NJD-iScience

№177

The Norwegian Journal of Development of the International Science

№177/2026

**Norwegian Journal of development of the International Science**

ISSN 3453-9875

It was established in November 2016 with support from the Norwegian Academy of Science.

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# CHEMICAL SCIENCES

## THE IMPACT OF PROJECT-BASED LEARNING IN THE STEM SYSTEM ON THE DEVELOPMENT OF CRITICAL THINKING IN GRADE 8–9 STUDENTS

**Nurekenova A.**
*candidate of biological Sciences, associate professor,*
*Department of chemistry and biology,*
*«Shakarim University of Semey»*
**Kakibayeva I.**
*Master of 1 courses*
*of the Department of chemistry and biology,*
*«Shakarim University of Semey»*

## «ВЛИЯНИЕ ПРОЕКТНОГО ОБУЧЕНИЯ В СИСТЕМЕ STEM НА РАЗВИТИЕ КРИТИЧЕСКОГО МЫШЛЕНИЯ УЧАЩИХСЯ 8–9 КЛАССОВ»

**Нурекенова А.Н.**
*кандидат биологических наук,*
*доцент кафедры химии и биологии*
*«Университета имени Шакарима города Семей»*
**Какибаева И.А.**
*магистрант*
*«Университета имени Шакарима города Семей»*
https://doi.org/10.5281/zenodo.19292657

**Abstract**

The article explores the methodology of implementing project-based learning within the STEM framework as a strategic tool for developing critical thinking skills in 8th and 9th-grade students during chemistry lessons. The author analyzes the core components of the STEM approach (Science, Technology, Engineering, Mathematics) and their role in fostering analytical and evaluative competencies. The paper provides specific examples of interdisciplinary chemistry projects and evaluates their impact on the cognitive activity of learners. A pedagogical experiment results are presented, demonstrating the effectiveness of the STEM-project approach in enhancing students' ability to solve complex, real-world problems.

**Аннотация**

В статье исследуется методика реализации проектного обучения в системе STEM как стратегического инструмента развития навыков критического мышления учащихся 8–9 классов на уроках химии. Автором проанализированы основные компоненты STEM-подхода (наука, технологии, инженерия, математика) и их роль в формировании аналитических и оценочных компетенций. Представлены конкретные примеры междисциплинарных химических проектов и оценено их влияние на познавательную активность обучающихся. Описаны результаты педагогического эксперимента, подтверждающие эффективность применения STEM-проектов для повышения способности учащихся решать сложные прикладные задачи.

**Keywords:** STEM education, project-based learning (PBL), critical thinking, chemistry in middle school, interdisciplinary integration, functional literacy, cognitive skills.

**Ключевые слова:** STEM-образование, проектное обучение, критическое мышление, химия в средней школе, междисциплинарная интеграция, функциональная грамотность, когнитивные навыки.

Современный этап развития школьного химического образования характеризуется переходом от трансляции фактологических знаний к формированию функциональной грамотности учащихся. В рамках данного процесса критическое мышление рассматривается как базовая когнитивная компетенция. Согласно теоретическим разработкам Т. А. Ивановой, структура функциональной грамотности включает в себя как глубокие предметные знания, так и когнитивные умения оценивать информацию [6, 125–129]. Особую значимость это приобретает в 8–9 классах, когда закладывается фундамент естественнонаучного мировоззрения..

Несмотря на наличие глубоких теоретических разработок, традиционная методика преподавания химии зачастую оставляет нерешенным вопрос прикладной значимости предмета для повседневной жизни учащегося. В качестве эффективного механизма преодоления этого разрыва выступает STEM-подход (Science, Technology, Engineering, Mathematics), обеспечивающий междисциплинарную интеграцию и вовлечение школьников в активную инженерно-конструкторскую деятельность на базе химического контента [1,94–97].

Актуальность темы исследования подтверждается требованиями международных стандартов оценки качества образования (PISA-2025), где акцент смещен на способность учащихся использовать научные методы для решения реальных про-

блем технологического общества [4, 110–112]. Проектное обучение в системе STEM позволяет трансформировать кабинет химии в исследовательскую лабораторию, где развитие критического мышления происходит через прохождение всех этапов научного поиска: от постановки проблемы до оценки жизнеспособности созданного продукта [7, 34–38].

Объектом исследования является процесс обучения химии в основной школе, а предметом — методика использования STEM-проектов как средства развития критического мышления учащихся 8–9 классов. В данной статье нами проанализирован опыт внедрения междисциплинарных заданий и представлены результаты экспериментальной проверки их эффективности в образовательном процессе [5, 72–75].

Методологические принципы

Для эффективного внедрения STEM-проектов необходимо соблюдение трех ключевых методических принципов:

1. Принцип актуальности: проект должен затрагивать современные проблемы науки и экологии.
2. **Принцип междисциплинарности:** интеграция знаний из химии, физики, биологии и математики.
3. **Принцип проблемности:** задания должны стимулировать поиск решений, а не простое воспроизведение фактов. [2, 83–86]

**Методология исследования**

Исследование организовано по принципу квазиэкспериментального дизайна. Процесс работы над проектом строился по алгоритму инженерного проектирования (Engineering Design Process), который в современной педагогической литературе рассматривается как ключевой фактор развития исследовательских компетенций [7, с. 35]: постановка вызова → исследование → конструирование → тестирование и улучшение. Для сбора данных использовались тестирование, наблюдение и статистическая обработка с применением t-критерия Стьюдента. [3, с. 52–56] В эксперименте приняли участие 48 учащихся, ученики двух параллельных 9-х классов (ЭГ — 24 чел., КГ — 24 чел.). Диагностика показала отсутствие исходных различий между группами ($p > 0.05$). Эксперимент длился три месяца. Экспериментальная работа была организована в три логически взаимосвязанных этапа:

**I этап — Констатирующий (Диагностический):** Проведение комплексного тестирования для определения стартового уровня функциональной грамотности. Инструментарий включал задания, направленные на оценку аналитических способностей и умения выдвигать научные гипотезы. На данном этапе фиксировались затруднения учащихся при работе с неструктурированной информацией.

**II этап — Формирующий (Внедренческий):** Системная реализация модели STEM-обучения в экспериментальной группе. В течение учебного полугодия образовательный процесс в ЭГ дополнялся циклом междисциплинарных проектов («Чистая вода», «Биопластик» и др.), требующих прохождения всех стадий инженерного цикла: от анализа теоретической проблемы (Science) до конструирования и испытания прототипа (Engineering). В контрольной группе обучение продолжалось по традиционной методике с опорой на стандартные лабораторные работы.

**III этап — Контрольно-обобщающий:** Повторная диагностика уровня критического мышления и анализ динамики когнитивного развития. Проводилась качественная оценка защиты проектных работ и статистическая обработка количественных данных тестирования для верификации гипотезы исследования.

Система междисциплинарных заданий разрабатывалась с опорой на три критерия:

1. **Директивное соответствие:** полная интеграция с действующей школьной программой по химии для 9 класса.
2. **Практическая детерминированность:** использование кейсов, моделирующих реальные технологические и экологические вызовы.
3. **Когнитивная направленность:** включение задач на поиск ошибок, оценку достоверности данных и синтез новых решений, что является основой развития критического мышления».

**Процесс работы над проектом строился по алгоритму инженерного проектирования (Engineering Design Process):**

1. **Постановка вызова (Ask):** Формулировка экологической или технической проблемы.
2. **Исследование (Imagine):** Изучение химических свойств веществ и поиск путей решения.
3. **Планирование и конструирование (Plan/Create):** Выбор реагентов и создание экспериментальной модели.
4. **Тестирование и улучшение (Test/Improve):** Анализ ошибок и корректировка методики на основе полученных данных.

Для реализации обучения была разработана система проектов разного уровня сложности (Таблица 1).

**Таблица 1.**

**Содержательно-технологическая карта STEM-проектов**

| **Уровень и название проекта** | **Содержание учебной деятельности (компоненты STEM)** | **Междисциплинарная интеграция** | **Критерии оценивания (индикаторы критического мышления)** |
|---|---|---|---|
| **Уровень 1: Прикладной**<br><br>«Чистая вода: конструирование биофильтра» | **S (Science):** Изучение процессов адсорбции и свойств природных сорбентов (уголь, песок, цеолит).<br>**T (Technology):** Использование цифровых датчиков (pH-метры, солемеры) для анализа проб.<br>**E (Engineering):** Сборка многослойной колонны фильтрации.<br>**M (Math):** Расчет скорости фильтрации (мл/мин) и процента очистки. | **Химия + Экология + Математика.** Изучение методов очистки сточных вод и расчет экономической эффективности бытовых фильтров. | 1. Умение обосновать выбор сорбента на основе его химических свойств.<br>2. Точность интерпретации данных цифровых датчиков.<br>3.Способность предложить доработку конструкции при низкой эффективности очистки. |
| **Уровень 2: Исследовательский**<br><br>«Альтернативный ток: фруктовая батарейка» | **S (Science):** Исследование электрохимического ряда напряжений металлов и роли электролита.<br>**T (Technology):** Применение мультиметра для замера силы тока и напряжения.<br>**E (Engineering):** Создание последовательной и параллельной цепи из органических элементов.<br>**M (Math):** Построение графиков зависимости напряжения от кислотности (pH) среды. | **Химия +Физика + Алгебра.** Изучение окислительно-восстановительных реакций и законов постоянного тока. Построение функций. | 1. Глубина анализа причин возникновения ЭДС.<br>2. Умение прогнозировать изменение напряжения при смене электродов.<br>3. Логичность выводов о возможности практического применения таких источников. |
| **Уровень 3: Творческо-инженерный**<br><br>«Биопластик: полимеры будущего» | **S (Science):** Синтез полимерного материала из крахмала, изучение влияния пластификаторов (глицерина).<br>**T (Technology):** Регулирование температурных режимов в процессе варки полимера.<br>**E (Engineering):** Разработка формы и отливка опытного образца упаковки.<br>**M (Math):** Расчет пропорций реагентов для получения нужной эластичности. | **Химия + Технология + Экономика.** Изучение поликонденсации и анализ рынка биоразлагаемых материалов. | 1. Способность оценить экологические риски производства.<br>2. Умение выявить ошибки в составе при получении хрупкого образца.<br>3. Креативность в решении проблемы утилизации отходов. |

**Результаты исследования:**

Анализ изменений уровня знаний и навыков проводился с помощью статистических методов (t-критерия Стьюдента). Данные представлены в таблице 2.

**Таблица 2.**

**Сравнительные результаты развития критического мышления**

| Группы и этапы исследования | Аналитический компонент | Оценочный компонент | Прогностический компонент | Средний балл по группе | Прирост (%) | t-критерий Стьюдента (p) |
|---|---|---|---|---|---|---|
| Контрольная группа (КГ) | | | | | | |
| До эксперимента | 62.4 | 61.8 | 60.2 | 61.5 | — | $p > 0.05$ |
| После эксперимента | 65.8 | 64.2 | 62.5 | 64.2 | 4.4% | (незначимо) |
| Экспериментальная группа (ЭГ) | | | | | | |
| До эксперимента | 61.9 | 62.1 | 59.8 | 61.3 | — | $p > 0.05$ |
| После эксперимента | 82.5 | 78.4 | 76.2 | 79.0 | 28.9% | $p < 0.05$ |

Как видно из таблицы 2, исходные показатели групп были идентичны ($p > 0.05$). Однако после внедрения системы STEM-проектов, средний балл экспериментальной группы вырос на 28.9%. Наиболее выраженная динамика наблюдается в аналитическом компоненте (82.5 балла), что связано с регулярной практикой декомпозиции комплексных междисциплинарных проблем в ходе выполнения проектов "Чистая вода" и "Биопластик"». Статистический анализ с применением t-критерия Стьюдента подтвердил значимость различий ($p < 0.05$). Качественное наблюдение зафиксировало положительные изменения в деятельности учащихся ЭГ:

**1. Самостоятельность и 40% реже обращения за подсказками**:

Это прямое следствие роста **аналитического компонента** (с 61.9 до 82.5 балла). Когда у ученика развит анализ, он может сам разбить сложную задачу на части и не нуждается в постоянной помощи учителя.

**2. Аргументация и рост терминов в 1.5 раза**:

Это подтверждается ростом **оценочного компонента** (с 62.1 до 78.4 балла). Чтобы оценить данные и доказать свою правоту, ученику необходимо оперировать точными научными фактами и терминологией.

**3. Гибкость и 2–3 варианта решения**:

Это результат развития **прогностического компонента** (с 59.8 до 76.2 балла).

Прогнозирование позволяет ученику видеть разные пути развития химического процесса и предлагать альтернативные инженерные решения. Исследование подтверждает эффективность проектного обучения в системе STEM для развития критического мышления учащихся 8–9 классов. STEM-проекты позволяют видеть связь химии с реальной жизнью, что способствует глубокому усвоению материала. Для успешной интеграции рекомендуется внедрять один краткосрочный STEM-проект (2–4 урока) в конце каждого крупного учебного раздела химии. Внедрение данной методики целесообразно для формирования ключевых компетенций в современной технологической и наукоемкой среде.

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# EARTH SCIENCES

## MAIN DIRECTIONS FOR IMPROVING THE QUALITY OF LIFE OF THE POPULATION IN THE REGIONS (ON THE EXAMPLE OF THE GANJA–DASHKASAN ECONOMIC REGION)

**Jabrayilova F.**
*Researcher in Geographical Sciences,Ministry of Science and Education, Institute of Geography,Baku, Republic of Azerbaijan*
https://orcid.org/0000-0001-9784-9366
https://doi.org/10.5281/zenodo.19292659

**Abstract**
This article provides a comprehensive analysis of the dynamics of changes in the quality of life of the population in the Ganja-Dashkasan economic region since 2004. The study employs key indicators such as employment, social infrastructure, utility provision, and migration. The results of the analysis indicate that, overall, the quality of life in the region has improved; however, structural problems and intra-regional disparities have not been fully eliminated.

**Keywords:** quality of life, regional development, social infrastructure, employment, migration

**Introduction**

The Ganja–Dashkasan economic region is located in the western part of the Republic of Azerbaijan and is distinguished by its predominantly mountainous and foothill terrain, abundant mineral resources, and favorable natural-geographical conditions. The region's climatic diversity, water resources, and recreational potential play a significant role in shaping and developing its economic structure.

As a result of the administrative-territorial reforms carried out in 2021, this territory was separated from the former Gazakh–Dashkasan economic region and established as an independent economic region. The primary objective of this reorganization was to ensure more efficient utilization of natural resources and to accelerate the socio-economic development of the region.

This economic-geographical region includes the administrative districts of Ganja, Dashkasan, Goranboy, Goygol, Naftalan, and Samukh.

**Table 1.**

**Ganja–Dashkasan Economic Region (2025)**

| Economic Region | Area | | Population | | Urban Population | | |
|---|---|---|---|---|---|---|---|
| | (thousand sq. km) | Share (%) | (thousand persons) | Share (%) | (thousand persons) | Urbanization (%) | Share (%) |
| Azerbaijan | 86,6 | 100 | 10224,9 | 100 | 5562,9 | 54,4 | 100 |
| Ganja–Dashkasan | 4,5 | 5,2 | 1300,0 | 12,7 | 800,0 | 61,5 | 14,4 |

Source: Population of Azerbaijan. Baku: SSC (State Statistical Committee), 2025.

Although the Ganja–Dashkasan economic region occupies a middle position among the country's economic regions in terms of territorial size, it has a relatively high share in both total population and urban population. This can be explained by the fact that the level of urbanization in the region exceeds the national average (Table 1).

Within the territorial structure of the economic region, the Dashkasan district has the largest area, while the city of Naftalan has the smallest. The region's relief is predominantly mountainous and is particularly notable for its richness in ore mineral resources.

The city of Ganja plays a leading role in the socio-economic development of the economic region. As the second largest city in the country, Ganja is an important industrial, transport, and cultural center. At the same time, areas such as the Goygol district stand out for their natural recreational resources and tourism potential.

Thus, the Ganja–Dashkasan economic region is characterized by the integrated development of industry, agriculture, and tourism, and is considered one of the key economic-geographical regions with a high level of urbanization.

The relevance of the topic lies in the fact that improving the quality of life of the population in the Ganja–Dashkasan economic region serves as one of the key indicators of socio-economic development and determines the efficient territorial organization of production and social infrastructure within the region. At the same time, increasing employment, raising incomes, and expanding access to social services have a positive impact on public welfare, thereby contributing to demographic stability and sustainable development[1].

In regional development policy, the quality of life of the population is considered one of the main evaluation criteria. This concept is not limited to economic indicators alone; it also encompasses factors such as accessibility of social services, infrastructure provision, employment opportunities, and demographic stability[2].

The Ganja–Dashkasan economic region is one of the important economic zones of Azerbaijan,

characterized by the integrated development of industry, agriculture, and the service sector. Since 2004, the changes that have taken place in this region have led to noticeable improvements in the living standards of the population.

**Methodology**

In this study, reference was made to the scientific works of local scholars such as Z.N. Eminov, S.I. Rzayeva, and T.M. Huseynova, who have examined the factors affecting quality of life. These researchers have conducted comprehensive analyses of the socio-economic, demographic, and environmental factors influencing the population's well-being.

To identify the directions for improving the quality of life in the Ganja–Dashkasan economic region, the study employed comparative-statistical analysis, dynamic analysis, and a systematic approach. The data sources for the research included official statistical records, regional reports, and analytical observations.

**Analysis and Discussion**

Since 2004, the quality of life of the population in the Ganja–Dashkasan economic region has gradually taken shape and developed in stages. In the initial phase, living standards were largely determined by the availability of social infrastructure. In the city of Ganja, social facilities were renovated, roads and communication lines were restored, and healthcare and educational institutions were modernized. The construction of new residential complexes for internally displaced persons positively influenced population growth and improved social welfare.

In the districts of Naftalan, Dashkasan, Goranboy, Goygol, and Samukh, measures were also taken to repair roads, upgrade electricity and communication networks, and support agricultural development.

However, limited employment opportunities in rural areas, inadequate gas and water supply, underdeveloped industrial sectors, and ongoing migration remained key challenges. In subsequent years, with increased economic activity, employment opportunities in the region expanded, marking a new qualitative stage in its development. The establishment of industrial enterprises (aluminum, steel, and food industries) as well as the expansion of transport and social infrastructure contributed to a rise in employment. The development of the industrial and service sectors also led to increased incomes for the population. At the same time, improvements in road infrastructure and energy provision positively affected living conditions[3].

The commissioning of large industrial and cultural facilities in the city of Ganja strengthened its role as an economic center. In other districts, the development of agriculture, support for entrepreneurship, and construction of social facilities continued.

After 2014, the modernization of infrastructure and the development of industry and agriculture were further strengthened. In the Dashkasan district, the growth of the mining industry, the creation of new jobs, and the renovation of road infrastructure enhanced the region's economic potential. During this period, an increase in the accessibility of social services was also observed. The expansion and modernization of educational and healthcare institutions positively impacted the social well-being of the population.

However, weak technical support in agriculture, as well as issues with gas supply, irrigation, and employment in some villages, hindered the full realization of the region's economic potential.

In the most recent period (2019–2025), large-scale infrastructure projects were implemented in the region. The road network was renovated, water supply and sewage systems were established, and electricity and gas provision were improved[4].

The implementation of water supply and sewage projects, the construction of new substations, and the development of the mining industry in Dashkasan district have yielded significant results. In the districts of Ganja, Naftalan, and Goygol, employment opportunities have expanded in tourism, agriculture, and small business sectors[5].

At the same time, the COVID-19 pandemic and the wartime conditions had a certain impact on the region's socio-economic development. However, with state support, these effects were partially mitigated, and the measures taken had a positive impact on the population's health indicators[6].

Analyses indicate that despite the achievements in the region, the following problems have not been fully resolved:

- Limited employment opportunities and ongoing migration in rural areas;
- Underdevelopment of the industrial sector in certain districts;
- Deficiencies in water supply, sewage, and gas provision;
- Uneven development of the material and technical base of healthcare and educational institutions;
- Limited technical and financial resources in agriculture.

**Table 2.**

**Dynamics of Quality of Life Indicators**

| Indicator | 2004-2008 | 2009-2013 | 2014-2018 | 2019-2025 |
|---|---|---|---|---|
| Employment | Moderate | Increasing | Stable | Increasing |
| Water Supply | Poor | Partially Improved | Moderate | Good |
| Gas Supply | Low | Moderate | Increasing | High |
| Educational Infra-structure | Being Renovated | Increasing | Good | High |
| Healthcare Services | Limited | Improving | Moderate-Good | Good |
| Migration | High | Moderate | Moderate | Relatively Decreas-ing |

The analysis of Table 2 shows that positive dynamics are observed across all key indicators. Significant progress has been recorded, particularly in gas supply and educational infrastructure. Developments in water supply have proceeded at a slower pace, mainly due to existing infrastructure problems in rural areas.

Although an increase in employment has been observed, it does not fully meet the overall demand of the population. For this reason, migration remains a relevant issue. While a decreasing trend in migration is noticeable, the process has not come to a complete halt.

**Conclusion**

The study has shown that the quality of life in the region has gradually improved, with social and engineering infrastructure serving as the main drivers of development. Differences between urban and rural areas persist, and employment and industrial development remain key challenges.

In the future, a comprehensive approach will be required to further enhance the quality of life in the region. In particular, accelerating industrialization, modernizing agriculture, and ensuring the equitable distribution of social services are essential.

The following priority directions should be considered for improving the quality of life of the population in the Ganja–Dashkasan economic region:

- Establishment of processing enterprises in the regions.
- Modernization of agriculture and development of irrigation systems.
- Strengthening of social infrastructure (education, healthcare, and services).
- Creation of new jobs and expansion of employment opportunities.
- Improvement of living conditions in the regions to reduce migration.
- Protection of the environment and ensuring sustainable development.

As a result, state programs implemented between 2004 and 2025 have played an important role in the socio-economic development of the region and in improving the living standards of the population. At the same time, it is necessary to implement comprehensive and continuous measures to address the remaining challenges.

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# ECONOMIC SCIENCES

## THE IMPACT OF DIGITAL TRANSFORMATION ON FINANCIAL REPORTING QUALITY UNDER IFRS: EVIDENCE FROM EMERGING ECONOMIES

**Kerimova M.**
*Professor, PhD in Economics*
*Department of Economics*
*Azerbaijan Technological University*
*Ganja, Azerbaijan*
*ORCID: https://orcid.org/0009-0008-7906-9452*
**Kerimov F.**
*Professor, PhD in Economics*
*Azerbaijan Technological University*
*Ganja, Azerbaijan*
*ORCID: https://orcid.org/0009-0002-2041-5839*
**Mammadli A.**
*Senior Lecturer*
*Azerbaijan Technological University*
*Ganja, Azerbaijan*
*ORCID: https://orcid.org/0009-0001-2253-6936*
**Nuriyeva S.**
*Assistant*
*Department of Physics and Technical Sciences*
*Azerbaijan Technological University*
*Ganja, Azerbaijan*
*ORCID: https://orcid.org/0009-0006-2600-9662*
https://doi.org/10.5281/zenodo.19292661

**Abstract**

Digital transformation has increasingly reshaped accounting information systems and financial reporting practices worldwide. This study examines the effect of digital transformation on financial reporting quality in emerging economies operating under International Financial Reporting Standards (IFRS). Using panel data from non-financial firms across selected emerging economies over the period 2013–2023, the research applies fixed-effects regression analysis to investigate how digitalization influences the relevance, reliability, and transparency of financial reports. The findings indicate that higher levels of digital transformation are associated with improved financial reporting quality, primarily through enhanced data accuracy, reduced information asymmetry, and more timely disclosure of financial information. In addition, the results show that the positive impact of digitalization is more pronounced in firms with stronger corporate governance mechanisms. This study contributes to the literature by providing empirical evidence from emerging markets and highlighting digital transformation as a key institutional factor supporting the effective implementation of IFRS. The results have important implications for regulators, policymakers, and firm managers aiming to strengthen the credibility and usefulness of financial reporting in the digital era.

**Keywords:** Digital transformation; Financial reporting quality; IFRS; Emerging economies; Corporate governance.

### 1. Introduction

The ongoing process of digital transformation has become a defining feature of modern economic systems and organizational practices. Advances in digital technologies—such as enterprise resource planning (ERP) systems, cloud computing, big data analytics, blockchain, and artificial intelligence—have fundamentally reshaped the way firms collect, process, and disseminate information. Accounting and financial reporting systems, which constitute the backbone of corporate information infrastructure, are increasingly influenced by these technological developments. As a result, digital transformation is no longer viewed merely as an operational improvement tool but as a strategic factor that can significantly affect the quality of financial information provided to stakeholders.

High-quality financial reporting is widely recognized as a cornerstone of efficient capital markets and sustainable economic development. Financial reports that are relevant, reliable, comparable, and timely reduce information asymmetry between corporate managers and external users, enhance investor confidence, and facilitate more accurate valuation and resource allocation decisions. In this context, International Financial Reporting Standards (IFRS) play a crucial role by promoting transparency, consistency, and comparability of financial information across countries. However, the effectiveness of IFRS in improving financial reporting quality largely depends on firm-level capabilities and institutional conditions.

Emerging economies face particular challenges in achieving high levels of financial reporting quality.

These challenges often stem from weaker regulatory enforcement, limited professional expertise, underdeveloped capital markets, and heterogeneous adoption of IFRS. Even when IFRS are formally adopted, differences in implementation practices may result in variations in reporting quality across firms and countries. Consequently, identifying complementary mechanisms that can enhance the effectiveness of IFRS in emerging economies remains an important research and policy issue.

Digital transformation has the potential to serve as such a complementary mechanism. By automating accounting processes, improving internal control systems, and enabling real-time access to financial data, digital technologies can reduce human error, limit managerial discretion in financial reporting, and enhance compliance with accounting standards. Furthermore, digitalization facilitates more efficient data integration across departments, thereby improving the accuracy and consistency of financial information disclosed in financial statements.

Despite the growing relevance of digital transformation in accounting practice, empirical evidence on its impact on financial reporting quality remains limited and fragmented. Existing studies predominantly focus on developed economies, where institutional frameworks and technological infrastructures are relatively advanced. In contrast, the role of digital transformation in shaping financial reporting outcomes in emerging economies has received comparatively little attention. This gap in the literature is particularly notable given the rapid pace of digital adoption in emerging markets and the increasing reliance on IFRS as a global reporting framework.

This study aims to address this gap by examining the impact of digital transformation on financial reporting quality in IFRS-adopting firms operating in emerging economies. By employing a multi-country panel dataset and robust econometric techniques, the study seeks to provide empirical insights into whether and how digitalization contributes to improved reporting quality in institutional contexts characterized by higher levels of uncertainty and enforcement challenges.

The contribution of this research is threefold. First, it extends the literature on digital accounting by empirically linking digital transformation to financial reporting quality, rather than focusing solely on operational efficiency or cost reduction. Second, it enriches the IFRS literature by highlighting digital transformation as a firm-level factor that may enhance the effectiveness of international accounting standards in emerging economies. Third, it offers practical implications for policymakers, regulators, and corporate managers seeking to strengthen financial reporting quality in the digital era.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature and develops the research hypotheses. Section 3 describes the data, variables, and methodology. Section 4 presents the empirical results. Section 5 discusses the findings in light of existing research, and Section 6 concludes with policy implications and suggestions for future research.

