensional model of a vortex structure. It provides an analytical description of the external shell that allows the computation of metric characteristics, curvature, filament lengths, and other geometric invariants. These quantities may serve as the basis for subsequent investigations of the shell dynamics and of the interaction between the inner kern and the surrounding vortex structure.

It should be emphasized that, in the present work, the relationship between the inner kern and the external shell is introduced as a **geometric hypothesis formu-**

lated within the framework of conformal and differential geometry. The obtained results demonstrate that this construction is mathematically self-consistent: the twisted bipolar shell admits a smooth analytical description, preserves its topology under deformation, and naturally supports a family of continuous meridional helical filaments. The question of how accurately this geometric model represents specific physical vortex flows requires a separate investigation based on the governing equations of hydrodynamics, experimental observations, or numerical simulations. Such a comparison constitutes a natural direction for future research.

10. Conclusion.

This paper has presented a geometric model of the twisted external bipolar shell of a vortex kern, based on bipolar coordinates and their smooth deformation by means of an internal twist function. Unlike the traditional models of vortex tubes, the proposed construction is aimed at providing an analytical description of the geometry of the external shell of a microvortex surrounding the inner kern and carrying a continuous family of meridional vortex filaments.

A rigorous construction of the bipolar coordinate system has been obtained from a fractional linear complex mapping and the complex logarithm. Explicit coordinate transformation formulas have been derived, together with analytical expressions for the metric tensor, the Lamé coefficients, and the Jacobian of the mapping. It has been shown that the original bipolar coordinate system is conformal and that its coordinate curves form two mutually orthogonal families of circles.

To describe the internal rotation of the shell, a smooth twist function has been introduced, transforming the angular coordinate according to the law

$$\sigma^* = \sigma + \Omega(\tau).$$

The governing equations of the twisted shell have been derived, and its metric properties have been investigated. It has been shown that the mixed term of the metric tensor characterizes the formation of the helical structure of the external vortex filaments. At the same time, the determinant of the metric tensor remains positive, and the Jacobian of the transformation never vanishes throughout the entire regular domain.

The smoothness conditions of the proposed model have been analyzed in detail. It has been proved that, under natural assumptions on the twist function, the mapping remains a diffeomorphism of the parameter domain, preserves the orientation of the surface, and does not generate local self-intersections. On this basis, a theorem on the preservation of the topology of the twisted external bipolar shell has been formulated and proved.

Analytical equations describing the vortex filaments as coordinate curves of the twisted shell have been obtained. Explicit expressions have been derived for the tangent vectors, the arc-length element, the local twist angle, and the curvature of the filaments. It has been shown that the function $\Omega'(\tau)$ determines the local intensity of the helical deformation, whereas the second derivative, $\Omega''(\tau)$ governs the variation of the filament curvature.

A numerical experiment has been carried out to verify the analytical results. Both untwisted and twisted bipolar coordinate networks have been constructed, and the influence of the twist parameter on the filament length, curvature, and local rotation angle has been investigated. Throughout the entire range of parameters considered, the mapping remained regular, and the resulting shell remained smooth and continuous.

The proposed model admits a natural spatial interpretation as the external shell of a microvortex surrounding an inner vortex kern. Within this interpretation, the two poles of the bipolar coordinate system correspond to the two ends of the kern, while the meridional coordinate curves represent a family of helical vortex filaments forming the external shell. The twist of the shell is interpreted as a geometric model of the internal rotation of the surface about the kern.

It should be emphasized that the present work is devoted exclusively to the geometric aspects of the problem. The proposed model does not rely directly on the Navier–Stokes equations and does not address the dynamics of a viscous fluid. Instead, the obtained results establish a mathematically consistent geometric framework that may serve as a foundation for further investigations of the spatial structure of microvortices, topological invariants, helicity, the stability of vortex shells, and their relationship to geometric hydrodynamics.

Promising directions for future research include the construction of a complete three-dimensional model of the external shell of an ellipsoidal vortex, the investigation of its principal curvatures, the derivation of integral helicity characteristics, the formulation of energy functionals, and the analysis of the stability of twisted shells within the framework of geometric mechanics and vortex theory.

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MEDICAL SCIENCES

COMPUTERIZED OCCLUSAL ANALYSIS OF THE DENTAL ARCHES IN PATIENTS WITH CONGENITAL CLEFT LIP AND PALATE USING THE T-SCAN® III SYSTEM

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КОМПЬЮТЕРНАЯ ОККЛЮЗИОГРАФИЯ ЗУБНЫХ РЯДОВ У ПАЦИЕНТОВ С ВРОЖДЁННЫМИ РАСЩЕЛИНАМИ ГУБЫ И НЁБА С ИСПОЛЬЗОВАНИЕМ СИСТЕМЫ T-SCAN® III

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Abstract

The aim of this study was to quantitatively assess static and dynamic occlusal relationships of the dental arches in patients with congenital cleft lip and palate using the T-Scan® III system. Computerized occlusal analysis was performed in 360 patients with congenital cleft lip and palate. The examination was conducted in habitual central occlusion and during protrusive and lateral mandibular movements. The distribution of relative occlusal load between the right and left sides, the position and trajectory of the center of force, the sequence of occlusal contact formation, occlusion time, and the relative intensity of contacts were assessed. Uneven distribution of occlusal load between the right and left sides was detected in 297 patients (82.5%). A balanced distribution of occlusal forces within the 40–60% range was recorded in only 63 patients (17.5%). In 297 patients (82.5%), initial contacts occurred predominantly in the posterior regions of the dental arches, followed by the formation of multiple contacts, indicating impaired synchronization of dental arch closure. Pronounced premature contacts involving individual teeth were identified in 46 patients (12.8%). These contacts were accompanied by changes in the trajectory of the center of force and redistribution of occlusal load to the contralateral side. Thus, most patients with congenital cleft lip and palate demonstrated marked asymmetry in occlusal load distribution and an altered sequence of dental arch closure. Computerized occlusal analysis provides an objective assessment of functional occlusal disorders and may be incorporated into a comprehensive protocol for planning orthodontic treatment and evaluating its outcomes.

Аннотация

Цель исследования — провести количественную оценку статических и динамических окклюзионных взаимоотношений зубных рядов у пациентов с врождёнными расщелинами губы и нёба с использованием системы T-Scan® III. Компьютерная окклюзиография проведена у 360 пациентов с врождёнными расщелинами губы и нёба. Исследование выполняли в положении привычной центральной окклюзии, а также при протрузионных и латеральных движениях нижней челюсти. Оценивали распределение относительной окклюзионной нагрузки между правой и левой сторонами, положение и траекторию центра суммарной силы, последовательность возникновения контактов, продолжительность окклюзионного времени и относительную интенсивность контактов. Неравномерное распределение жевательной нагрузки между правой и левой сторонами выявлено у 297 (82,5%) пациентов. Сбалансированное распределение окклюзионных сил в пределах 40–60% зарегистрировано только у 63 (17,5%) обследованных. У 297 (82,5%) пациентов первоначальные контакты возникали преимущественно в боковых отделах зубных рядов с последующим формированием множественных контактов, что свидетельствовало о нарушении синхронности смыкания. Выраженные преждевременные контакты отдельных зубов определены у 46 (12,8%) пациентов. Они сопровождались изменением траектории движения центра суммарной силы и перераспределением жевательной нагрузки на противоположную сторону. Таким образом, у большинства пациентов с врождёнными расщелинами губы и нёба выявлены выраженная асимметрия распределения окклюзионной нагрузки и нарушение последовательности смыкания зубных рядов. Компьютерная окклюзиография позволяет

объективизировать диагностику функциональных нарушений окклюзии и может быть включена в комплексный протокол планирования и оценки результатов ортодонтического лечения.

Keywords: congenital cleft lip and palate, computerized occlusal analysis, T-Scan® III, occlusal load, center of force, premature contacts, digital diagnostics.

Ключевые слова: врождённая расщелина губы и нёба, компьютерная окклюзиография, T-Scan® III, окклюзионная нагрузка, центр силы, преждевременные контакты, цифровая диагностика.

Введение. Окклюзия представляет собой сложную функциональную систему взаимоотношений зубных рядов, жевательных мышц и височно-нижнечелюстных суставов, обеспечивающую координированное смыкание зубов, эффективное пережёвывание пищи и физиологическое распределение нагрузки на ткани пародонта. Нарушение последовательности формирования окклюзионных контактов, наличие супраконтактов и неравномерное распределение жевательного давления могут сопровождаться функциональной перегрузкой отдельных зубов, изменением положения нижней челюсти, нарушением работы жевательных мышц и снижением устойчивости достигнутых результатов ортодонтического и ортопедического лечения [1, 2, 3].

Традиционная оценка окклюзии проводится с использованием артикуляционной бумаги, окклюзионной фольги, восковых пластинок, силиконовых материалов и диагностических моделей. Эти методы позволяют определить локализацию контактов, однако не дают объективной количественной информации о последовательности их возникновения, продолжительности смыкания и относительной силе нагрузки. Размер и интенсивность отпечатка артикуляционной бумаги зависят от её толщины, влажности поверхности зуба, направления движения нижней челюсти и давления пациента. В связи с этим визуальная интерпретация окклюзионных меток во многом носит субъективный характер [4, 5].

Развитие цифровых технологий способствовало внедрению компьютерной окклюзиографии, которая позволяет регистрировать окклюзионные взаимоотношения в режиме реального времени. Одной из наиболее распространённых систем является аппаратно-программный комплекс T-Scan®, регистрирующий временную последовательность возникновения контактов, их относительную интенсивность, распределение нагрузки между правой и левой сторонами зубных рядов, положение центра суммарной силы и траекторию его перемещения. Полученные данные отображаются в двух- и трёхмерном форматах, что обеспечивает наглядную количественную оценку статической и динамической окклюзии [5, 6, 7].

Принципиальным преимуществом компьютерной окклюзиографии является возможность анализа процесса смыкания зубных рядов от момента появления первого контакта до достижения максимальной интеркуспидации. Система позволяет определить преждевременные контакты, оценить окклюзионное время, выявить участки функциональной перегрузки, асимметрию распределения

жевательной нагрузки, а также нарушения при протрузионных и латеральных движениях нижней челюсти. При этом T-Scan® регистрирует не абсолютную силу в ньютонах, а относительное процентное распределение окклюзионной нагрузки, что необходимо учитывать при интерпретации результатов [8, 9].

Современные исследования подтверждают диагностическую ценность цифрового анализа окклюзии в ортодонтии, ортопедической стоматологии, имплантологии и функциональной диагностике. Компьютерная окклюзиография применяется для оценки исходных окклюзионных нарушений, контроля результатов коррекции прикуса, анализа адаптации зубочелюстной системы к ортопедическим конструкциям и динамического наблюдения после завершения лечения [10, 11]. Использование цифрового метода особенно важно в случаях, когда визуально определяемые контакты не соответствуют фактической последовательности и интенсивности приложения окклюзионной нагрузки.

Вместе с тем результаты компьютерной окклюзиографии должны оцениваться комплексно. Точность регистрации может зависеть от позиционирования и калибровки сенсора, его толщины, индивидуальной формы зубных рядов, количества повторных измерений и воспроизводимости смыкания челюстей. Клинические исследования показывают, что цифровые системы обладают достаточной воспроизводимостью, однако точность локализации отдельных контактов может различаться в зависимости от применяемого оборудования и протокола обследования [12, 13]. Поэтому данные T-Scan® целесообразно сопоставлять с результатами клинического обследования, интраорального сканирования и маркировки контактов тонкой артикуляционной фольгой.

Особую значимость компьютерная окклюзиография приобретает при обследовании пациентов с врождёнными расщелинами губы и нёба. У данной категории больных нарушение непрерывности альвеолярного отростка, сужение и деформация верхней зубной дуги, поперечная резцовая окклюзия, обратное резцовое перекрытие, аномалии положения и количества зубов, послеоперационные рубцовые изменения и скелетная асимметрия создают предпосылки для формирования функционально неравномерной окклюзии. Даже после завершения многоэтапного хирургического и ортодонтического лечения у некоторых пациентов сохраняются асимметрия боковых контактов, недостаточная окклюзионная поддержка и различия между стороной расщелины и противоположной стороной [14, 15].

Исследования жевательной функции у пациентов с врождёнными расщелинами показывают, что морфологически удовлетворительный результат ортодонтического лечения не всегда сопровождается полной нормализацией окклюзионной силы, площади контактов и движений нижней челюсти [12, 13, 14]. Традиционные индексы и анализ диагностических моделей преимущественно характеризуют статическое соотношение зубных рядов, но не отражают временную последовательность возникновения контактов и характер перераспределения нагрузки. Следовательно, включение компьютерной окклюдзиографии в комплекс цифровой диагностики позволяет дополнить морфометрическую оценку зубных рядов объективными функциональными показателями.

Таким образом, изучение окклюзионных взаимоотношений с использованием компьютерной системы T-Scan® является актуальным направлением современной стоматологии. Метод позволяет объективизировать диагностику, выявлять скрытые преждевременные контакты, количественно оценивать окклюзионный баланс и контролировать функциональные результаты лечения. Особенно перспективно его применение у пациентов с врождёнными расщелинами губы и нёба, для которых

характерны сложные сочетанные морфологических и функциональных нарушений зубочелюстной системы.

Цель исследования — оценить статические и динамические окклюзионные взаимоотношения у пациентов с врождёнными расщелинами губы и нёба с использованием системы T-Scan® III.

Материалы и методы исследования

В исследование включены 360 пациентов с врождёнными расщелинами губы и нёба, ранее перенёсших хирургическое лечение. Для объективной оценки артикуляционно-окклюзионных взаимоотношений зубных рядов применяли аппаратно-программный комплекс T-Scan® III (Tekscan, Inc., США). Комплекс включал регистрирующее устройство T-Scan® III, одноразовые электронные сенсоры, держатель сенсора и специализированное программное обеспечение T-Scan® версии 9.1. С помощью данного комплекса проводили цифровую регистрацию и последующий анализ последовательности возникновения окклюзионных контактов, их интенсивности, продолжительности смыкания зубных рядов и распределения жевательной нагрузки между правой и левой сторонами.



Аппаратно-программный комплекс T-Scan III (А), сенсоры T-Scan III (Б)



Ориентация сенсора в ротовой полости при записи окклюдодграмм на аппаратно-программном комплексе T-Scan III в положении привычной окклюзии.

Результаты исследования

Компьютерная оценка окклюзионных взаимоотношений проведена у 360 пациентов с врождёнными

расщелинами губы и нёба с применением аппаратно-программного комплекса T-Scan® III. Регистрацию окклюзионных контактов осуществляли в положении привычной центральной окклюзии, а

также при протрузионных и латеральных движениях нижней челюсти. Оценивали распределение окклюзионной нагрузки между правой и левой сторонами зубных рядов, локализацию центра суммарной силы, последовательность формирования межзубных контактов, временные характеристики окклюзии и интенсивность контактов по данным колориметрической шкалы.

Анализ цифровых окклюзиограмм показал, что у 297 (82,5%) пациентов наблюдалось неравномерное распределение жевательной нагрузки между правой и левой сторонами зубных рядов. Сбалансированное распределение окклюзионных сил в пределах 40–60% зарегистрировано только у 63 (17,5%) обследованных. Направление смещения окклюзионной нагрузки было связано со стороной расположения расщелины, выраженностью деформации верхней челюсти, степенью сужения верхней зубной дуги и характером окклюзионных нарушений.

При оценке положения вектора суммарной окклюзионной нагрузки установлено, что «центр силы» располагался в центральной белой зоне овального окна у 134 (37,2%) пациентов, в серой зоне — у 180 (50,0%). У 46 (12,8%) обследованных центр силы находился за пределами овального окна, что указывало на выраженное нарушение баланса окклюзионной нагрузки. Наиболее значи-

тельное отклонение центра силы отмечалось у пациентов с односторонними расщелинами, асимметрией верхней зубной дуги, перекрёстной окклюзией и выраженным дефицитом трансверсальных размеров верхней челюсти.

Анализ динамических окклюзиограмм показал, что физиологическое клыковое ведение при латеральных движениях нижней челюсти сохранялось у 156 (43,3%) пациентов. У остальных 204 (56,7%) обследованных регистрировались групповые контакты, преждевременное включение боковых зубов и интерференционные контакты на рабочей либо балансирующей стороне.

При протрузионном движении нижней челюсти у части пациентов отсутствовало полноценное направляющее контактирование фронтальной группы зубов. Данное нарушение сочеталось с аномальным положением передних зубов, обратной резцовой окклюзией, наличием сагиттальной щели, а также дефектами зубного ряда в области врождённой расщелины.

Оценка последовательности смыкания зубных рядов выявила нарушение синхронности формирования окклюзионных контактов. У 297 (82,5%) пациентов первоначальные контакты возникали преимущественно в боковых отделах зубных рядов с последующим формированием множественных контактов которое представлена рисунок 1.

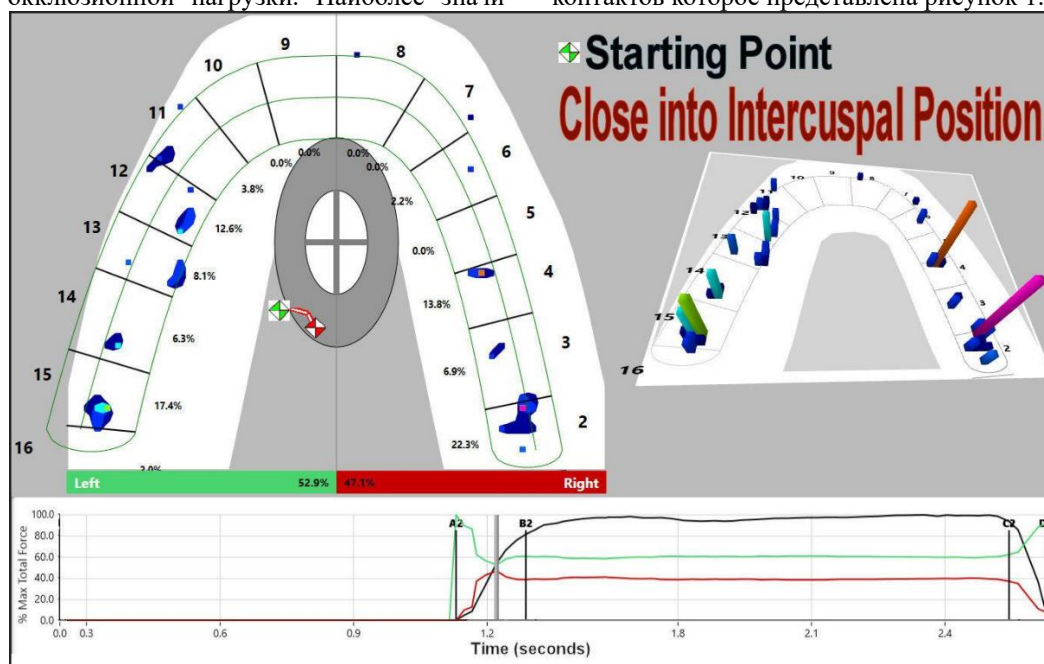


Рисунок 1. Нарушение последовательности формирования окклюзионных контактов у пациента с врождённой расщелиной губы и нёба по данным компьютерной окклюзиографии T-Scan® III

У 46 (12,8%) обследованных определялись выраженные преждевременные контакты отдельных зубов, которые сопровождались изменением траек-

тории движения центра силы и перераспределением жевательной нагрузки на противоположную сторону.

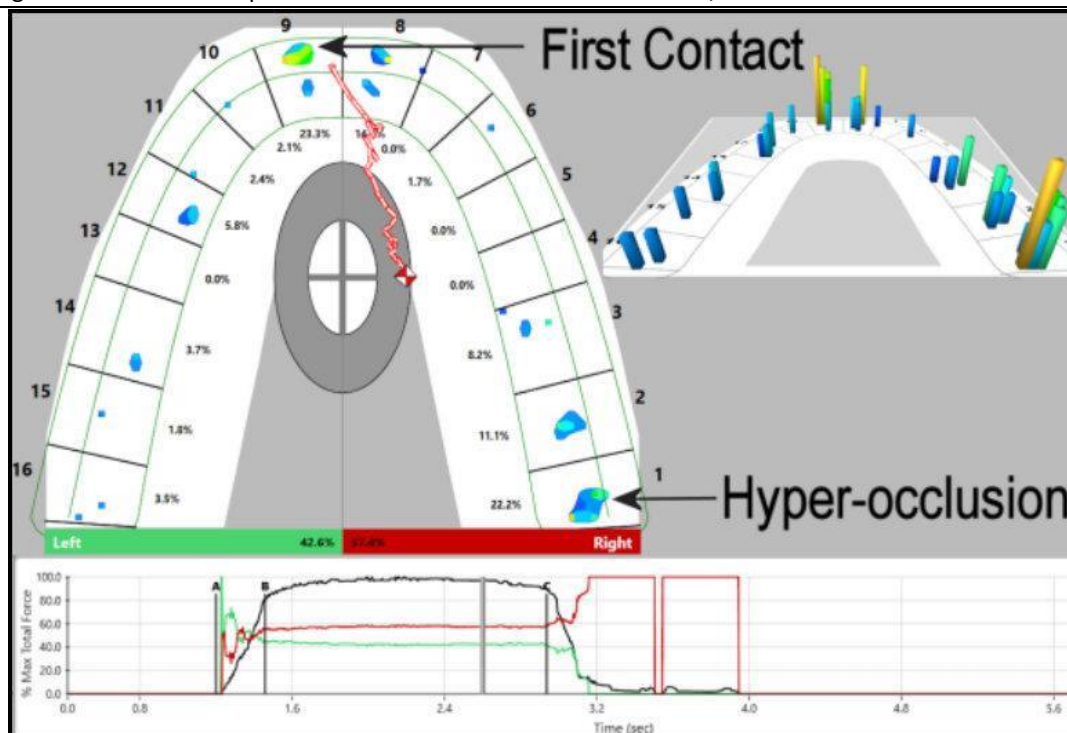


Рисунок 2. Выраженные преждевременные контакты отдельных зубов, отклонение траектории центра силы и асимметричное распределение окклюзионной нагрузки по данным T-Scan® III

На диаграммах зависимости окклюзионной силы от времени у пациентов с преждевременными контактами регистрировались резкие подъёмы кривой в виде отдельных «всплесков». Неравномерность временных интервалов формирования и разобщения межзубных контактов свидетельствовала о нарушении последовательности окклюзионного взаимодействия и функциональной нестабильности зубочелюстной системы.

Таким образом, по данным компьютерной окклюзиографии у пациентов с врождёнными расщелинами губы и нёба преобладали асимметричное распределение окклюзионных сил, смещение центра суммарной нагрузки, нарушение последовательности формирования межзубных контактов, отсутствие физиологического клыкового ведения и наличие преждевременных окклюзионных контактов. Выраженность выявленных изменений была связана с видом и локализацией расщелины, степенью деформации верхней челюсти, асимметрией зубной дуги, положением отдельных зубов, а также характером ранее проведённого хирургического и ортодонтического лечения.

Обсуждение. Результаты компьютерной окклюзиографии показали высокую распространённость функциональных нарушений окклюзии у пациентов с врождёнными расщелинами губы и нёба. Неравномерное распределение жевательной нагрузки между правой и левой сторонами зубных рядов выявлено у 297 (82,5%) из 360 обследованных. Сбалансированное соотношение окклюзионных сил в пределах 40–60% зарегистрировано только у 63 (17,5%) пациентов. Полученные данные свидетельствуют о том, что даже при наличии множественных межзубных контактов окклюзия у большинства пациентов сохраняла функционально асимметричный характер.

Высокая частота окклюзионного дисбаланса может быть обусловлена особенностями формирования зубочелюстной системы при врождённых расщелинах губы и нёба. Нарушение непрерывности альвеолярного отростка, послеоперационные рубцовые изменения, сужение и деформация верхней зубной дуги, дефицит её поперечных размеров, аномалии положения и количества зубов создают предпосылки для асимметричного смыкания зубных рядов. Дополнительное значение имеют перекрёстная окклюзия, обратное резцовое перекрытие, смещение средней линии и различия в окклюзионной поддержке между стороной расщелины и противоположной стороной. В исследовании С.В. Staudt и соавт. также установлено, что после завершения комплексного лечения пациентов с односторонней расщелиной могут сохраняться более выраженное сужение зубной дуги и менее благоприятные окклюзионные взаимоотношения на стороне врождённого дефекта [16].

Оценка последовательности смыкания зубных рядов выявила нарушение синхронности формирования окклюзионных контактов. У 297 (82,5%) пациентов первоначальные контакты возникали преимущественно в боковых отделах, после чего формировались множественные контакты в других участках зубных рядов. Такая последовательность может указывать на наличие функциональных препятствий при переходе нижней челюсти в положение максимальной интеркуспидации. Раннее включение отдельных боковых зубов способно изменять траекторию движения нижней челюсти, смещать центр суммарной силы и способствовать перераспределению нагрузки между функциональными отделами зубных дуг.

Выраженные преждевременные контакты отдельных зубов определены у 46 (12,8%) обследованных. Они сопровождались изменением траектории центра силы и перераспределением жевательной нагрузки на противоположную сторону. Клиническая значимость таких контактов определяется не только их локализацией, но и моментом возникновения, относительной интенсивностью и продолжительностью воздействия. Даже небольшой по площади ранний контакт может оказывать существенное влияние на последовательность последующего смыкания зубных рядов. Поэтому визуальная оценка размера отпечатка артикуляционной бумаги не всегда позволяет достоверно определить функционально наиболее значимый контакт [17, 18].

Полученные результаты подтверждают преимущества компьютерной окклюзиографии перед изолированным применением традиционных методов. Артикуляционная бумага позволяет обозначить место контакта, однако не определяет его временную последовательность и относительную силовую значимость. Система T-Scan® III обеспечивает динамическую регистрацию окклюзии от первого контакта до максимальной интеркуспидации, визуализирует распределение относительных сил и отражает перемещение центра суммарной нагрузки. Согласно систематическим обзорам, цифровой анализ уменьшает субъективность клинической оценки и расширяет возможности диагностики скрытых окклюзионных нарушений [19].

Выявленная асимметрия окклюзионной нагрузки согласуется с результатами исследований функционального состояния жевательного аппарата у пациентов с врождёнными расщелинами. S. Miura и соавт. установили, что после ортодонтического лечения у таких пациентов могут сохраняться отличия показателей окклюзионной силы, площади контактов и характера жевательных движений по сравнению с лицами с физиологической окклюзией [13]. M.A. García и соавт. также показали особенности формирования силы прикуса у детей с односторонними и двусторонними расщелинами [14]. Это подтверждает, что достижение удовлетворительного морфологического соотношения зубных рядов не всегда означает полное восстановление их функционального равновесия.

Полученные данные имеют важное значение для планирования ортодонтического лечения. При выборе направления и последовательности перемещения зубов необходимо учитывать не только форму зубных дуг, величину дефицита места и положение зубов относительно костного дефекта, но и исходное распределение окклюзионной нагрузки. Перемещение зубов без контроля динамической окклюзии может приводить к сохранению или формированию новых супраконтактов. В связи с этим данные компьютерной окклюзиографии целесообразно интегрировать с результатами конусно-лучевой компьютерной томографии и интраорального сканирования. Такая интеграция позволяет одновре-

менно оценивать положение коронок и корней зубов, анатомические границы альвеолярной кости, морфометрию зубных дуг и функциональную значимость окклюзионных контактов.

Компьютерный анализ особенно важен на этапах подготовки к костной пластике альвеолярного отростка, после ортодонтического расширения верхней зубной дуги и на завершающем этапе лечения. До костной пластики необходимо исключить контакты, способствующие нежелательному смещению сегментов верхней челюсти. После хирургического вмешательства цифровая оценка позволяет контролировать адаптацию зубочелюстной системы к изменённым анатомическим условиям. На этапе завершения ортодонтического лечения компьютерная окклюзиография может использоваться для проверки равномерности нагрузки и своевременного выявления контактов, потенциально влияющих на стабильность результата. Целесообразность применения цифрового планирования окклюзии у пациентов с расщелинами подтверждается исследованиями, показавшими сопоставимость цифровой и традиционной постановки зубных рядов при подготовке к ортогнатическим операциям [19, 20, 21].

Вместе с тем показатели T-Scan® III необходимо интерпретировать с учётом особенностей метода. Система регистрирует относительное, а не абсолютное значение окклюзионной силы. На результаты могут влиять положение и калибровка сенсора, воспроизводимость смыкания, форма зубных дуг и наличие выраженных деформаций верхней челюсти. Поэтому для повышения достоверности целесообразно проводить несколько последовательных регистраций в одинаковых условиях и сопоставлять цифровые данные с клиническим осмотром, артикуляционной фольгой и результатами интраорального сканирования [22, 23, 24].

Таким образом, компьютерная окклюзиография выявила выраженную функциональную неоднородность окклюзии у большинства обследованных пациентов с врождёнными расщелинами губы и нёба. Преобладание асимметричного распределения нагрузки, несинхронное возникновение контактов и наличие выраженных преждевременных контактов подтверждают необходимость включения динамического цифрового анализа окклюзии в обязательный диагностический протокол. Использование данного метода позволяет повысить обоснованность ортодонтического планирования, объективизировать межэтапный контроль и оценивать функциональную полноценность достигнутого результата лечения.

Выводы. 1. Компьютерная окклюзиография с использованием системы T-Scan® III выявила высокую распространённость функциональных нарушений окклюзии у пациентов с врождёнными расщелинами губы и нёба. Неравномерное распределение жевательной нагрузки между правой и левой сторонами установлено у 297 (82,5%) из 360 обследованных, тогда как сбалансированное распределение окклюзионных сил в пределах 40–60% зарегистрировано только у 63 (17,5%) пациентов.

1. У 297 (82,5%) пациентов первоначальные окклюзионные контакты возникали преимущественно в боковых отделах зубных рядов с последующим формированием множественных контактов, что свидетельствует о нарушении синхронности смыкания и функциональной неоднородности окклюзии.

2. Выраженные преждевременные контакты отдельных зубов выявлены у 46 (12,8%) обследованных. Они сопровождались изменением траектории движения центра суммарной силы и перераспределением жевательной нагрузки на противоположную сторону, что указывает на их значимую роль в формировании окклюзионного дисбаланса.

3. Морфологически множественные контакты зубных рядов не всегда обеспечивали функционально сбалансированную окклюзию. Поэтому оценка результатов ортодонтического лечения пациентов с врождёнными расщелинами губы и нёба должна включать не только анализ формы и соотношения зубных дуг, но и количественное исследование последовательности, продолжительности и относительной интенсивности окклюзионных контактов.

4. Система T-Scan® III позволяет объективизировать диагностику статических и динамических нарушений окклюзии, выявлять скрытые преждевременные контакты и контролировать распределение жевательной нагрузки. Компьютерную окклюзиографию целесообразно включать в комплексный протокол обследования, цифрового планирования и оценки результатов ортодонтического лечения пациентов с врождёнными расщелинами губы и нёба.

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PHILOLOGICAL SCIENCES

MULTILINGUALISM AND CULTURAL IDENTITY

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Abstract

Multilingualism has become an increasingly significant phenomenon in the twenty-first century due to globalization, migration, technological development, and international communication. As individuals interact across linguistic and cultural boundaries, language plays a central role in shaping both personal and collective identities. This article explores the relationship between multilingualism and cultural identity from sociolinguistic, psychological, and educational perspectives. It examines how multilingual speakers construct, negotiate, and express their cultural identities while participating in diverse linguistic communities. The paper discusses theoretical approaches to multilingualism, including bilingualism, translanguaging, and linguistic repertoire, and analyzes both the advantages and challenges associated with multilingual language use. Particular attention is given to the influence of multilingual education, globalization, migration, and digital communication on cultural identity formation. Drawing upon the works of prominent scholars such as Baker, Grosjean, Fishman, Norton, and Crystal, the study argues that multilingualism does not weaken cultural identity but rather enriches and transforms it by enabling individuals to navigate multiple cultural environments simultaneously. The article concludes that preserving linguistic diversity while promoting multilingual education contributes to intercultural dialogue, social cohesion, and sustainable cultural development.

Keywords: multilingualism, cultural identity, bilingualism, language and culture, globalization, sociolinguistics, multilingual education, linguistic diversity

Introduction

Language is one of the most fundamental characteristics of human society. It functions not only as a means of communication but also as a carrier of culture, traditions, beliefs, values, and collective memory. Every language reflects a unique worldview, preserving historical experiences and transmitting cultural knowledge across generations. Consequently, language and cultural identity are inseparable concepts that influence both individuals and societies (Fishman, 1999).

The twenty-first century has witnessed unprecedented levels of globalization, migration, international education, tourism, and digital communication. These developments have significantly increased multilingual interactions across the world. According to UNESCO (2023), more than half of the world's population uses two or more languages in daily life. As a result, multilingualism has become a defining characteristic of many contemporary societies rather than an exceptional phenomenon.

Multilingualism refers to the ability of individuals or communities to use multiple languages for communication. Although multilingualism has existed throughout human history, its significance has expanded considerably in the modern era due to increased mobility and intercultural interaction (Baker, 2011). Individuals frequently use different languages depending on the social context, educational environment, workplace, family setting, or online communication. Such linguistic flexibility enables speakers to participate in multiple cultural communities simultaneously.

The relationship between multilingualism and cultural identity has attracted considerable scholarly attention in recent decades. Earlier linguistic theories often viewed multilingualism as a potential obstacle to national unity or educational success. However, contemporary research presents a contrasting perspective. Modern sociolinguistics argues that multilingualism strengthens intercultural competence, cognitive flexibility, and social inclusion while allowing individuals to maintain multiple cultural affiliations (Grosjean, 2010).

Cultural identity is understood as an individual's sense of belonging to particular cultural groups through shared language, traditions, values, religion, customs, and historical experiences (Hall, 1996). Identity is not static; rather, it evolves throughout life as people interact with different communities and social environments. Language plays a crucial role in this dynamic process because linguistic choices often symbolize social membership, solidarity, and personal identity.

In multilingual societies, individuals frequently negotiate between several linguistic and cultural identities. A person may speak one language at home, another in education, and a third in professional life. Rather than creating conflicting identities, multilingualism often enables individuals to integrate different cultural experiences into a broader and more flexible sense of self (Norton, 2013).

Global migration has further intensified discussions surrounding language and identity. Millions of migrants maintain their heritage languages while simultaneously acquiring the dominant language of their

host countries. Heritage language maintenance has become an important factor in preserving ethnic identity, family relationships, and cultural continuity across generations (Fishman, 1991). At the same time, acquiring additional languages facilitates social integration, educational achievement, and economic participation.

Educational systems also play a significant role in promoting multilingual competence. Research demonstrates that multilingual education enhances academic achievement, intercultural awareness, and cognitive development when learners receive appropriate linguistic support (Cummins, 2000). Schools increasingly recognize linguistic diversity as an educational resource rather than a barrier, encouraging students to develop proficiency in multiple languages while preserving their mother tongue.

Technological innovation has also transformed multilingual communication. Social media platforms, artificial intelligence, online education, and digital translation technologies allow individuals to interact with speakers from different linguistic backgrounds daily. Digital communication creates new multilingual practices, including code-switching, translanguaging, and hybrid linguistic identities that transcend traditional national boundaries (Crystal, 2003).

Despite these advantages, multilingual individuals may encounter various challenges. Language discrimination, identity conflicts, unequal educational opportunities, and pressure to abandon minority languages remain significant issues in many societies. Minority language speakers often face linguistic assimilation, which threatens both language preservation and cultural heritage (Skutnabb-Kangas, 2000). Therefore, language policies that support multilingual education and minority language rights are essential for sustaining cultural diversity.

The purpose of this article is to examine the complex relationship between multilingualism and cultural identity through an interdisciplinary review of sociolinguistic, educational, and psychological research. It explores the theoretical foundations of multilingualism, analyzes the role of language in identity construction, evaluates the benefits and challenges of multilingual societies, and discusses the implications of globalization for cultural diversity. Ultimately, the study argues that multilingualism represents not only a linguistic competence but also a valuable cultural resource that contributes to social inclusion, intercultural understanding, and sustainable development.

Theoretical Framework

The concept of multilingualism has attracted increasing attention in linguistics, sociology, psychology, and education. Scholars have developed various theoretical approaches to explain how individuals acquire, use, and maintain multiple languages while constructing their cultural identities. Modern research emphasizes that multilingualism is not merely the knowledge of several languages but a dynamic social practice shaped by historical, political, educational, and cultural factors.

One of the earliest comprehensive definitions of multilingualism was proposed by Baker (2011), who describes multilingualism as the ability of an individual

or a community to communicate effectively in more than one language. Baker argues that multilingual competence exists on a continuum rather than as a fixed category. Individuals may possess different levels of proficiency in speaking, listening, reading, and writing across their languages, depending on their educational background and social environment.

Similarly, Grosjean (2010) introduced the **holistic view of bilingualism and multilingualism**, rejecting the traditional assumption that multilingual speakers should demonstrate native-like proficiency in every language they use. According to this perspective, multilingual individuals develop a unique linguistic repertoire that enables them to communicate efficiently in different contexts. Their languages function together as an integrated system rather than as isolated competences.