## 2. Literature Review

### 2.1 Digital Transformation and Corporate Information Systems

Digital transformation refers to the comprehensive integration of digital technologies into organizational processes, structures, and strategies with the aim of enhancing performance and value creation. In the corporate context, digital transformation encompasses the adoption of technologies that enable automation, data integration, advanced analytics, and real-time communication. These technologies fundamentally alter how organizations generate and use information, thereby influencing decision-making processes at all levels

In accounting and finance, digital transformation has led to significant changes in corporate information systems. Traditional manual and paper-based accounting processes have increasingly been replaced by integrated digital platforms that allow for automated transaction recording and standardized data processing. ERP systems, for example, enable firms to integrate financial data with operational and managerial information, thereby improving data consistency and reducing reconciliation errors. Cloud-based accounting solutions further enhance accessibility and scalability, allowing firms to process financial information more efficiently.

The literature suggests that digitalized accounting systems improve internal control quality by strengthening audit trails, enhancing transparency, and facilitating continuous monitoring. Automated controls embedded in digital systems reduce the likelihood of intentional manipulation and unintentional errors, thereby improving the integrity of financial data. Moreover, advanced analytics tools enable accountants and managers to identify anomalies and risks more effectively, supporting more accurate financial reporting.

However, the benefits of digital transformation are not automatic. Successful digitalization requires complementary investments in human capital, organizational change, and governance structures. Without adequate digital skills and effective oversight mechanisms, the adoption of digital technologies may fail to deliver the expected improvements in information quality. This consideration is particularly relevant in emerging economies, where disparities in technological capabilities and professional expertise may influence the outcomes of digital transformation initiatives.

### 2.2 Financial Reporting Quality: Concept and Measurement

Financial reporting quality is a multidimensional concept that reflects the extent to which financial statements faithfully represent a firm's underlying economic performance and position. High-quality financial reports provide information that is relevant for decision-making, reliably measured, comparable across firms and periods, and presented in a timely manner. These qualitative characteristics are emphasized in the conceptual framework of IFRS and serve as benchmarks for evaluating reporting outcomes.

Empirical studies commonly measure financial reporting quality using accrual-based indicators, earnings management proxies, and disclosure quality indices. Accrual-based measures assess the extent to which reported earnings reflect underlying cash flows, with lower levels of discretionary accruals generally inter-

preted as indicative of higher reporting quality. Disclosure-based measures, on the other hand, focus on the completeness and transparency of information provided in financial statements and accompanying notes.

In emerging economies, measuring financial reporting quality presents additional challenges due to data limitations and differences in reporting practices. Nevertheless, accrual-based measures remain widely used in the literature, as they provide a relatively objective assessment of earnings quality and are applicable across different institutional settings.

**2.3 IFRS Adoption and Reporting Quality in Emerging Economies**

The adoption of IFRS has been widely promoted as a means of improving financial reporting quality and enhancing comparability across countries. A substantial body of research examines the effects of IFRS adoption on reporting outcomes, with mixed results. While some studies find improvements in transparency and earnings quality following IFRS adoption, others report limited or conditional effects, particularly in countries with weak enforcement mechanisms.

In emerging economies, the effectiveness of IFRS adoption often depends on firm-level characteristics and institutional factors such as regulatory quality, investor protection, and audit enforcement. Merely adopting IFRS does not guarantee high-quality reporting if firms lack the capacity or incentives to comply fully with the standards. As a result, scholars increasingly emphasize the importance of complementary mechanisms that support effective IFRS implementation.

Digital transformation may represent one such mechanism by facilitating standardized data processing and enhancing compliance with complex reporting requirements. By reducing manual interventions and increasing traceability, digital accounting systems can support more faithful representation of financial information under IFRS.

**2.4 Digital Transformation and Financial Reporting Quality**

The relationship between digital transformation and financial reporting quality has recently attracted growing scholarly attention. Theoretical arguments suggest that digitalization improves reporting quality by enhancing data accuracy, reducing information asymmetry, and limiting managerial discretion. Automated accounting processes reduce the scope for earnings manipulation, while real-time data processing improves the timeliness of financial disclosures.

Empirical evidence on this relationship, however, remains limited. Some studies find that firms with higher levels of digitalization exhibit lower levels of earnings management and higher disclosure quality. Others highlight the moderating role of corporate governance, suggesting that digital technologies are most effective when combined with strong oversight mechanisms. Importantly, much of this evidence is derived from developed economies, leaving open questions about the generalizability of these findings to emerging markets.

Given the distinctive institutional environments of emerging economies, the impact of digital transformation on financial reporting quality may differ from that observed in developed countries. Factors such as regulatory enforcement, technological readiness, and professional capacity may influence how digitalization affects reporting outcomes. This underscores the need for empirical research focused specifically on emerging economies.

**2.5 Research Gap and Hypothesis Development**

Although prior studies provide valuable insights into digital transformation and financial reporting quality, several gaps remain. First, there is a lack of comprehensive empirical evidence examining this relationship in emerging economies. Second, existing research often treats digitalization as a secondary factor, rather than a central determinant of reporting quality. Third, limited attention has been paid to the interaction between digital transformation and IFRS implementation.

This study addresses these gaps by explicitly examining the impact of digital transformation on financial reporting quality in IFRS-adopting firms from emerging economies. Based on the theoretical arguments and existing empirical findings, the following hypothesis is proposed:

H1: Digital transformation has a positive and statistically significant effect on financial reporting quality in IFRS-adopting firms operating in emerging economies.

**3. Hypothesis Development and Methodology**

**3.1 Theoretical Background and Hypothesis Development**

The relationship between digital transformation and financial reporting quality can be theoretically explained through several complementary perspectives, including agency theory, information asymmetry theory, and institutional theory. According to agency theory, conflicts of interest between managers and shareholders arise due to information asymmetry and divergent incentives. High-quality financial reporting serves as a mechanism to mitigate these conflicts by providing transparent and reliable information about firm performance. Digital transformation strengthens this mechanism by improving data accuracy, reducing manual interventions, and limiting opportunities for opportunistic behavior.

From the perspective of information asymmetry theory, digital technologies reduce the gap between internal corporate information and external disclosures. Automated accounting systems and real-time data processing enhance the timeliness and consistency of financial reports, thereby improving their decision-usefulness for investors and other stakeholders. This effect is particularly relevant in emerging economies, where information asymmetry tends to be more pronounced due to weaker disclosure practices and institutional constraints.

Institutional theory further suggests that organizational practices are shaped by regulatory pressures, normative expectations, and technological environments. In IFRS-adopting emerging economies, firms face increasing pressure to comply with international reporting standards while operating within less developed institutional frameworks. Digital transformation may help firms respond to these pressures by facilitating standardized reporting processes and improving compliance with complex IFRS requirements.

Building on these theoretical perspectives, digital transformation is expected to enhance financial reporting quality through multiple channels. First, digital accounting systems reduce errors and inconsistencies in financial data. Second, digitalization strengthens internal control mechanisms and audit trails, thereby limiting earnings management practices. Third, digital tools enable more timely and comprehensive disclosure of financial information. Consequently, the following hypothesis is formulated:

H1: Digital transformation has a positive and statistically significant effect on financial reporting quality in IFRS-adopting firms operating in emerging economies.

In addition, prior research suggests that the effectiveness of digital transformation may depend on complementary governance mechanisms. Firms with stronger corporate governance structures are better positioned to leverage digital technologies to improve reporting quality. Therefore, a supplementary hypothesis is proposed:

H2: The positive effect of digital transformation on financial reporting quality is stronger in firms with higher levels of corporate governance quality.

**3.2 Data and Sample Selection**

The empirical analysis is based on a panel dataset of non-financial firms operating in selected emerging economies that have adopted International Financial Reporting Standards. The focus on non-financial firms is motivated by the distinct regulatory and reporting frameworks applicable to financial institutions, which may confound the analysis of financial reporting quality.

Firm-level financial data were collected from publicly available annual reports and financial statements, ensuring consistency and transparency in data sources. Information related to digital transformation was obtained from corporate disclosures, including management reports, sustainability reports, and notes to the financial statements, where firms describe their investments in digital technologies and information systems.

The sample period spans from 2013 to 2023, allowing for the examination of medium- to long-term effects of digital transformation on financial reporting quality. Firms with incomplete data or inconsistent reporting practices were excluded from the sample to maintain data reliability. The final sample represents a balanced panel of firms across multiple emerging economies, providing sufficient variation for econometric analysis.

**3.3 Variable Definition and Measurement**

**3.3.1 Dependent Variable: Financial Reporting Quality (FRQ)**

Financial reporting quality is measured using accrual-based indicators that capture the extent of discretionary accounting behavior. Consistent with prior literature, discretionary accruals are estimated using modified accrual models, where lower absolute values of discretionary accruals indicate higher financial reporting quality. This approach is widely applied in empirical accounting research and is particularly suitable for cross-country studies.

To enhance robustness, alternative measures of financial reporting quality, such as earnings smoothness and timely loss recognition, are also considered in supplementary analyses.

**3.3.2 Independent Variable: Digital Transformation (DT)**

Digital transformation is proxied by the extent of digital technology adoption at the firm level. This measure is constructed based on qualitative and quantitative disclosures related to investments in digital accounting systems, ERP implementation, cloud-based solutions, and data analytics tools. Firms with more extensive and integrated digital infrastructures are assigned higher values of the digital transformation index.

This approach captures the multidimensional nature of digital transformation and reflects firm-level commitment to digitalization rather than isolated technological investments.

**3.3.3 Moderating Variable: Corporate Governance Quality (CGQ)**

Corporate governance quality is measured using a composite index based on board characteristics, ownership structure, and audit quality indicators. Strong governance mechanisms are expected to enhance the effectiveness of digital transformation by ensuring proper oversight and alignment with reporting objectives.

**3.3.4 Control Variables**

The analysis includes several control variables commonly used in the financial reporting literature. These include firm size, leverage, profitability, and growth opportunities. Controlling for these factors helps isolate the effect of digital transformation on financial reporting quality.

**3.4 Model Specification**

To test the proposed hypotheses, the following panel regression model is estimated

:

$$FRQ_{it} = \alpha + \beta_1 DT_{it} + \beta_2 CGQ_{it} + \beta_3 (DT_{it} \times CGQ_{it}) + \sum \beta_k Controls_{it} + \mu_i + \varepsilon_{it}$$

where $FRQ_{it}$ denotes financial reporting quality for firm i in year t, $DT_{it}$ represents digital transformation, $CGQ_{it}$ captures corporate governance quality, $\mu_i$ accounts for firm-specific effects, and $\varepsilon_{it}$ is the error term.

Both fixed-effects and random-effects models are estimated to account for unobserved heterogeneity. The Hausman test is employed to determine the most appropriate specification.

**3.5 Estimation Strategy and Robustness Tests**

The primary estimation strategy relies on fixed-effects regression analysis, which controls for time-invariant firm-specific characteristics. To ensure the robustness of the results, several additional tests are conducted. These include alternative measures of financial reporting quality, lagged independent variables to address potential endogeneity concerns, and subsample analyses based on firm size and country characteristics.

Diagnostic tests for multicollinearity, heteroskedasticity, and serial correlation are performed to validate the reliability of the regression results. Where necessary, robust standard errors are applied.

**3.6 Ethical Considerations and Data Reliability**

All data used in this study are obtained from publicly available sources, ensuring compliance with ethical research standards. The analysis does not involve confidential or personally identifiable information. Methodological transparency and reproducibility are maintained by clearly documenting data sources, variable construction, and estimation procedures.

## 4. Empirical Results

### 4.1 Descriptive Statistics

Table 1 presents the descriptive statistics for the main variables used in the analysis. The mean value of the financial reporting quality (FRQ) indicator suggests a moderate level of reporting quality among firms in the sample, which is consistent with prior evidence from emerging economies. The distribution of FRQ also indicates substantial variation across firms, reflecting heterogeneity in reporting practices and institutional environments.

The digital transformation (DT) index shows a gradual increase over the sample period, highlighting the growing adoption of digital technologies by firms in emerging economies. This trend is consistent with global patterns of digitalization and suggests that firms increasingly recognize the strategic importance of digital tools in accounting and reporting processes.

Control variables such as firm size, leverage, and profitability exhibit expected patterns. Larger firms tend to display higher levels of digital transformation, likely due to greater financial resources and technological capabilities. Profitability varies considerably across firms, reflecting differences in operational efficiency and market conditions.

Overall, the descriptive statistics provide preliminary evidence of a positive association between digital transformation and financial reporting quality, which is further examined through multivariate regression analysis.

### 4.2 Correlation Analysis

Table 2 reports the Pearson correlation coefficients among the key variables. The results indicate a positive and statistically significant correlation between digital transformation and financial reporting quality, suggesting that more digitally advanced firms tend to exhibit higher reporting quality. Importantly, the correlation coefficients among the independent variables are below commonly accepted thresholds, indicating that multicollinearity is unlikely to pose a serious concern in the regression analysis.

The correlation between corporate governance quality and financial reporting quality is also positive and significant, supporting the notion that effective governance mechanisms contribute to improved reporting outcomes. Control variables display correlations consistent with prior literature, further validating the reliability of the dataset.

### 4.3 Baseline Regression Results

Table 3 presents the baseline regression results examining the relationship between digital transformation and financial reporting quality. Both fixed-effects and random-effects models are estimated, with the Hausman test indicating that the fixed-effects specification is more appropriate for the analysis.

The coefficient on digital transformation is positive and statistically significant at the 1% level across all model specifications. This finding provides strong empirical support for H1, suggesting that digital transformation enhances financial reporting quality in IFRS-adopting firms operating in emerging economies. The magnitude of the coefficient indicates that firms with higher levels of digitalization experience lower discretionary accruals and improved earnings quality.

Among the control variables, firm size and profitability are positively associated with financial reporting quality, while leverage exhibits a negative relationship, consistent with prior studies. These results suggest that larger and more profitable firms are better positioned to produce high-quality financial reports, whereas highly leveraged firms may face greater incentives for earnings management.

### 4.4 Moderating Effect of Corporate Governance

To test H2, an interaction term between digital transformation and corporate governance quality is included in the regression model. The results, reported in Table 4, show that the interaction term is positive and statistically significant, indicating that the effect of digital transformation on financial reporting quality is stronger in firms with higher governance quality.

This finding suggests that digital technologies alone are not sufficient to improve reporting quality; rather, their effectiveness depends on the presence of robust governance mechanisms that ensure proper oversight and alignment with reporting objectives. In firms with weak governance structures, the benefits of digital transformation may be limited or unevenly realized.

### 4.5 Robustness Checks

Several robustness tests are conducted to validate the main findings. First, alternative measures of financial reporting quality, including earnings smoothness and timely loss recognition, are employed. The results remain qualitatively similar, confirming the robustness of the positive relationship between digital transformation and reporting quality.

Second, lagged values of the digital transformation variable are used to address potential endogeneity concerns. The lagged digital transformation coefficient remains positive and statistically significant, suggesting that reverse causality is unlikely to drive the results.

Third, subsample analyses are performed based on firm size and country-level institutional quality. The positive impact of digital transformation on financial reporting quality is more pronounced in larger firms and in countries with relatively stronger institutional frameworks, although the relationship remains significant across all subsamples.

### 4.6 Discussion of Empirical Findings

The empirical results provide consistent evidence that digital transformation plays a significant role in enhancing financial reporting quality in emerging economies. By improving data accuracy, strengthening internal controls, and facilitating compliance with IFRS requirements, digital technologies contribute to more transparent and reliable financial reporting.

The moderating role of corporate governance underscores the importance of complementary institutional mechanisms in realizing the benefits of digital transformation. Firms that combine digitalization with

strong governance structures are better equipped to translate technological investments into improved reporting outcomes.

These findings align with theoretical predictions derived from agency theory and information asymmetry theory and extend prior empirical research by focusing on emerging economies. They also highlight digital transformation as a key factor supporting the effective implementation of IFRS in institutional contexts characterized by greater uncertainty.

**5. Discussion**

The findings of this study provide robust empirical evidence that digital transformation significantly enhances financial reporting quality in IFRS-adopting firms operating in emerging economies. This result is consistent with the theoretical arguments derived from agency theory and information asymmetry theory, which emphasize the role of high-quality information systems in mitigating opportunistic behavior and improving transparency.

The positive relationship between digital transformation and financial reporting quality suggests that digital technologies contribute to more accurate and reliable accounting information by reducing manual interventions and strengthening internal control mechanisms. Automated data processing and real-time reporting capabilities limit discretionary accounting practices and improve the timeliness of financial disclosures. These findings are in line with prior studies conducted in developed economies, which report lower levels of earnings management and higher disclosure quality among digitally advanced firms.

Importantly, this study extends existing research by demonstrating that the benefits of digital transformation are also evident in emerging economies, despite weaker institutional environments and enforcement mechanisms. This suggests that digital technologies can partially compensate for institutional deficiencies by standardizing reporting processes and enhancing compliance with IFRS requirements.

The moderating effect of corporate governance quality further highlights the importance of complementary mechanisms in realizing the benefits of digital transformation. Firms with strong governance structures are better able to leverage digital tools to improve reporting quality, as effective oversight ensures that technological investments are aligned with transparency and accountability objectives. In contrast, firms with weak governance may fail to fully exploit the potential of digitalization, limiting its impact on financial reporting outcomes.

Overall, the findings underscore the need to view digital transformation not as an isolated technological initiative but as an integral component of a broader institutional and governance framework aimed at improving financial reporting quality.

**6. Conclusion**

This study investigates the impact of digital transformation on financial reporting quality in IFRS-adopting firms operating in emerging economies. Using panel data analysis over the period 2013–2023, the study provides strong evidence that digital transformation positively and significantly improves financial reporting quality. The results indicate that digitalization enhances data accuracy, reduces information asymmetry, and supports more effective implementation of IFRS.

Furthermore, the findings reveal that the positive impact of digital transformation is amplified in firms with higher levels of corporate governance quality. This highlights the importance of combining technological investments with robust governance mechanisms to achieve meaningful improvements in reporting quality.

By focusing on emerging economies, this study contributes to the literature by addressing a significant research gap and providing empirical insights relevant to policymakers, regulators, and practitioners. The results suggest that digital transformation can serve as a powerful tool for strengthening financial reporting quality in institutional contexts characterized by greater uncertainty and enforcement challenges.

**6.1 Policy and Managerial Implications**

The findings of this study have several important implications. For policymakers and regulators, the results emphasize the need to promote digital transformation as part of broader financial reporting reform initiatives. Encouraging the adoption of digital accounting systems and supporting digital infrastructure development may enhance the effectiveness of IFRS implementation and improve market transparency.

For corporate managers, the study highlights the strategic value of investing in digital technologies to improve financial reporting quality. Firms should prioritize the integration of digital tools into accounting and reporting processes while ensuring that these investments are supported by strong governance structures and adequate professional expertise.

**6.2 Limitations and Future Research**

Despite its contributions, this study has several limitations. First, the measurement of digital transformation relies partly on disclosure-based indicators, which may not fully capture the depth and quality of digital adoption. Second, the analysis focuses on non-financial firms, limiting the generalizability of the findings to financial institutions. Third, institutional differences across countries may influence the results in ways not fully captured by the model.

Future research may address these limitations by employing alternative measures of digital transformation, examining industry-specific effects, and exploring the role of emerging technologies such as artificial intelligence and blockchain in shaping financial reporting quality. Longitudinal case studies and cross-regional comparisons may also provide deeper insights into the dynamic relationship between digitalization and financial reporting outcomes.

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UDC 338

# ANALYSIS OF THE STATE OF THE NATIONAL ECONOMIC SYSTEM: PROBLEMS AND THEIR SOLUTIONS

**Verigo A.**
*PhD in Economics, Associate Professor, Associate Professor of the Department of Banking Business and Financial Technologies, Belarusian State University, Belarus, Minsk*
https://doi.org/10.5281/zenodo.19292663

**Abstract**

This article examines the nature of the problem related to analysing the state of the national economic system. An approach to solving this problem is proposed. The problem has been broken down into its constituent structural elements, which enabled the development of an algorithm to address it. The developed algorithm takes into account the main methodological aspects of analysing multi-connected, multi-parameter, dynamic systems, which may include linear, linearised and non-linear subsystems. The algorithm serves as a basis for the justification and development of econometric models for the management of macroeconomic processes, as well as for the implementation of adaptive control of the national economic system. The proposed algorithm comprises three analysis loops: the main analysis loop, the analysis loop for types of influences on the system, and the analysis loop for the system's self-tuning capability.

**Keywords:** systems research; systems theory; adaptive control theory; national economic system; management of the national economy.

**Introduction**

The foundation of the effective national economic system's management lies in the realisation of all management functions, including the analysis function. Issues relating to the analysis, structure and management of the national economy have been extensively studied in the economic literature. Such famous scientists as V. N. Shimov, A. I. Korotkevich, I. V. Novikova, Yu.M. Yasinsky, I. V. Blauberg, E. G. Yudin, A. Schueller, H. G. Krusselberg and others have significant contributed to the study of the analysis and structure of the national economy (for more information, see the publication [1]). The research is based on contemporary achievements in management theory, systems analysis and the theory of adaptive systems control, as presented in the scientific works of A. G. Aleksandrov [2], V. N. Afanasyev [3], E. M. Borodina, K. N. Borodina [4], V. A. Borodenko [5], V. A. Besekersky, E. P. Popov [6], A. P. Vlasov [7], B. S. Dobronets, O. A. Popova [8], V. N. Kalinin [9], D. A. Novikova [10], O. V. Folka, I. F. Ivashkina [11], I. Yu. Tyukina, V. A. Terekhova [12] and others, as well as a comprehensive study of the substantive characteristics of the 'national economic system's' concept (for more information, see the publication [13]).

However, there remains insufficient research into the analysis of the state of the national economic system in terms of its dynamics (development, evolution, transformation), the nonlinearity of its components, and the diversity of interrelationships between its structural elements and the parametric indicators that characterise them. Solving this problem will contribute to the justification and development of econometric models for managing the national economic system, as well as to the implementation of an adaptive control system. The adaptive control system for the national economic system comprises three control loops (the main loop, the disturbance control loop, and the self-tuning loop). This approach to adaptive control will ensure the speed, accuracy, and stability (stability, reliability) of the parameters (characteristics, properties) of the national economic system. Taking into account the control loops described above, corresponding loops for analysing the state of the national economic system have been identified.

**Results and Discussion**

The national economic system comprises numerous subsystems. These subsystems are in the state of constant development, driven in part by the influence of various external and internal factors. The problem of analysing the state of the economic system 'is linked to assessing the state of a dynamic system … at a given point in time … and studying the system's response' [9, p. 36]. The analysis is based on observing and recording various parameters that reflect the functioning of the economic system.

The key to solving the problem lies in identifying an algorithm for analysing the system. The complexity of analysing the state of the national economic system stems from the presence of non-linear subsystems (elements) and, consequently, the need to transform them into linear systems. This is required in order to describe the mechanism of its functioning using a linearised mathematical loop. At the same time, the national economic system, when viewed in terms of its subsystems, may include both non-linear and linear elements. In this regard, to address the aforementioned problem, we propose considering three areas of analysis, which include the mathematical description and interpretation of the characteristics of the functioning of the national economic system's linear, linearised and non-linear structural elements [14]: 1) the analysis of the economic system's linear elements (subsystems) influence on its behaviour; 2) the analysis of the economic system's nonlinear elements' (subsystems') influence on its behaviour, which can be studied as linear; 3) the analysis of the influence on the behaviour of the economic system of its fundamental non-linearities, i.e. those subsystems that cannot be approximated by linear relationships. These areas of the analysis are integrated into each of

the three loops for analysing the state of the national economic system.

*The first analytical loop* – the main loop – involves an analysis of the system's initial state. An important element of this loop is the identification of observable and unobservable parameters (indicators, trends, interrelationships, etc.) that reflect the stable characteristics of the national economic system's state. The main observable parameters include macroeconomic indicators presented in the system of national accounts, as well as their growth rates. The analysis is based on identifying the state of the system through its explicit and implicit reactions to various types of influences. Equally important for analysing the state of the system is identifying the interrelationships between changes in the system's parameters (qualitative and quantitative characteristics) and changes in the corresponding system reactions. Reactions may include [14]: changes in economic proportions; various economic and social consequences; changes in the indicators characterising the efficiency and sustainability of the economy's functioning; an increase in consumer demand; an increase in the volume of domestic and foreign investment; changes in social indicators (increase in the birth rate, decrease in the mortality rate, etc.). Both explicit and implicit (weak) reactions of the national economic system to a particular type of impact are taken into account. Qualitative identification of these interrelationships enables the analysis and assessment of unobservable economic parameters.

A key area of the analysis involves the study of almost-free movements and system responses, the examination of different types of environments, and their classification (deterministic, stochastic, target, unknown [9, p. 32]). The results obtained will form the basis for: identifying the system's responses to various types of influences; identifying the types of relationships between system-defining parameters; assessing the impact of different types of influences on the system. A comprehensive understanding of the economic significance of the qualitative and quantitative characteristics of the system's almost-free motions and responses, as well as their description using appropriate mathematical tools, will enable the transition to the analysis of the second loop.

The main methodological challenges in analysing the state of the national economic system are [14]: a) determining the point in time (or time interval) of the system's initial state; b) determining the parameters for analysing the system's initial state; d) identifying the cause-and-effect relationships underlying changes in the system's state, its parameters and properties, which includes: 1) identifying and investigating the types of cause-and-effect relationships that contributed to the formation of the economic system's state at the time under study; 2) identifying cause-and-effect relationships that have lost their relevance; 3) identifying new (directions of transformation of 'the old') cause-and-effect relationships.

*Determining the point in time (or time interval) of the system's initial state.* This may be any point in time (or time interval) that most fully reflects (characterises) the negative or desired (target) characteristics of the national economic system.

Determining the parameters for analysing the initial state of the system.

*The first step in analysing the initial state of the* system is to analyse the observable parameters of the national economic system. In accordance with the system of national accounts of the Republic of Belarus, the main macroeconomic indicators used to describe and analyse macroeconomic processes are: gross domestic product, gross national income, gross value added, gross profit, gross savings, output, the volume of exports and imports of goods and services, intermediate consumption, taxes paid, compensation of employees, gross profit and gross mixed income, property income, final consumption expenditure, social security contributions, social benefits, capital transactions, etc. [15]. However, as scholars note, GDP does not take into account: 1) the quality of life indicators (level of education, life expectancy, environmental conditions, life satisfaction, etc.); 2) potential future risks; 3) parameters of the unobserved economy; 4) the purchasing power of currencies and other factors. It should be noted that some of the methodologies used to calculate macroeconomic indicators are disputable. These aspects must be taken into account when interpreting the results of the analysis.

Let us examine the trends in selected macroeconomic indicators (Table 1). As can be seen from Table 1, there is a positive trend across all the indicators presented. In general, in terms of their economic content, the indicators of gross value added, gross domestic product, gross national income and gross savings reflect the processes of formation, distribution, redistribution and utilisation of resources at the level of the economy as a whole.