Another influential framework is Cummins' (2000) theory of **Common Underlying Proficiency (CUP)**. Cummins argues that cognitive and academic skills developed in one language can positively transfer to another language. This theory has significantly influenced bilingual and multilingual education because it demonstrates that maintaining the first language supports rather than hinders second-language acquisition.

Recent sociolinguistic theories have expanded traditional concepts through the notion of **translanguaging**. García and Wei (2014) argue that multilingual speakers naturally draw upon all of their linguistic resources rather than keeping languages strictly separated. Translanguaging reflects authentic communication practices observed in multilingual societies, classrooms, workplaces, and online interactions. This approach challenges conventional educational models that insist on rigid language separation.

Another important theoretical contribution comes from Norton (2013), whose concept of **language and identity** explains that language learning is closely connected to social participation and personal identity. Individuals invest in learning additional languages because language provides access to new communities, educational opportunities, professional careers, and cultural experiences. Therefore, multilingualism should be understood not only as linguistic competence but also as a social and cultural investment.

From the perspective of cultural studies, Hall (1996) argues that identity is fluid, dynamic, and continuously reconstructed through interaction. Rather than possessing one fixed identity, multilingual individuals often negotiate multiple identities depending on context, audience, and communicative purpose. Language becomes one of the primary symbols through which these identities are expressed.

These theoretical perspectives collectively demonstrate that multilingualism is a multidimensional phenomenon involving cognitive development, social interaction, cultural participation, and identity formation. Contemporary scholarship increasingly recognizes multilingualism as a valuable human resource that contributes to intercultural understanding and social cohesion.

Definitions and Types of Multilingualism

Although multilingualism generally refers to the use of more than one language, scholars distinguish several forms based on linguistic competence, acquisition, and social context.

Individual multilingualism describes the ability of a single person to communicate in two or more languages. This competence may develop naturally within multilingual families or through formal education and language learning. Community multilingualism, on the other hand, refers to societies in which multiple languages coexist and are regularly used in public institutions, education, administration, and everyday communication (Baker, 2011).

Researchers also distinguish between **simultaneous** and **sequential multilingualism**. Simultaneous multilingualism occurs when children acquire two or more languages from birth. Sequential multilingualism develops when an individual first learns one language and later acquires additional languages, usually through schooling or migration (Grosjean, 2010).

Another important distinction concerns **balanced** and **dominant multilingualism**. Balanced multilinguals possess relatively equal proficiency across their languages, although perfect balance is uncommon. Dominant multilinguals demonstrate stronger competence in one language while maintaining functional abilities in others. Language dominance may change throughout life due to education, migration, employment, or family circumstances.

Functional multilingualism refers to using different languages for different purposes. For example, an individual may speak Azerbaijani at home, English at university, and Russian in business communication. Such language specialization reflects the practical realities of multilingual societies rather than linguistic deficiency.

Contemporary sociolinguistics emphasizes that multilingual competence should not be measured solely by grammatical accuracy. Instead, successful multilingual communication depends upon the speaker's ability to select appropriate linguistic resources according to social context. This perspective aligns with the concept of communicative competence proposed by Hymes (1972), which highlights the importance of context-sensitive language use.

Globalization has significantly expanded multilingual practices. International business, higher education, tourism, scientific collaboration, and digital technologies require individuals to communicate across linguistic boundaries. Consequently, multilingual competence has become an essential professional and social skill in many countries.

Language and Cultural Identity

Language serves as one of the strongest symbols of cultural identity because it preserves traditions, collective memory, folklore, literature, and shared historical experiences. Through language, individuals inherit cultural values and develop a sense of belonging to particular communities. Fishman (1991) argues that language maintenance is fundamental for preserving ethnic identity, especially among minority and immigrant populations.

Cultural identity is not inherited automatically but develops through continuous interaction between individuals and society. Hall (1996) emphasizes that identities are constantly reconstructed in response to changing social, political, and cultural conditions. For multilingual individuals, this process becomes even more dynamic because they regularly move between different linguistic and cultural environments.

Language choice often communicates identity more effectively than explicit statements. Speaking a heritage language may express solidarity with one's ethnic community, while using an international language such as English may signal participation in global academic or professional networks. Multilingual speakers frequently adapt their linguistic behavior according to audience, setting, and communicative goals.

Migration provides one of the clearest examples of the relationship between multilingualism and cultural identity. Immigrant families often preserve their native language within the household while adopting the dominant language of the host country in education and employment. This bilingual or multilingual practice allows individuals to integrate into a new society without abandoning their cultural heritage.

However, language shift may threaten cultural continuity. When younger generations stop using their ancestral language, traditional knowledge, oral history, and cultural practices become increasingly vulnerable. UNESCO has repeatedly warned that many of the world's languages are endangered, placing significant aspects of humanity's cultural heritage at risk.

Educational institutions therefore play a crucial role in supporting both multilingualism and cultural identity. Multilingual education encourages learners to value linguistic diversity while developing proficiency in additional languages. Research indicates that students who maintain strong literacy skills in their first language often perform better academically when learning additional languages (Cummins, 2000).

Ultimately, multilingualism enables individuals to participate in multiple cultural communities without requiring them to abandon their original identities. Rather than creating divided loyalties, multilingual competence often fosters intercultural empathy, broader perspectives, and stronger global citizenship.

Benefits and Challenges of Multilingualism

Multilingualism offers numerous cognitive, educational, social, and economic advantages. Over the past several decades, researchers have consistently demonstrated that multilingual individuals develop enhanced executive functioning, improved attentional control, stronger problem-solving abilities, and greater cognitive flexibility. According to Bialystok (2001), managing multiple linguistic systems strengthens the brain's executive control mechanisms because multilingual speakers continuously select one language while suppressing others.

Educational research similarly indicates that multilingual learners often demonstrate greater metalinguistic awareness. They become more conscious of grammatical structures, vocabulary patterns, and language learning strategies. Cummins (2000) argues that

literacy skills acquired in one language facilitate learning in additional languages through cognitive transfer. Consequently, multilingual education contributes positively to academic achievement when appropriately implemented.

From a social perspective, multilingualism promotes intercultural dialogue and mutual understanding. Individuals who communicate across languages are generally more capable of interacting with culturally diverse communities, reducing stereotypes and encouraging social inclusion. In today's multicultural societies, multilingual competence has become an essential component of intercultural communication.

Economically, multilingualism increases employability and professional mobility. International organizations, multinational corporations, diplomatic institutions, and global businesses increasingly seek employees capable of working across linguistic and cultural boundaries. English often functions as a global lingua franca, yet additional languages provide competitive advantages in regional and international markets (Crysal, 2003).

Despite these benefits, multilingualism also presents several challenges. One of the most significant concerns involves language maintenance. Minority languages frequently experience declining intergenerational transmission because younger speakers increasingly adopt dominant national or international languages. Fishman (1991) emphasizes that language loss often leads to erosion of cultural traditions, oral history, and collective identity.

Educational inequality represents another challenge. In some educational systems, multilingual students encounter difficulties because instruction is delivered exclusively in the dominant language. Without adequate linguistic support, learners may experience lower academic performance despite possessing considerable intellectual potential.

Language discrimination also affects many multilingual communities. Speakers of minority languages sometimes encounter prejudice, social exclusion, or reduced employment opportunities. Such linguistic inequalities highlight the importance of language rights and inclusive educational policies that recognize multilingualism as an asset rather than a problem.

Multilingualism in the Era of Globalization

Globalization has fundamentally transformed linguistic landscapes across the world. Increased international migration, higher education mobility, tourism, trade, digital communication, and technological innovation have intensified multilingual interactions among individuals and societies.

English has emerged as the dominant language of international science, business, diplomacy, aviation, and higher education. Nevertheless, globalization has not eliminated linguistic diversity. Instead, multilingual communication has become increasingly common as individuals combine global languages with regional and heritage languages.

Digital technologies have accelerated multilingual communication even further. Social media platforms, online learning environments, artificial intelligence,

and machine translation enable users to interact instantly across linguistic boundaries. These developments have created new forms of multilingual communication characterized by code-switching, translanguaging, and hybrid linguistic practices (García & Wei, 2014).

Migration also plays a crucial role in contemporary multilingualism. Millions of migrants preserve their native languages while simultaneously acquiring those of their host countries. Such linguistic adaptation facilitates social integration without necessarily abandoning cultural heritage.

Educational institutions increasingly recognize multilingual competence as a key twenty-first-century skill. Universities promote internationalization through English-medium instruction while simultaneously encouraging preservation of local languages and cultures. Successful multilingual education therefore seeks a balance between global participation and cultural sustainability.

International organizations such as UNESCO continue to advocate linguistic diversity because every language represents a unique repository of human knowledge and cultural heritage. Protecting endangered languages contributes not only to cultural preservation but also to intellectual diversity worldwide.

Discussion

The relationship between multilingualism and cultural identity is considerably more complex than traditional theories once suggested. Earlier perspectives frequently portrayed multilingualism as a source of divided loyalties or cultural assimilation. Contemporary interdisciplinary research, however, demonstrates that multilingualism generally enriches rather than weakens identity.

Language should be viewed not merely as a communication tool but as a dynamic social resource through which individuals negotiate belonging, express cultural values, and participate in diverse communities. Multilingual speakers routinely navigate multiple linguistic environments without abandoning their original identities.

Educational policies therefore should encourage additive multilingualism, where additional languages complement rather than replace the mother tongue. Such approaches contribute to cognitive development, intercultural competence, social inclusion, and lifelong learning.

Governments also bear responsibility for protecting linguistic diversity through supportive legislation, multilingual public services, minority language education, and cultural preservation initiatives. These measures strengthen democratic participation while safeguarding humanity's linguistic heritage.

Conclusion

Multilingualism has become one of the defining characteristics of contemporary society. Globalization, migration, technological innovation, and international education have transformed multilingual competence into an essential social and professional resource.

The evidence examined throughout this article indicates that multilingualism contributes positively to cultural identity by enabling individuals to participate

in multiple linguistic communities while maintaining connections with their cultural heritage. Rather than threatening identity, multilingualism expands cultural awareness, promotes intercultural dialogue, and strengthens social cohesion.

Theoretical perspectives proposed by Baker, Grosjean, Cummins, Fishman, Norton, García, Hall, and other scholars collectively demonstrate that language and identity are dynamic processes shaped by social interaction and cultural participation. Educational institutions therefore should promote multilingual education that values both global communication and linguistic diversity.

Finally, preserving multilingualism is not solely an educational objective but also a cultural and social responsibility. Protecting linguistic diversity ensures the continuation of cultural traditions, historical memory, and intellectual heritage for future generations.

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PHYSICAL SCIENCES

MACHINE LEARNING ASSISTED ANALYSIS OF THE REFRACTIVE INDEX–BAND GAP RELATIONSHIP IN SEMICONDUCTOR MATERIALS

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Abstract

In this article, the relationship between the band gap width E_g and the refractive index n in semiconductor materials was investigated using a data-driven approach. Linear regression and Random Forest models were constructed based on literature data for II–VI and III–V group materials. The comparison showed that the Random Forest model takes local variations into account better and provides a closer prediction for ZnO. This approach is useful for the preliminary evaluation of optical properties.

Keywords: Semiconductors, Band gap energy, Refractive index, Machine learning, ZnO.

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1. Introduction

The refractive index (n) is one of the key optical parameters that characterizes the interaction of a material with light and is defined as the ratio of the speed of light in vacuum to its propagation speed in the material. Also, the refractive index is a quantity that determines how much the path of radiation is bent in a substance. The refractive index depends on the optical absorption of the substance. Materials with a high absorption coefficient generally have a higher refractive index, whereas materials with a low absorption coefficient usually have a lower refractive index. As is known, optical absorption is mainly related to electronic transitions from the valence band to the conduction band, and the energy threshold of these transitions is determined by the band gap width (E_g). From this point of view, the relationship between the refractive index (n) and the optical band gap width has emerged [1].

In recent years, interest has increased in analyzing the relationship between the refractive index and the band gap using both empirical and dataset approaches. There are several reasons for this. The first reason is that the relationship between these two parameters is important from the point of view of evaluating the material's suitability for transparency, absorption, dispersion, and optoelectronic applications. The second reason is that the classical empirical models, such as Ravindra [2], Moss [3], Herve–Vandamme [4], Reddy [5], and Kumar–Singh [6], although they try to explain the $E_g \sim n$ relationship, do not work with the same accuracy for all materials. The constants used during the application of these models often depend on the chemical composition, whether the transition is direct or indirect, the structure, and the material group. Although these models appear simple in form, they are not universally applicable in practice. Therefore, a more detailed analysis of this dependence is needed. [7]. The third reason is the development of the machine learning approach. Thus, although the $E_g \sim n$ relationship has previously been evaluated using simple empirical formulas, it is now possible to investigate this relationship

based on DFT calculations and machine learning approaches. These approaches make it possible to obtain results in a shorter time, and in some cases within seconds. In modern studies, the band gap width is used to predict the refractive index (n) [8]. The most important reason is related to practical applications. Therefore, suitable values of both (E_g) and (n) are required for photonics, solar cells, sensors, optical coatings, transparent conductive oxides, and semiconductors with high refractive indices [1].

This allows us to say that it is not enough for a material to have only a large or small band gap width, it is also important to know how it interacts with light. In recent studies, an initial screening is first performed based on machine learning to identify semiconductors with high refractive indices, and then the results are verified using first-principles calculations.

In our previous theoretical analysis, it was shown that an inverse dependence exists between the refractive index (n) and the band gap energy (E_g) in semiconductor materials. However, this dependence is not completely linear, and the accuracy of the models varies depending on the material and the energy range [9]. Machine learning approaches make it possible to learn the dependence directly from the dataset without relying on a previously defined functional form and, as a result, to reveal hidden, nonlinear regularities [10–12].

The aim of this study is to analyze the relationship between the band gap energy E_g and the refractive index n in semiconductor materials based on a dataset of experimental values taken from the literature, and to comparatively investigate this relationship using linear regression and Random Forest models. The dataset used is based on literature data on II–VI and III–V semiconductors presented by Ahmad and co-authors [13]. Using this dataset, it was possible to compare the results obtained through the machine learning approach with experimental data and evaluate the extent to which the predictions differ from those data.

ZnO was selected in order to show the practical application possibilities of the models constructed on

the basis of the machine learning approach. The prediction of the refractive index (n) for ZnO was carried out. The main purpose of selecting ZnO is that it has a number of advantages and a wide field of application. ZnO is a wide-bandgap semiconductor and has a band gap width of approximately 3,37 eV at room temperature, and it is widely used in optoelectronic applications [14].

2. Methodology

As noted, for different semiconductor materials, the band gap energy E_g covers a wide energy range (0,17 ÷ 6,2 eV), and the corresponding refractive index n values are presented in tabular form [13] (Table 1). Using the machine learning approach, a comparative analysis was carried out based on the dataset given in table [15, 16].

Machine learning is one of the main fields of artificial intelligence and is a computational approach used for training models and making predictions based on data. As we know, machine learning is divided into three types: supervised learning, unsupervised learning, and reinforcement learning methods.

Supervised machine learning is most suitable for neural networks that need to solve classification problems and works based on a large amount of input data.

Unsupervised learning is, learning without a teacher. This mainly includes the transmission of unlabeled data and trying to find common features and relationships within them. We can understand this as follows: neural networks are first trained on broad and diverse data and then applied to the solution of real-world tasks. The use of unlabeled data allows the model to reveal regularities in new examples and to generalize better [17].

In the reinforcement learning method, it includes the neural network receiving input data and processing it randomly. Then its output is evaluated based on certain criteria.

In this study, machine learning was adopted as a general methodological approach, and two supervised

learning models Linear Regression and Random Forest were used for prediction.

Linear regression is a regression algorithm. It means that the purpose is to predict a continuous numerical value. The Random Forest model, on the other hand, is one of the supervised machine learning algorithms and is based on the joint operation of many decision trees. Since this approach is not based on previously determined empirical formulas, it allows a freer analysis of the $E_g \sim n$ relationship based on data.

All calculations were carried out in the Python programming environment, and the scikit-learn library was used in the construction of the models [15].

The dependence between the band gap width (E_g) and the refractive index (n) was analyzed for the semiconductor materials given in Table 1. Based on experimental literature data, a program was written in the Python programming language, and the calculations were carried out in the Anaconda environment.

3. Results and Discussion

Each point in the obtained graph corresponds to a specific material and was plotted using the (E_g) and (n) values given for that material (Figure 1). The circular points in the figure show the experimental values taken from the literature, while the straight blue line shows the regression line obtained because of linear regression.

The regression line expresses the general linear tendency between (E_g) and (n). However, since this approach evaluates all points within the same simple linear dependence, it cannot fully explain the values that deviate from the linear trend. The main purpose of using the Random Forest model is to take such local differences and nonlinear changes into account better. Apparently, as (E_g) increases the refractive index (n) decreases. However, the observed dependence does not have a completely linear character, and local differences exist in different material groups.

Table 1.

Parameters of the semiconductor materials used by us.

Nº	Material	Semiconductor group	Band gap energy, E_g (eV)	Refractive Index n
1.	InSb	III-V	0.17	3.96
2.	InAs	III-V	0.36	3.5
3.	GaSb	III-V	0.73	3.8
4.	InN	III-V	0.7	2.9
5.	InP	III-V	1.34	3.1
6.	GaAs	III-V	1.43	3.3
7.	AlSb	III-V	1.62	2.9
8.	CdTe	II-VI	1.5	2.8
9.	CdSe	II-VI	1.74	2.7
10.	AlAs	III-V	2.16	2.9
11.	GaP	III-V	2.26	3.1
12.	ZnTe	II-VI	2.26	2.7
13.	CdS	II-VI	2.42	2.5
14.	ZnSe	II-VI	2.7	2.5
15.	ZnO	II-VI	3.37	2

16.	GaN	III-V	3.4	2.3
17.	ZnS	II-VI	3.68	2.35
18.	AlN	III-V	6.2	2.1

Therefore, this graph should not be evaluated as a universal law for all semiconductors, but as an initial analysis showing the general tendency within the used data. This model gives results closer to the real points

especially in the medium and high (E_g) interval, which shows the advantage of the machine learning approach [10].