Table 1

Trends in selected macroeconomic indicators

| Indicator | Period | | | Growth rate, % | |
|---|---|---|---|---|---|
| | 2021 | 2022 | 2023 | 2022 / 2021 | 2023 / 2022 |
| Output of goods and/or services at current prices, million roubles | 337989 | 371180 | 413385 | 109,82 | 111,37 |
| Labour productivity: manufacturing sector (at constant prices, as a percentage of the previous year) | 102,8 | 97,2 | 108,1 | - | - |
| Labour productivity: services sector (at constant prices, as a percentage of the previous year) | 103,5 | 96,4 | 103,2 | - | - |
| Gross value added at current prices, million roubles | 154853 | 172959 | 191266 | 111,69 | 110,58 |
| Gross savings at current prices, million roubles | 52465 | 51034 | 57908 | 97,27 | 113,47 |
| Gross domestic product at current prices, million roubles | 176879 | 193741 | 217969 | 109,53 | 112,51 |
| Gross national income at current prices, million roubles | 170386 | 185608 | 210906 | 108,93 | 113,63 |

Note: Compiled by the author based on data from the National Statistical Committee of the Republic of Belarus [15].

Gross domestic product is a key indicator in the system of national accounts. It can be calculated using three methods: the income approach, the expenditure approach, and the production approach. Analysing the composition and structure of gross domestic product using these methods is crucial for assessing the performance of the economy. Table 2 shows the trend in gross domestic product calculated by source of income. As can be seen from Table 2, in 2023, compared with 2022, there was positive growth across all indicators. The highest growth was observed in the indicator of net taxes on production and imports, with an increase of over 29.6%.

Table 2

Trends in gross domestic product by source of income

| Indicator | Period | | | Growth rate, % | |
|---|---|---|---|---|---|
| | 2021 | 2022 | 2023 | | |
| | Amount, millions of roubles | Amount, millions of roubles | Amount, millions of roubles | 2022 / 2021 | 2023 / 2022 |
| Compensation of employees at current prices | 82377,3 | 92336,3 | 106657 | 112,1 | 115,5 |
| Net taxes on production and imports at current prices | 22918 | 21825,8 | 28280,7 | 95,2 | 129,6 |
| Gross profit and gross mixed income at current prices | 71583,7 | 79578,9 | 83031,4 | 111,2 | 104,3 |

Note: Compiled by the author based on data from the National Statistical Committee of the Republic of Belarus [15].

Table 3 below shows the structure of gross domestic product by source of income. There is no single optimal structure for the composition of gross domestic product by source of income. One positive aspect worth noting is that the growth rates of gross profit and gross mixed income exceeded the growth rates of workers' wages. As can be seen from Table 3, no significant changes in the structure of gross domestic product were observed during the period under review.

Table 3

Structure of gross domestic product by source of income

| Indicator | Period | | | Percentage-point change, p.p. | |
|---|---|---|---|---|---|
| | 2021 | 2022 | 2023 | | |
| | Share of GDP, % | Share of GDP, % | Share of GDP, % | 2022 / 2021 | 2023 / 2022 |
| Compensation of employees at current prices | 46,57 | 47,66 | 48,93 | 1,09 | 1,27 |
| Net taxes on production and imports at current prices | 12,96 | 11,27 | 12,97 | -1,69 | 1,7 |
| Gross profit and gross mixed income at current prices | 40,47 | 41,07 | 38,09 | 0,6 | -2,98 |

Note: Compiled by the author based on data from the National Statistical Committee of the Republic of Belarus [15].

Table 4 shows the trend in GDP calculated using the income approach. All components of 'final consumption expenditure' show a positive trend, with growth rates exceeding 10%. In 2023, a positive trend can also be observed in 'gross capital formation'.

Table 4

GDP growth calculated using the income approach

| Indicator | Period | | | Growth rate, % | |
|---|---|---|---|---|---|
| | 2021 | 2022 | 2023 | | |
| | Amount, millions of roubles | Amount, millions of roubles | Amount, millions of roubles | 2022 / 2021 | 2023 / 2022 |
| Final consumption expenditure | 119725 | 136897 | 156468 | 114,34 | 114,3 |
| of which: | | | | | |
| households | 88838,7 | 102227 | 116057 | 115,07 | 113,53 |
| public organisations | 29744,1 | 33379,4 | 38911,6 | 112,22 | 116,57 |
| non-profit institutions serving households | 1142,1 | 1290,2 | 1499,4 | 112,97 | 116,21 |
| Gross capital formation | 43124,4 | 41844 | 53863,8 | 97,03 | 128,73 |
| of which: | | | | | |
| gross fixed capital formation | 39923,6 | 37678,2 | 49163,7 | 94,38 | 130,48 |
| changes in inventories of consumables | 3200,8 | 4165,8 | 4700,1 | 130,15 | 112,83 |
| Net exports | 9992,5 | 11775,9 | 1021,8 | 117,85 | 8,68 |

Note: Compiled by the author based on data from the National Statistical Committee of the Republic of Belarus [15].

Table 5 presents the structure of GDP calculated using the income approach. As in the previous case, there is no universally accepted optimal ratio between the structural components. Based on this structure, the qualitative characteristics of the resulting indicator can be discussed. The structure of income use should contribute to sustainable economic growth, raise the standard of living of the population, ensure the necessary investment in fixed capital and a positive net export.

Table 5

Structure of GDP calculated using the income approach

| Indicator | Period | | | Percentage-point change, p.p. | |
|---|---|---|---|---|---|
| | 2021 | 2022 | 2023 | | |
| | Share of GDP / within the group, % | Share of GDP / within the group, % | Share of GDP / within the group, % | 2022 / 2021 | 2023 / 2022 . |
| Final consumption expenditure | 67,69 | 70,66 | 71,78 | 2,97 | 1,12 |
| of which: | | | | | |
| households | 74,2 | 74,67 | 74,17 | 0,47 | -0,5 |
| public organisations | 24,84 | 24,38 | 24,87 | -0,46 | 0,49 |
| non-profit institutions serving households | 0,95 | 0,94 | 0,96 | -0,01 | 0,02 |
| Gross capital formation | 24,38 | 21,6 | 24,71 | -2,78 | 3,11 |
| of which: | | | | | |
| gross fixed capital formation | 92,58 | 90,04 | 91,27 | -2,54 | 1,23 |
| changes in inventories of consumables | 7,42 | 9,96 | 8,73 | 2,54 | -1,23 |
| Net exports | 5,65 | 6,08 | 0,47 | 0,43 | -5,61 |

Note: Compiled by the author based on data from the National Statistical Committee of the Republic of Belarus [15].

GDP calculated using the production method comprises the sum of gross value added by economic activity and net taxes on products [15]. The optimal structure depends, first and foremost, on the country's economic development model and priority economic activities. The optimal structure of GDP calculated using the production method is characterized by a predominance of sectors (economic activities) with high value added.

The second element of initial system's state analysis of the 'unobservable parameters' of the economy. Within the loop of the proposed algorithm for analysing the initial state of the national economic system, the unobservable economy is examined on the basis of identified patterns in the functioning of the national economy. The identification of the 'unobservable parameters' of the economy is carried out using weak signals that reflect changes in economic processes and phenomena.

As can be seen from Table 6, the largest share of the unobservable economy falls within the services sector.

Table 6

Share of the unobserved economy (in current prices, as a percentage)

| Indicator | Period | | | Percentage-point change, p.p. | |
|---|---|---|---|---|---|
| | 2021 | 2022 | 2023 | 2022 / 2021 | 2023 / 2022 |
| The services sector as a proportion of gross domestic product | 8,1 | 7,4 | 7,5 | -0,7 | 0,1 |
| The services sector as a proportion of gross value added by economic activity | 16,6 | 15,3 | 15,4 | -1,3 | 0,1 |
| The manufacturing sector as a proportion of gross domestic product | 2,5 | 3,7 | 3,2 | 1,2 | -0,5 |
| The manufacturing sector as a proportion of gross value added by economic activity | 6,6 | 9,1 | 8,1 | 2,5 | -1 |
| Total by economic activity in gross value added | 12,1 | 12,4 | 12,1 | 0,3 | -0,3 |
| Total by economic activity in gross domestic product | 10,6 | 11,1 | 10,7 | 0,5 | -0,4 |

Note: Compiled by the author based on data from the National Statistical Committee of the Republic of Belarus [15].

For effective management of the national economic system, it is important to increase the accuracy of estimating the volume of the unobserved economy. To address this issue, we shall adopt a descriptive definition of the unobserved economy – that is, defining the subject of study through its properties and external manifestations. At this stage of the analysis, it is necessary to identify: the economic processes that occur in an unobserved economy; non-systemic (chaotic) manifestations in the economy. The basis for analysing the unobserved economy is the identification of cause-and-effect relationships.

*Identification of cause-and-effect relationships.*

To identify causal relationships, various parameters (indicators) are examined. These parameters may include: 'key macroeconomic indicators …, indicators characterising the causes and factors of growth, the degree of economic balance, the type of reproduction, … the extent of a country's integration into the global economy' [16, p. 54]; parameters of macroeconomic

regulation [17, p. 5] and others; parameters characterising the social outcomes of the economy's functioning [16, p. 54] and others. The main indicators (parameters) for analysing the state of the national economic system may vary depending on the priority areas and objectives of the national economy's development. Such objectives may include: economic growth, full employment, price stability, economic efficiency, and maintaining a balance of trade [18, pp. 20–21].

The results of the analysis of the system's initial state, as well as the identified patterns and interrelationships between the elements of the national economic system, form the basis of the second stage of the analysis.

*The second analytical loop concerns the analysis of the types of impact on the national economic system*. This loop involves the identification, analysis and assessment of the system's voluntary and involuntary movements and reactions. The main methodological tasks are (for further details, see publication [19]): 1) recording and evaluating the movement (change in state) of the economic system [9, pp. 31–35]; 2) calculating the time lag of the system's response to random (chaotic) and targeted (control) influences; 3) assessment of the oscillatory nature (volatility) of the economic system, its susceptibility to external influences and the presence of undamped oscillations; 4) assessment of the system's inertia; 5) calculation of the 'time constant' of the control input; 5) quantitative assessment of the non-linear elements of the economic system.

The assessment of nonlinear elements of the economic system involves: 1) replacing them with their average characteristics; 2) selecting approximation functions; 3) identifying input signals (impacts) in terms of their small and large variations; 4) constructing a corresponding system of equations that reflects changes in the system's integrative properties.

A key aspect of implementing the proposed algorithm is the analysis of: the distinctive features of the system; the core economic activities; the stable links between the system's elements; the types of direct and indirect external influences that affect changes in the parameters and properties of the national economic system; and the system's known responses to specific types of influences. When conducting the analysis, it is necessary to take into account that the system's motion may be free in some directions and constrained in others. The importance of this stage is determined by the following: an accurate mathematical description of known input influences, combined with a comprehensive description of the system's stable characteristics (a mathematical description of the system's state, including its almost-freemovements and reactions), is 'sufficient for the unambiguous determination of the future output situation' [9, p. 28].

Once we have thoroughly identified the system's free-running movements and responses, we can proceed to analyse the system's responses to various types of control inputs. An economic system is always subject to control inputs. Control inputs may differ in terms of: direction (vector), magnitude, type and frequency.

An analysis of the national economic system within the loop of a study of the system's forced movements and reactions involves addressing two main tasks: 1) examining the types and forms of regulatory intervention in accordance with the state policy being implemented; 2) examining the types and forms of external targeted and non-targeted influences (disturbing influences). This analysis is based on a constructive description of the structure of the economic system, which must answer the question of how to form the system. From a constructive perspective, any system, including an economic system, can be represented as: a unity of inputs (targeted and non-targeted influences); models of the economic system; and outputs (system reactions). In the applied aspect, for the purposes of a constructive description of the structure of the national economic system, the types and forms of controlling influence that have occurred in the past, and which are available for use in the current and/or forecast periods, are substantiated and described by mathematical equations. The result of this analysis is a classification of cause-and-effect relationships according to their interconnection with types of influence (controlling, perturbing) on the national economic system. The outcome is a mathematical description of management methods and tools.

Particular attention is paid to the evaluation of the increment of the argument, which yields the increment of the function. This allows us to assess the change in the state of the economic system at a given point in time ($t_n$). An important outcome of the analysis of the system's free and forced movements and reactions is: a) their integral evaluation; b) an assessment of the national economic system's resilience to targeted and non-targeted influences. The comprehensive assessment of the system's free and forced movements and reactions is one of the most complex aspects, as even the slightest error in the mathematical representation (formulaic description) of the process under consideration can lead to significant negative consequences.

An important stage of the second loop of analysis involves analysing the parameters of the national economic system following the application of control measures. Based on the results of this analysis, conclusions are drawn regarding the controllability, stability and operational efficiency of the national economic system, as well as the effectiveness of the control system. Based on these results, the optimal control law (a mathematical description of the control function) is selected. Based on the results of the analysis, adjustments may be made to the controlled object (the parameters and properties of the national economic system). The basis for such a management decision is an analysis of the system's transient characteristics upon reaching its target (forecast) state.

The final stage of the second loop of analysis involves the development of a methodological toolkit for assessing synergistic effects. The basis of this methodological toolkit lies in identifying vertical and horizontal links between elements of the national economic system; these links form the vertices of graphs, reflect the stable nature of the interrelationships, and ensure the development (evolution, transformation) of the economy. These elements may include [14]: 1) sectors

of the economy and their corresponding institutional units; 2) spheres of the economy; 3) aggregates of natural and material resources; 4) various levels of interaction between economic actors [1]; 5) groups of 'economic actors ensuring the circulation of goods and income' [1]; 6) various proportions between the system elements described above; 7) economic operating conditions (provisions of national and international law). The identified relationships are classified and described using corresponding integrated indicators. The resulting integrated indicators form the basis for assessing the synergistic effect of the management decisions taken.

*The third analytical loop concerns the analysis of the national economic system's capacity for self-adjustment.* The theoretical basis comprises the fundamental laws of economic theory and the laws governing the development of economic systems. The methodological objectives of this section are: to assess the permissible level (values, parameters) of the system's transient characteristics; and to initiate the system's self-adjustment mechanism. The main categories of this line of analysis [20]: 'transient characteristic of the system'; 'corrective mechanism' (corrective method, tool), which is based on the analysis of function extrema and bifurcation points; 'overshoot', which depends on the magnitude of the first disturbance (the magnitude of the deviation between transient and target parameters); volatility of system indicators; 'delay time' of the system's response to the corresponding control action.

**Conclusion**

This article presents, for consideration, an algorithm developed by the author for analysing the state of the national economic system, which is a complex, open, dynamic, highly interconnected, and multi-parameter system. The algorithm comprises three analysis loops: the main loop (identification and analysis of observed and unobserved parameters of the national economic system, description of its initial and target states); a loop for analysing types of impact on the national economic system (analysis of intended and unintended impacts, which includes analysis of free and forced movements and reactions of the system); a loop for analysing the national economic system's capacity for self-adjustment, which enhances its adaptability to various types of impact. The developed algorithm for analysing the state of the national economic system is designed to reflect objective processes in the economy and will enable the acquisition of comprehensive, multi-level, quantitative and qualitative information regarding its characteristics, properties, parameters and reactions to various types of impacts. The application of the algorithm will enable the formation of an adaptive management system for the national economic system, which will ensure the speed, accuracy and stability (reliability) of the system's parameters (characteristics and properties).

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# MEDICAL SCIENCES

## SHELL TECHNIQUE WITH CORTICAL BONE FROM THE LATERAL BUCCAL WALL FOR HORIZONTAL RIDGE AUGMENTATION IN ASSOCIATION WITH SINUS AUGMENTATION: A CASE REPORT WITH A 10 YEARS FOLLOW-UP

**Berberi A.**
*BDS, MSc, PhD, HDR. Professor, Dean, Faculty of Dental Medicine, Lebanese University Orcid: https://orcid.org/0000-0002-7658-1361*
https://doi.org/10.5281/zenodo.19292665

**Abstract**
The objective of this case report is to describe a clinical situation in which an external sinus lift was required to facilitate implant placement, and the buccal bone wall was used as a 2D scaffold to reconstruct a mesial bone defect with AM. Three Astra Tech EV implants were subsequently placed and restored three months later, with a 10-year follow-up.

**Keywords:** Sinus Lift, Bone reconstruction, Dental Implants, Buccal wall.

**Introduction**

Maxillary sinus augmentation (MSA) procedures are widely recognized as highly reliable and safe methods, often selected when the remaining alveolar bone height in the maxillary premolar-molar region measures less than 2–4 mm [1]. This surgical technique involves osteotomy of the buccal bone using the outfracture technique [1] or removal of the bone wall [2], followed by elevation of the Schneiderian membrane and placement of grafting materials between the crestal bone and the membrane [1–3]. Numerous studies have explored sinus augmentation using various materials, including autogenous bone (AB) [4,5], allograft materials (AM) [6–8], synthetic grafts (SG) or xenografts (XG) [8,9], combinations [9], or even graft-less techniques [10,11].

This procedure facilitates subsequent dental implant placement, either simultaneously or in a delayed approach [11,12]. The long-term stability of implants is closely linked to the viability and integration of grafting materials with newly formed bone, which gradually develops from the residual maxillary bone [13,14].

Various guided bone regeneration (GBR) techniques and grafting protocols are employed to reconstruct alveolar bone defects, depending on the defect's morphology [15]. Minor horizontal defects may be corrected through a single-stage augmentation procedure [16]. The use of barrier membranes resorbable or non-resorbable combined with tenting screws helps preserve the gained volume and prevent resorption [17]. Consequently, restoring substantial defects requires horizontal and/or vertical augmentation using AB grafts or bone substitutes [15,16]. AB grafts are considered the "gold standard" for bone grafting due to their osteogenic, osteoinductive, and osteoconductive properties [18]. However, harvesting AB necessitates an additional surgery, increasing patient morbidity [19]. To mitigate these risks, various SG, XG biomaterials, or AM have been employed as bone substitutes because of their osteoconductive scaffold and bone-forming capacity [6–9].

For two-dimensional (2D) bone defects, grafts harvested from the chin or retromolar regions have been utilized [20]. Pikos [21] introduced the inlay technique, which involves the precise placement of block grafts that fit the defect. The shell technique has also been described for 2D bone reconstruction [22,23]. Thin cortical bone shells can be harvested from the retromolar region using a specialized diamond disk and positioned to reconstruct the cortical plate, shielding the harvested bone placed between the shells and the defect from resorption [22,23]. These procedures require both augmentation of the recipient site and harvesting from an intraoral donor site, necessitating two surgeries [22,23].

An alternative MSA technique involves the outfracture osteotomy, where a complete 360-degree osteotomy is performed, and the lateral window bone is separated from the membrane [24–26]. The bony window can replace an absorbable membrane or be crushed and mixed with graft material [24,26]. If the lateral bone wall is thick (>2 mm), cortical bone can be harvested and used as graft material [27,28].

The objective of this case report is to describe a clinical situation in which an external sinus lift was required to facilitate implant placement, and the buccal bone wall was used as a 2D scaffold to reconstruct a mesial bone defect with AM. Three Astra Tech EV implants were subsequently placed and restored three months later, with a 10-year follow-up.

**Case Report**

A 55-year-old female patient, classified as ASA I and in good health, was referred to our clinic by her dentist for evaluation of her edentulous maxillary area. Clinical examination revealed edentulism extending from the canine to the second molar in the left maxilla, with minor pain in the right anterior and left posterior maxillary regions.

Preoperative radiographic evaluation using panoramic radiographs and cone beam computed tomography (CBCT) revealed insufficient bone volume for standard implant placement and a horizontal bone defect in the premolar region. Consequently, sinus bone elevation via the lateral approach and 2D reconstruction were deemed necessary (Figure 1a, b, c, d).

The procedure was discussed thoroughly with the patient, explaining all available treatment options.

MSA was performed under local anesthesia (4% articaine with 1:100,000 adrenaline). Preventive antibiotic therapy (2 g amoxicillin-clavulanic acid or 600 mg clindamycin for penicillin-allergic patients) was administered one hour preoperatively, followed by 1 g/300 mg twice daily for five days. Analgesics (600 mg ibuprofen) were prescribed preoperatively and as needed postoperatively, along with instructions for daily 0.12% chlorhexidine gluconate oral rinses for one week.

A crestal incision was made in the edentulous area, with two vertical incisions mesially and distally. Access to the maxillary buccal bone was achieved through a full-thickness mucoperiosteal flap. Osteotomy of the buccal bony window was performed using a piezo-ultrasonic device as planned on CBCT. The rectangular bone was detached from the sinus membrane and elevated with the membrane tip of the piezo unit, followed by sinus curettes.

A solvent-dehydrated mineralized cortical-cancellous bone allograft (MCBA) (Puros Cortical-Cancellous particulate 0.25–1.0 mm; ZimVie, Carlsbad, USA) was hydrated in sterile saline and condensed into the sinus cavity, then sealed buccally with a collagen membrane (CollaTape; ZimVie, Carlsbad, USA) (Figure 2a, b, c, d, e, f, g, h).

Small perforations were made in the bone defect using a round bur to stimulate vascularization from the bone to the MCBA. The removed cortical bone wall was repositioned and fixed with two bone screws (Profix, Osteogenics, Lubbock, USA, 1.5 mm × 12 mm). The space between the cortical bone and the defect was packed with MCBA. A bovine pericardium membrane (CopiOs Pericardium Membrane, ZimVie) covered the graft site and was fixed with four tacks. The flap was closed with simple sutures (Monocryl 3/0, Ethicon, Johnson & Johnson, Somerville, NJ, USA).

Weekly clinical and radiographic follow-up was conducted. After six months, panoramic radiographs and CBCT revealed complete healing of the defect and sinus cavity. Four Astra Tech EV implants were placed in the augmented areas using a similar flap design. (Figure 3 a, b, c, d, e, f).

Eight weeks later, healing abutments were placed through a limited crestal incision. Two weeks afterward, impressions were taken using polyvinyl siloxane, and final crowns were fabricated using glass ceramic and cemented onto Ti Design abutments with glass ionomer cement (Figure 4 a, b).

Clinical assessments and standardized intraoral radiographs were obtained during follow-up visits up to ten years using the long-cone paralleling technique (Figure 5 a, b).

**Discussion**

MSA and GBR have demonstrated favorable results clinically, radiographically, and histologically for bone reconstruction in dental implants [6–8,16,18]. Maxillary sinus membrane elevation and grafting is widely recognized as the preferred treatment for implant placement in edentulous posterior maxilla with bone height deficiency [14,27,28].

GBR enhances alveolar bone volume in defects of varying shapes and dimensions [16,18]. Several techniques manage the lateral sinus bony window in MSA, including elevating it into the sinus cavity, crushing and mixing with particulate bone grafts, or repositioning it [25]. The lateral window bone can serve as an autogenous graft when horizontal or vertical crestal defects adjacent to the augmented sinus require reconstruction [22–24,26].

Proper immobilization and vascularization are critical for 2D reconstruction success. The lateral window bone used to create the necessary space is secured with two fixation screws [20–23]. Integration of 2D bone reconstruction and barrier membranes minimizes volumetric changes by reducing surface resorption during healing [17].

The described method offers clinical advantages by condensing the procedure into a single session, eliminating a second surgery. Sinus elevation and horizontal augmentation are performed simultaneously, and implants can be placed in the grafted sinus and augmented area [24].

Bone substitutes, such as allografts, provide scaffolds for vascular infiltration and hard tissue regeneration, integrating smoothly into newly formed bone [6,7,9,14,29,30]. MCBA, according to histological studies, is gradually replaced by autogenous bone while demonstrating excellent integration [7,9,29,30].

Isolation of the bone substitute from the oral cavity is crucial to prevent fibrous tissue infiltration [17]. Dense pericardial membranes exhibit stable resorption and effectively support bone regeneration [31]. The increase in bone width from 3.05 to 6.99 mm post-grafting suggests enhanced vascularization, promoting tissue regeneration [17]. Osteogenesis relies on progenitor cells from bone marrow stroma and pericytes from small blood vessels in connective tissue [29,30]. Perforating the underlying compact bone during GBR opens marrow spaces, accelerating vascularization and enhancing bone regeneration [32].

The primary limitation of this technique is the potential risk of sinus membrane perforation during bony wall reflection or fracturing the bony wall during fixation.

**Conclusion**

The shell technique using cortical bone from the lateral buccal wall, in combination with allograft materials and lateral sinus augmentation, provides a reliable method for horizontal ridge reconstruction. This approach enables simultaneous sinus elevation and horizontal augmentation, reducing surgical interventions while maintaining predictable outcomes for implant placement. Long-term follow-up demonstrates stable bone volume and successful integration of graft materials, confirming the technique's efficacy for managing complex maxillary defects.