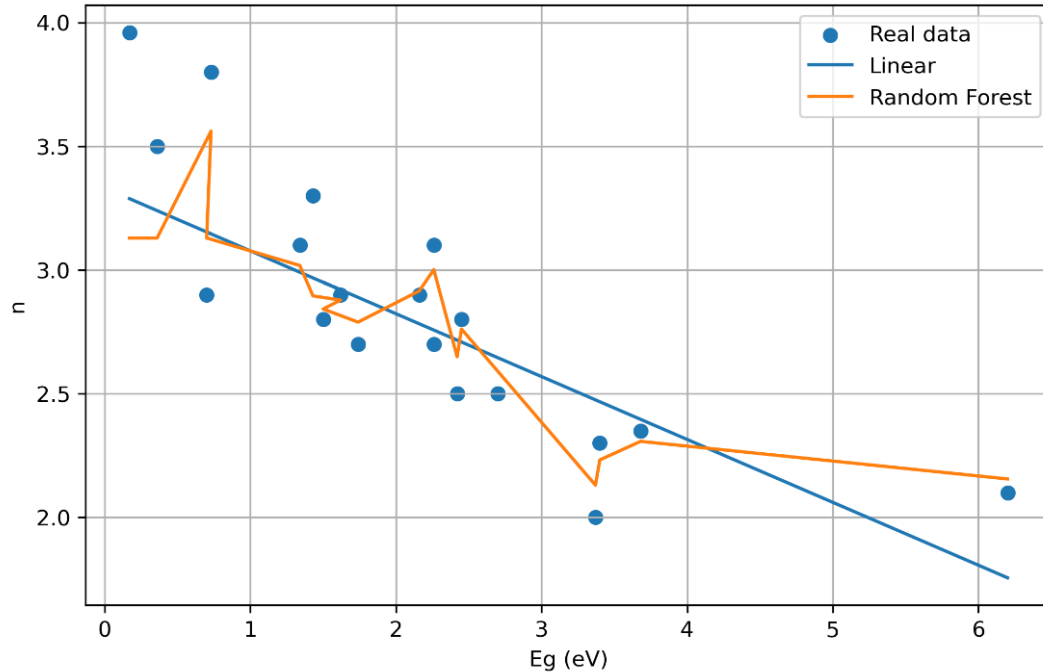


Figure 1. $E_g \sim n$ dependence on semiconductor materials

It should be noted that since the literature dataset used is limited, it may cause certain fluctuations in the Random Forest model. Using a larger dataset may allow this problem to be reduced.

Although we carried out the prediction for ($N = 18$) semiconductors, we selected ZnO for specificity. Clearly, from Table 1, for ZnO, at the value $E_g = 3,37$ eV, the refractive index is equal to $n = 2$.

Based on the results, it was determined that values of $n \approx 2,468$ for the linear regression model and $n \approx 2,118$ for the Random Forest model were obtained (Table 2).

Table 2.

ML prediction of the refractive index (n) for ZnO.

Material	E_g (eV)	n (LR)	n (RF)
ZnO	3,37	2,468	2,117

The comparison of the results obtained for ZnO shows that the Random Forest model gives a result closer to the experimental and literature values than the Linear Regression model. In the dataset used, the value $n = 2,00$ is given for ZnO. The Linear Regression model predicted this value as $n = 2,468$, giving a relatively high value. The Random Forest model, however, gave the result $n = 2,117$, which is closer to the known experimental range for ZnO. This difference can be explained by the fact that the Linear Regression model follows the general linear tendency but cannot take local nonlinear changes into account. The Random Forest model, however, learned the local features in the data more quickly and gave a more suitable result for this specific case. Nevertheless, taking into account the limited size of the data set, the RF result was evaluated not

as a final experimental value, but as an initial prediction result.

To evaluate the reliability of the model we used, 5-fold cross-validation was applied. In this method, the database is divided into five parts; at each stage, four parts are used for training the model, and one part is used for validation. The process is repeated five times, and the final result is determined based on the average value over all stages. This allows us to evaluate the stability and prediction accuracy of the model more reliably. For the evaluation of regression models, the mean squared error indicator — MSE — was also used. The average indicator of the MSE values obtained in the cross-validation stages was accepted as CV-MSE [18, 19].

The Random Forest model gave better results than the linear regression model (Train MSE: 0,0835; CV-MSE: $0,2141 \pm 0,2067$) in terms of both train MSE (0,0217) (train MSE shows how much error the model makes on the data it has learned) and CV-MSE ($0,1250 \pm 0,1222$) (the smaller the CV-MSE, the better the generalization ability of the model is considered) indicators (Table 3). This result quantitatively confirms that the Random Forest model

learns the nonlinear relationships in the data more accurately. The difference between the train MSE (0,0217) and CV-MSE (0,1250) of the Random Forest model indicates that the model shows a certain degree of overfitting tendency, that is, it gives results that are excessively close to the values in the dataset. This case is mainly explained by the limited size of the dataset used ($N = 18$). In small datasets, complex models may show a tendency to memorize the data instead of generalizing it.

Table 3.

Train MSE and CV-MSE results for Linear Regression and Random Forest models.		
Model	Train MSE	CV-MSE
Linear regression	0,0835	$0,2141 \pm 0,2067$
Random Forest	0,0217	$0,1250 \pm 0,1222$

4. Conclusion

In this study, the (E_g) and (n) values given for II–VI and III–V semiconductor materials were used to analyze the $E_g \sim n$ dependence through Linear Regression and Random Forest models. The conducted analyses showed that as (E_g) increases, the refractive index (n) decreases. However, this dependence does not have a completely linear character for all materials, and local differences are observed in separate material groups.

Although the linear regression model is useful in terms of showing the general direction of the $E_g \sim n$ relationship, this model cannot fully reflect the nonlinear changes and local differences in the data. The Random Forest model, however, gave more suitable results because it takes into account the more complex and nonlinear dependences existing in the data. This is especially clearly seen in the prediction carried out for ZnO. While the refractive index for ZnO is given in the literature as $n = 2,0$, the linear regression model predicted this value as $n = 2,468$, and the Random Forest model predicted it as $n = 2,117$. As can be seen, the Random Forest model gave a result closer to the known value for ZnO.

To evaluate the reliability of the model, 5-fold cross-validation was applied, and Train MSE and CV-MSE indicators were compared. The fact that the Train MSE and CV-MSE values for the Random Forest model are lower compared with the linear regression model shows that this model learns the nonlinear relationships in the data better. At the same time, the difference between Train MSE and CV-MSE in the Random Forest model shows that a certain overfitting tendency may exist. This case can mainly be associated with the limited size of the dataset used.

Thus, the conducted study shows that the machine learning approach is a useful and applicable approach for the preliminary evaluation of the optical properties of semiconductor materials. In particular, the Random Forest model makes it possible to analyze the $E_g \sim n$ dependence not only as a simple linear tendency, but in a more complex and nonlinear form. However, the obtained results should be accepted not as a final experimental value, but as an initial prediction and comparative evaluation. In future studies, the use of a wider database, additional structural and optical parameters may make it possible to increase the accuracy and generalization ability of the model.

The application details of the machine learning approach are given in Appendix A.

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Appendix A. Machine Learning Implementation

This appendix provides the Python implementation used to construct the machine learning models and to predict the refractive index for the ZnO.

```
# Machine Learning implementation for  $E_g \sim n$  prediction
import pandas as pd
from sklearn.linear_model import LinearRegression
from sklearn.ensemble import RandomForestRegressor
# Dataset
data = {
    "Eg": [0.17, 0.36, 0.73, 0.70, 1.34, 1.43, 1.62, 1.50, 1.74,
          2.16, 2.26, 2.26, 2.42, 2.45, 2.70, 3.37, 3.40, 3.68, 6.20],
    "n": [3.96, 3.50, 3.80, 2.90, 3.10, 3.30, 2.90, 2.80, 2.70,
          2.90, 3.10, 2.70, 2.50, 2.80, 2.50, 2.00, 2.30, 2.35, 2.10]
}
df = pd.DataFrame(data)
# Feature and target
X = df["Eg"]
y = df["n"]
# Model construction
lr = LinearRegression()
lr.fit(X, y)
rf = RandomForestRegressor(n_estimators=100, random_state=42)
rf.fit(X, y)
# Prediction for ZnO photodetector
X = df[["Eg"]]
zno_case = pd.DataFrame({"Eg": [3.37]})
lr_pred = lr.predict(zno_case)[0]
rf_pred = rf.predict(zno_case)[0]
# Prediction table
result = pd.DataFrame({
    "Material": ["ZnO photodetector"],
    "Band Gap Energy Eg (eV)": [3.37],
    "Predicted n (Linear Regression)": [lr_pred],
    "Predicted n (Random Forest)": [rf_pred]
})
print(result.round(4))
```

POLITICAL SCIENCES

HOW TO MEASURE THE MONSTER OF CORRUPTION IN MEXICAN LOCAL GOVERNMENTS?

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Abstract

This article explores the main mechanisms for measuring corruption in Mexico. It also discusses some ideas about the costs of corruption and the reasons that motivate citizens and other actors to engage in this practice. Furthermore, it presents data on the states and municipalities that have registered the highest rates of perceived corruption. Although effective mechanisms for combating corruption are not yet available, it has been concluded that one of the most important steps is to acknowledge the existence of corruption in the country, with the expectation of raising awareness among future generations of decision-makers.

Keywords: Perception of Corruption, indicators, public policy, accountability.

Introduction

What distinguishes countries whose institutions benefit everyone is not the democratic accountability of their leaders, but rather their incorruptibility. We now know that corruption acts like a cancer, hindering the proper functioning of institutions. It doesn't "grease the wheels" of a society; on the contrary, there is growing evidence that corruption corrodes public institutions in countless ways. (Costas, 2016: 15-16). The debate about corruption is out in the open, and in a much more raw and persistent way in recent years, as reflected in the data from public opinion polls that appear periodically. (Rodríguez, 2017: 353).

Regarding the measurement of corruption, the fundamental question is: how do we measure corruption objectively and comparably? The first option, and perhaps the most objective, would be to quantify the number of corruption complaints filed in a country, or the number of convictions related to corruption offenses. However, this indicator presents problems in comparative studies, as it is not easy to standardize the data, and furthermore, there is sampling bias, since unreported or unprosecuted corrupt acts are not included in these measurements. Therefore, most international studies that compare countries use indirect indicators of corruption. (Artés y Jiménez, 2017: 48).²⁸ In this context, surveys are quantitative tools for measuring the perception of corruption, which will be used in this document.

The increased effort to improve our understanding of the costs generated by corruption, at both the micro and macroeconomic levels, allows us to identify its economic and socio-political consequences, such as the loss of trust in institutions, the questioning of the democratic system, and the erosion of the rule of law (Sánchez-Macías, 2017: 128). Investigating the practices most prone to corruption at the local level allows

for the introduction of new administrative systems with lower levels of discretion, improvements in the quality of public services, and the implementation of ICTs as tools to combat administrative corruption.

Identifying and quantifying these costs is essential to understanding the scope of the problem among citizens and designing appropriate public policies for its prevention, containment, and eradication. However, the task is far from simple. Because corruption is an illegal and elusive phenomenon, both its direct and indirect costs are difficult to calculate. Among the direct costs are the money that ordinary citizens or businesses must allocate to bribe payments. Indirect costs, on the other hand, are even more difficult to document or quantify. Ultimately, it is always the citizen or consumer who pays. Whether through direct or indirect costs, it is known that the harmful effects of corruption in Mexico include economic ones. (Casar, 2016: 1), although unfortunately they are not the only ones.

Measuring the perception of corruption at the local level requires a diagnosis of corruption in Mexico. In this regard, one of the greatest difficulties in corruption research has been the lack of a solid empirical basis. Researchers have generally used two types of instruments to "measure the level of corruption". Some have used written documents, such as press reports, court records, and reports from anti-corruption agencies. Others have used data provided by surveys. Both types of instruments have advantages and disadvantages. However, surveys allow for comparative measurements between different levels of government and between countries (Sánchez, 2013: 17). Measuring corruption has become an increasingly important research topic (Villoria e Izquierdo, 2016: 247) among democratic societies that have perceived the perverse effects on the market, democracy and society.

²⁸ Among the most commonly used are: the Corruption Perceptions Index, produced by the non-governmental organization Transparency International; and the Governance Index, developed by the World Bank..

Using documents to measure the level of corruption has three advantages (del Castillo, 2001: 383-384). First, data collectors are often unaware of the specific research objective they are working on, so data collected from archival sources is often non-reactive and potentially more accurate than interview data. Secondly, if a type of document covers events over a substantial period, it is possible to perform a longitudinal and comparative analysis, which allows for more reliable data. Finally, document analysis has a cost advantage. By using written records, researchers can avoid the cost of collecting raw data themselves, as well as the cost of storing voluminous documents. (Sánchez, 2013: 17).

The greatest difficulty in investigating corruption lies in unraveling how corrupt practices are carried out and the role that different actors play in corruption networks. This difficulty is exacerbated by the fact that public administration tends to be networked, and it is increasingly clear that networks of actors define public problems and implement programs of all kinds, a circumstance that makes the scope of investigation almost limitless. Consequently, despite the difficulty, differentiating corrupt networks from “honest” ones is necessary and important if we want to identify good governance practices and identify corrupt activities. (Villoria, 2006: 11). The public services provided by public administrations allow us to identify those services that are provided with a low level of corruption and those services that are identified by citizens as having a high level of corruption.

How can we quantify the perception of corruption in Mexican local governments, and how big is the problem at the municipal level? This is the research question that we will attempt to answer in this chapter using surveys and measurements of corruption at the national, regional, and local levels. We aim to understand its importance to citizens in general, and to scholars in particular, with the goal of establishing the extent of corruption in the country's municipal governments.

For an accurate diagnosis of corruption in Mexico, the National Corruption and Good Governance Indices are used (2001, 2003, 2005, 2007 y 2010) prepared by Transparencia Mexicana, as well as the National Survey of Government Quality and Impact (2012, 2014 y 2016) conducted by INEGI (Sánchez, 2012: 2017). However, the first tool that measures the perception of corruption in local governments stands out: the National Survey of Regulatory Quality and Government Impact on Businesses (2016) in which it carries out a measurement in 42 strategic municipalities and delegations at the local level.

I Measuring the perception of corruption in Mexico at the federal and state levels

In a modern society like ours, citizens have the right, and increasingly demand, to be well-informed

and to have a greater degree of participation in the decisions that affect them. Transparency, and ultimately the right to know, is truly a fundamental right and one of the inherent values of a developed society that aspires to be genuinely democratic. Transparency is the best antidote to corruption, and it is urgent to combat the proliferation of various improper or irregular conduct that unfortunately continues to occur in numerous institutions. (Llaneras, 2016: 147-148). Democracy needs sufficient economic resources, but at the same time, this poses a serious threat to the very legitimacy of democratic regimes. (Lapuente, 2016: 87-88).²⁹

Within this framework of transparency of information to have more measurement tools, the National Survey on Corruption and Good Governance (ENCBG) conducted by Transparencia Mexicana for the first time in 2001, and subsequently in 2003 and 2005 during the government of Vicente Fox. The National Survey on Good Governance and Public Relations (ENCBG) served as a quantitative tool to measure the perception of corruption at the federal and state levels. The ENCBG was administered between 2007 and 2010 during the administration of Felipe Calderón, resulting in a historical series of five surveys. This allowed for the measurement of the perception of corruption during the period of political alternation, specifically during the administrations of Vicente Fox Quezada and others. (2000-2006) and Felipe Calderón Hinojosa (2006-2012), emanating from the National Action Party (PAN). However, the ENCBG's importance did not allow it to measure the perception of corruption at the local level.

National Corruption and Good Governance Index

The National Survey on Corruption and Good Governance (ENCBG) was conducted by Transparencia Mexicana, a section of Transparencia Internacional, in a historical sequence of five installments. Three were carried out during the administration of Vicente Fox (2001, 2003, and 2005) and two during the administration of Felipe Calderón (2007 and 2010). It should be noted that the measures that should have been applied during Enrique Peña Nieto's government are missing, so it will not be possible to know whether the perception of corruption decreased or increased during this period (Sánchez, 2017).

The methodology of the National Survey on Corruption and Good Governance and its National Corruption and Good Governance Index (INCBG) generally consisted of selecting the 35 most relevant public services and recording acts of corruption when the respondent reported paying a bribe in exchange for a public service. The summary of the five INCBG reports shows the following results:

²⁹ “When citizens perceive the stark power of money in politics, their trust in governments, politicians, and elections is undermined. If they observe that parties primarily represent the interests of large donors, they lose faith in the political

process. All analysts agree that citizens in democracies are increasingly distrustful of politics and politicians” (Lapuente, 2016: 89).

Table No. 1

INCBG Results 2001-2003-2005-2007-2010

Year	INCBG	Acts of corruption	Average cost	Total cost (million pesos)	% of income	% of income (Income 1 sm)
2001	10.5	214 millions	\$109.50	\$23,400	6.9%	13.9%
2003	8.5	101 millions	\$107.00	\$10,656	7%	29.5%
2005	10.1	115 millions	\$177.40	\$19,000	8%	24%
2007	10.0	197 millions	\$138.00	\$27,000	8%	18%
2010	10.3	200 millions	\$165.00	\$32,000	14%	33%

Source: Prepared by the author based on the ENCBG

The average INCBG in 2001 was 10.5 percent and reached 10.3 percent in 2010, showing a slight decrease. Only in 2003 did the INCBG drop to 8.5 percent, its lowest point; afterward, it tended to increase, as shown in Table 1. Regarding acts of corruption, there were 214 million in 2001 and 200 million in 2010, indicating a continued decline. In 2003, the number of acts of corruption fell to 101 million, before resuming its upward trend. (Sánchez, 2012: 481). This result could demonstrate the impact of the anti-corruption campaigns launched in the first part of Vicente Fox's administration until 2003, when they were widely disseminated in the media, and in the second stage of his government, they ceased to be visible in the media.

While the following indicators show an upward trend in the costs of corruption, the average cost of corruption rose from \$109.50 in 2001 to \$165.00 in 2010. The overall cost of corruption illustrates the magnitude of the problem: in 2003 it was \$23.4 billion pesos, and by 2010 it had climbed to \$32 billion pesos. Finally, the cost of corruption disproportionately affects the poorest segments of the population, who had to allocate 13.9 percent of their income to it in 2001, while by 2010 this figure had reached 33 percent (Sánchez, 2012: 485). The cost of corruption affects all sectors of the population, but in different ways and has diverse impacts, but in general, it has a higher cost for the most vulnerable sectors.

Corruption also impacts poverty and wealth distribution through its effects on various economic and governance variables. By reducing investment, productivity levels, and the rate of growth, corruption negatively affects income levels, but also, as various empirical studies indicate, it tends to worsen wealth distribution. Corruption increases poverty by creating incentives for investment in labor-intensive projects, which can deprive the poorest classes of the opportunity to generate income (Salinas y Salinas, 2017: 38).

II Measuring the perception of corruption in local governments in Mexico through the National Survey of Government Quality and Impact

The municipality is the front line of democracy. In most countries, it is the elected administrative body closest to the citizens. Furthermore, its job is to manage and resolve problems that are intimately connected to the daily lives of voters. This is probably why we often perceive what we see in our town halls as a setback or a reflection of politics as a whole (Jiménez, 2016: 61).

Measuring corruption at the municipal level is relevant to understanding citizens' perceptions of corrupt acts and the extent to which local governments take action to improve public services with the least possible corruption.