**Figures:**

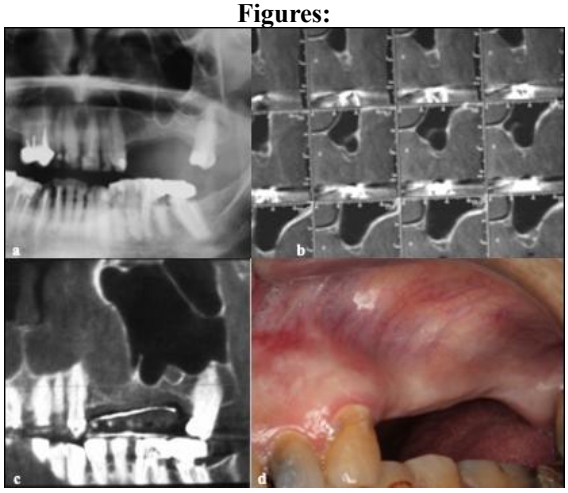

*Figure 1:*

*a: Panoramic radiograph showing the height in the posterior part of the maxilla.*
*b: para-axial cuts of the CBCT showing the bone defect in the premolar area and the crestal extension of the maxillary sinus.*
*c: panoramic reconstruction of the CBCT*
*d: clinical view of the area to be grafted, note the buccal defect in the premolar area.*

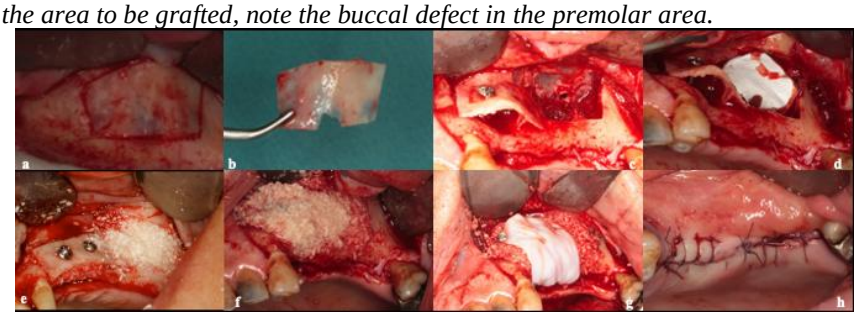

*Figure 2:*

*a: the osteotomy of the buccal wall*
*b: the buccal wall retrieved in one piece*
*c: the buccal wall is fixed with screws in the buccal defects, note the small perforation of the sinus membrane*
*d: the preformation was closed with a collagen membrane*
*e: the space and the sinus were filled with MCBA*
*f: collagen membrane covered the augmented area*
*h: sutures of the flap.*

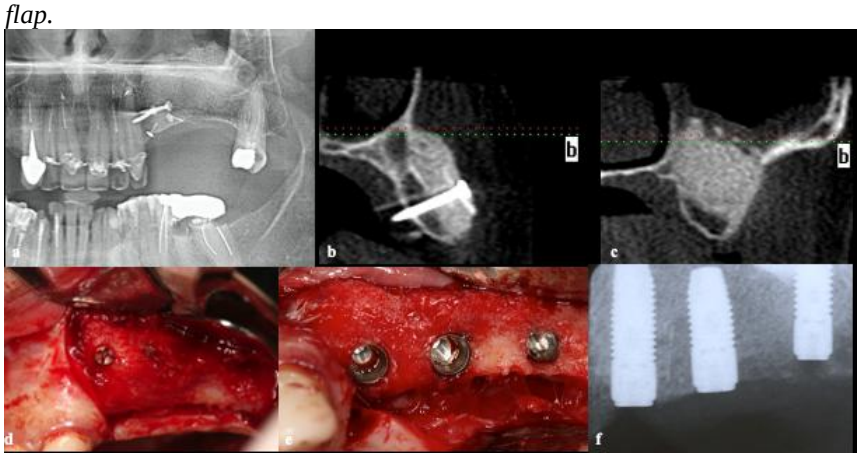

*Figure 3:*

*a: post-operative panoramic radiograph*
*b: Para-axial cut of the CBCT showing the augmented area*
*c: Para-axial cut of the CBCT showing the augmented sinus with respect to the sinus cavity*
*d: 4 months later a clinical view showing the augmented area, note that the new bone is covering the screw.*
*e: 3 Eve implants were placed in the augmented area.*
*f; Intra-oral radiograph showing the 3 implants.*

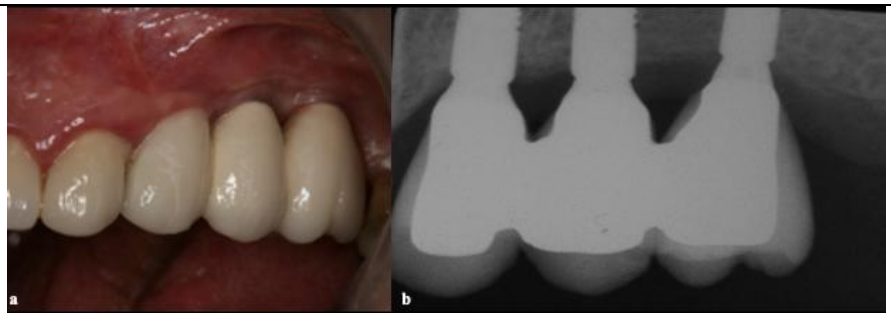

*Figure 4:*
*a: clinical view with fixed crowns on the implants.*
*b: intra oral radiograph of the implants and crowns.*

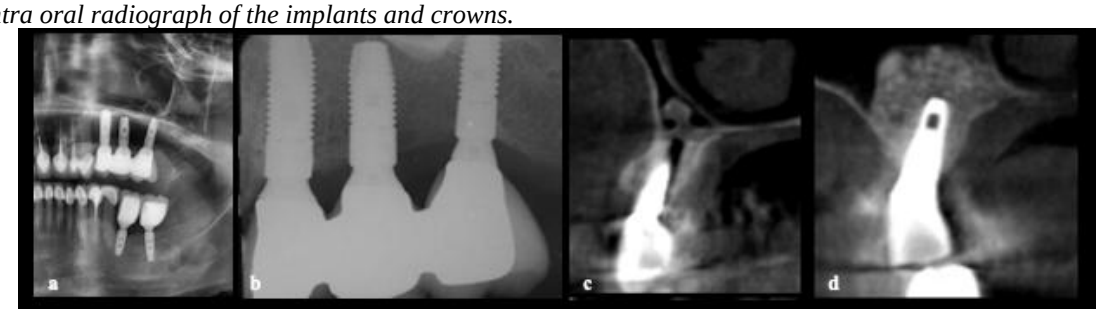

*Figure 5: Post-Operative radiographs at 10 years*
*a: Panoramic radiograph*
*b: Intra oral radiograph of the implants and crowns, note that there is no bone loss around the neck of the implants.*
*c: Para-axial CBCT of the premolar area reconstructed in 2D.*
*d: Para-axial CBCT of the molar region with sinus grafting the continuity of the grafted materials with respect to the sinus membrane is well noted.*

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UDC: 616.441-006.6-002-073.75

# CLINICAL ASPECTS OF EARLY DIAGNOSIS OF THYROID PATHOLOGY: THE ROLE OF ULTRASOUND IN THE DETECTION OF INFLAMMATORY, PRECANCEROUS DISEASES AND THYROID CANCER

**Khozhayev A.**
*Sonographer, Oncologist,*
*Professor of the S.N. Nugmanov Department of Oncology,*
*Asfendiyarov Kazakh National Medical University, Almaty, Kazakhstan*
**Zholdybaeva G.**
*Assistant Professor,*
*Department of Oncology and Radiation Diagnostics,*
*Karaganda Medical University, Karaganda, Kazakhstan*
**Zhumagaliyeva I.**
*Lecturer,*
*Department of Oncology and Radiation Diagnostics,*
*Karaganda Medical University, Karaganda, Kazakhstan*
**Aubakirova K.**
*Resident radiologist,*
*Department of Oncology and Radiation Diagnostics,*
*Karaganda Medical University, Karaganda, Kazakhstan*
**Maksatkyzy B.**
*Resident radiologist,*
*Department of Oncology and Radiation Diagnostics,*
*Karaganda Medical University, Karaganda, Kazakhstan*
**Balta A.**
*Resident radiologist,*
*Department of Oncology and Radiation Diagnostics,*
*Karaganda Medical University, Karaganda, Kazakhstan*
**Mekenbaykizi S.**
*Resident radiologist,*
*Department of Oncology and Radiation Diagnostics,*
*Karaganda Medical University, Karaganda, Kazakhstan*
**Serikbay N.**
*First-year PhD student,*
*Department of Obstetrics, Gynecology and Perinatology,*
*Karaganda Medical University, Karaganda, Kazakhstan*
https://doi.org/10.5281/zenodo.19292669

**Abstract**

This scientific and analytical work systematizes the clinical applications of ultrasound diagnostics for various thyroid diseases. Diffuse and focal changes, echogenicity variations, nodular and cystic lesions, inflammatory changes, and neoplastic processes in this organ are covered in detail. It is emphasized that ultrasound examination occupies a leading place both in the initial diagnosis and as part of a comprehensive patient examination. The article presents a detailed and comprehensive review of modern ultrasound diagnostic methods using various modes: B-mode only, Doppler techniques, microangiographic technologies, elastography, contrast-enhanced ultrasound, and digital analysis algorithms using artificial intelligence, as well as their features and informative value in the differential and early diagnosis of thyroid pathological conditions. Current recommendations for ultrasound diagnostic specialists in accordance with the TI-RADS standard are presented. The article presents clinical protocols for the diagnosis and treatment of various thyroid pathologies, and also describes in detail current international practices and trends in the field of oncological surveillance and early diagnosis of thyroid cancer using ultrasound examination.

**Keywords:** thyroid gland, thyroid, thyroid lesions, radiology, ultrasound, ultrasound diagnostics, region of interest, B-mode, color Doppler, ultra-microangiography, ultra-microvascular imaging technology, elastography, contrast ultrasonography, computer-assisted diagnosis, artificial intelligence, fine needle aspiration biopsy, oncology, thyroid cancer.

Today, ultrasound diagnostics of various thyroid gland pathologies, including diffuse changes, decreased and increased echogenicity, nodular and cystic lesions, inflammatory changes, and thyroid cancer, is a leading method for both primary diagnosis and comprehensive examination. According to current protocols for the diagnosis and treatment of thyroid pathology in the Republic of Kazakhstan, ultrasound diagnostics occupies a leading position both in diagnostics and for monitoring [1-4].

As noted by Zhou H. et al. [5] thyroid cancer is

one of the most common malignant tumors of the endocrine system. Thyroid nodules in 5% ~ 15% thyroid cancer are malignant. The incidence rate of thyroid cancer is increasing year by year. The incidence rate in women is generally higher than that in men. Papillary thyroid carcinoma is the most common clinical feature of thyroid cancer. It has the characteristics of high differentiation, low malignancy, good prognosis, and long survival. However, local metastasis and distant metastasis can also occur. Studies have shown that the rate of lymph node metastasis in papillary thyroid carcinoma is 84.7%, of which two-thirds have 70% lymph node metastases to thyroid cancer, and the incidence rate of thyroid cancer ranges from 70% to 85%. Local invasion or distant metastasis of thyroid cancer may increase the chance of postoperative recurrence. Therefore, metastasis of thyroid cancer is one of the important factors affecting the prognosis of patients. Early detection of thyroid cancer metastasis can help clinicians to estimate the surgical conditions. Ultrasound is the most important imaging method for the diagnosis of thyroid cancer metastasis, which is not only convenient but also accurate and reliable. With the continuous improvement of instrument performance, high-frequency ultrasound can not only sensitively display the internal structure of lesions but also provide blood flow information or judge the quality of lesions. In 2009, the American Thyroid Association emphasized the significance of ultrasound in thyroid nodules in the diagnosis and treatment manual of thyroid nodules and differentiated thyroid cancer and evaluated the ultrasonic thyroid examination as Grade A. Ultrasound examination is of great significance for early detection of thyroid cancer metastasis, early treatment, and improving the survival rate and quality of life of patients and has an important impact on the prognosis of patients.

A very interesting study was conducted by Kennedy E. et al. [6]. Our colleagues investigated which indications most commonly prompt referral for thyroid ultrasound and the diagnostic utility by indication. Extractors categorized referral reasons into (1) suspected palpable nodule (SPN) on physical examination; (2) chronic symptoms (CS) - e.g., globus sensation and dysphagia; (3) metabolic symptoms (MS; e.g., fatigue, weight change, and heat intolerance); (4) screening due to high risk for thyroid cancer (e.g., multiple endocrine neoplasia, Pendred syndrome, and family history of thyroid cancer); (5) follow-up of incidental thyroid nodule detected on another imaging study; or (6) combination of aforementioned factors. Suspected cases of goiter were included in the physical examination findings of a palpable thyroid nodule or mass. Additional variables extracted included the date of ultrasound, maximum diameter of largest nodule identified, if a biopsy was recommended by the interpreting radiologist, and if fine needle aspiration biopsy (FNAB) was performed. Demographic variables extracted included patient age, sex, race/ethnicity (White, Black, Asian, and Hispanic), insurance status (Medicaid, Medicare, private insurance, and uninsured), and Charlson Comorbidity Index (CCI) - 0, 1, and 2+. The primary outcome of interest was the percentage of thyroid ultrasounds performed that had an identifiable nodule for each referral indication. The secondary outcome evaluated "biopsy-recommended" nodules specifically, which were defined as nodules that the radiologist recommended for biopsy. Radiologists at institution routinely utilize the Thyroid Imaging Reporting and Data System (TI-RADS), and recommendations for biopsy are based on nodule size and TI-RADS category; however, specific TI-RADS scores were not abstracted. The percentage of biopsy-recommended nodules among all ultrasounds performed was compared among each referral indication.

In all, 3459 discrete neck ultrasounds were identified between 2017 and 2019. Of these, 1739 (50%) met inclusion criteria. The majority of patients were female (76%), White (86%), privately insured (62%), and healthy (76% with CCI 0); the mean age was 53 years standard deviation (SD). The most common indication for thyroid ultrasound referral was an SPN on physical examination (40% of all ultrasounds performed). The next leading referral indication was follow-up of a nodule identified on incidental imaging (28%). Referral for CS and MS made up 13% and 6% of ultrasounds, respectively. Only 2% of patients were referred for thyroid ultrasound due to high-risk factors. Patients referred for a combined indications accounted for 11% of thyroid ultrasounds. The combined indication was most often (45%) due to a patient presenting with CS and an SPN on examination. Among all ultrasounds performed, 62% identified a thyroid nodule. Patients referred for incidental findings had the highest percentage of ultrasounds with thyroid nodules present at 94%. Several possible reasons exist for the 6% of incidental findings that lacked a thyroid ultrasound correlate. For example, some were imaging "suggestive" of a nodule, but not definitively a nodule. These findings typically derived from imaging that was not optimal for the thyroid (e.g., chest or cervical spine computed tomography scan and nuclear imaging); and the suggestive nodule was ultimately not detectable on dedicated thyroid ultrasound [6].

In comparison, patients referred because of an solid pseudopapillary neoplasm (SPN) on examination and for CS identified nodules on 55% and 39% of ultrasounds, respectively. Patients with MS had a nodule on ultrasound 43% of the time. Among those referred for high-risk factors, 57% had a nodule present. Patients referred for combined indications had nodules on 42% of ultrasounds. Analysis of variance (ANOVA) indicated the difference in nodule detection rate between indications was statistically significant ($p < 0.05$). Only 27% of ultrasounds identified a thyroid nodule that was recommended for biopsy. Those referred from incidental imaging had the highest percentage of biopsy-recommended nodules (55%). This was followed, in order, by patients referred for physical examination of a palpable thyroid nodule (21%), high-risk factors (20%), combined indications (16%), MS (10%), and CS (6%). The overall mean maximum diameter of identified thyroid nodules was 1.9 cm (SD 1.3 cm). Of note, 32 radiology reports identified a thyroid nodule but did not record size and were, therefore, excluded from this specific analysis. Patients referred for incidentally found thyroid nodules had the largest mean nodule size at

2.4 cm (SD 1.2 cm). All other groups had a mean nodule size between 1.2 and 1.8 cm. The difference in average size of nodule was statistically significant ($p < 0.05$). A logistic regression model evaluated the association of patient age, sex, ethnicity, CCI, insurance status, and referral indication with identification of a nodule on ultrasound. Compared with patients referred for an SPN on examination, those with incidental nodules were over 10 times more likely to have a nodule found on ultrasound (odds ratio [OR] = 10.6 [confidence interval (CI) 7.0–16.0]). Conversely, patients referred for CS were half as likely to have an identifiable nodule compared with those referred for physical examination findings (OR = 0.5 [CI 0.4–0.7]). In addition, the odds of finding a nodule increased with age, especially for those aged 65 years and above (vs. age <45 OR = 3.6 [CI 2.2–5.9]). Finally, females were twice as likely to have a nodule found on thyroid ultrasound (OR = 2.0 [CI 1.5–2.6]). Results were similar when evaluating only biopsy-recommended nodules. Compared with patients referred for an SPN on examination, those referred for incidental findings were significantly more likely to have a biopsy-recommended nodule (OR = 4.7 [CI 3.5–6.3]), while those referred for CS were significantly less likely to have a biopsy-recommended nodule on ultrasound (OR = 0.3 [CI 0.1–0.5]. There was no difference in identifying biopsy-recommended nodules between sexes (female vs. male OR = 1.2 [CI 0.9–1.6]). In conclusion, the authors emphasize that only a quarter of dedicated thyroid ultrasounds yielded a nodule recommended for biopsy, and 39% did not have a nodule present at all. Moreover, only half of ultrasounds performed to evaluate a suspected nodule on physical examination actually identified one. Ultrasound referrals for symptoms had the lowest diagnostic yield, with fewer than 10% identifying a biopsy-recommended nodule. These findings suggest that re-evaluation of guidelines on thyroid ultrasound referral may be necessary to decrease the overutilization of thyroid ultrasound and the downstream consequences of detection of small potentially irrelevant nodules [6].

Wu J. et al. [7] to study the application value of SMI technology (ultra-microvascular imaging technology) and contrast-enhanced ultrasound in the differential diagnosis of thyroid benign and malignant nodules. According to the authors, thyroid disease has always been a common and frequent disease in clinical medicine, and its disease detection rate has been increasing year by year. Thyroid diseases are mainly divided into two categories: thyroid diseases treated by medical treatment and thyroid diseases treated by surgery. Thyroid cancer has also become one of the most common malignant secretory tumor diseases today. Ultrasound examination is a commonly used method for diagnosing thyroid diseases. During the diagnosis process, doctors need to observe the characteristics of ultrasound images and combine professional knowledge and clinical experience to give the patient's disease status.

The thyroid is an important organ of the human body, and it plays an important role in maintaining the health of the human endocrine system and the physical and mental health of the human body. With the advancement of medical ultrasound technology, ultrasound examination has become one of the most commonly used early detection methods for diseases due to its advantages such as low price, safety, noninvasiveness, convenient use, and ability to reflect the actual situation of tissues. A thyroid nodule refers to a mass in normal thyroid tissue that is different from normal glandular tissue. Thyroid nodules can be divided into two categories according to their nature: benign nodules and malignant nodules. Among them, benign nodules can be divided into nodular goiter, thyroid adenoma, and Hashimoto's thyroiditis (HT); the main type of malignant nodules is thyroid papilloma, which is the most common pathological type with the highest incidence of malignant thyroid nodules, while other pathological types are relatively rare. Due to the superficial location of the thyroid, the boundary between the outer envelope and surrounding soft tissues is clear, which provides favorable conditions for ultrasound diagnosis. The self-regulation of thyroid function refers to the regulation of the secretion of thyroxine by the amount of iodine supplied by the thyroid itself in the absence of thyroid-stimulating hormone (TSH) or the concentration of TSH is unchanged. Therefore, for the identification and diagnosis of benign and malignant thyroid nodules, ultrasound has always been one of the preferred imaging methods. With the continuous improvement of the level of science and technology, ultrasound inspection technology has also improved. When using ultrasound to diagnose thyroid diseases, thyroid neoplastic lesions can be displayed more clearly on the ultrasound images, and the lesions can be found in time and medical measures can be taken to control the condition. However, thyroid diseases are complex and changeable, especially malignant thyroid nodules, which are difficult to diagnose and control. During an ultrasound examination, benign and malignant nodules overlap on the two-dimensional sound image, which makes the diagnosis more difficult. Especially when some nodules have both benign and malignant characteristics, it is difficult to distinguish and qualitatively diagnose their nature based on the sonogram alone, which directly affects the choice of clinical treatment and surgical methods. This puts forward higher requirements for the initial qualitative diagnosis of lesion formation for ultrasound diagnosticians. Therefore, medicine urgently needs more advanced ultrasound diagnostic technology to overcome the difficulties encountered when using conventional ultrasound examination methods to diagnose thyroid diseases so as to help clinicians better diagnose and treat thyroid diseases and protect the health of patients. There is a clinical need for an intelligent diagnosis technology of thyroid diseases based on ultrasound images, which can provide objective and reliable auxiliary diagnosis opinions for thyroid diseases through the texture, shape, and other information of the images, freeing doctors from heavy work [7].

The study states that SMI technology is a new ultrasound diagnostic imaging method proposed by Canon in Japan in 2014. The principle basis of SMI technology is the motion suppression technology used to isolate and eliminate clutter but retain the vulgar blood flow signal. It includes ultrasound diagnostics,

ultrasound therapy, and biomedical ultrasound engineering. Therefore, ultrasound medicine has the characteristics of combining medicine, science, and engineering. It involves a wide range of contents and has a high value in the prevention, diagnosis, and treatment of diseases. In the motion suppression technology, the ultrasonic detection image subtracts the change of the structure position from one frame to another, leaving only the color imaging part. SMI technology uses an adaptive wall wave to suppress clutter noise and minimize the flash artifacts of the image. Ultrasound technology is a high-tech developed in the 20th century. It is an emerging, interdisciplinary, and borderline science, which has attracted extensive attention of scientific and technological workers in countries such as the United States, Germany, Canada, Japan, and China. Contrast-enhanced ultrasound technology is a very prominent technological development in the field of ultrasound imaging diagnostics in recent years, and it can also be called the third leapfrogging revolution in the history of ultrasound imaging. Contrast-enhanced ultrasound uses low mechanical index (MI0.2) pulse contrast sequence imaging technology for ultrasound inspection, so it reduces the damage to microbubbles and greatly improves the signal-to-noise ratio of the image. In the project of acquiring a dynamic image by contrast-enhanced ultrasound, although the detected object can hold the breath for a short time, the slight movement of the organs cannot be completely eliminated, and the organ movement may be more serious after the breath-hold is over. In order to comprehensively use multiple imaging modes or co-modal changes to provide more complete information, the ultrasound contrast motion correction algorithm often integrates all effective information to make up for information deficiencies and better serve clinical diagnosis and treatment. In the work of our colleagues, the experimental methods of this study are as follows: first, 40 cases of benign and malignant thyroid nodules in China in 2018 were randomly selected. Among them, there were 20 cases of benign and malignant nodules. The maximum diameter of the nodules was 0.6~3.9 cm, with an average of 2.10.3 cm. The pathological results of all nodules were obtained through fine-needle aspiration biopsy or surgical treatment. Then, according to the standard blood flow distribution pattern of thyroid nodules, SMI technology and contrast-enhanced ultrasound were used to judge, and two different selected nodule cases composed of 20 nodules in each group (10 benign and malignant nodules) compared the distribution pattern of blood flow and the morphological characteristics of blood vessels. According to the standard blood flow distribution pattern of thyroid nodules, in this experiment, SMI technology was used to judge the blood flow distribution pattern of nodules 4 times. That the analysis of the blood flow distribution pattern of SMI technical nodules in 20 cases of benign and malignant thyroid nodules in this group showed that the number of central and mixed nodules was the same, and the number of peripheral nodules was the least. After evaluation, through 4 repeated judgments, the blood flow distribution pattern of the nodules under SMI technology is completely consistent with the actual case. It shows that SMI technology has a high accuracy rate for displaying the blood flow distribution pattern of thyroid nodules. SMI angiography showed that the vascular morphology of malignant nodules was stump type and crab foot type, with more tortuous and chaotic directions, and more irregular small branches, which was in line with the actual situation. This shows that SMI technology has a good imaging effect on nodular blood vessels [7].

In conclusion, the authors come to the conclusion that with the improvement of medical technology in today's society and the enhancement of people's health awareness, people's attention to thyroid diseases continues to increase. However, thyroid diseases, such as malignant secretory tumor diseases, are more complex and changeable, especially for malignant thyroid nodules, which are difficult in clinical diagnosis and treatment. Conventional thyroid ultrasound examination methods also have certain limitations, such as: for benign and malignant thyroid lesions, two-dimensional detection images sometimes overlap, which can also lead to different images of the same disease, and the same frequency of different diseases; at the same time, the blood flow with a low flow rate will not be displayed. And usually, it can only clearly display the larger blood vessel images, but the new microvascular network of the tumor cannot show its full picture, which means that thyroid cancer with less blood supply is easy to be missed. These deficiencies in conventional ultrasound examinations will directly affect the clinical treatment of thyroid diseases. Therefore, the medical field of thyroid diseases urgently needs more advanced ultrasound diagnostic technology to overcome the difficulties encountered in the diagnosis of thyroid diseases so as to help clinicians better diagnose and treat thyroid diseases and protect the health of patients. With the improvement of science and technology, two more advanced ultrasound detection technologies, SMI technology and contrast-enhanced ultrasound, have emerged in medicine. SMI technology can detect very low blood flow in thyroid lesions and can noninvasively and truly reflect the blood perfusion state of the nodules; contrast-enhanced ultrasound can continuously and dynamically observe the vascular distribution and blood perfusion of thyroid nodules, showing that the possibility of tumor neovascularization has also been improved. Therefore, SMI technology and contrast-enhanced ultrasound technology can solve the current problems in the diagnosis and treatment of thyroid diseases to a certain extent by virtue of their own advantages and have begun to be used in the identification and diagnosis of thyroid benign and malignant nodules. The research in this article has proved through experiments that SMI technology and contrast-enhanced ultrasound have high diagnostic sensitivity for the identification and diagnosis of benign and malignant thyroid nodules, that is they have better diagnostic efficiency and application value. And from the comparison of sensitivity, the diagnostic sensitivity of SMI technology is slightly higher than that of contrast-enhanced ultrasound, which shows that SMI technology has slightly better diagnostic performance and application value than contrast-enhanced ultrasound. The findings of this article provide a meaningful reference for the medical

community to better apply SMI technology and contrast-enhanced ultrasound in the diagnosis and treatment of thyroid diseases. The number of features extracted manually in the research of thyroid nodular disease in this article is relatively small. In the future, more features can be added to study the interaction between artificial features and neural network features to achieve better classification results [7].

Jacome C.S. et al. [8] провели познавательное исследование, посвященное эффективности пальпаторного выявления узлов в щитовидной железе и корреляции этих результатов с последующими ультразвуковыми исследованиями. The authors conducted a retrospective observational study and identified adult patients (>18 years old) who underwent thyroid or neck ultrasounds (TUS) for the first time between January 1, 2015, and September 30, 2017, from ultrasound database. An initial search identified 5,938 patients with a TUS, from which our colleagues randomly selected a cohort of 500 patients who had a TUS ordered for any reasons (e.g., screening, workup of thyroid dysfunction). Of these, 327 patients were found to have both a TUS ordered and documented physical examination of the thyroid, which was performed either as part of the thyroid-related workup (e.g., thyroid function test abnormalities, personal or family history of thyroid cancer) or as a routine neck examination. In all those instances, the TUS was ordered after the physical examination had been conducted.

The researchers piloted and applied an extraction form to collect patient demographics and the specialty of the clinician who conducted the physical exam. From the physical exam documentation, they extracted the types of findings (solitary nodule, multinodular goiter, enlargement without nodularity, normal thyroid, and an "other category" for patients with indeterminate findings such as thyroid asymmetry). Additionally, study's authors documented the precise locations (right lobe, left lobe, isthmus or bilateral) where these findings were encountered, whenever the data was accessible. In a similar fashion, researchers carefully extracted the TUS findings (solitary nodule, multinodular goiter, enlargement without nodularity, no finding, and "other category" to group patients who had thyroiditis without the presence of nodules or lymphadenopathy) and noted the corresponding locations of the described findings. When there was a nodular finding in the ultrasound, authors extracted the largest diameter from the largest nodule. Given that the accuracy of thyroid physical exam may be affected by previous knowledge of thyroid-related symptoms, our colleagues also documented whether there was presence of symptoms associated with thyroid nodules or masses (e.g., neck fullness, dysphagia, odynophagia, choking, etc). The authors summarized continuous variables using means and standard deviations, and categorical variables using frequencies and percentages. Using the TUS findings as the reference standard, they calculated the accuracy of the findings noted from the thyroid palpation. First, our colleagues calculated the sensitivity, specificity, accuracy, and positive predictive value (PPV) and negative predictive value (NPV) of the thyroid palpation in the identification of any abnormal thyroid findings (any abnormality yes/no in thyroid palpation compared with any abnormality yes/no in thyroid ultrasound). Then, study's authors estimated the accuracy of the physical exam in detecting thyroid nodules (single thyroid nodule [yes/no] detected by thyroid palpation compared to thyroid nodule [yes/no] detected on confirmatory thyroid ultrasound), and multinodular goiters (multiple nodules [yes/no] found by thyroid palpation compared to multiple nodules [yes/no] identified on a thyroid ultrasound). Additionally, they calculated the accuracy and PPV of the thyroid physical exam to determine the location (e.g., right lobe, left lobe, isthmus or bilateral) of the thyroid findings when data was available in the medical records. Finally, authors calculated the proportion of additionally findings derived from a positive thyroid palpation as 1) the number of patients who had a solitary nodule palpated and were found to have multiple nodules on the subsequent ultrasound, or 2) patients who had a thyroid enlargement in the physical exam and found to have one or more thyroid nodules on the subsequent ultrasound. When possible, researchers conducted subgroup analyses by patient sex, patient weight (obese or overweight vs. normal weight based on body mass index (BMI) categories), size of the thyroid nodule (≤2 cm or >2cm), symptoms of nodular disease (yes and no), and by clinician specialty (primary care vs. specialties). Scientific researchers conducted a test interaction to evaluate for statistically significant subgroup differences [8].

Our colleagues included 327 patients, the majority were female (213/327, 65.1%) and white (275/327, 84.1%) with a mean age [standard deviation – (SD)] of 50.8 years old (16.9). Most patients were obese or overweight (225/327, 71.2%) and had the thyroid physical exam performed by a primary care clinician (178/327, 54.4%). Additionally, most patients did not present any symptoms of thyroid nodular disease (231/327, 70.6%). Regarding finding any thyroid abnormality, the thyroid physical exam had a sensitivity of 71.8% (n= 189/263; 95% CI 66%-72.2%), specificity of 35.9% (n= 23/64; 95% CI 24.2%-49.9%), accuracy of 64.8% (212/327; 95% CI 59.4%-70.0%), NPV 23.7% (23/97; 95% 17.5%-31.3%) and PPV 82.1% (189/230; 95% CI 79.1%-84.9%). When the diagnostic accuracy was estimated by an individual thyroid palpation finding (thyroid nodule or multinodular goitre), the physical exam had a sensitivity of 20.3% (n=12/59; 95% CI 12.3%-36.2%), specificity of 79.1% (212/268; 95% CI 73.7%-83.2%), accuracy of 68.5% (n=224/327; 95% CI 59.4%-70.0%), NPV 81.8% (n=212/259; 95% 81.5%-85.8%) and PPV 17.6% (n=12/68;95% CI 11.1%-27.1%) in detecting a thyroid nodule; and a sensitivity of 10.8% (n-=17/157; 95% CI 6.4%-16.7%), specificity of 96.5% (n=164/170; 95% CI 92.4%-98.7%), accuracy of 55.4% (n=181/327; 95% CI 49.78%-60.8%), NPV 53.9% (n=164/304; 95% 52.4%-55.4%) and PPV 73.9% (n=17/23; 95% CI 53.4%-87.5%) in finding a multinodular goiter. Out of 327 patients, 60 physical exams included the side of the thyroid nodule. Among these, the overall accuracy, and the PPV of the physical examination in identifying the location (e.g., right lobe, left lobe, isthmus, or bilateral) of the thyroid finding were 46.6% and 37.5%, respectively. Physical exams among symptomatic patients demonstrated superior

performance than those conducted among asymptomatic patients, with higher specificity (100% vs. 62%; p<0.01), accuracy (83% vs. 62%; p<0.01), and NPV (87% vs. 79%; p<0.01) for detection of solitary nodules, as well as a higher NPV for detection of multinodular disease (61% vs. 51%; p<0.01). In addition, higher PPV for detecting multinodular disease was observed when a specialist conducted the physical exam compared to a primary care provider (100% vs. 60%; p<0.01) and when the nodule detected by physical examination was greater than 2 cm (100% vs. 73% for nodules ≤2 cm; p=0.026). The study's authors found that out of 68 solitary nodules palpated, 37 (54%) were found to have additional findings such as, multinodular goiter on a subsequent TUS; similarly, out of 88 patients for whom the physical exam identified an enlarged thyroid, 56 (64%) of these were subsequently found to have a solitary nodule (16 cases) or a multinodular goiter (40 cases) on the TUS. The authors emphasize that in this retrospective observational study, scientific researchers found that, while a thyroid physical exam can detect thyroid abnormalities, these findings were rarely concordant with findings identified on a subsequent thyroid ultrasound. Furthermore, the diagnostic accuracy of specific thyroid physical exam findings was low, particularly for the PPV of solitary thyroid nodules. For instance, out of every 100 patients with a physical exam consistent with a solitary thyroid nodule, approximately 18 had a thyroid nodule, while out of every 100 patients with a physical exam consistent with multinodular goiter, about 74 had the same finding in the ultrasound. In the course of the study, the authors state that thyroid physical exam has limited diagnostic performance and leads to additional findings when followed by a thyroid ultrasound. As such, thyroid physical exams in asymptomatic patients may play an important role in the overdiagnosis and overtreatment of thyroid cancer. To determine if any patient subgroups derive some benefit from thyroid physical exams beyond their use as a diagnostic approach, further research is necessary. Additionally, potential interventions should be explored to improve the accuracy of thyroid physical exams [8].

Next, we consider a study aimed to examine the potential associations between Doppler parameters and clinical characteristics of hypothyroid patients, such as the autoimmune nature of the disease and adequacy of LT4 replacement [9]. Angelopoulos N. et al. in their work note that While hormonal assays are commonly used for thyroid function assessment, Doppler sonography provides valuable information on vascularization and blood flow.

A total of 400 consecutive patients with hypothyroidism attending an Endocrinology outpatient clinic for annual follow-up visit were evaluated for eligibility. Autoimmune thyroiditis was considered the underlying disease of hypothyroidism based on high serum concentrations of antithyroid antibodies [thyroid peroxidase (anti-TPO) and/or thyroglobulin (anti-Tg) antibodies]. Exclusion criteria were history of Graves' disease or subacute thyroiditis, malignancies, pregnancy, previous use of medications that can affect thyroid stiffness (amiodarone, tamoxifen, anti-neoplastic) and nodular abnormalities of the thyroid gland (nodules > 3 mm detected by conventional B-mode ultrasound. A total of 338 patients treated for hypothyroidism [females: n = 292 (86.4%); males: n = 46 (13.6%)] were enrolled in the study. Demographic characteristics (age, sex, BMI), treatment parameters (LT4 daily dose) were recorded and thyroid hormones [TSH, free thyroxin (fT4)] were measured. All included subjects were residents of a geographical area of low-prevalence iodine deficiency disorders. The study protocol was conducted by the tenets of the Declaration of Helsinki and all patients agreed to participate in the study, which was approved by the Bioethics Committee of the Aristotle University of Thessaloniki, Greece. Conventional B-mode thyroid ultrasound and strain elastography [(real-time elastography (RTE)] were performed on a General Electric P9 machine (LOGIQ-P9; GE Medical Systems, Milwaukee, WI, USA) with an 8–12 multifrequency linear probe. Conventional grey-scale ultrasound was initially performed to measure transverse (two dimensions) and longitudinal (one-dimension) diameters and thyroid volume. Three linear dimensions were measured for each lobe: the length (L) was assessed on the sagittal view and the anterior–posterior (A-P) and width (W) diameters of each lobe were assessed on the transverse view. Given that the normal thyroid shape is ellipsoid, the volume of each lobe was automatically calculated by recording the abovementioned three linear dimensions (ellipsoid equation with a correction factor: V (ml) = L (cm) × A-P (cm) × W (cm) × 0.523). Thyroid vascularity was examined with color Doppler and patients were classified into four patterns: Pattern I (normal thyroid vascularity, blood flow limited to the peripheral thyroid arteries, absent parenchymal flow); Pattern II (minimally increased thyroid vascularity, mildly increased parenchymal flow); Pattern III (increased blood flow with a diffuse homogenous distribution, increased parenchymal flow with a diffuse homogenous distribution pattern) and Pattern IV (markedly increased parenchymal flow with a homogenous distribution, including the "thyroid inferno"). The probe was placed perpendicularly to the skin for RTE examination, and repetitive light compression was applied in the longitudinal plane. The ideal pressure on the target lesion was confirmed based on the cine-memory data. A cine-memory stores data obtained through the transmission and reception of ultrasound. A cine-memory generally has a storage capacity allowing storage of multiple numbers of frames obtained in time sequence. In a cine-memory, the newest input data overwrites the oldest data which is already stored in the memory, and this process is repeated. The patients held their breath while the images were obtained to avoid respiratory motion artifacts. The strain index (elastography ratio, E2/E1) was used that represents the ratio of the strain of thyroid parenchyma (E2) to that of sternocleidomastoid muscles (E1). Region of interest (ROI) for E2 was free-handed and designed at the peripheral edge of the gland to include the whole longitudinal image of each lobe; ROI for E1 was the sternocleidomastoid muscle in front of the ipsilateral thyroid parenchyma [9].

An endocrinologist with twenty years of experience in sonography, who was blinded to the clinical status, performed all thyroid ultrasound examinations. The

Doppler spectral analysis was of the right and left inferior thyroid arteries in the transverse scanning, in which the vessels crossed the common carotid arteries posteriorly, or in the longitudinal scanning of the ascending parts of the arteries, in which the vessels lie parallel to the common carotid arteries for the superior thyroid arteries. The superior thyroid artery was assessed with the probe positioned in the oblique sagittal plane, close to the superior thyroid pole. The inferior thyroid artery was assessed in the oblique transversal plane, close to the transition between the mid and inferior third of the thyroid. The cursor for evaluating the inferior thyroid artery was set close to the trachea to avoid artifacts from the common carotid artery and the internal jugular vein. Parameters for color Doppler are frequency 4.4–6.6 MHz, Gn 40%, pulse-repetition frequency (PRF) 2–8 kHz and Wall Filter (WF) 25–80 Hz. The angle correction cursor was parallel to the flow direction and the Doppler angle was kept at or below 60°. The sampling gate was set to 2 mm. The peak systolic velocity (PSV), end-diastolic velocity (EDV), and pulsatility indices (PI) and the resistive index (RI) values in the superior and the inferior thyroid arteries were obtained in both thyroid lobes. The mean value of the right and left lobes was used as the outcome parameter. Serum TSH and fT4 concentrations were measured by the immunochemistry method with enzyme chemiluminescence immunoassay (reference range: 0.27–4.5 mUI/ml and 0.8–1.5 ng/dl, respectively). Measurements were performed on the Cobas 8000 platform by Roche (Basel, Switzerland). Data were presented as mean ± SD or range (min—max). The Kolmogorov–Smirnov test was used to evaluate data distribution. The Student's t-test was used for group comparisons of continuous variables with a normal distribution (age, BMI, weight) and Mann–Whitney test was used for variables with a nonparametric distribution. Spearman and Pearson correlation coefficients were used to investigate correlations between variables. The Chi-squared test ($\chi 2$-test) was used for group comparisons of categorical variables. Predictive models were compared using Receiver Operating Characteristic (ROC) – Area Under the Curve (AUC) statistics. The optimal threshold values were determined from the ROC curve analysis and the Youden Index and its associated criterion values. The sensitivity, specificity, positive likelihood ratio and negative likelihood ratio values were calculated. A p-value $< 0.05$ was considered statistically significant [9].

In total, 288 patients (85.2%) had autoimmune thyroiditis, while 50 (14.8%) had no history of increased thyroid autoantibodies. A total of 68 patients (20.1%) had TSH concentrations $\geq 4$ mIU/l (50 with autoimmune thyroiditis and 10 without autoimmune disease) and were considered suboptimally treated at the time of the enrolment, while 270 (79.9%) had TSH concentrations within the reference range (< 4 mIU/l) and were considered optimally treated ( 230 with autoimmune disease and 40 without). In patients with autoimmune thyroiditis, the LT4 dose (expressed as dose/weight) needed to achieve optimal thyroid treatment was higher ($1.1 \pm 0.4$ vs. $0.8 \pm 0.4$ mcg/kg, $p < 0.001$). The elastography ratio was increased in patients with autoimmune thyroiditis ($0.86 \pm 0.52$ vs. $0.77 \pm 0.54$, $p = 0.026$) compared with patients without autoimmune thyroiditis. There was a positive association between autoimmune thyroiditis and vascularity [$\chi 2(3) = 13.28$, $p = 0.004$, Cramér's $V = 0.2$]. In patients with no autoimmune thyroiditis, the total thyroid volume was lower in those with suboptimal LT4 replacement ($5.3 \pm 3.0$ vs. $6.3 \pm 3.7$ ml, $p = 0.032$) compared with those with optimal replacement. There was no association between suboptimal LT4 replacement and vascularity [$\chi 2(3) = 2.11$, $p = 0.551$, Cramér's $V = 0.08$]. PSV and EDV of the inferior thyroid artery were higher in patients with suboptimal LT4 replacement compared with those with optimal replacement (PSV: $41.9 \pm 17.0$ vs. $35.1 \pm 11.2$, $p = 0.004$ and EDV $18.5 \pm 9.0$ vs. $14.7 \pm 6.0$, $p = 0.004$, respectively). RI was lower in patients with suboptimal LT4 replacement compared with those with optimal replacement ($0.63 \pm 0.08$ vs. $0.66 \pm 0.09$, $p = 0.024$). The severity of hypothyroidism, as expressed by LT4 dose/BMI, was negatively correlated with thyroid volume ($r = -0.190$, $p < 0.001$) and EDV values of superior ($r = -0.16$, $p = 0.009$) and inferior thyroid arteries ($r = -0.17$, $p = 0.008$). A weak positive correlation was found between LT4 dose/BMI with elastography ratio ($r = 0.180$, $p < 0.001$). This correlation was significant only in patients with autoimmune thyroiditis ($r = 0.156$, $p = 0.007$) but not in those without it ($r = 0.255$, $p = 0.07$). A positive correlation was found between dose/BMI and PI and RI of both arteries (PI superior: $r = 0.130$, $p = 0.031$; PI inferior: $r = 0.140$, $p = 0.023$; RI superior: $r = 0.140$, $p = 0.024$; RI inferior: $r = 0.150$, $p = 0.014$). A backward stepwise logistic regression analysis was performed to identify possible predictors of suboptimal LT4 replacement. All ultrasound indices (PSV, EDV, PI, RI, elastography ratio) were included as independent variables. Only RI and PSV of the inferior thyroid artery remained in the final model, [$\chi 2(2) = 14.93$, $df = 2$, $p = 0.001$). ROC curve analysis was performed for PSV of the inferior thyroid artery to define the optimal threshold for predicting suboptimal LT4 replacement (defined as TSH > 4 or > 5 mIU/ml). The AUC for TSH > 4 mIU/ml was 0.625 ($p = 0.002$, Youden Index: 0.238, associated criterion: > 31.2, sensitivity 81.8%, specificity 42%). For TSH > 5 mIU/ml, the corresponding AUC was 0.672 ($p < 0.001$, Youden Index: 0.305, associated criterion: > 37.7, sensitivity 61.8%, specificity 67%) [9].

In conclusion, our colleagues state that this is the largest study to have applied the concurrent evaluation of multiple ultrasound parameters of the thyroid gland in patients with hypothyroidism and the first to have used thyroid artery measurements to evaluate the therapeutic efficacy. Lymphocytic infiltration in autoimmune thyroiditis affects tissue echogenicity and causes a diffuse increase in parenchymal vascularization. In the natural history of the disease, as hypofunction gets severer, elasticity, volume of the gland and blood flow are reduced, indicating a fibrotic degeneration process. Effective monitoring and evaluation of LT4 supplementation are crucial to anticipate relapse of hypothyroidism. The monitoring is mainly based on thyroid hormone measurements since clinical symptoms may be absent in borderline TSH increases. However, in cases where blood tests are difficult to obtain, a color Doppler ultrasound can be used as an alternative tool in

estimating responses to therapy and distinguishing those patients who should be further evaluated by hormonal examinations [9].

In the work of Soltani K. et al. [10] the authors note that the diagnostic role of Doppler ultrasonography regarding HT is not fully established. Our colleagues examined intraparenchymal RI as a Doppler parameter, thyroidal vascularity and other Gray-Scale findings in adults with HT in order to evaluate the clinical feasibility of RI in the diagnosis of this disease. This study is designed based on the cross-sectional analysis of sonographic findings in newly diagnosed patients with HT. The target population was selected from patients referred to the radiology department of Modarres Hospital from the endocrinology clinics of Modarres and Loghman Hospitals between 2013 and 2014. Subclinical hypothyroid patients were identified based on the clinical assessment of an endocrinologist. Exact laboratory data (TSH, FT4) were not available. Newly diagnosed patients without any history of receiving treatment for HT, who were either euthyroid or sub-clinically hypothyroid at the time of sonography, were included. Forty-eight females recently diagnosed with HT aging between 20 and 50. All the participants underwent Gray-scale (determining gland size, volume, and echogenicity) and color Doppler (evaluating vascularity and calculating RI of each lobe in 2 points) sonography by 1 radiology resident using a Medison X8 sonography device with a 7 MHz probe. Thyromegaly in females was defined as thyroid gland volume exceeding 15 mL. Gray-scale findings were classified into 4 grades (1–4) using the classification system introduced by Sostre and Reyes (Sostre S., Reyes M.M., 1991). Color Doppler findings were divided into 4 patterns (0–III) based on a visual scale provided by Schulz et al., 2003. The settings of the ultrasound equipment (gain and PRF) were calibrated such that aliasing of the carotid artery and jugular vein could not be seen. The RI (minimum PRF and maximum gain) of both upper and lower poles of each thyroid lobe were calculated by the ultrasound device using the formula below and the mean RI measured from both lobes was considered as the total RI of the thyroid gland. In addition, 45 controls aged between 20 and 70 years with normal thyroid laboratory results and without any prior history of thyroid disease were examined sonographically and the RI of those participants whose Gray-scale results proved to be normal was measured in 3 different points in each lobe. The mean RI of each participant from each of these 2 groups was calculated and compared to the mean RI of the control group.

Based on the definition provided by the World Health Organization, out of every 48 patients with HT, 30 (62.5%) had a normal thyroid gland volume (thyroid gland volume < 15mL) and 18 had thyromegaly (thyroid gland volume > 15mL). Based on the Gray-scale grading, 13 patients (27.08%) were classified as grade 1, 12 patients (25.00%) as grade 2, 18 patients (37.50%) as grade 3, and 5 patients (10.42%) as grade 4. The parenchymal vascularity of the thyroid gland (color Doppler appearance) presented as pattern 0 in 22 patients (45.83%), pattern I in 15 patients (31.25%), pattern II in 6 patients (12.5%), and pattern III in in 5 patients (10.42%). The RI ranged between 0.50 and 0.70 in the patient group and 0.47 and 0.70 in the control group. The average RI in the patient group was 0.5733 ± 0.05012and 0.5453 ± 0.05061 in the control group. Independent t-testing of the average RI showed a statistically significant difference between the patient and control groups (P = 0.009). The highest average RI was seen in Grade 1 (0.5808 ± 0.04173) and the lowest in Grade 4 (0.5500 ± 0.03808). One-way ANOVA of the average RI between different Gray-scale grading groups showed no statistically significant difference (P = 0.352). Furthermore, participants with grade 1 Gray-scale findings were considered as part of the normal or near-normal group and those with grades 2, 3, and 4 as part of the substantial Gray-scale changes group. The average RI of the normal or near-normal group was 0.5808 ± 0.04173 and 0.5706 ± 0.05319 in the substantial Gray-scale changes group. Independent t-testing showed no statistically significant difference in average RI when comparing the normal or near-normal with the substantial Gray-scale changes group (P = 0.537). The highest RI was seen in pattern 0 of color Doppler findings (0.5845 ± 0.04828) and the lowest in pattern II (0.5300 ± 0.04817). ANOVA results showed no statistically significant difference in average RI among different groups of color Doppler findings (P = 0.109). Results of Kruskal–Wallis test followed by pairwise comparisons showed a statistically significant relationship in terms of average RI between the grade 1 patient group and control group (P = 0.010) and between the grade 3 patient group and control group (P = 0.015). But the same comparison showed no statistically significant relationship between the grade 2 patient group and control group (P = .406) and between the grade 4 patient group and control group (P = 0.752). Results of Kruskal–Wallis test followed by pairwise comparisons showed a statistically significant relationship in terms of average RI between the pattern 0 patient group and control group (P = 0.003) and between the pattern I patient group and control group (P = 0.034). But the same comparison showed no statistically significant relationship between the pattern II patient group and control group (P = .418) and between the pattern III patient group and control group (P = 0.381). Summarizing the study, the authors state that the results of this study show that, regardless of gray-scale views and color Doppler patterns, the intraparenchymal RI of patients diagnosed with HT was higher compared to normal controls and, thus, this sonographic parameter may be a useful yet noninvasive modality in the diagnosis of HT [10].

It is impossible to ignore technological developments and the increasingly active development of thyroid ultrasound examination using artificial intelligence (AI).

In the clinical trial by Edström A.B. et al. [11] it was examined how the articifial intelligence (AI)-based diagnostics system S-Detect (this is a built-in AI feature in ultrasound machines that helps the doctor analyze the detected formations) for Thyroid influences the ultrasound diagnostic work-up of thyroid ultrasound performed by different ultrasound users in clinical practice and how different ultrasound users influences the diagnostic accuracy of S-Detect. The researchers conducted a clinical trial with 20 participants, including medical

students, ultrasound novice physicians, and ultrasound experienced physicians. Five patients with thyroid nodules (one malignant and four benign) volunteered to undergo a thyroid ultrasound scan performed by all 20 participants using the same ultrasound systems with S-Detect installed. Participants performed a focused thyroid ultrasound on each patient case and made a nodule classification according to the European Thyroid Imaging Reporting And Data System (EU-TIRADS) [12]. They then performed a S-Detect analysis of the same nodule and were asked to re-evaluate their EU-TIRADS reporting. From the EU-TIRADS assessments by participants, authors derived a biopsy recommendation outcome of whether FNAB was recommended.

In this clinical trial, our colleagues observed that using S-Detect did not improve the thyroid diagnostic work-up of thyroid nodules among novice and intermediate ultrasound operators. Furthermore, they observed that the operator had a strong impact on the AI-generated ultrasound diagnosis, with a variation in diagnostic accuracy ranging from 40 to 100%, even though the same patients and ultrasound machines were used in the trial. A strength of this study is the controlled experimental setup, including participants with different ultrasound experiences who used S-Detect on the same ultrasound equipment and patient cases. In this way, we could measure the impact of the ultrasound operator's influence on the diagnostic accuracy of AI-assisted thyroid nodule diagnosis and how AI influenced the operator's assessments. Another strength is that we had a cytological/histological diagnosis on all the patients, and three experts were used to define the reference standard for the ultrasound characteristics. The authors believe that for AI-assisted ultrasound diagnosis to be successfully implemented in clinical settings, the technology should be developed with a clear purpose as a tool for the clinician in mind. Future research should focus more on how AI-assisted tools are affected by the image quality obtained by the ultrasound operator and how they affect the diagnostic process, including time use and patient outcomes. In conclusion, they observed that using S-Detect did not enhance the diagnostic accuracy of thyroid nodule evaluation among novice and intermediate ultrasound operators. The operator significantly influenced the AI-generated ultrasound diagnosis, with diagnostic accuracy ranging from 40 to 100%, despite the same patients and ultrasound machines used. While AI systems like S-Detect have the potential to improve the diagnostic work-up of thyroid nodules, more research is needed to ensure how it should be used in the diagnostic process to save time and improve final patient outcomes [11].

A fundamental study concerning multimodal imaging of solid thyroid lesions was conducted by Jung E.M. et al. [13]. Goal of the study was the assessment of AI-assisted diagnosis of solid thyroid foci with multimodal modern ultrasound imaging. 50 patients (26–81 years, 54.7±13.1 years) were included in the study. Multimodal ultrasound imaging by means of B-mode with linear probe (4–12 MHz) with option of automated documentation of findings by means of AI, with supplementary ultra-microangiography (UMA) was used. Macrovascularisation was assessed by dynamic contrast ultrasonography (CEUS) with parametric evaluation and perfusion analysis, and microvascularization was assessed by combined strain and shear wave elastography on a novel high-performance ultrasound system (Resona R9/Mindray) by an experienced examiner with independent reading. The evaluation was performed according to TI-RADS III-V. Inclusion criterion was preparation for immediate surgery by indication through interdisciplinary case conferences with endocrinologic, nuclear medicine, and surgical evaluation. All examinations with CEUS were performed after written consent. The evaluation of the examinations was performed retrospectively with the approval of the local ethics committee. The examinations were requested after preliminary examinations by special outpatient clinics with the question of the assessment of solid thyroid lesions that had been noticed in out-of-town preliminary examinations. An evaluation according to TI-RADS III-V had to be performed and it had to be decided to what extent a histological clarification was necessary or whether a follow-up should be performed. All examinations were performed by an experienced investigator (more than 3000 examinations per year, over more than 20 years) using a linear multifrequency probe (L 4–12 MHz) on high-performance ultrasound equipment with digital image documentation. This allowed independent subsequent evaluation by experienced readers. According to the predefined scheme of an AI image evaluation program, both thyroid lobes were measured in longitudinal and transverse axis with length, depth and width, the volume was calculated, the echogenicity was evaluated as homogeneous, discrete inhomogeneous or inhomogeneous and the echo pattern was judged as echo-complex or echo-normal. The ultrasound elastography techniques available in parallel mode as strain or shear wave elastography were used to assess compaction of thyroid tissue and solid foci. The pulsatile region of a carotid artery was bypassed as much as possible to avoid artifacts. Image quality could be assessed automatically, optimally with 5 green stars. False colors informed about homogeneous or inhomogeneous compaction. Measured values over individually adjusted ROI could be recorded in m/s or kPA, with values>2.5 m/s or>30 kPA considered suspicious for possible malignant lesions.

Detectable solid lesions were also measured by AI in three planes, and the rim contour was bypassed for volumetric detection. Then, marginal contour had to be assessed as regular, lobulated or irregular, rim as complete or incomplete, or absent, growth axis, parallel or directed in depth, shape as oval or roundish, and possible macro- or microcalcifications and entered into a predetermined scheme. After localization of the suspicious lesion, the evaluation according to TI-RADS III-V was then color-coded in a final scheme with topogram. This then also considers a possible tumor vascularization, as irregular malignancy-suspicious, or as regular marginal benign. UMA was used to assess the vascularization of tumor foci in as much detail as possible with velocity ranges<10 cm/s. Vascular patterns were recorded dynamically in short cine loops up to 10 s. This also captured possible conspicuous lymph

nodes with regular benign vascularization from the hilus or malignancy-typical from the margin. Macrovascularization of thyroid lobes and foci was classified as normal, enhanced, or decreased, and that of foci as regular or irregular. Color-coded duplex sonography, flow with glazing flow, and UMA were used for this purpose. The criterion for benign findings was a regular vascular pattern, especially a marginal vascularization, for example in adenomas. Irregular vascularization was considered suspicious for malignancy. This was then additionally investigated with CEUS to determine the extent to which irregular arterial hypervascularization with delayed wash out occurs, which is evaluated as a malignancy criterion. CEUS after bolus administration of 1 to 1.5 ml of sulphuhexafluoride microbubbles with 10 ml of saline solution cubital, if possible, was used to assess dynamic microvascularization of the suspicious solid lesions. When possible, cine loops of incipient arterial vascularization after 10 to 15 s up to one minute were then evaluated parametrically and by time intensity curve using the High-End Devices internal perfusion program. ROI were individually matched, in the center, at the edge of the lesion to be assessed compared with surrounding thyroid tissue. Parametric color maps were fitted to the corresponding perfusion parameters such as time to peak, peak, mean transit time, wash in area under the curve (wash in AUC) and tabulated at the end [13].