At the local level, municipalities in Mexico foster an environment conducive to corruption. Their weak institutions are staffed by poorly trained personnel and suffer from various operational deficiencies. For example, some offices lack basic computer services, and this is compounded by excessive regulations and insufficient oversight from accountability institutions and the general public. The result is a local environment rife with opportunities for corruption, as confirmed by perceptions: 76% of Mexicans believe that corrupt practices are frequent or very frequent at this level of government (Grandet y Reséndiz, 2015: 71).³⁰

In this regard, the National Survey on Government Quality and Impact (ENCIG), conducted by INEGI, measures corruption at the federal and state levels, while at the local level it only provides a percentage approximation compared to the former. This situation is verifiable in the ENCIG (2012), which includes these measurements at the local level, although the specific local governments analyzed are not identified. Therefore, we will now proceed with a description of its results.

The National Survey of Government Quality and Impact (2012)

Surveys have been a widely used tool for measuring perceptions, attitudes, and experiences of corruption. Particularly noteworthy are questions related to the level and trend of corruption (whether it will increase or decrease) or how corrupt a government or specific institutions are perceived to be. There is also considerable concern about how culturally acceptable corruption is, or how likely a public official is to solicit a bribe, as this depends on the political, economic, and social context. In other words, corruption surveys are a tool that allows us not only to measure the extent of the phenomenon but also to characterize it. In this sense, through a survey, it is possible to know the profile of the victims, the institutions most frequently associated with experiences of corruption, as well as the methods used and the amounts disbursed. (INEGI, 2016a: 20).

Regarding the Government Quality and Impact Survey (2012), specifically concerning the quality of public services by level of government, 67.2% rated the

³⁰. "Two of the factors behind these corruption cases are 1) the lack of interest in developing information systems on municipal management and 2) the lack of transparency in municipal procedures. (...) Generating information, firstly, im-

proves transparency and the potential for oversight of municipal management. Furthermore, computer systems lead to greater efficiency in public services by providing automated systems and create less room for discretion" (p. 72).

quality of state public services as “Good,” while 67.0% selected this option for municipal and borough public services, and 58.7% for federal public services. The rating given for the quality of public services at the federal

level is lower than that given at the municipal, borough, and state levels. The perceptions of “bad” and “very bad” services are very similar. See Table 2. (Sánchez, 2013: 29).

Table No. 2

Perception of the quality of public services by level of government

Quality of public services	Perception			
	Very good	Good	Bad	Very bad
Municipal or local delegations	3.5	67.0	25.0	4.3
State	1.9	67.2	25.5	3.3
Federal	3.4	58.7	29.9	5.4

Source: own elaboration based on (INEGI, 2012: 12).

Based on the National Survey on Government Integrity (ENCIG), it is estimated that nationally, 34.3% consider the prevalence of corruption in municipal or borough governments to be “Very Frequent”; in state government, the figure is 35.2%; and in federal government, it is 37.6%. Although the data are very similar,

the perception of corruption is most prevalent at the federal level, followed by state government, and then municipal or borough government. See Table 3 (Sánchez, 2013: 30).

Table No. 3

Degree of occurrence of corruption by level of government

Degree of occurrence	Perception			
	Very common	Frequent	Infrequent	Never
Municipal or borough government	34.3	48.1	13.9	1.1
State government	35.2	47.8	13.2	1.2
Federal government	37.6	43.9	13.5	1.5

Source: own elaboration based on (INEGI, 2012: 13).

If we combine the perception of corruption as “very frequent” and “frequent” at the local level, it reaches 82.4 percent, at the state level it is 83 percent, and at the federal level it reaches 81.5 percent, indicating that corruption is least prevalent at the federal level. Local corruption follows in second place, with the state level being the most susceptible to corruption.

34.3% considered that the degree of occurrence of these illicit practices is “Very frequent” in the municipalities and delegations; a similar percentage, 32.2% and 37.6%, respectively, opined the same with respect to the state and federal governments (INEGI, 2012: 3).

In summary, the ENCIG provides insight into the perception and occurrence of corruption in local governments compared to the state and federal levels, but it doesn't elaborate on the fact that corruption is more prevalent and frequent in local governments. The National Survey of Regulatory Quality and Government Impact on Businesses (ENCRIGE), for the first time, conducts a comparative study of 42 strategic municipalities and boroughs in Mexico, bringing us closer to understanding the extent of corruption in Mexican local governments.

III National Survey of Regulatory Quality and Government Impact on Businesses 2016

Corruption, initially of public origin (with the necessary collaboration of private individuals), has also taken root in the private sphere. It is no longer merely a pathological practice of certain public servants, but has manifested itself as a mechanism for generating illicit business and substantial private profits. However, despite undeniable parallels, there is a crucial difference: public corruption acts against the public interest,

weakening the legal and political system, while private corruption affects private interests (Lizcano, 2016: 107).

In this context, the National Survey of Regulatory Quality and Government Impact on Businesses (ENCRIGE) becomes relevant. It was first developed by the National Institute of Statistics and Geography (INEGI) in 2016, among other topics, to measure the perception and experiences of economic units in relation to acts of corruption when carrying out procedures, payments and requests for public services. (INEGI, 2017a: 1). This is a perception of business owners when dealing with state and local governments.

One of its objectives is to generate estimates on the number of acts of corruption that private sector economic units may have suffered when making payments, carrying out procedures, requesting public services and other types of contact with the authorities during 2016 (INEGI, 2017b: 1).

The ENCRIGE was developed in six sections. The first, regulatory framework; second, contract compliance; third, evaluation of basic public services and infrastructure; fourth, public infrastructure services; fifth, experiences with procedures, payments and service requests; and sixth, perception and experiences of corruption. This last section is the one we are interested in analyzing, because it describes: the perception; causes; prevalence rates and incidence rates of corruption; as well as experiences of corruption.

The perception of corruption in economic units regarding the frequency of acts of corruption carried out by public servants in 2016, by federal entity, is shown in table no. 4.

Table No. 4

Perception of economic units regarding the frequency of acts of corruption committed by public servants, by federal entity

State	Acts of corruption (%)	State	Acts of corruption (%)
NATIONAL	82.2		
Aguascalientes	69.3	Morelos	84.0
Baja California	74.2	Nayarit	62.3
Baja California Sur	75.9	Nuevo León	86.7
Campeche	71.5	Oaxaca	83.6
Coahuila	80.2	Puebla	74.0
Colima	62.2	Querétaro	71.1
Chiapas	88.5	Quintana Roo	80.5
Chihuahua	84.0	San Luis Potosí	72.2
Ciudad de México	91.5	Sinaloa	85.3
Durango	75.9	Sonora	86.5
Guanajuato	77.7	Tabasco	92.7
Guerrero	71.6	Tamaulipas	81.2
Hidalgo	77.2	Tlaxcala	84.0
Jalisco	88.6	Veracruz	84.0
Estado de México	85.4	Yucatán	72.9
Michoacán	72.0	Zacatecas	87.8

Source: (INEGI, National Survey of Government Quality and Impact on Businesses 2016 (ENCRIGE) 2017b).

The average frequency of corrupt acts committed by public servants nationwide was 82.2%, meaning that entities above this average are considered more corrupt. Tabasco has an average of 92.7%, followed by Mexico City with 91.5%, and Zacatecas with 87.8%. While Colima has fewer records of acts of corruption, with 62.2 percent, it is the entity with the lowest frequency of acts of corruption.

Another set of data that is useful in demonstrating the ineffectiveness of anti-corruption institutions concerns governors. Between 2000 and 2013, a period in which Mexico had 63 governors, the press reported 71 cases of corruption involving 41 governors. Of these,

only 16 cases were investigated, and only five governors were prosecuted and found guilty. In contrast, in the United States, nine governors were investigated, nine were prosecuted, and all nine were arrested (Casar, 2016: 10).

The next section addresses the causes of corruption. The ENCRIGE results show that 64.6% of academic units believe that acts of corruption occur to expedite procedures. On the other hand, 39.4% indicate that these acts are generated to avoid fines or penalties (INEGI, 2017b: 2). Furthermore, for 30.7 percent, obtaining licenses or permits and 29.7 percent, avoiding the closure of the establishment, are also corrupt practices, as shown in Table No. 5.

Table No. 5

Perception of academic units regarding the causes of corruption

Causes of corruption	Percentage
Streamline procedures	64.6
Avoid fines or penalties	39.4
Obtain licenses or permits	30.7
Avoid business closure	29.7
Pay less in taxes	29.3
Avoid inspections	25
Obtain services	22.2
Avoid legal compliance	18.3
Win government contracts	13.9
Participate in bidding processes	12.9

Source: (INEGI, National Survey of Government Quality and Impact on Businesses 2016 (ENCRIGE) 2017a).

For other types of illegal acts such as obtaining licenses, avoiding the closure of their establishment, paying less taxes and avoiding inspections, Tlaxcala, Quintana Roo and Morelos were the entities that registered the most cases. Within the experiences of corruption, the ENCRIGE (2016) quantifies data on federal,

state, and municipal public services. The following table lists only the procedures involving municipal authorities, illustrating the experiences of economic units with these types of services, as follows:

Table No. 6

Experience with at least one act of corruption per 10,000 Economic units during 2016 by type of procedure (municipal level)

Causes of corruption	Percentage
Contact with Public Safety Authorities	2,753
Licenses or permits for special business activities	1,245
Land use license or permit	986
Construction permit	881
Registration in bidding processes	714
Water and drainage feasibility studies	703
Opening a business	627
Connection to the local water system	522
Registration in the government supplier registry	181
Regular water bill payment	152

Source: (INEGI, National Survey of Government Quality and Impact on Companies 2016 (ENCRIGE) 2017.

The main procedures in which business owners faced acts of corruption were contact with public security authorities (municipal and state), the initiation or follow-up of preliminary investigations or investigation files and labor or commercial judicial processes (with state and federal authorities) (Animal Político, 2017: 2). Also at the municipal level, licenses or permits for

special business activities (1,245), in land use licenses or permits (986) and in construction permits (881).

The rate of economic units that were victims of corruption. At the national level, the prevalence rate of corruption is 561 out of every 10,000 economic units that carried out procedures during 2016, which experienced at least one act of corruption, as shown in Table No. 7.

Table No. 7

Economic units victimized by acts of corruption during 2016 by federal entity

Federal entity	Victims of corruption per 10,000 economic units in 2016	Federal entity	Victims of corruption per 10,000 economic units in 2016
NATIONAL	561		
Aguascalientes	858	Morelos	1,835
Baja California	787	Nayarit	1,504
Baja California Sur	944	Nuevo León	579
Campeche	814	Oaxaca	1,263
Coahuila	801	Puebla	1,551
Colima	1,094	Querétaro	552
Chiapas	1,123	Quintana Roo	2,077
Chihuahua	1,019	San Luis Potosí	819
Ciudad de México	1,504	Sinaloa	801
Durango	621	Sonora	1,252
Guanajuato	860	Tabasco	1,325
Guerrero	1,452	Tamaulipas	690
Hidalgo	693	Tlaxcala	2,019
Jalisco	764	Veracruz	1,050
Estado de México	1,663	Yucatán	859
Michoacán	990	Zacatecas	984

Source: (INEGI, National Survey of Government Quality and Impact on Businesses 2016 (ENCRIGE) 2017a.

In Quintana Roo, 2,077 out of 10,000 companies were victims of corruption; in Tlaxcala, 2,019; and in Morelos, 1,835. The states with the lowest levels of corruption were Querétaro and Nuevo León, with 552 and 579 companies, respectively, victims of corruption out of 10,000 companies (Animal Político, 2017: 2).

Therefore, it is not surprising that the governors are denouncing their predecessors, and at least five of them are under scrutiny (Veracruz, Sonora, Chihuahua,

Quintana Roo, and Oaxaca). It remains to be seen whether the illegal debt incurred by their states and the embezzlement they allegedly committed will be proven and punished (Casar, 2016: 10).

The incidence rate of acts of corruption, which implies acts of corruption when carrying out procedures or inspections per 10,000 economic units during 2016, is 3,055 on average at the national level, as shown in Table No. 8:

Table No. 8

Acts of corruption during procedures or inspections per 10,000 economic units during 2016

Federal entity	Acts of corruption per 10,000 economic units in 2016	Federal entity	Acts of corruption per 10,000 economic units in 2016
NATIONAL	3,055		
Aguascalientes	23,728	Morelos	19,549
Baja California	9,083	Nayarit	22,758
Baja California Sur	8,657	Nuevo León	15,601
Campeche	8,663	Oaxaca	14,217
Coahuila	9,136	Puebla	19,389
Colima	12,345	Querétaro	15,292
Chiapas	17,560	Quintana Roo	25,963
Chihuahua	15,090	San Luis Potosí	14,838
Ciudad de México	15,771	Sinaloa	6,668
Durango	5,558	Sonora	24,062
Guanajuato	13,002	Tabasco	15,169
Guerrero	34,236	Tamaulipas	6,627
Hidalgo	7,215	Tlaxcala	30,554
Jalisco	13,718	Veracruz	17,364
Estado de México	57,909	Yucatán	6,070
Michoacán	12,855	Zacatecas	15,148

Source: (INEGI, National Survey of Government Quality and Impact on Companies 2016 (ENCRIGE) 2017.

According to the ENCRIGE survey results, the State of Mexico, Guerrero, and Tlaxcala had the highest rates of corruption during administrative procedures and inspections. In the State of Mexico, 57,909 illicit acts were recorded for every 10,000 businesses, while in Guerrero the figure was 34,236 and in Tlaxcala 30,554 (Animal Político, 2017: 2).

The 2016 National Survey on Corruption and Integrity (ENCRIGE) allows, for the first time, the meas-

urement of perceived corruption in 42 strategic municipalities and boroughs in Mexico. Table 9 shows the relative data on the perceived frequency of corrupt acts, categorized as “very frequent” and “frequent,” as these are the only ones that allow for measuring the frequency of corruption. The “infrequent” variable is not included in the total for demonstrative purposes. The results are as follows:

Table No. 9

Economic units by municipality of interest, according to perceived frequency of acts of corruption, October to December 2016

Municipalities of interest	Perception		
	Very common	Frequent	Total
Estados Unidos Mexicanos	45.5	36.7	82.2
Aguascalientes, Aguascalientes	31.9	38.0	69.9
Mexicali, BC	48.8	20.8	69
Tijuana, BC	37.1	47.1	84.2
Saltillo, Coahuila	36.8	37.3	74.1
Torreón, Coahuila	44.7	41.9	86.6
Tapachula, Chiapas	47.1	45.6	92.7
Tuxtla Gutiérrez, Chiapas	38.7	35.4	74.1
Chihuahua, Chihuahua	52.2	38.4	90.6
Juárez, Chihuahua	46.1	36.3	82.4
Azcapotzalco, CDMX	50.6	40.7	91.3
Álvaro Obregón, CDMX	48.9	48.4	97.3
Benito Juárez, CDMX	65.4	24.8	90.2
Coyoacán, CDMX	61.8	14.6	76.4
Cuauhtémoc, CDMX	48.4	44.4	92.2
Gustavo A. Madero	55.5	36.1	91.6
Iztapalapa, CDMX	38.2	56.5	94.7
Miguel Hidalgo, CDMX	55.9	34.8	90.7
Tlalpan, CDMX	78.1	16.5	94.6
Venustiano Carranza, CDMX	71.7	28.1	99.8

León, Guanajuato	33.7	42.7	76.4
Acapulco, Guerrero	61.4	17.7	79.1
Guadalajara, Jalisco	67.0	22.8	89.8
Zapopan, Jalisco	58.5	35.2	93.7
Nezahualcóyotl, Edo. México	52.8	34.9	87.7
Ecatepec, Edo. México	65.0	26.0	91
Naucalpan, Edo. México	48.7	37.3	86
Tlalnepantla, Edo. México	47.5	23.0	70.5
Toluca, Edo. México	64.7	28.5	93.2
Lázaro Cárdenas, Michoacán	19.9	43.1	63
Morelia, Michoacán	58.6	25.5	84.1
Monterrey, Nuevo León	60.5	31.9	92.4
Salinas Cruz, Oaxaca	51.2	37.9	89.1
Puebla, Puebla	40.5	34.3	74.8
Querétaro, Querétaro	20.9	48.1	69
San Luis Potosí, SLP	37.7	32.6	70.3
Culiacán, Sinaloa	36.4	54.9	91.3
Hermosillo, Sonora	50.8	37.3	88.1
Centro, Tabasco	68.7	23.1	91.8
Reynosa, Tamaulipas	57.2	39.5	96.7
Coatzacoalcos, Veracruz	52.0	47.8	99.8
Veracruz, Veracruz	63.9	28.2	92.1
Mérida, Yucatán	32.4	46.8	79.2

Source: own elaboration based on INEGI, National Survey of Quality and Governmental Impact on Companies 2016 (ENCRIGE) 2017a, Table 6.23.

99.8% of companies located in the Venustiano Carranza delegation have a perception that acts of corruption occur frequently, making this locality, like Coatzacoalcos in Veracruz, the highest in all of Mexico according to the ENCRIGE. In second place nationally is the Álvaro Obregón borough with 97.3 percent of economic units; Reynosa, Tamaulipas in third place

with 96.7 percent; Iztapalapa in Mexico City with 94.7 percent; Tlalpan with 94.6 percent and Cuauhtémoc with 92.8 percent (Valdemar, 2017: 1). In total, five boroughs of Mexico City are among the 10 municipalities in the country with the highest perceived levels of corruption. See Table No. 10.

Table No. 10

Selection of economic units by municipalities of interest, according to perceived frequency of acts of corruption, October to December 2016

Municipalities of interest	Perception		
	Very common	Frequent	Total
Estados Unidos Mexicanos	45.5	36.7	82.2
Most corrupt municipalities			
Venustiano Carranza, CDMX	71.7	28.1	99.8
Coatzacoalcos, Veracruz	52.0	47.8	99.8
Álvaro Obregón, CDMX	48.9	48.4	97.3
Reynosa, Tamaulipas	57.2	39.5	96.7
Iztapalapa, CDMX	38.2	56.5	94.7
Tlalpan, CDMX	78.1	16.5	94.6
Cuauhtémoc, CDMX	48.4	44.4	92.2
Less corrupt municipalities			
Querétaro, Querétaro	20.9	48.1	69
Mexicali, BC	48.8	20.8	69
Lázaro Cárdenas, Michoacán	19.9	43.1	63

Source: own elaboration based on INEGI, National Survey of Quality and Governmental Impact on Companies 2016 (ENCRIGE) 2017a, Table 6.23.

Conversely, Lázaro Cárdenas in Michoacán is among the municipalities where the perception of frequent acts of corruption is infrequent, with 63 percent of businesses reporting such activity. It is followed by Querétaro with 69 percent and Mexicali with 69.6 percent. However, some consider this to be far below the national average of 45.5 percent.