50 cases (26–81 years, mean age: 43±7 years) were examined with multimodal imaging consisting of B-mode, UMA, elastography and CEUS with parametric and perfusion analysis with good to very good image quality in all cases, according to the internal evaluation mode especially in the shear wave elastography technique with clearly>85% or 5 green stars. The volume of the thyroid lobes on both sides averaged 39 ml±5 ml (27 to 69 ml). All echo-poor, irregularly vascularized, inhomogeneously indurated lesion>1 cm were identified as highly suspicious for malignancy with early wash out kinetics and were also confirmed surgically. The 13 cases of histologically confirmed thyroid carcinoma (8 papillary, 2 medullary, 2 microfollicular, 1 anaplastic carcinoma) with a mean size of 15 mm±6 mm (9–21 mm) were correctly evaluated by TI-RADS IV based on irregular shape, induration>2.5 m/s or>30kPA and appositional wash-out kinetics using CEUS (TI-RADS V). Tumor lymph nodes could be correctly detected preoperatively only in one case of medullary carcinoma according to the surgical findings, based on irregular vascularization with UMA in roundish shape with cortex>4 mm with a transverse diameter up to 11 mm. In 25 cases of inhomogeneous nodular goiter, evaluation with TI-RADS III was performed in 31 cases, evaluation with TI-RADS IV was performed in 4 cases with incomplete marginal contour, partial marginal vascularization with UMA and partial wash out with indurations up to 2.5 m/s or 30 kPA, and surgical excision was performed for nodular goiter. In 12 cases of adenomas with diameters of 1.7 to 3.5 cm, mean 26 cm±0.5 cm, nodular goiter resulted in proportionately regressive nodular changes. Only in 7/12 cases a typical echo-poor rim and a typical rim vascularization were found. In 5 cases, the rim was incomplete. CEUS also showed a partial central wash out in these cases with but preserved marginal vascularization and elastography revealed partial induration up to 2.5 m/s or 30 kPA an assessment with TI-RADS III or IV rating. Using the AI tool, the 20 of 25 goiter nodes were evaluated as TI-RADS III, 7 of 12 adenomas, 5 goiter nodes and 5 adenomas as TI-RADS IV, 5 of 13 carcinomas as TI-RADS IV and 8 of 13 carcinomas as TI-RADS V. Microcalcification as a definite malignancy criterion was automatically detected in 5 of 13 malignancies, an echo-poor irregular echo structure in all cases, and in intracystic tumors in 2 cases. The shape was irregular in all cases, proportionately lobulated, but oriented in depth in only 8 of 13 cases. Of the 25 struma nodules evaluated as possibly also malignant, partial necrosis and inhomogeneous microvascularization with also induration on elastography occurred in all cases. For 37 patients both classifications were identical. From the 12 cases, histologically classified as TI-RADS V, 11 were also classified as TI-RADS V by the AI-based diagnosis. Of the 13 remaining cases in which there were discrepancies between the two methods, 12 were histologically confirmed grade 3 carcinoma. Using AI-based diagnostic they were classified at least one grade higher by AI (n=12, including 2 two grades higher) and in one case a histologically confirmed as TI-RADS V case one grade lower. During the course of the work, the authors established the new multimodal ultrasound modalities offer the possibility of early detection of malignant foci. Multicenter evaluation is needed to evaluate the possibility of additional AI in terms of differentiation from TI-RADS III to TI-RADS V [13].

In conclusion, it is worth noting that modern thyroid ultrasound diagnostics is a high-tech, multi-level system for assessing structural and functional changes in the organ, providing high clinical information value in identifying thyroid lesions, including solitary or multinodular thyroid nodules, inflammatory processes, and tumors. B-mode diagnostic ultrasound remains the primary method, allowing for the assessment of size, contours, echogenicity, echostructure, and calcifications, as well as precise ROI selection for subsequent quantitative analysis.

In thyroid cancer diagnostics, ultrasound risk stratification based on the TI-RADS standardizes descriptions and defines indications for fine needle aspiration biopsy, improving the clinical validity of invasive interventions. The additional use of Color Doppler ultrasound and microcirculation imaging technologies, including UMA and ultra-microvascular imaging technology, enables detailed analysis of the vascular pattern of nodular lesions. Evaluation of hemodynamic parameters such as PRF, PSV, EDV, PI, and RI expands the possibilities for differentiating between benign and malignant processes.

Elastography significantly contributes to increased diagnostic specificity, including the quantitative elastography ratio, which reflects tissue mechanical properties and the degree of fibrosis. This method is particularly informative in chronic inflammatory diseases such as autoimmune thyroiditis, including the most common form, HT, as well as in conditions accompanied by hypothyroidism. A comprehensive as-

sessment of ultrasound features, combined with laboratory values for thyroid-stimulating hormone and free thyroxin, provides a comprehensive picture of the functional state of the thyroid gland.

A promising approach is CEUS, which allows for the analysis of the perfusion characteristics of lesions. The concept of multimodal imaging, consisting of B-mode, UMA, elastography, and CEUS, significantly improves diagnostic accuracy by integrating morphological, vascular, and biomechanical parameters.

The implementation of computer-assisted diagnosis (CAD) systems and artificial intelligence algorithms enables automated image processing, objectivization of ROI assessment, and reduction of operator dependence. The use of intelligent technologies contributes to the improvement of positive predictive value (PPV) and negative predictive value (NPV), increasing the reliability of risk stratification and clinical decisions.

Thus, the integration of B-mode, Doppler techniques, microangiographic technologies, elastography, contrast-enhanced ultrasound, and digital analysis algorithms forms the modern standard for comprehensive thyroid ultrasound examination. Ultrasound diagnostic techniques for various thyroid pathologies in general, and thyroid cancer in particular, are an important link in the specialty of "Radiology." Their high information content, sensitivity, and specificity often allow for an accurate diagnosis without resorting to more complex examination methods, which often carry a fairly high risk of complications and/or radiation exposure, and make it possible to conduct targeted, specialized treatment for these patients.

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# PEDAGOGICAL SCIENCES

## FORMATİON OF SKİLLS SPECİFİC TO THE SUBJECT OF İNFORMATİON CULTURE AND TECHNOLOGİCAL LİTERACY İN STUDENTS OF GENERAL EDUCATİON SCHOOLS

**Ibrahimov F.**
*Professor of the Sheki branch of the Azerbaijan State Pedagogical University*
*https://orcid.org/0000-0002-0775-1048*
**Kilinjova A.**
*Teacher at school No. 244, Baku city,*
*https://orcid.org/0009-0003-8855-9721*
https://doi.org/10.5281/zenodo.19292671

**Abstract**

The article shows that intellectual and creative activity of everyone living in the "Techno-democratic-information society" becomes a paramount requirement, and for this it is desirable for every member of this society to rise to the level of a subject of intellectual skills, they must have information culture and technological literacy.

The research paper presents the characteristics of "Education 4.0" in terms of the formation of intellectual skills (skills specific to the subject of information culture and technological literacy) in education, and the groups of skills in question formulated on a certain logical basis in this system.

The article draws attention to the fact that the tasks are designed on the principle of modeling the structure of various intellectual skills. As students complete them, they acquire intellectual skills such as determining the purpose of their work, systematizing educational material from this point of view, independently collecting material, etc.

The work focuses on the didactic principles that are necessary for the selection and systematization of tasks to be applied and the organization of students' activities on them, in order to form the skills (intellectual skills) specific to the subject of information culture and technological literacy.

**Keywords:** intellectual skills; metacognition; metacognitive skills; creative thinking; idea; task; interactive learning; psychological support; facilitator; motivation; reflection.

***Relevance of the topic:*** In modern times, to succeed, it is not enough to just be able to read and write, have knowledge of mathematics and natural sciences, and more competences are required. The characteristics of the 21st century require that a person develop the necessary qualities for creative activity (decision-making, problem-solving, independent learning, cooperation, teamwork, evaluating different approaches, putting forward new ideas, taking initiative, etc.) to live and advance in a rapidly changing, developing world. This creates conditions for sustainability for the future development of society. Everyone living in a “techno-democratic-information society” must engage in intellectual, creative activity. For this, a person must rise to the level of skills (intellectual skills) specific to the subject of information culture and technological literacy. Therefore, it is necessary to determine the optimal ways to acquire intellectual skills and regulate the environment that includes adequate ways. However, the methodological system for solving the problem in question has not been developed on a sufficiently scientific basis. Therefore, we assert the relevance of the research on the topic of "Formation of skills specific to the subject of information culture and technological literacy among students in secondary schools."

The purpose of the study is to identify the directions of pedagogical influence aimed at the formation of information culture and technological literacy skills in students in the process of implementing general education; it is taken into account that: an idea is an important value; the world of human activity is always based on an idea; everyone takes steps to check the adequacy of the results of their activities to the idea they consider acceptable.

***Methodological basis of the research:*** In the process of conducting the research, L. Bertalanfi's "Idea of System Analysis" [2;8] was used (an idea whose meaning is explained as an attempt to study the properties of an object based on the properties of its parts). The "System-structural approach", which has been formed as an important branch of dialectics and has risen to the level of its alternative, empirical, empirical-theoretical and theoretical methods of scientific cognition, the internal relationships of the forms of scientific cognition, and various pedagogical and psychological research generalizations were used as a methodological basis.

***Interpretation of generalizations from research materials:*** It is undeniable that education, which is a process of sharing human experience, has developed in stages as a product of social practice (especially pedagogical science) by incorporating the characteristics of industrial revolutions. In the era of the IV industrial revolution, an education system that can form a creative, innovative and globally competitive generation is required, and currently the impact of the aforementioned revolution on the educational process and the issue of "education of the future" are being discussed on various platforms and the necessary steps are being taken accordingly.[11], [12; 92-97].

The Fourth Industrial Revolution has different implications for different areas of our lives. From this perspective, there are both opportunities and challenges

for education. The use of different technologies such as IoT, 3D printing, quantum computing, artificial intelligence, etc. allows for more efficient information transfer and the development of a new “educational framework”. [9;288], [14; 78-94].

Currently, there is a system called the "Techno-democratic-information society" that makes people stronger. Members of the "Techno-democratic-information society" must have information culture and technological literacy, otherwise they will not be able to assert themselves as active and creative members of the society in question.

Providing all members with adequate and sufficient information and providing high-level information services is a special feature of the society in question.

The information society, unlike the industrial society, is a more intellectual society and creates conditions for the highly educated, skilled, determined, and comprehensive development of people. The main characteristics of the information society are: mass satisfaction of information needs in society; information economy in society; high level of information needs of society members; high information culture in society, expansion of open information networks for society members; prospects for the formation and development of a single information environment; information security for society members; level of globalization and integration, etc.

Information culture is the knowledge, intellectual skills, and habits necessary for a person to adapt to the information society. The role of the computer network in the formation of information culture is great.

Information culture: is the ability to use information resources and information communication tools of society; is the application of advanced achievements in the field of informatization and the development of information technology tools in society; is the ability to obtain and transmit information using modern technical means and methods, computer technologies.

*Technological literacy*–the ability of people to use various digital technologies, analyze data, and operate safely in a digital environment. “This skill is not limited to using a computer and the internet, but also includes: 1) Adhering to digital safety and cybersecurity rules; 2) Working with artificial intelligence and automation; 3) Digital analytics and data processing skills; 4) Using cloud technologies; 5) Quickly adapting to new technologies”[5]

Technological literacy includes the ability to use information and communication technologies. Digital education allows people to participate independently in social life. In addition, the reality of digital education and the digital revolution requires fundamental changes in the forms and methods of moral education, leading to the emergence of digital skills as the most important skills. [16;58-64]

Developing digital skills is essential to ensure that they can engage safely and effectively with digital technologies in the future. Education systems need to take a comprehensive and integrated approach, supporting all learners to develop the skills to be active and ethical users of digital technologies.[17; 57-79]

In order to ensure accessibility to digital technologies, students are provided with devices that they can use at school and at home, or BYOD (Bring Your Own Device) strategies are used. A number of steps can be taken to develop digital skills, such as updating the curriculum, developing “learning frameworks”, involving educators in training, and developing digital educational resources. [15]

Digitally empowered learners can learn with peers from around the world and develop solutions to problems as a team. There is no doubt that developing learners’ digital skills will enable them to participate more actively in society as digital citizens in the future. [15], [17; 57-79]

In order for students to demonstrate their skills and abilities in new areas emerging under the influence of the Fourth Industrial Revolution, it is necessary to implement fundamental changes in technology and the curricula of the subjects taught. By reviewing the curricula of the subjects formed on the basis of chemistry, biology, physics, etc., which are considered "basic sciences" in the new curricula, more attention should be paid to the teaching of computer science subjects, which play a key role in the formation of the Fourth Industrial Revolution literacy. Naturally, more attention should be paid to the teaching of the subjects in question. [20; 432-466]

Due to the rapid development of technology, the knowledge and skills that students acquire during their education are outdated by the time they graduate. In order to help develop and shape the use of today's fastest-growing technologies in scientific and technical education, it is necessary to train students and prepare them for the digital environment. Adapting to a rapidly changing environment will make it necessary for students to stay in touch with educational institutions even after graduation, providing both workers with updated skills and young students (and faculty) with a new direction related to the rapidly changing realities of the industrial and corporate sectors.[18; 25-30], [19; 579-592]

In our modern era, parameters such as relevance, practicality, effectiveness, and sustainability are the indicators of the quality of an educational program, while the indicators of its success are the quality of acquisition by learners and the extent to which learners can effectively use what they have acquired for their personal, social, cognitive, psychological, and emotional development. [3; 5].It is worth emphasizing that the expected paradigmatic changes in the education system and the implementation of global education reform have been further accelerated by the influence of the Fourth Industrial Revolution.[21; 147-171]. In the era of the Fourth Industrial Revolution, education must have the potential to develop society, complex and dialectical opportunities. Educational institutions must achieve that students acquire digital and technological literacy (digital and technological literacy) - intellectual skills, in addition to acquiring knowledge. [10]

In connection with Industry 4.0, we would not be wrong to say that “innovation has begun to dominate

education systems". Educational institutions will have to see innovation not only as a means of ensuring increased global competitiveness under the influence of globalization, but also as one of the main parts of the education system. In accordance with the requirements of the times, the teaching of new technologies will be accepted as one of the main needs on a logical basis. "Lifelong learning" will be the main motto of the education system. Naturally, the content of education should also take into account the skills of the 21st century: in addition to knowledge, the development of abilities and skills such as complex problem solving, critical thinking, creativity, leadership, digital literacy, emotional intelligence, global citizenship, cooperation, discussion, judgment and decision-making will also be accepted as the main learning outcomes.

Education 4.0 should serve the formation of skills (intellectual skills) that help learners develop in accordance with changes in society. Education 4.0 aims to prepare individuals to be creative and innovative. Education should adapt to the environment in which learners live and provide them with a reliable and successful future. This new system uses "smart" school management systems, learning management programs, communication tools and teaching and learning tools. [13; 238-254]. In the Education 4.0 approach, it has been determined that, going beyond constructivist education systems and Bloom's taxonomy, an environment-based learning process will be applied, focusing on the formation and development of intellectual skills, especially based on the following directions: 1) 3R (Recalling, Relating, Refining) regulating understanding; 2) 3I (Inquiring, Interacting, Interpreting) that encourages research; 3) 3P (Participating, Processing, Presenting) that is based on drawing conclusions.[22; 92-98], [23; 40-45]

Education 4.0, which provides an effective environment for the formation of skills specific to the subject of information culture and technological literacy in students, has the following characteristics: 1) Learning regardless of time and place (lifelong learning, e-learning, etc.); 2) The opportunity to receive personalized education according to the skills and abilities of students; 3) Taking into account the suggestions of students when preparing the curriculum; 4) Predominance of project-based learning; 5) Formation of students' ability to conduct analysis on large-scale data (Big Data); 6) Assessment of students' knowledge in the process of applying them to projects; 7) Becoming a part of the education system of developing new technologies, etc. [11-12]

In the era of the Fourth Industrial Revolution, "smart" educational tools and resources should enable individuals to acquire more advanced experience, knowledge, and skills, and to reveal their innovative perspectives.

The way of forming intellectual cognitive skills in education is adequate to the merits of innovative teaching applied in our modern era.

Scientific sources indicate that in the process of implementing general education, the student (student) must acquire the necessary intellectual skills to realize his intellectual qualities and purposefully regulate cognitive activity. Intellectual skills are numerous. Taking into account the research of NA Menchinskaya in this area, intellectual skills can be divided into the following groups: 1. General intellectual skills (planning, working with books, self-control); 2. Intellectual skills necessary for the organization of mental activity (distinguishing the main idea in the text, dividing the text into parts according to its meaning, comparing events, etc.); 3. Specific intellectual skills (they reflect the characteristics of this or that subject, for example, graphic skills). Another classification of intellectual skills, authored by I. Unt, is as follows: 1. Skills related to the perception of educational material (reading, observation, listening skills); 2. Ability to perform logical operations with educational material (attribution of what is important, comparison, ability to draw conclusions, etc.); 3. Creative skills (ability to build a composition, etc.) [1; 60].

The main function of the skills inherent in the subject of information culture and technological literacy is related to the exteriorization of intellectual operations (mental activity is considered external, practical activity is considered internal, and mental activity is considered external - transformation into something external): the content of cognitive activity is conditioned by intellectual operations, and their realization in the process of activity directly depends on the level of intellectual skills [1; 60], [7; 174].

In school practice, the psychology of cognitive activity has not been studied enough, and although students are interested in the characteristics of their memory or thinking, their interests have not been satisfied. In modern American psychology, this issue has been brought into the spotlight and studied as a metacognitive system. It has been established that as children develop, certain ideas about cognitive processes are formed in them and they begin to regulate their mental activity.

It is worth emphasizing that self-monitoring, self-regulation, and self-assessment are metacognitive skills, which are related but distinct concepts. It is a person's awareness and understanding of their own cognitive processes. Self-monitoring involves observing and following their actions, behaviors, and cognitive processes during a task. Here, the learner does not try to control themselves, judge, or evaluate their own performance. They simply collect information about their performance by observing themselves. The main components of this process are: observation; awareness; feedback. Self-regulation is the ability of a person to monitor and manage their cognition, emotional state, and behavior to achieve a goal. The main components of this process are: goal setting; planning; emotional regulation; adaptation. Self-assessment is the ability to judge or evaluate their own performance or learning. The main components of this process are: evaluation; reflection (3;50).

Flavell has studied and described in detail some of the functions of metacognition. Among them are the following: 1. Problem formulation and identification of possible solutions; 2. Knowing which cognitive processes are necessary to solve a task; 3. Activating cognitive rules and methods; 4. Confidence in the capabilities of thinking; 5. Attempting to solve tasks more efficiently.

These functions are interconnected. The first function is conditioned by the formation of ideas about the goals of the activity in children. As they grow older, they learn to apply known methods to various situations. Gradually, students form ideas about cognitive processes. They understand that in order to remember the material, it is necessary to listen carefully to the teacher, and to remember in order to remember. When the student's ideas about these psychological processes are clear, he activates attention in one case, and memory in another, depending on the nature of the task. In this process, his competence gradually increases: he looks for new ways to solve the problem. When the student believes in the possibilities of his thinking, he does not shy away from difficulties, even if he fails, he thinks and tries to solve the problem. In this process, his attitude towards himself also changes. He solves the task not in a hurry, not in a hasty, headlong manner, but in efficient ways [1; 60].

According to P.Massen, C.Kenger, C.Kogan and A.Houston, the mentioned functions develop to one degree or another in all children. However, the level of their development is significantly influenced by the upbringing conditions. [7;192]. They should be developed by all means. The relevance of the issue should be clearly understood from a scientific-methodological aspect and systematic work should be carried out in this area at school.

A system of special tasks is applied to form skills specific to the subject of information culture and technological literacy in students. These tasks are designed on the principle of modeling the structure of various intellectual skills. As students complete them, they acquire intellectual skills such as determining the purpose of their work, systematizing educational material in this regard, independently collecting material, writing an essay, etc. From the point of view of the principle of developmental training, this method is considered effective. However, in order to use it purposefully, the system and content of intellectual skills in classes and subjects must be thoroughly developed.

According to our subjective understanding, by creatively using the curriculum model currently being applied in secondary schools (which is conditioned by the teacher's scientific and theoretical training and pedagogical mastery), it is possible to form a system of tasks that also aims to develop skills (intellectual skills) specific to the subject of information culture and technological literacy in students.

In the preparation of tasks for active learning aimed at general, specific learning outcomes and performance indicators, the hierarchy of thinking types is established from simple to complex in the following order: logical thinking - critical thinking - creative thinking. The operations of thinking provide the basis for determining its type. This factor can also be used in the management of learning.

***Tasks and their system:*** should be consistent with the purpose of the lesson and aimed at solving the research problem set (according to the type of thinking, information sources, form of presenting results, etc.); should be appropriate to the age, knowledge and intellectual level, abilities and interests of students, and should be differentiated; should be based on the state program and national values; should be relevant, related to real life and students' experiences; should be interesting, attractive, and encourage discovery; should be clearly stated; should contain clear and open questions.

The formation of a system of tasks is only part of the work aimed at developing students' intellectual skills in the learning process. One of the important issues is to achieve the formation of cognitive activity of students when working on tasks and its (continuous) maintenance throughout the entire process. It should be noted that four main mechanisms of learning-centered learning, in other words, active (interactive) learning (the main goal of this process is research), lead to the formation and maintenance of cognitive activity during the lesson. These are the following: Creating a problem situation (the student is presented with a problem and is directed to solve it, which results in cognitive activity); The student's role as a researcher, the teacher as a facilitator (during active (interactive) learning, the student should stand in the position of a subject, be an equal participant in this process, he should independently acquire knowledge during research); The need for dialogue and cooperation (active (interactive) learning is carried out in a dialogical, collaborative environment). Psychological support: respect and trust (The means of maintaining students' cognitive activity is their psychological support, which is possible thanks to the teacher's benevolent attitude, respect and trust towards students, and confidence in their abilities) [8; 49-50]. .

It is possible for a student to act in the position of a researcher when the content of the training material, the form of action of the tools and methods (in the training process, the content of the training material, tools and methods take precedence over the content in terms of the organizational form) are in accordance with the research process. The organizational form of training organized in accordance with the research process has a unique structure (the structure of the active lesson resembles the stages of the research process).

***This form, called active learning, includes the following stages:***

1. Motivation stage (posing a problem, putting forward hypotheses); 2. Research stage (searching for facts to test hypotheses); 3. Information exchange stage (presentation of the obtained data); 4. Information discussion and organization stage (discussion of the obtained data, correlation of various facts, their systematization); 5. Generalization and conclusion stage (generalizations, comparison of results with hypotheses and conclusion on their confirmation or refutation, answer to the research question); 6. Productive (creative) application stage (application in new conditions, solution of practical problems); 7. Evaluation or reflection stage (evaluation of activity, mastering the rules of learning, reflection in consciousness of the already completed process, one of the main mechanisms that allows analyzing and understanding all stages of knowledge acquisition)

[4; 646-652].

In selecting and systematizing tasks to be applied in order to form skills specific to the subject of information culture and technological literacy in students, and organizing students' activities on them, the following principles should be kept in focus: completeness of the learning process; creation of equal opportunities in learning; student-centeredness; development-orientedness; stimulation of activity; creation of a supportive environment.

***Scientific novelty of the study:*** The idea of the directions of pedagogical influence aimed at the formation of skills specific to the subject of information culture and technological literacy in students in the process of implementing general education has been identified.

***Theoretical significance of the study:*** The research on the presented topic has a specific function in directing further scientific activity for a broad study of theoretical and practical ways to solve the problem of creating conditions for sustainability for the future development of society.

***Practical significance of the study:*** In the real pedagogical process, practical educators have the opportunity to benefit from the idea of the directions of pedagogical influence of information culture and technological literacy skills on students in their activities.

***Conclusion:*** 1. Intellectual and creative activity of everyone living in the "techno-democratic-information society" becomes a paramount requirement, and for this, it is necessary for each member of this society to rise to the level of a subject of information culture and technological literacy; 2. The presence of information culture and technological literacy in each member of the society formed in accordance with the calls of the IV industrial revolution is a desirable quality; 3. The education system adequate to the "techno-democratic-information society" has taken its place in scientific sources and pedagogical practice under the term "Education 4.0" and has been interpreted as a superstructure on logical grounds; 4. "Education 4.0", which exhibits an effective environment for the formation of intellectual skills, has specific characteristics, and it is possible to divide the intellectual skills that need to be formed in this system into groups on a certain logical basis; 5. In general education schools, a system of special tasks is applied to form skills (intellectual skills) specific to the subject of information culture and technological literacy in students, and it is advisable to compile these tasks based on the principle of modeling the structure of various intellectual skills; 6. In selecting and systematizing tasks to be applied for the purpose of forming intellectual skills and organizing students' activities on them, the following principles should be kept in focus: 1) Completeness of the educational process; 2) Creation of equal opportunities in education; 3) Student orientation; 4) Development orientation; 5) Stimulation of activity; 6) Creation of a supportive environment.

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# METHODOLOGICAL PRACTICES OF THE PRYKARPATTIA SCHOOL OF PHYSICS IN THE CONTEXT OF THE MODERN EDUCATIONAL PARADIGM

**Lishchynskyi I.**
*Candidate of Physical and Mathematical Sciences, Professor of the Department of Physics and Astronomy, Vasyl Stefanyk Carpathian National University*
**Ilyn M.**
*Postgraduate Student at the Department of Physics and Astronomy, Vasyl Stefanyk Carpathian National University*
https://doi.org/10.5281/zenodo.19292673

**Abstract**

The article presents a comprehensive analysis and scholarly-methodological reinterpretation of the innovations of the Prykarpattia School of Physics, founded at the Ivano-Frankivsk Pedagogical Institute (now Vasyl Stefanyk Precarpathian National University), with an emphasis on their potential for adaptation to the modern competency-based and digital educational paradigm. The point of departure is the identification of current problems in the practice of teaching physics in Ukraine: formalized acquisition of knowledge, insufficient experimental training, fragmentation of learning material, and the need to combine digitalization with the continuity of proven didactic models. It is shown that the methodological approaches of the school's representatives (H. Haiduchok, P. Kyrychok, I. Luchkiv, and others) in the 1970s–1980s were ahead of widespread practices and remain relevant to the contemporary priorities of the New Ukrainian School: the development of critical thinking, research skills, technological literacy, and the applied use of knowledge.

It is substantiated that H. M. Haiduchok's idea of generalized experimental skills can be naturally scaled through digital laboratories, interactive simulations, and STEM projects. At the same time, AI tools can personalize the experimental learning trajectory, diagnose learning difficulties, and shift from the "fixation of an error" to its explanation and correction. Approaches to the differentiation of experimentation (H. Haiduchok) are interpreted as a methodological prototype of adaptive learning, particularly relevant in inclusive and distance education. P. P. Kyrychok's positions on the fundamentalization of teacher training align with the need for modern pedagogical education to integrate scientific, practice-oriented, and technological components. It is concluded that the legacy of the Prykarpattia School of Physics constitutes an effective methodological resource for modernizing physics education in schools, professional colleges, and universities amid digital transformation and the development of AI.