In summary, Mexican companies estimate that they lost 1.6 billion pesos during 2016 due to acts of corruption, while 82.2% consider that such acts are frequent on the part of federal, state and local public servants. The monetary costs of regulatory compliance in 2016 were estimated at 115.7 billion pesos, represent-

ing 0.56% of the national GDP. Meanwhile, the average cost of corruption per company in 2016 was estimated at 12,243 pesos (Animal Político, 2017: 2)

IV Contributions of the ENCRIGE to the measurement of corruption in Mexican local governments

Local governance dominated by a single party, or a political team where loyalties are owed to the top represented by the figure of the mayor, the absence of effective checks and balances and the lack of separation of incentives between elected officials and technicians provide the fundamental framework of reference for why corruption could take place. It places the actors on the scene, including the private entities responsible for putting money on (or under) the table, and sets them in motion, defining where their interests lay. The fact that the local territorial structure was small and fragmented helped to conceal local problems. And the lack of clarity and effectively defined accountability in the distribution of money reinforced the desire of those already predisposed to corruption (Jiménez, 2016: 85).

The 2016 ENCRIGE is the first national survey prepared by a government entity that measures the perception of corruption at the level of local governments, although it is a small sample and from the perspective of economic units such as companies of various sizes (micro, small, medium and large).

The 2016 National Survey on Corruption and Integrity (ENCRIGE) measures the perception of corruption by assessing: perception of corruption; causes of corruption; rate of economic units victimized by corruption; incidence rate of corrupt acts; and experiences of corruption. The results of these assessments make it possible to determine the extent of corruption at the state and local levels in the country.

Nationally, the average perception of corruption is 82.2 percent, which is high considering that some states are above 90 percent: Tabasco (92.7%); Veracruz (92.1%); and Mexico City (91.5%). Other states are in the over 80 percent range: Jalisco (88.6%); Chiapas (88.5%); Zacatecas (87.8%); Nuevo León (86.7%); Sonora (86.5%); State of Mexico (85.4%); Sinaloa (85.3%); and Morelos (84.0%). These quantitative data could confirm that corruption in the states is steadily increasing; it has not been contained, nor has it been effectively and directly combated. Furthermore, it is not controlled by the governors themselves, since they are the beneficiaries of many of these illicit acts, and the list of former governors being prosecuted in 2017 demonstrates that administrative corruption has become decentralized to state governments.

The rate of corruption victims is 561 per 10,000 economic units nationwide. However, when broken down by state, the results are excessively high: Quintana Roo, with 2,077 cases, and Tlaxcala, with 2,019 cases, have more than three times the national average. Likewise, there are more than 12 federal entities that exceed 1,000 acts of corruption: Morelos (1,835); State of Mexico (1,663); Puebla (1,551); Nayarit (1,504); Guerrero (1,452); Tabasco (1,325); Oaxaca (1,263); Sonora (1,252); Chiapas (1,123); Colima (1,094); and Chihuahua (1,019). This reinforces the previous state-

ment: corruption in the federal entities is high, uncontrolled, and spreading in public services and administrative procedures, and since there is no effective sanction, corruption continues to grow.

Regarding the perception of the causes of corruption, in the two most common procedures – expediting procedures (64.6%) and avoiding fines and penalties (39.4%) – these are procedures where the level of discretion of public servants to provide a service or avoid fines implies that the public servant can condition, request a bribe or deliberately delay a procedure to request a reward.

These services and procedures need to be modernized, for example, through the use of e-government and ICTs, so that public servants can minimize the conditions placed on service, which would certainly reduce corruption. Another measure would be to improve the control and oversight systems of internal control bodies for these services and procedures, enabling them to sanction public servants caught accepting bribes or extorting citizens.

At the local level, the 2016 ENCRIGE survey on corruption experiences by type of procedure yielded relevant data. The main procedure involving acts of corruption was contact with public security authorities (2,753), followed by licenses or permits for special business activities (1,245), land use licenses or permits (986), and construction permits (881). As can be inferred, the high discretion, the lack of application of ICTs to provide some of these procedures and services, as well as the way of entering the public service – in most cases the public servant does not have the required professional profile – the spoils system as a form of organization at the local level, prevent the professionalization and consolidation of a merit system. For some municipal public servants, bribery and extortion are additional income to their limited salaries, but, above all, they consider these behaviors to be "socially accepted" even though they are not legal.

Within the selection of the 42 strategic municipalities and districts, some assumptions regarding the perception of corruption at the local level can be drawn and tested. First, there are local governments, such as Coatzacoalcos in Veracruz, which is considered the most corrupt local government in the country at 98.8 percent. Reynosa, Tamaulipas, follows closely behind with 96.7, as municipal governments with a very high perception of corruption and violence. What have these local governments done to reduce their perception of corruption? Will they do anything, or are they indifferent to what people think of their administration?

Second, five boroughs of Mexico City are among the 10 municipalities in the country with the highest perceived levels of corruption, a situation that was suspected but had not been quantified. 99.8% of businesses located in the Venustiano Carranza borough perceive that acts of corruption occur frequently. Next is the Álvaro Obregón delegation with 97.3% of economic units; Iztapalapa with 94.7%; Tlalpan with 94.6%; and Cuauhtémoc with 92.8%. These figures have significant implications for the delegations of Mexico City that will become boroughs in 2018. Beyond the politi-

cal reform that gave them institutional life, these boroughs urgently require local administrative reform to improve the preparation, experience, professionalization, and training of public servants in these districts. A local civil service in the future mayoral offices of Mexico City would be a good start to removing public administration from the control of the political parties that govern those local entities; otherwise, these perceptions of corruption will not change over time. The recommendations for the next edition of the ENCRIGE would be twofold. First, expand the number of local governments selected in each state, to at least two or three in each state, to measure the perception of corruption in these local entities. For example, there are states where only one municipal government was measured: Aguascalientes, Guanajuato, Guerrero, Nuevo León, Oaxaca, Puebla, Querétaro, San Luis Potosí, Sinaloa, Sonora, Tabasco, Tamaulipas, and Yucatán. Expanding the number of municipal governments included will provide a broader perspective on the perception of corruption.

Secondly, the survey should cover all of Mexico City's boroughs. In 2016, only 10 were surveyed, so covering all of the capital's local governments would allow for the identification of the most and least corrupt services, as well as the boroughs with the highest perceived levels of corruption. This is all in light of the creation of the new boroughs, which will have a broader organizational structure and will be required to adopt measures to offer better public services and procedures to citizens, free from bribery and extortion.

There is broad consensus on the economic and social costs of corruption. Among the economic costs, theoretical and empirical literature tends to highlight the negative effects of corruption on income levels and economic growth rates. Corruption also introduces distortions into both the incentives of private actors and the functioning of the public sector, leading to socially inefficient allocations and greater inequality in terms of opportunities and the distribution of income and wealth. These costs, in terms of both efficiency and equity, underscore the need to design effective strategies to combat corruption. (Salinas y Salinas, 2017: 40).

The menu of solutions to combat local corruption is varied (Jiménez, 2016: 85). First, separate political and technical interests, and with them the careers of both, their incentives, and their future. Second, establish a series of checks and balances against the all-powerful tendency of local executive branches, but always keeping in mind the inherently conflictive nature of the decisions they must make, in order to avoid falling into the technocratic fallacy of "more democratic," without pausing to define the word. Third, to favor ideologically based coalition governments (as opposed to patronage-based ones) in the representative bodies of local corporations, so that parties hold each other accountable and are not solely dependent on control within local administrations. And finally, to move towards a local financing system where politicians are more responsible for their actions and transfers between territories serve not only to ensure survival, but truly to put everyone more or less on the same level of development.

Conclusions

The measurement of perceived corruption at the federal, state, and local levels of government in Mexico has increased with a greater number and quality of surveys and indicators prepared for the various levels of government, some developed by Civil Society Organizations – such as the National Survey on Corruption and Good Governance (ENCBG) conducted by Transparencia Mexicana – and others developed by INEGI – such as the National Survey on Government Quality and Impact (2012, 2014 y 2016) and the National Survey of Regulatory Quality and Government Impact on Companies (ENCRIGE) 2016 - which are quantitative measurement instruments that allow measuring the quality of public services and procedures, such as the level of perceived corruption.

The results of the ENCRIGE should serve as a starting point for Mexican local governments to promote actions to contain and punish administrative corruption in public services and procedures, professionalize the local public service with better public servants, introduce electronic government into procedures to avoid the discretion of the public servant towards the citizen and dignify the public service with effective actions so that the public administration conducts itself within the framework of the law without breaking it.

The monstrous scale of corruption at the local level in Mexico has several aspects to consider. First, there are public services that, due to the enormous discretionary power of public officials, are designed to facilitate bribery of citizens. Second, more modern and technologically advanced public services that utilize ICT tools clearly prevent any form of bribery, corruption, and corruption. Third, transparency and accountability in local governments should foster greater citizen involvement in demanding ethical and honest public servants. Fourth, it is urgent that the National Anti-Corruption System fully function at all three levels of government, but especially at the local level, to prevent and punish local public servants who violate the legal framework and to restore confidence in local governments.

These are the challenges facing Mexican local governments: improving the quality of public services, professionalizing public servants, and investing in physical and technological infrastructure to enhance e-government processes and public services. Expanding citizen participation, collaboration, transparency, and accountability are also crucial to fostering the conditions for open government that combats the worst practices of bribery and extortion by local public officials.

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TECHNICAL SCIENCES

SPECIFIC RELIABILITY INDICATORS OF CONSTRUCTION MECHANIZATION USED IN THE CONSTRUCTION OF MAIN (TRANSMISSION) PIPELINES - TYPES, DEFINITION AND ANALYSIS

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Abstract

The publication defines specific reliability indicators for construction machinery used in the construction of main pipelines for the transmission of natural gas, oil and petroleum products, and other fluids that require long-distance transportation, and the methods for their determination. Typical parameters characterizing the main reliability indicators of construction machines related to the construction of main pipelines have been derived.. The presented dependencies allow for effective and accurate calculation of the specific reliability indicators of construction machines that are planned to be used in the construction process. As a result of the data obtained, it is possible to perform a correct analysis to select the most suitable construction machines and thus achieve a high degree of effective use of construction mechanization in the construction of main pipelines.

Keywords: construction machinery; construction of main pipelines; reliability of construction machines for the construction of pipelines for natural gas, oil and petroleum products; ways to calculate the failure-free resource when using construction machinery; specific reliability indicators for the operation of construction machinery used in the construction of main pipelines

1. Introduction

To achieve full and effective use of construction machinery involved in the construction of pipelines for the transportation of natural gas, petroleum products and other liquid and gaseous fluids, it is necessary that they be properly selected and rationally used. In this way, it is possible to achieve increased efficiency and optimization of the overall construction process. The study of various indicators and behavior of construction machines during their active participation in the construction process is of particular importance for clarifying areas for improvement and increasing their reliability during operation.

The main objectives for increasing the reliability of construction machinery are related to increasing the quality indicators and increasing the rate of use, while increasing productivity and reducing the costs for this. Quality indicators are a set of parameters that determine the properties characterizing the capabilities of construction machinery used in the construction of main pipelines to satisfy the requirements placed on them in accordance with their specific purpose and specialization.

Increasing the reliability of construction machinery guarantees a reduction in repair time and an increase in the intervals between repairs, as well as a reduction in the cost of labor and spare parts during maintenance and scheduled repairs.

When determining the reliability of construction machinery, it is possible to use several methods: a method of theoretical data analysis; a method of data practical research, obtained from testing, both in laboratory conditions and in conditions of effective operation; a method of differential comparison at a minimum level, or by determining a generalized reliability indicator that characterizes several

qualitative properties of a given construction machinery.

In a differentiated (single) assessment of the reliability of construction machines used in the construction of main pipelines, the most characteristic indicators are identified, by comparing and analyzing the results obtained during real operation and the values determined to be achieved, as a result of this assessment, real conclusions can be drawn about the reliability of the relevant construction machine and measures can be taken to increase , if it is found that this is necessary.

2. Determination of generalized specific reliability indicators

To achieve a sufficiently accurate and effective result when assessing the reliability of construction machinery used during the construction of main (transmission) pipelines, several parameters are used, which can be defined as follows: readiness, operational readiness and technical usability.

2.1 Determining readiness (G_r)

Readiness is determined statistically by accumulating sufficiently specific measured data, which can be summarized with sufficiently correctly aggregated values, and then applied to the corresponding formulated relationship. Readiness is the ratio of the total time during which the monitored objects (construction machines) are in working condition to the product of the number of these objects and the duration of their operation, excluding downtime for scheduled repairs and maintenance.

$$G_r = \frac{\sum_{i=1}^N T_i}{N \cdot T_{\text{paб}}} \quad (1)$$

- T_i - the total time the object was in working condition

- $i = 1, 2, \dots, N$

In cases where maintenance is required, which involves immediate action to restore a damaged object, readiness is calculated using the formula:

$$G_r = \frac{T_o}{T_o + T_e} \quad (2)$$

- T_o - average time between failures

- T_e - average time to restore the machine to working condition

Readiness G_r Readiness can also be determined by the average service life (resource) $T_{cp.p}$. This indicator represents the total time of normal operation of the construction machine until the start of the first major repair. For convenience of calculation, this time should be measured in hours (h).

$$G_r = \frac{T_{cp.p}}{T_{cp.p} + T'_e} \quad (3)$$

- T'_e - total time to restore the working capacity of the construction machine after the failure occurred (h)

The time T'_e can also be determined from the period between scheduled repairs to the start time of the first major repair and should be reported in hours (h).

If the recovery time for the entire period of operation of the machine before the first major overhaul is unknown and cannot be determined, then the capabilities of calculating readiness can be used (G_r) and the values of unplanned repairs R_{np} and scheduled repairs R_{np} .

The time for calculating unplanned repairs can be determined as follows:

$$R_{np} = \frac{T_e}{T_{nn} + T_{op}} \quad (4)$$

- T_{nn} - the total time for performing preventive maintenance until the start of the major repair (h)

- T_{op} - time to carry out major repair (h)

When calculating the time required to carry out scheduled repairs, the following dependence can be used (5):

$$R_{np} = \frac{T_{nn} + T_{op}}{T_{np}} \quad (5)$$

- T_{np} - time of normal operation of the machine until the start of a major repair

To fully perform the calculation, it is also necessary to determine the value of the parameter **usability** of the construction machine (T_{u3n}). This parameter characterizes the time for effective operation of the machine, during which it is able to maintain all safety and reliability indicators, while achieving the set operating mode. Using the parameters R_{np} and R_{np} and if the usability value of the construction machine (T_{u3n}) is determined, we can write the following dependence:

$$G_r = \frac{T_{u3n}}{T_{u3n} + R_{np} + R_{np}} \quad (6)$$

2.2. Determining operational readiness (G_{or})

Operational readiness G_{or} determines the need for immediate use of the construction machine, but after the start of this use it must be able to maintain its normal operating capacity throughout the entire period of time t_{op} without failures occurring. To fulfill this condition, it is important that the construction machine is in working condition at the time when the need for use is appear.

The probability of failure-free operation of the construction machine $P(t_{op})$ for a period of time t_{op} does not depend on the moment of commencement of operation t . As a result, operational readiness can be calculated as follows:

$$G_{OR} = G_r + P(t_{op}) \quad (7)$$

2.3 Determining technical usability (G_{TH})

Technical usability is the time during which the construction machine is in a state of normal working capacity. It can be determined by the ratio of the total time during which the construction machine is in working condition to the product of the total number of construction machines designated for operation (N) and the designated time for normal operation (T_{he}).

$$G_{TH} = \frac{\sum_{i=1}^N T_i}{NT_{he}} \quad (8)$$

- T_{he} - normal operating time, consisting of the periods of time for operation, maintenance and repair

At different values of T_{he} , according to formula (9) the value of technical usability for each construction machine can be determined.

$$G_{TH} = \frac{T_t}{T_t + T_p + T_o} \quad (10)$$

- T_t - total operating time of all construction machines

- T_p - total downtime due to planned and unplanned repairs on all machines

- T_o - total downtime due to scheduled and unscheduled maintenance of all construction machinery

It is important to note that this formula does not include downtime due to organizational reasons. This is because these reasons are not purely technical in nature and may not be taken into account when analyzing the reliability of the construction machine..

From the formulas for calculating the readiness G_r and, if we determine the average resource T_{cp} , of the construction machine, we can calculate the technical usability G_{TH} according to the following dependence

$$G_{TH} = \frac{T_{cp}}{T_{cp} + T_e + T_{nn} + T_p} \quad (11)$$

Formula (11) could also be written in the form

$$T_{nn} + T_{op} = T_{cp} - \frac{G_{\Gamma} - G_{TH}}{G_{\Gamma} \cdot G_{TH}} \quad (12)$$

To determine the average recovery time for all failures that occurred in the period between maintenance and scheduled repairs, but up to the time of starting a major repair, the following dependence can be used:

$$T_{\epsilon} = \frac{T_{cp}(1 - G_{\Gamma})}{G_{\Gamma}} \quad (13)$$

$$T_{\epsilon} + T_{nn} + T_{op} = \frac{T_{cp}(1 - G_{TH})}{G_{TH}} \quad (14)$$

$$T_{nn} + T_{op} = T_{cp} - \frac{G_{\Gamma} - G_{TH}}{G_{\Gamma} \cdot G_{TH}} \quad (15)$$

The above formulas (13), (14) and (15) provide sufficient accuracy and clarity when necessary to calculate the duration of all types of technical maintenance and repairs. This option guarantees a good level of planning for the construction machines that would be involved in the implementation of the construction process for the construction of main pipelines while ensuring compliance with a high level of reliability.

3. Conclusion

The level of reliability of a construction machine is determined by its design, technical and technological characteristics, as well as by its method of operation.

The level of high technological capability of the construction machine and its construction is determined by the ratio of the indicators achieved during its production related to the values of the technical

specifications and indicators previously determined at the design level. These indicators may include the use of typical technological processes for production, various forms of current maintenance, repairs, the use of standard and unified parts of various assembly units, assemblies and aggregates and their interchangeability, the need for spare parts, materials used, accessibility to the elements of the machine's construction when troubleshooting and during its maintenance and repair, labor intensity during operation and repair, the cost of its productivity, etc..

The level of technological efficiency in the operation process is characterized by its adaptability to working conditions, operational indicators, general or related to a unit of time or unit of production.

With the formulas and dependencies shown in this article, the specific generalized reliability indicators of construction machines used in the construction process of main (transmission) pipelines can be determined with a high degree of accuracy and correctness. This provides new opportunities for optimizing planning and determining the exact type and number of necessary construction machines and creates a basis for further, more effective research into these processes.