**Keywords:** Prykarpattia school of physics, physics education methodology, generalized experimental skills, digital laboratories, STEM education, adaptive learning, artificial intelligence, competence-based approach.

**Introduction.** The development of physics teaching methodology in Ukraine is taking place against the backdrop of rapidly changing educational standards, digitalization, and the growing demand for competence-based learning outcomes. At the same time, educational practice continues to face persistent problems, including the formalized assimilation of knowledge, insufficient experimental training, and the fragmented presentation of instructional material. In this context, there is a pressing need to reconsider national methodological traditions capable of providing instruments for renewing the content and technologies of physics teaching without breaking with well-established didactic models [4]. A significant resource for such reconsideration is the legacy of the Prykarpattia School of Physics, formed at the Ivano-Frankivsk Pedagogical Institute (now Vasyl Stefanyk Precarpathian National University), whose representatives, notably H. M. Haiduchok, P. P. Kyrychok, and I. M. Luchkiv, proposed, in the 1970s and 1980s, approaches that were ahead of the dominant educational practices of their time. Although these methodological proposals were developed several decades ago, they have not lost their relevance, as they align with the current priorities of the New Ukrainian School: the development of critical thinking, inquiry skills, technological literacy, and the ability to apply knowledge in practical situations. The problem is that these achievements often remain confined to the "archives" of historical pedagogy, whereas contemporary technical means enable them to be translated into applied educational solutions.

The scholarly relevance of this study is обусловлений? Need to continue in English. Let's craft.

The scholarly relevance of this study is determined by the need to demonstrate how H. M. Haiduchok's idea of developing generalized experimental skills can be implemented through digital laboratories, STEM projects, and interactive simulations, while also being enhanced by artificial intelligence tools that individualize learning trajectories [3]. It is equally important to analyze the line of instructional technologization developed by H. M. Haiduchok and I. M. Luchkiv, namely, technical teaching aids, programmed assessment, and rapid feedback [6], which, in the contemporary educational environment, can evolve from the mere "identification of an error" to its explanation and personalized correction through learning analytics and generative models. Approaches to the differentiation of experimental activity proposed by H. M. Haiduchok and V. H. Nyzhnyk also require separate consideration, as they acquire new significance under the conditions of inclusive education and distance learning formats [7]. No less relevant is the methodological training of teachers and the concept of "scientific school studies" emphasized by P. P. Kyrychok, since contemporary teacher

education requires models that combine fundamental academic grounding, practice orientation, and technological competence [5]. Thus, the scholarly problem consists in identifying ways to adapt the innovations of the Prykarpattia School to contemporary digital conditions and in demonstrating their applied value for the educational process not only in school education, but also in professional colleges and universities.

**The purpose** of the article is to provide a comprehensive analysis and scholarly-methodological reinterpretation of the methodological practices of the Prykarpattia School of Physics, in particular its approaches to the development of generalized experimental skills, the technologization of instruction and programmed assessment, the differentiation and individualization of learning activities, the methodological training of teachers, and the integration of knowledge into a holistic scientific worldview, to identify the possibilities for their adaptation and implementation in the contemporary educational process of schools, professional colleges, and universities through digital platforms, virtual laboratories, STEM tools, and artificial intelligence technologies.

**Methods.** The study employs historical-pedagogical and historical-genetic methods to reconstruct the formation of the Prykarpattia methodological school of physics and the evolution of its approaches from programmed instruction practices and technical teaching aids to contemporary digital solutions. The methods of analysis and synthesis are used to identify the key methodological innovations, namely, the development of generalized experimental skills, programmed assessment and feedback, the differentiation of experimental activity, the fundamentalization of teacher training, and the integration of knowledge, and to establish their logical connections with the competence-based paradigm of the New Ukrainian School. A comparative method is applied to correlate the approaches proposed in the 1970s and 1980s with contemporary practices, including STEM, digital laboratories, interactive simulations, adaptive learning, and elements of COIL, and to determine their didactic equivalence. The method of theoretical modeling (instructional design) is employed to formulate possible ways to implement the school's ideas on digital platforms and through the use of artificial intelligence tools to personalize learning trajectories and diagnose learning difficulties. In addition, an interpretive-hermeneutic approach is applied to examine the content of the works and methodological recommendations of the school's representatives, taking into account their historical context and the potential for contemporary reinterpretation.

**Results.** The development of the national methodology of teaching physics may be understood as a continuous historical process in which each stage not only reflects the demands of its era but also creates the preconditions for subsequent didactic transformations. A particularly prominent center of such development was the Prykarpattia School of Physics, established at the Ivano-Frankivsk Pedagogical Institute (now Vasyl Stefanyk Precarpathian National University). Its representatives, in particular H. M. Haiduchok, P. P. Kyrychok, and I. M. Luchkiv proposed several approaches to renewing the content, organization, and technologies of physics teaching, which, in the 1970s and 1980s, were ahead of the prevailing educational practices and at the same time laid down methodological guidelines consonant with the current priorities of competence-based education and digitalization. For this reason, the innovations of the Prykarpattia School may be reinterpreted as a methodological resource for the development of contemporary educational practices, including the use of artificial intelligence technologies.

One of the school's conceptual innovations was H. M. Haiduchok's idea of developing generalized experimental skills and abilities [3]. Its central emphasis was that, under conditions of scientific and technological advancement, what becomes decisive is not the mere sum of reproduced theoretical information, but the student's ability to organize experimental activity: to select and set up instruments, control experimental parameters, interpret results, assess errors, and draw well-grounded conclusions. The contemporary educational paradigm reproduces this logic through the development of scientific and technological competencies, while its practical implementation is increasingly associated with interactive simulations, STEM projects, and digital laboratories. Given that H. Haiduchok's concept placed significant emphasis on the staged character of learning activity and differentiated support for the learner [1], the potential of artificial intelligence may be employed for the individualization of learning: algorithms are capable of tracking the trajectory of performing a virtual experiment, identifying typical difficulties, and providing targeted prompts at the stages where errors occur, thereby reproducing the methodological idea of pedagogical "scaffolding" and support for learning progress.

A second important line of innovation within the Prykarpattia School was the introduction of technical teaching aids and programmed assessment of knowledge. In the works of H. M. Haiduchok and I. M. Luchkiv, the structure of lectures was described as an integral cycle consisting of an introductory, main, and concluding part, within which special control devices were used to provide rapid feedback on students' mastery of the material [6]. In its historical context, such solutions may be regarded as prototypes of modern learning management systems oriented toward the prompt diagnosis of learning outcomes and the correction of learning activity. The distinctive feature of the contemporary stage lies in the fact that artificial intelligence is capable of moving from mere error detection to error explanation: not simply identifying an incorrect answer, but determining its probable cause, that is, a typical misconception or a gap in understanding, and automatically offering personalized learning material to eliminate the identified problem. At the same time, the idea of intensifying independent work, which the school's methodologists associated with technical teaching aids, acquires additional possibilities in the digital environment: generative models can sustain educational dialogue, assist in constructing virtual models, explain physical phenomena in different ways, and stimulate argumentation, thereby developing the format of the "lecture-conversation", in which the technological tool functions not as a passive carrier of illustrations but as an interactive participant in cognitive interaction.

An organic continuation of the technologization of instruction within the Prykarpattia School was its attention to the differentiation and individualization of experimental activity, particularly in the works of H. M. Haiduchok [2]. In substantiating a differentiated approach to frontal experimentation, these scholars proposed additional tasks for more advanced students, support cards for those requiring assistance, and home experiments as a form of independent inquiry. Under contemporary conditions of inclusive education and the spread of distance-learning formats, these solutions align with the logic of adaptive learning, in which the level of difficulty and types of tasks are selected in accordance with the learner's academic achievements and educational needs. The practical equivalent of paper-based "cards" is now represented by interactive worksheets and digital platforms that can modify the learning trajectory based on task performance results. Virtual laboratories, in turn, make it possible to reproduce experimental situations of varying complexity and provide a space for creative inquiry in which the learner can make personal "discoveries" through planning the experimental procedure, varying parameters, and interpreting data, which corresponds to the heuristic orientations embedded by the methodologists of the Prykarpattia School.

A distinct and methodologically significant dimension of the legacy of the Prykarpattia School of Physics is associated with its understanding of teacher training as a holistic process that combines profound subject-matter competence, methodological culture, and the capacity for pedagogical reflection. In the works of P. P. Kyrychok and his colleagues, the idea was consistently affirmed that high-quality professional training for the future physics teacher cannot be limited to mere assimilation of specialized discipline content. It must rest on a high level of scientific and theoretical instruction, the systematic comprehension of teaching methodology, a continuous connection between pedagogical theory and school practice, and the formation, in the future teacher, of the ability to analyze the educational process as a complex, dynamic, and scientifically organized system. It is precisely in this context that the development of a specific form of "scientific school studies" within teacher education acquires significance, since it oriented students not only toward mastering instructional material, but also toward understanding the regularities governing the functioning of the school, the logic of lesson construction, the specific features of organizing the learning environment, and the mechanisms through which students' cognitive activity is formed.

A substantial role in implementing this approach was played by methodological seminars, which were not auxiliary elements of training but served as a full-fledged instrument of the future teacher's professional development. It was through seminar work that the discussion of typical difficulties in teaching physics, the analysis of the content of school curricula, the testing of methodological solutions, the reflection on the results of pedagogical observations, and the generalization of best practices were ensured. Such a model contributed to the fundamentalization of professional training, since the future teacher was formed not as a narrow transmitter of knowledge, but as a teacher-researcher capable of selecting teaching methods in a reasoned manner, designing educational situations, and critically evaluating their own practice. Under contemporary conditions, this approach has not lost its relevance; on the contrary, it has acquired new meaning. Higher education today operates within the framework of modular-rating technologies, the credit-modular organization of the educational process, the competence-based approach, and the growing role of practice-oriented models of professional training. Under such circumstances, the ideas of the Prykarpattia School may be reinterpreted as a methodological foundation for combining academic fundamentalization with pedagogical mobility, digital literacy, and the capacity for innovative activity. Their value lies in offering not a fragmented but a systemic model of physics teacher formation, in which scientific rigor, methodological soundness, and practical orientation function not as separate components but as interrelated elements of professional competence.

A final, yet fundamentally important, line of innovation within the Prykarpattia School was its orientation toward systematicity and the integration of knowledge, particularly through generalizing lessons in the school physics curriculum on the topics of "The Electromagnetic Field" and "The Contemporary Scientific Worldview", where emphasis was placed on the interrelationship of fundamental concepts and principles [2]. Such instruction ensured the formation of a holistic worldview and an understanding of physics as a system rather than as a collection of disconnected topics. In the contemporary context, these ideas are manifested in integrated science courses and STEM education, where knowledge from physics, mathematics, computer science, and technology is combined within project-based tasks. The use of artificial intelligence can further strengthen this integrative effect by supporting interdisciplinary projects, from consultations on the scientific and historical context of discoveries (thus implementing the principle of historicism) to assistance in modeling processes through programming and data analysis, thereby making the systematic nature of knowledge practically tangible for the learner.

**Conclusions.** Thus, the methodological innovations of the Prykarpattia School of Physics constitute a significant layer of Ukrainian pedagogical thought that demonstrates the continuity of ideas from the early forms of the technologization of instruction to the contemporary digital transformation of education. The generalization of experimental skills, technological feedback and assessment, the differentiation of learning activities, the fundamentalization of teacher training, and the integration of knowledge into a holistic picture of the world form a conceptual core consonant with the competence-based paradigm of the New Ukrainian School. The reinterpretation of these approaches within the framework of digital platforms and artificial intelligence opens up possibilities for transitioning from "programmed assessment" to personalized learning trajectories, for developing high-tech STEM environments grounded in the laboratory method, and for ensuring high-quality distance education through virtual experimentation and learning analytics. Reflection on

and adaptation of this experience are important preconditions for shaping a competitive system of physics education in Ukraine that combines national methodological traditions with openness to global innovations.

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# TECHNICAL SCIENCES

## CRITICAL BREAK POINTS IN THE ATTACK CYCLE: A SIX-STAGE MODEL FOR PROACTIVE DEFENSE AGAINST SOCIAL ENGINEERING

**Marinov A.**
*PhD in Economic Sciences, associate Professor at the Cybersecurity Competence Center, Irkutsk National ResearchTechnical University, Irkutsk, Russia*
*https://orcid.org/0000–0003–2238–2751*
**Kolenchenko D.**
*student of group ISb-23-1, School of Information Technology and Data Science, Irkutsk National ResearchTechnical University, Irkutsk, Russia*
*https://orcid.org/0009-0002-7222-1462*

## ВЫЯВЛЕНИЕ КРИТИЧЕСКИХ ТОЧЕК РАЗРЫВА ЦИКЛА АТАКИ: ПРИМЕНЕНИЕ ШЕСТИЭТАПНОЙ МОДЕЛИ ДЛЯ ПРОАКТИВНОГО ПРОТИВОДЕЙСТВИЯ СОЦИАЛЬНОЙ ИНЖЕНЕРИИ

**Маринов А.А.**
*кандидат экономических наук, доцент центра компетенций по кибербезопасности, ФГБОУ ВО «Иркутский национальный исследовательский технический университет», г. Иркутск, Россия.*
*https://orcid.org/0000–0003–2238–2751*
**Коленченко Д.И.**
*Студент группы Ибб-23-1, Институт ИТ и АД, ФГБОУ ВО «Иркутский национальный исследовательский технический университет», г. Иркутск, Россия.*
*https://orcid.org/0009-0002-7222-1462*
https://doi.org/10.5281/zenodo.19292675

**Abstract**

This paper presents an overview of modern social engineering methods enhanced by generative AI technologies. The dominant role of data in the success of cyberattacks is examined using empirical data. The inadequacy of classical linear models for describing the adaptive nature of AI-mediated threats is revealed. A six-stage conceptual model of the life cycle of a social engineering attack is proposed. The attack is presented as a cyclical, iterative process with stages of goal formulation, reconnaissance, preparation (with data verification), initiation of contact, exploitation, and completion (with reflection). The key advantages of the model are its consideration of adaptability, the allocation of data verification to AI content generation, and the ability to influence the victim's subconscious mechanisms. The practical significance of this work lies in the possibility of constructing proactive defense systems with attack interruption points at any stage of its implementation. The mathematical justification of the model using the apparatus of probability theory and Markov processes, and the corresponding flowchart of the algorithm, confirming the cyclical nature of modern threats and the possibility of their formalized description, was developed.

**Аннотация**

В работе представлен обзор современных методов социальной инженерии, усиливаемых технологиями генеративного ИИ. Рассмотрена доминирующая роль в успешности кибератак на основе эмпирических данных. Выявлена несостоятельность классических линейных моделей для описания адаптивной природы ИИ-опосредованных угроз. Предложена шестиэтапная концептуальная модель жизненного цикла социоинженерной атаки. Атака представлена как циклический итеративный процесс с этапами формулировки цели, рекогносцировки, подготовки (с верификацией данных), инициации контакта, эксплуатации и завершение атаки (с рефлексией). Ключевыми преимуществами модели являются учет адаптивности, выделение верификации данных для ИИ-генерации контента и возможность воздействия на подсознательные механизмы жертвы. Практическая значимость работы заключается в возможности построения проактивных систем защиты с точками прерывания атаки на любом этапе ее реализации. Математическое обоснование модели с использованием аппарата теории вероятностей и марковских процессов, а также разработана соответствующая блок-схема алгоритма, подтверждающая циклическую природу современных угроз и возможность их формализованного описания.

**Keywords:** cyber threat, generative artificial intelligence (generative ai), attacker, cyberattack, conceptual model of the attack lifecycle, social engineering, vulnerability, countermeasures against social engineering, defense against social engineering.

**Ключевые слова:** киберугроза, генеративный искусственный интеллект, злоумышленник, кибератака, концептуальная модель жизненного цикла атаки, социальная инженерия, уязвимость, противодействия социальной инженерии, критические точки разрыва цикла атаки.

## Введение

Глобальная цифровизация, охватывающая все сферы человеческой деятельности с конца XX века, повышает производительность труда и качество жизни, однако одновременно актуализирует специфические проблемы информационной безопасности. Несмотря на то, что вопросы защиты на программно-техническом и правовом уровнях системно прорабатываются профильными ведомствами, а результаты НИОКР воплощаются в современных средствах защиты и адаптируемой нормативной базе, в любой защищенной системе наиболее уязвимым элементом остается пользователь – носитель индивидуальных поведенческих особенностей, объединяемых понятием «человеческий фактор». Именно это обуславливает высокую эффективность техник социальной инженерии как способа реализации кибератак: манипуляция человеческим фактором позволяет обходить классические, преимущественно технологические системы защиты и получать несанкционированный доступ к конфиденциальным данным [1, 2]. Дополнительным стимулом для злоумышленников в текущих реалиях служит обострение мировой социально-политической и экономической нестабильности, превращающее атаки на основе социальной инженерии в инструмент ведения гибридной войны [3].

Таким образом, к наиболее актуальным задачам информационной безопасности относятся как анализ методик социальной инженерии, используемых злоумышленниками, так и разработка блок-схемы, в деталях описывающая жизненный цикл современных социоинженерных атак.

Цель настоящего исследования состоит в проведении анализа современных методов и приемов социальной инженерии и разработке обоснованной концептуальной модели цикла социоинженерной атаки, отражающего специфику современных угроз.

## Социальная инженерия

Термин «социальная инженерия» вошел в академический дискурс относительно недавно, однако методика получения информации путем информационно-психологического воздействия, где пользователь выступал субъектом доступа к защищаемым данным. Согласно источникам [1, 2, 3, 5], в предметной области информационной безопасности социальная инженерия определяется как комплексная методология получения несанкционированного доступа к конфиденциальной информации посредством информационно-психологического воздействия, где доступ реализуется преимущественно через эксплуатацию уязвимостей человеческого фактора, а не через прямой технический взлом. Ключевое отличие от традиционных кибератак заключается в том, что технические средства применяются лишь на отдельных этапах (доставка фишингового письма, размещение вредоносного контента), но не определяют успех операции. Основой служит психологическая манипуляция: создание правдоподобного предлога, формирование ложного контекста, использование авторитета или срочности для побуждения жертвы к целевому действию [2, 4]. Соответственно, социоинженерные атаки – это вид кибератак, направленных на получение доступа к личным данным или объектам информатизации и основанных преимущественно на эксплуатации человеческого фактора.

Высокая эффективность таких атак обусловлена тем, что любой человек, будучи субъектом информационных отношений, обладает особенностями и слабостями, воздействие на которые способно реализовать сценарий, выгодный злоумышленнику [2, 3]. Речь идет о множественных психологических техниках, образующих стратегии воздействия на сознание и поведение жертвы.

## Анализ статистики актуальных киберугроз

Эмпирические данные ведущих компаний, в частности ежеквартальные отчеты Positive Technologies «Актуальные киберугрозы» [3, 4], подтверждают активный рост атак на основе социальной инженерии. Согласно отчету за I–II кварталы 2025 года, социальная инженерия доминирует в атаках на частных лиц (93%, рост на 5 п.п.) [6, 7]. В атаках на организации метод применяется в 50% успешных инцидентов, при этом в 97% таргетированных атак злоумышленники используют социальную инженерию, а в 43% случаев технические векторы не задействуются вовсе [6].

Анализ каналов доставки выявляет устойчивые различия в тактике злоумышленников: в атаках на организации доминирует электронная почта (88% инцидентов), тогда как на частных лиц – вебсайты (69%) [7]. Примечательным трендом стал рост использования мессенджеров в атаках на частных лиц на 92% [6], что обусловлено применением утекших персональных данных, взломанных аккаунтов и технологий генеративного ИИ.

Эффективность социальной инженерии подтверждается результатами атак: утечки данных зафиксированы в 52% случаев атак на организации и в 74% – на частных лиц, преимущественно похищаются учетные и персональные данные [6, 7, 8]. Рост использования мессенджеров и социальных сетей коррелирует с развитием прогрессивных методик на базе ИИ, включая дипфейки и гиперперсонализированный фишинг [7, 9]. Это свидетельствует о качественном изменении природы угроз: от массовых неперсонализированных атак к целевым операциям с автоматизированной генерацией контента. Социальная инженерия остается наиболее эффективным методом реализации кибератак, а ее эволю-

ция в сторону ИИ-опосредованных операций требует переосмысления подходов к противодействию.

**Прогрессивные методы атак**

Наиболее рационален подход к рассмотрению социоинженерных атак со стороны злоумышленников, использующего коммуникационные среды (Интернет, почта, соцсети) [2, 4, 5]. Поскольку методы атак на организации и физических лиц отличаются, необходима классификация с разделением цели. Аналитические данные [1, 2, 5] демонстрируют, что наиболее эффективно реализуются атаки с использованием техник фишинга, претекстинга и генеративного ИИ. Лидирующими методами по распространенности и эффективности на сегодняшний день являются Deepfake, Spear phishing, Quishing, ClickFix, Typosquatting [6, 7, 8, 9].

Технология deepfake, основанная на генеративно-состязательных сетях (GAN) и трансформерных архитектурах, позволяет создавать синтетический мультимедийный контент, визуально или акустически неотличимый от оригинала [9, 10]. В контексте социальной инженерии она реализуется в четырех модификациях: подмена лица, синтез речи (клонирование голоса), полная генерация видео «с нуля» и интерактивная видеоконференция с дипфейком. Ключевой эксплуатируемой уязвимостью является доверие к мультимодальным каналам коммуникации, что делает традиционные методы верификации неэффективными и требует внедрения дополнительных факторов аутентификации для критически важных операций [11, 12].

Спирфишинг с использованием ИИ автоматизирует подготовку атаки через большие языковые модели (LLM), заменяя ручной сбор данных и написание писем [13]. LLM генерируют гиперперсонализированные сообщения на основе открытых данных, учитывая контекст и стиль жертвы [14], что затрудняет обнаружение. По данным Avast, персонализированные фишинговые атаки с применением ИИ демонстрируют в 3-5 раз более высокий показатель конверсии по сравнению с массовыми кампаниями [15]. Традиционные модели не отражают данный уровень автоматизации и скорости создания контента.

Векторы доставки (квишинг, ClickFix) реализуют переход к пассивному «выжиданию»: создаются приманки (QR-коды, поддельные CAPTCHA), рассчитанные на автоматическое действие пользователя [7, 16]. При квишинге QR-код во вложении DOCX перенаправляет на фишинговый сайт [17], при ClickFix вредоносная команда копируется в буфер обмена через поддельную CAPTCHA для вставки пользователем. Рост методов показателен: использование мессенджеров выросло на 92%, а доля атак с ClickFix в H1 2025 увеличилась более чем на 500% относительно H2 2024 [7]. Фокус сместился на создание «ловушек», эксплуатирующих привычное поведение.

Тайпсквоттинг в экосистемах с открытым кодом (npm, PyPI) сочетает уязвимость человека и системы: разработчик загружает вредоносный пакет вследствие опечатки в названии [18]. В первом полугодии 2025 года зафиксировано более 4200 инцидентов, что на 73% превышает показатель аналогичного периода 2024 года [6, 7]. Это демонстрирует многослойность атаки, затрагивающую технические и человеческие компоненты.

Таким образом, прогрессивные методы знаменуют качественный сдвиг от массовых операций к целевым атакам с применением ИИ. Их объединяет использование современных технологических трендов и усиление психологического воздействия. Существующие модели, разработанные в эпоху ручных операций, не отражают специфику ИИ-атак (автоматизированная верификация, генерация синтетического контента, адаптивная рефлексия). Это обосновывает необходимость разработки новой концептуальной модели, адекватно описывающей жизненный цикл современных угроз.

**Обзор существующих подходов к моделированию цикла атаки**

Современные модели цикла атаки, включая четырехэтапную модель лаборатории Касперского [19] и подходы отечественных исследователей [4, 20, 21, 22], созданы по прицепу линейной структуры. Данный подход не отражает адаптивную природу современных ИИ-атак, требующих коррекции стратегии по обратной связи. Классическая модель (исследование, контакты, использование информации), несмотря на возможность итерации шагов, также не учитывает специфику современных угроз [23]. Ключевые недостатки традиционных моделей проявляются в трех аспектах:

1) традиционные модели игнорируют рефлексивный компонент, после завершения операции злоумышленник анализирует эффективность проведенной атаки, используя полученные сведения в дальнейшем (отсутствие этапа рефлексии делает модель неспособной описывать адаптивную природу современных угроз) [22];

2) этап подготовки в существующих моделях чрезмерно является абстрактным и игнорирует верификацию данных[1];

3) классические модели предполагают активный характер инициации контакта [2].

[1] В эпоху генеративного ИИ качество входных данных определяет убедительность контента. Современная подготовка включает сбор данных и их автоматизированную верификацию. Как отмечает А.О. Хлобыстова, этап «анализ и верификация» является ключевым [23]. Традиционные модели не отражают технологической специфики ИИ-опосредованных операций.

[2] Современные атаки часто реализуются через пассивные «ловушки», где жертва сама инициирует компрометацию. Авторами [23], [24] предлагается объединить этапы контактов в «активация общения», где происходит побуждение лица к разглашению информации.

Кроме того, существующие подходы игнорируют воздействие на подсознание жертвы: действия атакующих направлены на уровень подсознания, которое, в отличие от сознания, не сопротивляется воздействию [24]. Таким образом, модели утратили релевантность в условиях внедрения ИИ. Их неспособность отразить рефлексивность, верификацию данных и пассивные векторы обосновывает необходимость разработки новой концептуальной модели жизненного цикла ИИ-опосредованных социоинженерных атак.

**Модель цикла атаки на основе социальной инженерии**

Авторами представлена шестиэтапная концептуальная модель жизненного цикла социоинженерной атаки. Суть данное разработки в отличие от линейных подходов: модель представляет атаку как циклический, итеративный процесс, отражающий адаптивную природу злоумышленника. Модель включает следующие этапы: формулировка цели, рекогносцировка, подготовка атаки, инициация контакта, эксплуатация и завершение атаки (рисунок 1).

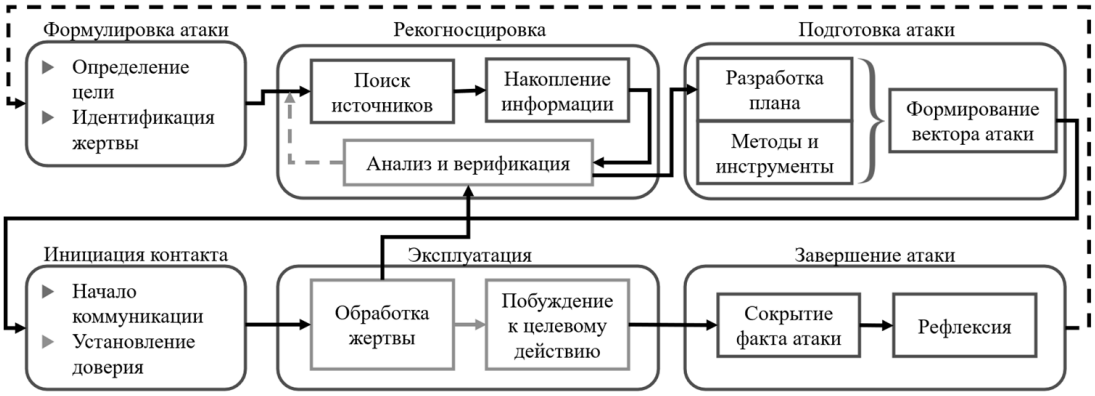


*Рис. 1. Концептуальная модель жизненного цикла социоинженерной атаки*

В рамках предлагаемой модели атака представляется как циклический процесс, основные этапы представлены в табл. 1.