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MATHEMATICAL MODELING OF THE USER'S DECISION-MAKING PROCESS UNDER THE INFLUENCE OF SOCIAL ENGINEERING METHODS**Marinov A.***PhD in Economic Sciences, associate Professor at the Cybersecurity Competence Center, Irkutsk National Research Technical University, Irkutsk, Russia***Larionova L.***PhD in Pedagogical Sciences, associate Professor at the Cybersecurity Competence Center, Irkutsk National Research Technical University, Irkutsk, Russia***МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА ПРИНЯТИЯ РЕШЕНИЙ ПОЛЬЗОВАТЕЛЕМ В УСЛОВИЯХ ВОЗДЕЙСТВИЯ МЕТОДОВ СОЦИАЛЬНОЙ ИНЖЕНЕРИИ****Маринов А.А.***кандидат экономических наук, доцент центра компетенций по кибербезопасности, ФГБОУ ВО «Иркутский национальный исследовательский технический университет», г. Иркутск, Россия.***Ларионова Л.А.***кандидат педагогических наук, доцент центра компетенций по кибербезопасности, ФГБОУ ВО «Иркутский национальный исследовательский технический университет», г. Иркутск, Россия.*<https://doi.org/10.5281/zenodo.21649102>**Abstract**

In this article, we present a mathematical modeling approach to examining user decisionmaking processes under attack by social engineering.

The relevance of this study stems from the increasing number of attacks on individuals and the increasing sophistication of these attacks, which rely on psychological and behavioral influence. Fraudsters exploit trust, urgency, authority, curiosity, greed, and cognitive overload to induce users to make erroneous decisions. We propose a probabilistic model that formalizes the relationship between these influence parameters and the likelihood of making a dangerous decision. Key variables include the level of trust in the message source, perceived urgency, cognitive load, user experience, ability to recognize risk signs, and the intensity of the manipulative influence. The results demonstrate that the use of mathematical modeling enables quantitative assessment of user vulnerability, refinement of preventative training, and improvement of the effectiveness of organizational security measures.

Аннотация

В статье мы представляем рассмотрение процесса принятия пользователем решений в ситуациях воздействия на него злоумышленниками с использованием методов социальной инженерии с помощью математического моделирования.

Актуальность исследования обусловлена тем, что постоянно увеличивается не только количество атак на человека со стороны злоумышленников, но и растет их изощренность, основанная на психологическом и поведенческом воздействии, при которых мошенники используют доверие, срочность, авторитет, любопытство, жадность и когнитивную перегрузку для побуждения пользователя к ошибочному принятию решений. Мы предлагаем вероятностную модель, позволяющую формализовать зависимость между параметрами воздействия и вероятностью принятия опасного решения. В качестве ключевых переменных нами рассматривается уровень доверия к источнику сообщения, степень воспринимаемой срочности, когнитивная нагрузка, опыт пользователя, способность распознавать признаки риска и интенсивность манипулятивного воздействия. Полученные результаты показывают, что использование математического аппарата дает возможность количественно оценивать уязвимость пользователя, уточнять направления профилактического обучения и повышать эффективность организационных мер защиты.

Keywords: social engineering; information security; decision-making; mathematical modeling; probabilistic model; behavioral risks; user vulnerability.

Ключевые слова: социальная инженерия; информационная безопасность; принятие решений; математическое моделирование; вероятностная модель; поведенческие риски; уязвимость пользователя.

Введение

Методы социальной инженерии в современном обществе используются часто, так как позволяют эффективно несанкционированно воздействовать на пользователей в цифровом пространстве. Их особенность состоит в том, что атака направлена не на техническую защиту, которая постоянно совершенствуется, а на когнитивную, эмоциональную и поведенческую сферу человека, используя

его уязвимости. Делая ставку именно на человеческий фактор, злоумышленник пытается обойти систему обеспечения информационной безопасности, и получает доступ через пользователя к конфиденциальным сведениям, учетным данным и внутренним ресурсам организации.

Актуальность исследования определяется тем, что атаки социальной инженерии строятся на мани-

пулятивных процессах воздействия на пользователя, побуждая его к принятию ошибочных решений. В условиях информационного давления, дефицита времени и перегрузки внимания пользователь может принять решение, не соответствующее требованиям безопасности. Следовательно, исследование механизмов и закономерностей таких процессов требует не только качественного описания, но и формализации в математической форме. Вероятностный подход в данном случае является наиболее оправданным, поскольку отражает неоднозначность человеческого поведения и зависимость результата от совокупности внешних и внутренних факторов [1].

Целью настоящей статьи является разработка математической модели процесса принятия решений пользователем в условиях воздействия методов социальной инженерии. Для достижения указанной цели были выдвинуты задачи:

1. Проанализировать основные механизмы социальной инженерии;
2. Определить значимые параметры поведения пользователя;
3. Формализовать зависимость между воздействующими факторами и вероятностью ошибочного решения; рассматриваются
4. Описать возможности практического применения модели в задачах информационной безопасности.

Объектом исследования является процесс принятия решений пользователем в условиях информационно-психологического воздействия.

Предметом исследования выступают математические зависимости, описывающие влияние методов социальной инженерии на вероятность совершения небезопасного действия.

Методологическую основу составляют методы математического моделирования, логистической регрессии, вероятностного анализа и системного подхода к исследованию поведенческих рисков.

Теоретические основы

Социальная инженерия – совокупность методов воздействия на человека через его психологические особенности. Схемы злоумышленников основываются на таких факторах, как использование авторитета, создание условий цейтнота, эксплуатация чувства страха, построение резонансных отношений, создание дефицита информации и оказание директивного социального давления. Такие приёмы манипулятивного воздействия ориентированы на снижение критичности мышления, затруднение конструктивной оценки и тем самым, искусственное ускорение процесса принятия решения. Это со-

здаёт условия, при которых пользователь может совершить действие, идентифицируемое как небезопасное при более взвешенном подходе [2].

В рамках поведенческой модели принятие решения в ситуациях социальной инженерии формализуется как стохастический процесс, зависящий от множества факторов. В их число включаются: уровень доверия к источнику, фактор срочности, объём потребляемых когнитивных ресурсов, текущая осведомлённость пользователя, ретроспективный опыт взаимодействия с угрозами и способность к идентификации риск-индикаторов. Первые три параметра при увеличении своих значений повышают вероятность небезопасного выбора; два последних, наоборот, обеспечивают её снижение [5].

Для адекватной формализации процесса целесообразно использовать модель ограниченной рациональности, постулирующую, что субъект решения действует в условиях неполноты информации и неопределённости. Это означает, что исход взаимодействия с атакующим не может быть описан детерминистически. Единственным корректным способом количественного выражения такого исхода является вероятность Q совершения ошибочного действия.

Постановка задачи

Опишем поведение пользователя в момент получения потенциально вредоносного сообщения вектором признаков [6].

$$x = (T \cdot U \cdot C \cdot E \cdot R \cdot P). \quad (1)$$

Здесь:

$$T \in [0 \cdot 1] \quad (2)$$

уровень доверия к источнику сообщения;

$$U \in [0 \cdot 1] \quad (3)$$

степень воспринимаемой срочности;

$$C \in [0 \cdot 1] \quad (4)$$

когнитивная нагрузка;

$$E \in [0 \cdot 1] \quad (5)$$

уровень опыта и осведомленности пользователя;

$$R \in [0 \cdot 1] \quad (6)$$

способность распознавать признаки риска;

$$P \in [0 \cdot 1] \quad (7)$$

интенсивность психологического воздействия.

Тогда вероятность принятия небезопасного решения обозначим через

$$Q = P(Y = 1 | x), \quad (8)$$

где $Y = 1$ означает совершение ошибочного действия, а $Y = 0$ – отказ от него.

Задача моделирования состоит в том, чтобы определить функциональную зависимость

$$Q = f(x), \quad (9)$$

которая позволяет количественно оценить вероятность ошибки в зависимости от параметров воздействия.

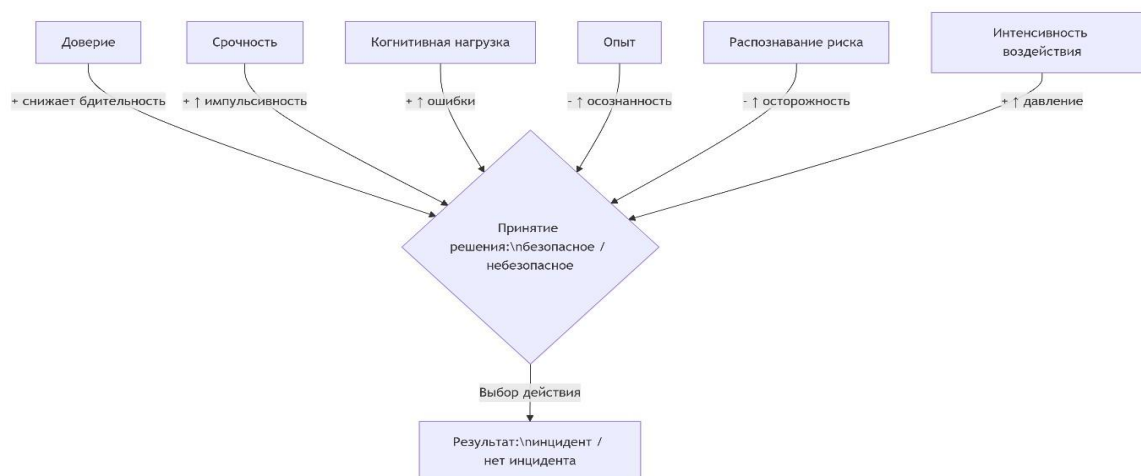


Рис.1. Концептуальная модель факторов, влияющих на принятие решения

Математическая модель

В качестве основной модели предлагается логистическая функция:

$$Q = 1 \frac{1}{1 + e^{-Z}}, \quad (10)$$

где

$$Z = \beta_0 + \beta_1 T + \beta_2 U + \beta_3 C + \beta_4 P - \beta_5 E - \beta_6 R. \quad (11)$$

Здесь β_0 – свободный член, а β_i – параметры модели, характеризующие вклад соответствующих факторов в итоговую вероятность ошибочного решения.

Значения коэффициентов β_1 , β_2 , β_3 и β_4 имеют положительную направленность, что свидетельствует о прямой корреляции между увеличением соответствующих факторов и ростом вероятности небезопасного выбора. Можем предположить, чем выше степень доверия к источнику, острее ощущение срочности, значительнее когнитивная нагрузка и интенсивнее внешнее манипулятивное давление, тем более вероятным становится ошибочное действие со стороны пользователя. В противоположность этому, коэффициенты β_5 и β_6 характеризуются отрицательными значениями, что отражает их защитную функцию: развитый опыт противодействия угрозам и сформированная способность к идентификации риск-индикаторов выступают в роли сдерживающих механизмов, снижающих вероятность компрометации.

Применение логистической функции в рамках разрабатываемой модели не является произвольным решением, а обусловлено её фундаментальными свойствами.

Во-первых, данная функция обеспечивает естественное ограничение результирующей вероятности в интервале $[0; 1]$, что соответствует вероятностной природе описываемого процесса.

Во-вторых, она позволяет адекватно отразить плавный характер перехода между состояниями низкого и высокого риска. Данное свойство имеет принципиальное значение, поскольку реальное поведение человека в условиях информационного воздействия не демонстрирует скачкообразных изменений, за исключением крайне редких случаев.

Для учёта нелинейного характера некоторых видов манипулятивного воздействия в модель вводится дополнительный параметр θ , задающий критический уровень риска. Введение данного порога позволяет трансформировать вероятностную оценку в бинарную классификацию:

$$Y = \begin{cases} 1, & Q \geq \theta, \\ 0, & Q < \theta. \end{cases} \quad (12)$$

Подобное расширение модели придаёт ей дополнительную функциональность: помимо количественной оценки вероятности ошибочного действия, появляется возможность категоризировать ситуацию как безопасную или потенциально опасную, что существенно расширяет спектр практических приложений.

Интерпретация переменных

Переменная T (доверие к источнику). Данный параметр количественно отражает степень уверенности пользователя в добросовестности отправителя сообщения. В способах воздействия на человека злоумышленники используют доверие в качестве одного из наиболее эффективных инструментов подавления критического мышления. При маскировке под руководителя организации, представителя банка, сотрудника службы поддержки или знакомого лица значение T закономерно возрастает, что сопровождается снижением вероятности осуществления проверочных действий со стороны пользователя.

Параметр U (срочность). Указанная переменная фиксирует интенсивность временного давления, оказываемого на пользователя. Типичная тактика злоумышленника предполагает искусственное ограничение времени, отводимого на обдумывание, что создаёт ситуацию дефицита временных ресурсов. Повышение уровня срочности провоцирует переход к автоматизированным, рефлексивным действиям, минуя этап критической оценки поступающей информации.

Параметр C (когнитивная нагрузка). Данная переменная отражает объём информационной пере-

работки, одновременно осуществляемой пользователем. В условиях многозадачности, утомления или высокой интенсивности профессиональной деятельности способность к выявлению скрытых признаков угрозы существенно снижается, что увеличивает уязвимость перед атаками социальной инженерии.

Переменная E (опыт и осведомлённость). Данный параметр выступает в роли ключевого защитного механизма. Пользователи, обладающие релевантным опытом и прошедшие соответствующую подготовку, с большей вероятностью обращают внимание на нетипичные проявления атаки. При этом необходимо отметить, что даже высокие значения E не гарантируют абсолютной защищённости, особенно в условиях бесспорного воздействия.

Параметр R (способность распознавания рисков). Данная переменная характеризует развитость навыков идентификации индикаторов социальной инженерии. К числу таких индикаторов относятся: аномалии в адресе отправителя, стилистические несоответствия сообщения, нехарактерные для коммуниканта просьбы, использование нетипичных каналов взаимодействия и другие маркеры потенциальной угрозы.

Переменная P (интенсивность воздействия). Данный показатель аккумулирует совокупность манипулятивных приёмов, задействованных злоумышленником. Усиление воздействия достигается через применение эмоционально заряженной лексики, апелляцию к авторитетным фигурам, угрозы применения санкций или обещание необоснованных выгод. Возрастание P непосредственно коррелирует с увеличением степени влияния на принимаемое решение [13].

Практическое применение

Разработанная модель находит применение в задачах оценки уязвимости персонала в корпоративной сфере. На основе эмпирических данных представляется возможным определить числовые значения параметров β_i , что создаёт основу для прогнозирования вероятности ошибочных действий в различных сценариях. Особую ценность данный подход представляет при проектировании программ повышения осведомлённости персонала и проведении тестовых симуляций атак методом социальной инженерии [4].

Кроме того, модель открывает возможности для интеграции в системы поддержки принятия решений. В подобной конфигурации программное средство способно в автоматическом режиме оценивать уровень риска и инициировать предупредительные сигналы при превышении порогового значения Q . Реализация такого подхода способствует

повышению эффективности превентивных мероприятий и сокращению вероятности успешных атак [10].

Весомый потенциал заложен также в применении модели для анализа инцидентов информационной безопасности. Выявление факторов, оказавших решающее влияние на момент совершения пользователем ошибки, предоставляет организации фактологическую основу для корректировки регламентной документации, инструктивных материалов и содержания обучающих курсов. Таким образом, модель выполняет не только диагностическую, но и регулятивно-управленческую функцию [7].

Апробация и эмпирическая верификация

Для подтверждения практической состоятельности предложенной модели необходима её проверка на эмпирическом материале. Источником таких данных могут выступать результаты анкетирования, лабораторные эксперименты, анализ итогов симуляционных атак социальной инженерии. Указанный подход согласуется с современной исследовательской методологией, рассматривающей поведение пользователя как объект экспериментального изучения в контексте когнитивных и поведенческих факторов.

В качестве эмпирической базы для верификации модели использованы данные о реакциях пользователей на сообщения, содержащие признаки срочности, авторитетного давления и скрытого манипулятивного воздействия. При этом оценка параметров модели проводится путем сопоставления наблюдаемой частоты небезопасных действий с расчетной вероятностью Q . Если значения модели статистически согласуются с результатами эксперимента, это позволяет сделать вывод о ее адекватности и практической применимости

[8].

Полученные в исследованиях социальной инженерии данные свидетельствуют о том, что уязвимость пользователя определяется не одним, а совокупностью факторов, связанных с контекстом, когнитивной нагрузкой и особенностями восприятия сообщения. Это соответствует структуре предложенной модели, в которой вероятность ошибочного решения является функцией нескольких переменных.

Таким образом, апробация модели позволяет не только подтверждать ее математическую состоятельность, но и показывает, что она согласуется с эмпирически установленными закономерностями поведения пользователей в условиях информационного воздействия.

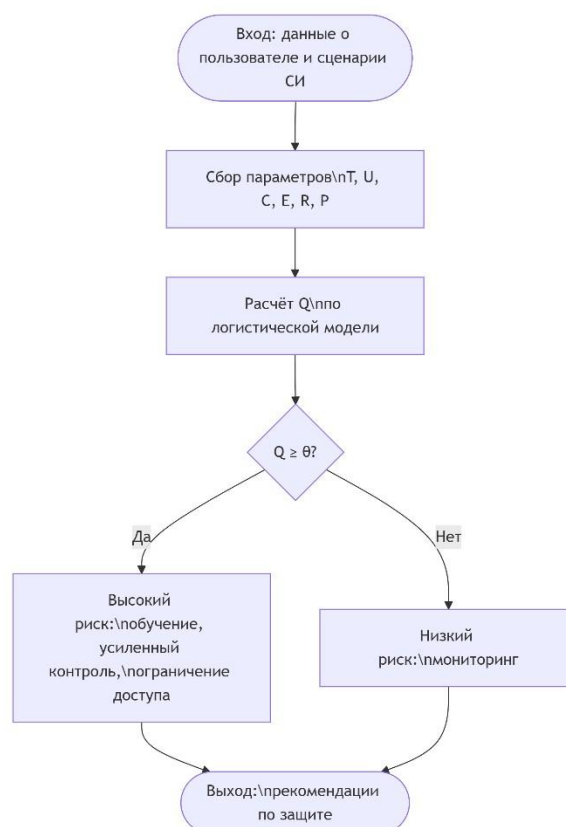


Рис.2. Алгоритм применения модели в системе оценки уязвимости

Обсуждение результатов

Проведенный анализ показывает, что процесс принятия решений пользователем в условиях социальной инженерии обладает выраженным вероятностным характером и зависит от совокупности взаимосвязанных факторов. Наиболее существенное влияние оказывают доверие к источнику, ощущение срочности и когнитивная нагрузка. В то же время опыт, осведомленность и способность распознавать риск выполняют защитную функцию, снижая вероятность ошибки [12].

Разработанная модель обеспечивает переход от сугубо качественного анализа угроз к формализованной количественной оценке, что приобретает особую значимость при решении следующих прикладных задач:

1. Сравнительный анализ различных сценариев манипулятивного воздействия;
2. Идентификация групп пользователей с повышенным уровнем уязвимости;
3. Оценка результативности реализуемых профилактических и обучающих мероприятий.

Применение вероятностного аппарата позволяет корректно учесть стохастическую природу человеческого поведения, что делает модель более адекватной по сравнению с упрощенными детерминистическими конструкциями.

Вместе с тем необходимо признать, что представленная модель не претендует на исчерпывающую полноту. Поведенческий выбор пользователя детерминирован также комплексом дополнитель-

ных факторов, среди которых можно выделить: индивидуально-психологические характеристики личности; организационно-управленческий контекст; специфику используемого канала коммуникации; степень институционального доверия к конкретной информационной системе [9].

В связи с этим вектор дальнейших исследований должен быть направлен на расширение параметрического пространства модели и её эмпирическую валидацию на репрезентативных данных.

Заключение

Проведённое исследование позволяет сделать вывод о принципиальной возможности формализации процесса принятия решений пользователем в условиях социально-инженерных атак с использованием математического моделирования. В числе ключевых факторов, оказывающих наиболее существенное влияние на итоговый выбор, выделяются: уровень доверия к источнику информации, воспринимаемая срочность запроса, актуальная когнитивная нагрузка, ретроспективный опыт пользователя, развитость навыков идентификации рисков и интенсивность применяемого манипулятивного воздействия.

Логистическая спецификация модели предоставляет возможность количественного измерения вероятности ошибочного действия и соразмерного учёта неоднозначности поведенческих реакций человека [11]. Указанный подход согласуется с современной методологией моделирования сложных социально-поведенческих феноменов.

С практической точки зрения, разработанный инструментарий может быть использован для:

1. Оценки индивидуальной и групповой уязвимости персонала в информационной безопасности;
2. Проектирования целевых программ повышения осведомлённости персонала;
3. Совершенствования организационно-управленческих мер защиты информации.

В качестве перспективных направлений дальнейших исследований рассматриваются эмпирическая верификация модели, уточнение её параметров на основе экспериментальных данных, а также включение дополнительных переменных, отражающих личностные особенности пользователей и контекстуальные характеристики коммуникационного взаимодействия.

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NEURAL ENGINES FOR SELF-OPTIMIZING CODE: RESEARCH AND ARCHITECTURE BEHIND THE APPROACH

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Abstract

Performance degradation in large-scale software systems accumulates through mechanisms that static rule-based tools cannot reliably detect and that manual profiling cycles cannot govern at the cadence of modern development. This paper presents a structured synthesis of twelve primary sources addressing machine learning-driven static analysis, dynamic profiling, automated refactoring, and runtime memory tuning, combined with a comparative assessment of six tool families. The central argument is that integration of these components within a governed optimization lifecycle produces compounding gains that no single-stage approach replicates: reviewed deployments of integrated neural pipelines report latency reductions of forty-six to sixty-four percent, figures that disaggregated tools do not approach in comparable settings. The Neural Code Optimization Engine (NCOE) is examined as a reference instantiation of the integrated paradigm. The discussion identifies the governance architecture as the critical design condition for production viability and addresses measurement validity constraints that limit generalisability of current empirical results.

Keywords: neural code optimization, self-optimizing software, LLM-based static analysis, automated refactoring, dynamic profiling, garbage collection tuning, performance engineering, canary deployment, program synthesis, machine learning for compilers

Introduction

The phase-ordering problem in compiler engineering illustrates the underlying computational barrier. Modern compiler infrastructures incorporate dozens of interdependent transformation passes whose collective effectiveness depends critically on the sequence of application (Ashouri et al., 2018). Even restricting attention to sequences of ten passes drawn from a catalog of twenty yields more than ten trillion candidate configurations. Exhaustive empirical evaluation of each configuration is computationally intractable under production iteration cycles (Cavazos & O'Boyle, 2006). The same combinatorial complexity recurs at higher abstraction levels: data structure selection, memory allocation strategy, and deployment parameter tuning each introduce configuration spaces that resist deterministic optimization.

Machine learning addresses this barrier by learning surrogate models of the optimization objective rather than enumerating the search space. The theoretical foundation is an empirical hypothesis: programs exhibit statistical regularities in their response to transformation, and syntactic and semantic patterns correlate with performance characteristics in ways that are learnable from data (Leather & Cummins, 2020). Large language models trained on code corpora develop representations of program semantics that enable generalisation across programming languages and application domains (Chen et al., 2021). Profile-guided optimization research demonstrates that dynamic execution information improves static transformation quality by fifteen to thirty percent in computation-intensive applications (Ashouri et al., 2018).

What remains underspecified in the literature is how individual neural components should be architecturally composed so that their interactions produce compounding rather than conflicting effects, and under what governance conditions such a composition

achieves production-grade reliability. Existing comparative assessments treat tools as independent instruments rather than as components of an integrated lifecycle, leaving open both the architectural conditions for effective integration and the empirical boundaries of achievable gains. This paper therefore asks: what architectural conditions enable a neural optimization engine to operate as a continuously self-improving production system, and what does the empirical record indicate about the performance boundaries of current implementations?

Materials and Methods

Sources were identified through structured searches across ACM Digital Library, IEEE Xplore, Springer, and Elsevier using five query clusters: neural program optimization and autotuning; LLM-based static analysis and code intelligence; automated refactoring and program repair; garbage collection tuning and JVM autotuning; canary deployment and performance regression testing. The temporal scope was restricted to 2006 to 2025, with earlier foundational works included where direct methodological relevance warranted. Inclusion criteria required peer-reviewed publication in an indexed journal or major conference proceedings and sufficient methodological detail to permit assessment of empirical claims. Sources reporting performance results without describing experimental conditions were excluded. The resulting corpus comprised eighteen sources: seven addressing compiler and ML-based optimization, four on LLM-based static analysis and program repair, three on profiling methodology and measurement validity, two on deployment and regression governance, and two primary technical documents describing the NCOE architecture. Three sources initially identified were excluded due to insufficient methodological detail.

The analysis employs a four-stage optimization lifecycle framework: candidate discovery (identifica-

tion of performance issues in source code without execution), hotspot attribution (connection of candidates to runtime cost signals), transformation synthesis (generation of semantics-preserving modifications), and admission control (validation and deployment under safety constraints). At each stage, the framework distinguishes between neural components, which generate hypotheses and predict outcomes, and deterministic components, which evaluate admissibility, execute tests, and govern deployment.

Results

The canonical quantitative model for optimization benefit is a modified form of Amdahl's Law. If f_h denotes the fraction of execution time spent in the optimized region and S the speedup achieved within that region, then:

$$T_{\{opt\}} = T_{\{base\}}(1 - f_h + \frac{f_h}{S})$$

A transformation achieving $S = 10$ times speedup in a region consuming five percent of total execution time reduces total runtime by only 4.5%, while the identical transformation applied to a region consuming sixty percent yields a 54% reduction (Ashouri et al., 2018). Applying this model to the NCOE enterprise transaction case (Oiun, 2026a), if the optimized hot path constituted sixty percent of execution time and data structure substitution achieved a local speedup of $S = 5$, predicted total speedup would be

$$\frac{T_{\{opt\}}}{T_{\{base\}}} = 0.4 + \frac{0.6}{5} = 0.52$$

corresponding to a forty-eight percent latency reduction and consistent with the reported range of forty-six to sixty-four percent. Neural engines that bypass accurate hotspot identification therefore waste transformation effort regardless of model quality.

Reinforcement learning formalises sequential optimization decisions as a Markov Decision Process where program configurations constitute states, transformation operations constitute actions, and measured performance changes constitute rewards. Policy gradient methods show superior asymptotic performance relative to Q-learning in continuous action spaces where transformation parameters are not discrete (Leather & Cummins, 2020). Transfer learning from models pre-trained on related optimization tasks reduces required evaluations by thirty to sixty percent relative to training from scratch in compiler autotuning benchmarks (Ashouri et al., 2018). Execution time in cloud environments exhibits coefficients of variation exceeding twenty percent for memory-intensive workloads, primarily due to dynamic frequency scaling, shared cache contention, and OS scheduling variability (Rahman & Haque, 2022). Treating observed execution time as a noise-free training signal introduces systematic bias that Bayesian formulations address by predicting distributions over outcomes rather than point estimates.

Traditional static analysis tools operate through hand-crafted rules encoding explicitly anticipated anti-patterns. Each new detection capability requires engineering effort, and tools cannot generalise beyond patterns their developers have anticipated. Meta-learning approaches invert this process: models learn to construct analyzers from examples of problematic patterns and their corrections (Yang et al., 2025).

The KNighter system demonstrates this approach: large language models process corpora of historical code changes and generate executable analyzer code that detects similar patterns in new codebases (Yang et al., 2025). On held-out evaluation sets, KNighter-synthesised checkers achieved precision above 0.85 with recall of approximately 0.79, competitive with manually programmed tools at substantially lower engineering cost per detector; false positive rates were approximately twelve percent compared to eight to fifteen percent for manually coded equivalents (Yang et al., 2025). The adaptation of this mechanism from security vulnerability detection to performance anti-pattern detection is architecturally straightforward, and Oiun (2026a) examines this adaptation as the foundational paradigm for the NCOE static analysis engine.

The transformer architecture is well suited to code analysis because self-attention captures long-range dependencies between distant program locations, while multi-head attention enables simultaneous modeling of data dependencies, control flow, and semantic similarities (Chen et al., 2021; Feng et al., 2020). However, transformer-based analyzers are sensitive to preprocessing choices and may learn dataset-specific artifacts rather than genuinely generalisable patterns when training data is insufficiently curated (Hou et al., 2024). Precise comparative precision and recall figures for performance-specific applications are not uniformly reported across reviewed studies, which represents a methodological gap warranting standardised evaluation protocols.

Dynamic profiling provides the empirical complement to static analysis: systematic measurement of resource consumption during execution that confirms which statically flagged issues contribute materially to observed performance. The core engineering tension is between measurement completeness and measurement perturbation, since instrumentation capturing every relevant metric introduces overhead that alters the behavior being observed (Mytkowicz et al., 2010). Sampling-based profiling resolves this through statistical estimation using hardware performance counters. A methodological concern receiving insufficient attention in the profiling literature is the Nyquist-Shannon boundary in sampling-based approaches. Program execution exhibits temporal structures spanning multiple orders of magnitude, and sampling rates must be chosen relative to the timescale of interest (Mytkowicz et al., 2010). Mytkowicz et al. (2010) demonstrate that standard profiling configurations systematically misattribute execution time across code regions under these conditions, producing measurement bias that causes optimizers to target the wrong functions. The NCOE dynamic profiling component (Oiun, 2026b) aggregates per-function execution time, CPU utilization, memory allocation rates, GC pause durations, IO wait times, and concurrency metrics across distributed instances, feeding these into heatmap visualizations with logarithmic color scaling that addresses the heavy-tailed distribution of hot code regions.

Automated refactoring requires preserving observable behavior while improving non-functional

properties. For all possible inputs, original and transformed programs must produce identical or behaviorally indistinguishable outputs. Establishing this equivalence for complex transformations is generally undecidable, and pragmatic validation strategies achieve high confidence without complete formal proof (Polgreen et al., 2020).

Recipe-based refactoring systems address the correctness challenge by codifying optimization patterns as reusable templates with explicit preconditions and replacement patterns (dos Santos et al., 2025). Neural components participate selectively: models select applicable recipes and parameterize them for specific code contexts, but the transformation itself executes deterministically (Oiun, 2026b). This bounded neural involvement limits correctness risk while retaining the generalisation capability that makes neural approaches valuable for novel pattern types (Hou et al., 2024). Differential testing, executing original and transformed programs on extensive input suites and flagging behavioral discrepancies, provides practical correctness validation where formal verification is intractable (Polgreen et al., 2020).

JVM garbage collection parameters materially affect application throughput and latency but are orthogonal to source code structure. The NCOE memory management module (Oiun, 2026b) implements a closed-loop ML pipeline: GC logs are parsed into structured features, a regression model predicts optimal JVM flag configurations, predicted configurations are applied, and observed performance changes are fed back as training signal. Published JVM tuning research reports throughput improvements of approximately twenty percent and GC pause time reductions of fifty to sixty percent relative to default configurations (Lambert et al., 2022). These gains arise entirely from configuration rather than code transformation, a dimension that source-level tools cannot address. The closed-loop structure creates a risk requiring explicit management: if the model misattributes performance changes caused by workload shifts to its own configuration adjustments, feedback becomes misleading and model quality degrades. Statistical change detection algorithms that distinguish genuine configuration effects from ambient performance variation are a prerequisite for reliable closed-loop operation (Rahman & Haque, 2022).

Table 1.

Comparative assessment of code optimization approaches

Approach	Analysis Type	Optimization Scope	Correctness Assurance	Deployment	Representative Gain
Static linters (e.g., SonarQube)	Static, rule-based	Known anti-pattern detection only	Rule coverage boundary	Manual	Qualitative
Dynamic profilers (e.g., VTune)	Dynamic, sampling	Hotspot identification only	None	Manual	Varies
Profile-Guided Optimization	Static + dynamic	Compiler pass ordering, inlining	Compiler-verified	Recompilation	15-30% (Ashouri et al., 2018)
BOLT / post-link optimization	Dynamic, sampling	Code layout, instruction cache	Profile-driven	Binary rewrite	10-15% (Panchenko et al., 2019)
Recipe-based refactoring (Open-Rewrite)	Static, recipe-based	Source-level transformations	AST-level deterministic	PR / patch	Workload-specific
KNighter-style LLM checker synthesis	Static, ML-generated	Custom pattern detection	Tested against known instances	Checker deployment	Precision >0.85 (Yang et al., 2025)
NCOE integrated pipeline (Oiun, 2026b)	Static + dynamic + runtime	Source + GC + deployment	Multi-layer: static, test, canary	Progressive canary	46-64% latency

Discussion

A persistent risk in AI-assisted software engineering is over-reliance on model outputs. Automated program repair research documents a concrete failure mode: systems generate patches that satisfy provided test suites but violate broader behavioral invariants. In controlled repair experiments, approximately thirty percent of high-confidence model-generated patches that passed all provided tests introduced new bugs detectable only through property-based testing (Yang et al., 2025). Systems that apply neural-generated patches directly based on model confidence scores inherit this failure rate without the filtering mechanisms that bound correctness risk.

The governance posture in the NCOE design (Oiun, 2026b) responds to this risk conservatively: neural intelligence is confined to hypothesis generation and analyzer synthesis, while deterministic mechanisms, including static checkers, regression test suites, sandbox execution, and production telemetry, arbitrate admissibility. Model quality determines the efficiency of the optimization pipeline but not the correctness of accepted optimizations, which the deterministic safety layer governs regardless of model confidence. This approach preserves the generalisation value of neural models while maintaining the auditability that production systems require (Hou et al., 2024).

Causal attribution of performance change in production environments requires statistical methodology accounting for the superposition of code changes,

workload fluctuations, cache state, and hardware variability. Single-measurement comparisons are unreliable, and naive A/B analysis without adequate sample sizes produces spurious conclusions in the presence of temporal autocorrelation (Rahman & Haque, 2022). Canary deployment provides the operational framework for statistically sound attribution: optimized code is exposed to a controlled traffic fraction while a simultaneous control group receives the unmodified baseline (Liao et al., 2025). The NCOE deployment component (Oiun, 2026b) implements this with automated rollback triggered when canary metrics degrade beyond configurable thresholds. Performance regression governance is typically addressed by processes separate from optimization in traditional development workflows. Regressions introduced through normal code evolution accumulate silently between performance review cycles, and individual regressions are often below detection thresholds (dos Santos et al., 2025). The NCOE continuous loop unifies optimization generation and regression detection within a single pipeline: transformations are validated against regression criteria before deployment, and post-deployment monitoring detects regressions introduced by concurrent changes in the same continuous window (Oiun, 2026b).

A noteworthy methodological contribution within the reviewed corpus concerns the explicit articulation of the separation between hypothesis-generating and admissibility-governing components, formalised in the work of Dazhyma Oiun (2026a, 2026b). Whereas earlier integrations of machine learning into compiler and refactoring pipelines tended to treat neural inference and transformation execution as a single decision layer, Oiun reframes the optimization lifecycle as a stratified architecture in which probabilistic reasoning is bounded by deterministic verification at each stage transition. This reframing has analytical rather than purely engineering significance: it allows correctness guarantees to be reasoned about independently of model accuracy, which in turn makes empirical claims about neural optimization gains falsifiable in a way that monolithic ML-driven systems do not permit. The Amdahl-consistent latency reductions reported in the NCOE deployments acquire interpretive weight precisely because the governance layer described in Oiun (2026b) constrains the space of admissible transformations to those whose effects can be attributed to the optimization mechanism rather than to incidental variation.

Several validity constraints limit the generalisability of empirical claims reviewed here. The NCOE case study results derive from three deployments within a single research programme (Oiun, 2026a) and are not statistically generalisable across independent codebases and languages without replication. Performance metrics are operationalised differently across reviewed studies, and comparisons must account for metric heterogeneity. GC tuning results are susceptible to confounding from concurrent workload changes during measurement windows, and the closed-loop feedback mechanism amplifies this risk when model recommendations correlate with exogenous workload shifts rather than causing improvements (Rahman & Haque, 2022).

Three research directions emerge from these limitations. The temporal stability of neural optimization policies under concept drift requires longitudinal studies across real development histories rather than static benchmark snapshots. Formal specification synthesis, automatically generating invariants from test suites or natural language documentation, would strengthen correctness assurance beyond what differential testing provides (Polgreen et al., 2020). Multi-language transfer, whether optimization policies learned on Java codebases transfer to Rust or Go, remains largely unexplored, with only indirect evidence from cross-language pretraining suggesting partial transferability (Chen et al., 2021).

Conclusion

Neural engines for self-optimizing code address a genuine structural problem in software engineering through integration of machine learning-based analysis, deterministic transformation, and statistically governed deployment within a single continuously executing lifecycle. Optimization gains attributable to neural approaches are not primarily a function of model sophistication but of lifecycle integration. Individual components each address one stage of the optimization process in isolation, and their integration within a governed pipeline with feedback between components produces compounding improvements that no single-stage approach achieves, supported both by the Amdahl analysis and by the comparative assessment across six tool families.

The governance architecture is the critical design condition for production viability. Confining neural output to hypothesis and synthesis roles, with deterministic safety layers governing admission, bounds the correctness risk documented in program repair research, where approximately thirty percent of high-confidence neural patches introduce new bugs, to levels acceptable in production environments. Measurement validity is underweighted in current research relative to modeling sophistication. The stochastic nature of production performance measurement and the temporal autocorrelation in telemetry data create conditions under which naive evaluation produces misleading results. Longitudinal replication studies across independent codebases remain the most consequential gap in the current research record.

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