Таблица 1.

Описание этапов социоинженерной атаки

| Этап | Описание | Формулы для описания |
|---|---|---|
| 1 – формулировка цели | На данном этапе злоумышленник определяет общую цель атаки (например, кража данных, финансовая выгода, репутационный ущерб) и идентифицирует потенциальную жертву или группу жертв. Здесь же формируется первичный «портрет цели» на основе доступных данных, в дальнейшем данные «жертвы» ранжируются по убыванию полезности для выбора оптимальной цели. | Процесс формализуется через расчет функции полезности атакующего – **формула 9**. Формирование первичного портрета – **формула 10**. |
| 2 – рекогносцировка | Классический этап сбора данных, который, однако, в современных условиях часто автоматизирован и/или ИИ-адаптирован. Он включает поиск всевозможных источников информации (социальные сети, корпоративные сайты, банки утечек данных) и агрегацию информации о жертве, такой как ее интересы, связи и поведенческие паттерны. При необходимости злоумышленник может дуплицировать все значимые действия этого этапа (поиск, накопление, анализ данных), поскольку именно он является основой для последующей персонализации атаки. Если качество данных ниже порогового значения, счетчик увеличивается и сбор повторяется. После достижения порога качества проводится верификация атрибутов через байесовскую оценку по формуле (14). Если достоверность ниже порога, алгоритм возвращается к повторному сбору данных, обеспечивая высокую надежность входной информации. | Подбор данных рассмотрен как итерационный цикл: инициализируется счетчик, выполняется сбор данных, **формула – 11**. Расчет метрики качества **формула – 12**. |
| 3 – подготовка атаки | Этап является ключевым для современных ИИ-опосредованных атак и детализирует классический этап подготовки. Он включает два подпроцесса:<br>- верификация данных: автоматизированная проверка достоверности и согласованности собранных на этапе | Выбор оптимального вектора атаки осуществляется путем многокритериальной оптимизации **формула – 16**. |

| | | |
|---|---|---|
| | рекогносцировки данных. Это критически важно для генеративных моделей, которые требуют качественной входной информации для создания убедительного контента;<br>- разработка плана: на основе верифицированных данных формируется вектор атаки (выбор канала: почта, мессенджер), разрабатывается детальный план (сценарий коммуникации, психологические триггеры) и подбираются инструменты (фишинговые шаблоны, deepfake-генераторы, вредоносные скрипты). | Расчет вероятности успеха – **формула 17**.<br>Генерация сценария коммуникации опирается на модель социального влияния – **формула 19**. |
| 4 – инициация контакта | На данном этапе злоумышленник создает условия для первого взаимодействия с жертвой. Цель – установить доверие за счет использования персональных типированных сведений, собранных на предыдущих этапах. Этот этап предполагает реализацию злоумышленником конкретного метода – отправку фишингового письма, инициацию видеозвонка с поддельным «руководителем» или размещение QR-кода на физическом носителе. | Уровень доверия формализуется через показатель, рассчитываемый – формула 23.<br>Данные моделируются под марковский процесс принятия решений (MDP) – формула 20; 21.<br>*Если данные ниже порогового значения, осуществляется коррекция сценария и попытка повторяется, что позволяет адаптивно подстраиваться под реакцию жертвы.* |
| 5 – эксплуатация | Это этап получения желаемого результата от жертвы. Здесь могут применяться уже тонкие психологические приемы и воздействие на стандартные медиаторы (страх, срочность, любопытство, жадность) для побуждения жертвы к целевому действию: вводу данных, переводу средств, установке ПО или выполнению вредоносного кода. Именно здесь проявляется уязвимость человеческого фактора как основного источника рисков. | Вероятность целевого действия вычисляется по формуле 24.<br>Успешность эксплуатации оценивается бинарной функцией – формуле 25.<br>В случае неудачи применяется адаптивная коррекция по принципу ε-greedy (предполагается смена тактики или исследование альтернативных стратегий) –формула 26. |
| 6 – завершение атаки | Этап включает сокрытие следов атаки (удаление логов, смена инфраструктуры) и, что наиболее важно, рефлексию. Злоумышленник анализирует эффективность использованных тактик, документирует успешные приемы и собирает обратную связь для работы над ошибками. Полученные сведения дорабатываются и используется в дальнейших схемах. Алгоритм проверяет условие сходимости: если оно не выполнено и доступны новые цели, осуществляется возврат к ***Этапу 1*** с обновленными параметрами, замыкая цикл атаки. | Реализуется через обновление параметров модели злоумышленника – формула 27.<br>Расчет функции потерь – формула 28.<br>Вероятности успешного завершения атаки – формула 29.<br>*Финальный вывод алгоритма включает вектор успешности, обновленные параметры модели, стационарные вероятности и общий риск.* |

На рисунке 2 представлена блок-схема модели цикла социоинженерной атаки. В отличие от традиционных линейных схем, модель учитывает динамические аспекты взаимодействия злоумышленника и жертвы.

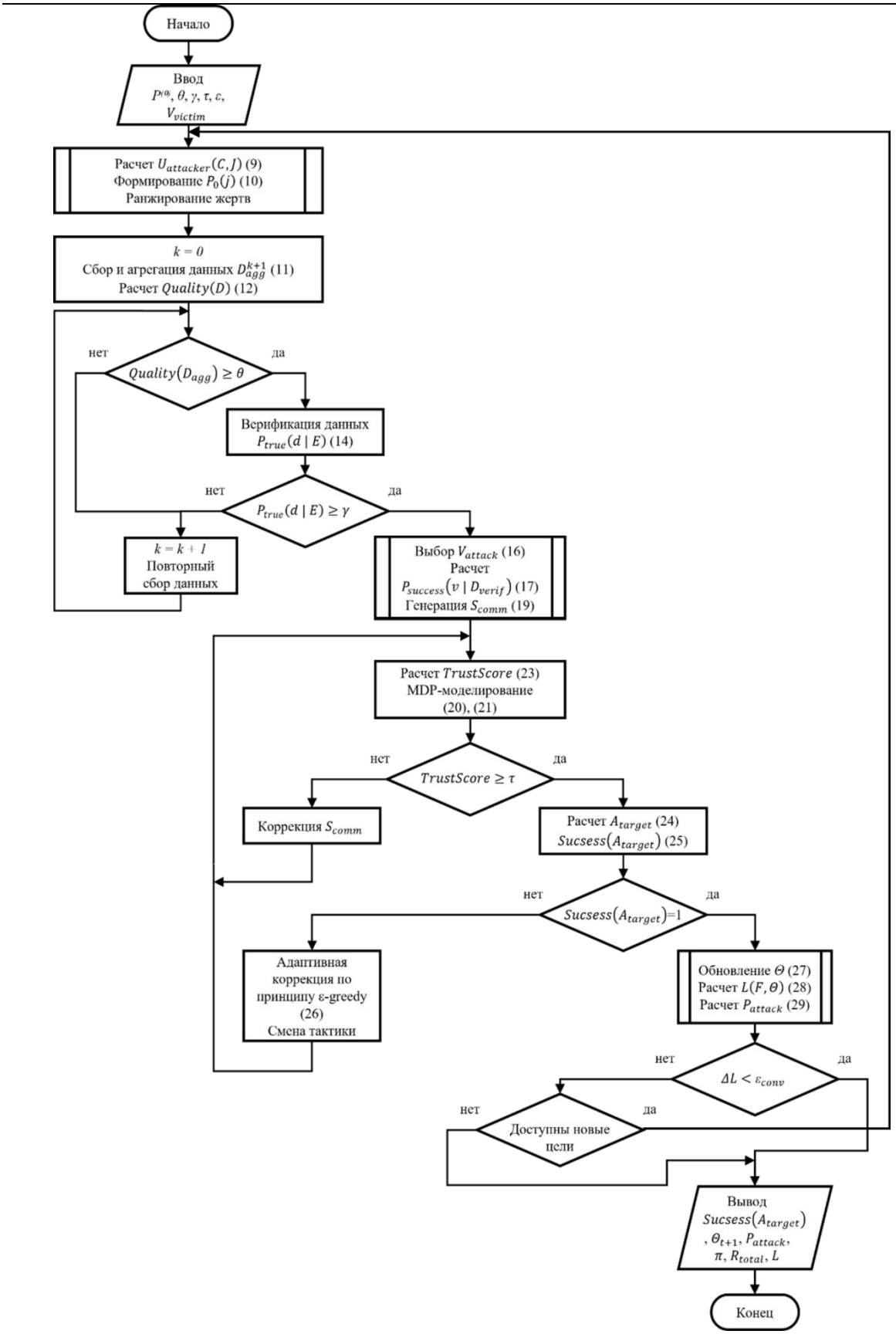


*Рис. 2. Блок-схема модели цикла социоинженерной атаки*

Ключевые преимущества модели заключаются во включении рефлексивного компонента (система обучения злоумышленника), выделении верификации данных (критично для ИИ-генерации) и признании итеративной природы атаки как цикла коррекции действий. В отличие от классических линейных построений, предложенная модель формализует процесс атаки как ориентированный граф с вероятностными переходами, что позволяет количественно оценивать риски на каждом этапе и прогнозировать развитие инцидента. Модель также

учитывает подсознательные аспекты манипуляции, что делает социальную инженерию особенно опасной [21] и позволяет описывать техники, эксплуатирующие бессознательные реакции. Интеграция виктимной модели жертвы, основанной на поколенческих уязвимостях и психологических профи-

**Математическое обоснование разрабатываемой модели**

В отличие от линейных описаний, предлагаемая модель трактует атаку как циклический итеративный процесс, что требует применения методов теории вероятностей, теории марковских процессов и моделей оценки рисков. Обоснование структуры модели базируется на представлении атаки как ориентированного графа, где вершинами выступают этапы взаимодействия злоумышленника с жертвой, а дугами – вероятностные переходы между ними. Такой подход позволяет учесть адаптивную природу современных угроз, когда злоумышленник корректирует свои действия на основе обратной связи, полученной в ходе реализации атаки [25].

В основе формализации жизненного цикла атаки лежит базовое представление риска как функции от вероятности реализации угрозы и величины потенциального ущерба:

$$R = P \cdot L, \quad (1)$$

где $R$ – базовый риск социоинженерной атаки;

$P$ – вероятность реализации угрозы;

$L$ – величина потенциального ущерба (в условных единицах).

Данная формула является фундаментальной для всех последующих вычислений и согласуется с общепринятыми подходами к оценке рисков информационной безопасности [26].

Для обоснования уязвимости человеческого фактора на этапах рекогносцировки и эксплуатации необходимо построить формальную модель жертвы. В основе виктимной модели лежит интегральная схема социального влияния, предложенная Т.В. Тулупьевой в [27], где злоумышленник выступает агентом влияния, а пользователь – реципиентом.

Виктимная модель жертвы $V_{victim}$ представляет собой входные параметры для всего алгоритма, включающий вектор психологических параметров жертвы (доверчивость, склонность к риску, когнитивная нагрузка, импульсивность), вектор поведенческих характеристик (цифровая грамотность, осведомленность о безопасности, история соблюдения правил), вектор технического контекста (защищенность устройства, методы аутентификации, сетевая экспозиция) и вектор ситуационных факторов (временное давление, социальное доказательство, сигналы авторитета) [27]. При этом функция интегральной уязвимости вычисляется как взвешенная линейная комбинация нормализованных параметров:

$$U(V_{victim}) = \sum_{i=1}^{K} \lambda_i \cdot \widetilde{x_i}, \quad (2)$$

где $K$ – общее количество параметров виктимной модели;

$\lambda_i$ – весовой коэффициент i-го параметра ($\sum \lambda_i = 1$);

$\widetilde{x_i}$ – нормализованное значение i-го параметра.

Нормализация параметров осуществляется по формуле:

$$\widetilde{x_i} = \frac{x_i - x_{min}}{x_{max} - x_{min}}, \quad (3)$$

где $x_i$ – актуальное значение i-го параметра;

$x_{min}$ – минимальное возможное значение параметра;

$x_{max}$ – максимальное возможное значение параметра.

Для учета нелинейных взаимодействий параметров применяется аппарат нечеткой логики [28]. Функция принадлежности определяет степень соответствия конкретного значения лингвистическому термину (например, «высокий уровень угрозы»). Выходное значение модели нечеткой логики вычисляется по формуле:

$$U_{fuzzy} = \frac{\sum_{i=1}^{n} w_i \cdot c_i}{\sum_{i=1}^{n} w_i}, \quad (4)$$

где $U_{fuzzy}$ – итоговое значение уязвимости после дефаззификации (метод центра тяжести)[3];

$w_i$ – весовой коэффициент i-го правила нечеткого вывода (степень активации правила);

$c_i$ – центр функции принадлежности i-го правила;

$n$ – общее количество правил нечеткой базы.

Данная модель согласуется с исследованиями Г.А. Остапенко и других авторов [29], которые выделяют особенности уязвимостей. Вероятность успешной атаки с учетом поколенческой специфики оценивается по формуле:

$$P_v^{gen} = 1 - \left(1 - \frac{1}{n}\right)^m, \quad (5)$$

где $P_v^{gen}$ – вероятность реализации атаки на поколение gen с учетом уязвимостей социального характера;

$m$ – количество уязвимостей для текущей возрастной категории;

$n$ – общее количество уязвимостей.

выражение $\left(1 - \frac{1}{n}\right)$ представляет вероятность того, что одна конкретная уязвимость не приведет к успешной атаке. Возведение в степень m дает вероятность того, что ни одна из m уязвимостей не сработает. Вычитание из единицы дает искомую вероятность успеха атаки [29].

[3] формула (4) реализует метод центра тяжести для дефаззификации, где числитель представляет собой взвешенную сумму центров функций принадлежности, а знаменатель – сумму весов всех активированных правил. Данный подход позволяет преобразовать нечеткие выводы в конкретное числовое значение уязвимости.

Жизненный цикл социоинженерной атаки представляется как ориентированный граф:

$$G = (V, E, P, W), \quad (6)$$

где $V = (v_1, v_2, \dots, v_6)$ – множество вершин графа, соответствующих шести этапам атаки;

$E \subseteq \mathrm{V} \times \mathrm{V}$ – множество дуг, представляющих возможные переходы между этапами;

$P = (p_{ij})$ – матрица вероятностей переходов размером 6×6, где $p_{ij} \in [0, 1]$ – вероятность перехода с этапа i на этап j;

$W = (w_1, w_2, \dots, w_6)$ – вектор весов вершин, характеризующих временные и ресурсные затраты на выполнение этапа i.

Для учета динамической важности отдельных этапов атаки и их взаимосвязей вводится коэффициент важности этапа, аналогичный подходу, предложенному Коцыняком и коллегами для таргетированных кибератак [30]:

$$A_i(t) = A_i^0 \cdot exp\left(\frac{t}{\tau_{\text{возд}}}\right), \quad (7)$$

где $A_i(t)$ – динамический коэффициент важности i-го этапа атаки;

$A_i^0$ – базовая важность этапа (начальное значение);

$t$ – текущее время реализации атаки;

$\tau_{\text{возд}}$ – среднее значение цикла воздействия (временной горизонт планирования атаки).

Данный коэффициент позволяет учесть, что важность отдельных этапов может изменяться в процессе реализации атаки, что особенно критично для адаптивных социоинженерных операций.

Также вводится коэффициент связности между этапами, характеризующий функциональную взаимосвязь последовательных стадий атаки:

$$\alpha_{ij} = \frac{\lambda_{ij}}{\sum_k \lambda_{ikr}}, \quad (8)$$

где $\alpha_{ij}$ – коэффициент связности между этапами i и j $(0 < \alpha_{ij} \leq 1)$;

$\lambda_{ij}$ – вес (интенсивность) перехода от этапа i к этапу j в общем потоке атаки;

$\sum_k \lambda_{ikr}$ – суммарная интенсивность всех переходов из этапа i (сумма по всем возможным целевым этапам k).

Использование данных коэффициентов позволяет более точно моделировать распределение ресурсов злоумышленника по этапам атаки и прогнозировать наиболее критические точки для вмешательства систем защиты [30].

Такая формализация позволяет трактовать атаку как стохастический процесс с памятью, где каждое состояние содержит достаточную информацию для определения вероятностей будущих переходов [28]. На стратегическом уровне злоумышленник определяет цель атаки и идентифицирует жертву, что формализуется через функцию полезности атакующего:

$$U_{attacker}(C, J) = \sum_{i=1}^{n} w_i \cdot E[R_i(C_i, J_i)] - \lambda \cdot Cost(C, J), \quad (9)$$

где $U_{attacker}(C, J)$ – функция полезности атакующего;

$C \in \{C_{data}, C_{fin}, C_{rep}\}$ – множество стратегических целей (кража данных, финансовая выгода, репутационный ущерб);

$J \in \{j_1, j_2, \dots, j_n\}$ – множество потенциальных жертв;

$R_i$ – случайная величина выгоды от атаки на жертву $j_i$ с целью $C$;

$w_i$ – весовой коэффициент значимости жертвы;

$\lambda$ – коэффициент чувствительности к затратам;

$Cost(C, J)$ – функция ресурсных затрат на реализацию атаки.

Первичный портрет цели формируется как отображение доступных данных в пространство признаков:

$$P_0(j) = \Phi(D_{avail}) = (\vec{x}_{dem}, \vec{x}_{behav}, \vec{x}_{tech}, \vec{x}_{psych}), \quad (10)$$

где $P_0(j)$ – первичный портрет цели j;

$D_{avail}$ – множество доступных данных о жертве;

$\Phi$ – функция извлечения признаков;

$\vec{x}_{dem}, \vec{x}_{behav}, \vec{x}_{tech}, \vec{x}_{psych}$ – векторы демографических, поведенческих, технических и психологических характеристик соответственно.

Процесс сбора и агрегации данных на этапе рекогносцировки описывается стохастической моделью с итеративной коррекцией качества:

$$D_{agg}^{k+1} = \alpha \cdot D_{agg}^{k} + (1 - \alpha) \cdot F_{new}(SRC, J), \quad (11)$$

где $D_{agg}^{k}$ – агрегированный набор данных на итерации k;

$\alpha \in [0, 1]$ – коэффициент инерции накопления знаний;

$F_{new}$ – функция извлечения новых данных из источников SRC о жертве J.

Критерий качества данных определяется через метрику полноты и достоверности:

$$Quality(D) = \beta_1 \cdot Completeness(D) + \beta_2 \cdot Consistency(D) + \beta_3 \cdot Freshness(D), \quad (12)$$

где $Quality(D)$ – интегральный показатель качества данных (от 0 до 1);

$Completeness(D)$ – доля заполненных атрибутов в наборе данных D;

$Consistency(D)$ – доля непротиворечивых записей;

$Freshness(D)$ – актуальность данных (обратная пропорциональность времени сбора);

$\beta_1, \beta_2, \beta_3$ – весовые коэффициенты (их сумма равна 1).

Итерационный цикл этапа 2 продолжается до достижения порогового значения $\theta$:

$$Quality(D_{agg}) \geq \theta, \quad (13)$$

где $\theta$ – минимально допустимый уровень качества данных для перехода к следующему этапу.

Для верификации данных применяется байесовская оценка достоверности каждого атрибута:

$$P_{true}(d \mid E) = \frac{P(E \mid d) \cdot P_{prior}(d)}{\sum P_{prior}(d')}, \quad (14)$$

где $P_{true}(d \mid E)$ – апостериорная вероятность истинности атрибута d при наличии свидетельств E;

$P(E \mid d)$ – вероятность наблюдения свидетельств E при истинности d;

$P_{prior}(d)$ – априорная вероятность истинности атрибута d.

Атрибут включается в верифицированный набор при условии:

$$P_{true}(d \mid E) \geq \gamma, \quad (15)$$

где $\gamma$ – порог доверия, устанавливаемый в зависимости от критичности атаки.

Выбор вектора атаки на этапе подготовки формализуется как задача многокритериальной оптимизации:

$$V_{attack} = max_{v \in V}\left[P_{success}\left(v \mid D_{verif}\right) \cdot impact(v) - Cost(v)\right], \quad (16)$$

где $V_{attack}$ – оптимальный вектор атаки;

$V$ – множество допустимых векторов (email, messenger, voice, physical);

$P_{success}\left(v \mid D_{verif}\right)$ – вероятность успеха вектора $v$ при верифицированных данных $D_{verif}$;

$impact(v)$ – ожидаемый ущерб от применения вектора $v$;

$Cost(v)$ – ресурсные затраты на реализацию.

Вероятность успеха моделируется на основе уязвимости жертвы и эффективности техники [26]:

$$P_{success}\left(v \mid D_{verif}\right) = max_{j \in J}\left[V_j \cdot T_v \cdot \left(1 - D_{org}\right)\right], \quad (17)$$

где $V_j$ – интегральная уязвимость жертвы j, вычисляемая по формуле (3);

$T_v$ – эмпирическая эффективность техники $v$ (отношение успешных атак к общему числу попыток);

$D_{org}$ – интегральный уровень организационной защиты.

Уровень организационной защиты рассчитывается как:

$$D_{org} = \sum \theta_I \cdot M_I, \quad (18)$$

где $M_I$ – эффективность l-й меры защиты (0–1);

$\theta_I$ – весовой коэффициент l-й меры (сумма всех весов равна 1).

Генерация сценария коммуникации опирается на модель социального влияния [27]:

$$S_{comm} = max_{s \in S} \sum \omega_m \cdot E[Response(s, m, P_{victim})], \quad (19)$$

где $S_{comm}$ – оптимальный сценарий коммуникации;

$S$ – множество возможных сценариев;

$M = \{M_{fear}, M_{urgency}, M_{curiosity}, M_{greed}, \dots\}$ – множество психологических медиаторов;

$\omega_m$ – весовой коэффициент медиатора m;

$Response(s, m, P_{victim})$ – функция отклика жертвы на сценарий $s$ с медиатором $m$ при профиле $P_{victim}$.

Процесс установления доверия на этапе инициации контакта моделируется как марковский процесс принятия решений (MDP) [25]:

$$M = (S, A, R, P), \quad (20)$$

где $S = \{Neutral, Trusted, Challenged, Blocked\}$ – пространство состояний взаимодействия;

$A = \{Cooperate, Deceive, Reset\}$ – множество действий злоумышленника;

$P(s' \mid s, a)$ – вероятность перехода из состояния $s$ в $s'$ при действии $a$;

$R(s, a, s')$ – функция немедленного вознаграждения.

Оптимальная стратегия определяется через уравнение Беллмана:

$$V(s) = max_{a \in A}[\sum R(s, a, s') + \gamma \cdot V(s')], \quad (21)$$

где$V(s)$ – оптимальная функция ценности состояния $s$;

$\gamma \in [0, 1]$ – коэффициент дисконтирования будущих вознаграждений.

Переход к этапу эксплуатации осуществляется при достижении состояния $Trusted$ с вероятностью, превышающей порог $\tau$:

$$P(TrustScore \geq \tau \mid P_0, S_{comm}, Context) \geq \tau, \quad (22)$$

где $TrustScore$ вычисляется как:

$$TrustScore = \delta \cdot Authority(M) + \varepsilon \cdot Urgency(M) + \zeta \cdot Personalization(V), \quad (23)$$

где $Authority(M)$ – сила авторитета сообщения $M \epsilon (0; 1)$;

$Urgency(M)$ – уровень срочности сообщения $M \epsilon (0; 1)$;

$Personalization(V)$ – степень персонализации по данным жертвы $V \epsilon (0; 1)$;

$\delta, \varepsilon, \zeta$ – весовые коэффициенты (сумма равна 1).

Действие жертвы на этапе эксплуатации моделируется как функция от психологического состояния, внешнего воздействия и контекстных факторов:

$$A_{target} = \sigma(\sum \alpha_m \cdot M_m \cdot S(P_{victim}, m) + \varepsilon), \quad (24)$$

где $A_{target}$ – целевое действие жертвы;

$\sigma(\cdot)$ – сигмоидальная функция активации (вероятность выполнения действия);

$\alpha_m$ – интенсивность применения медиатора $m$;

$S(P_{victim}, m)$ – функция восприимчивости жертвы к медиатору $m$;

$\varepsilon \sim N(0, \sigma^2)$ – стохастическая компонента, отражающая неопределенность человеческого поведения.

Успешность эксплуатации оценивается через бинарную функцию:

$$Sucsess\left(A_{target}\right) = I\left[U_{attacker}\left(A_{target}\right) > T\right], \quad (25)$$

где $Sucsess\left(A_{target}\right)$ – результат эксплуатации (1 – успех, 0 – неудача);

$U_{attacker}\left(A_{target}\right)$ – полезность действия для атакующего;

$T$ – пороговое значение полезности для считания атаки успешной;

$I(\cdot)$ – индикаторная функция (равна 1 при истинности условия, иначе 0).

В случае неудачи система осуществляет адаптивную коррекцию по принципу ε-greedy:

$$P(explore) = \varepsilon, P(exploit) = 1 - \varepsilon, \quad (26)$$

где $P(explore)$ – вероятность исследования альтернативной стратегии;

$P(exploit)$ – вероятность эксплуатации текущей оптимальной стратегии;

$\varepsilon$ – параметр исследования $(0 < \varepsilon < 1)$.

Рефлексивный компонент модели на этапе завершения атаки реализуется через механизм обновления базы знаний злоумышленника:

$$\Theta_{t+1} = \Theta_t + \eta \cdot grad\big(L(F_t, \Theta_t)\big), \quad (27)$$

где $\Theta_{t+1}$ – обновленные параметры модели злоумышленника на шаге t+1;

$\Theta_t$ – параметры модели злоумышленника на шаге t (стратегии, шаблоны, оценки уязвимостей);

$\eta$ – скорость обучения$(0 < \eta < 1)$;

$L$ – функция потерь на шаге t;

$F_t$ – функция потерь на шаге t.

Функция потерь определяется как:

$$L(F, \Theta) = (E_{Outcome} - A_{Outcome})^2, \quad (28)$$

где $L(F, \Theta)$ – значение функции потерь;

$E_{Outcome}$ – прогнозируемый результат атаки;

$A_{Outcome}$ – фактический результат атаки.

Вероятность успешного завершения атаки с учетом временных характеристик вычисляется по полумарковской модели [28]:

$$P_{attack} = 1 - \exp(-\Lambda \cdot T), \quad (29)$$

где $P_{attack}$ – вероятность успешной атаки за время $T$;

$\Lambda$ – матрица интенсивностей переходов между этапами;

$T$ – общее время реализации атаки.

Матрица интенсивностей переходов имеет вид:

$$\Lambda = \begin{vmatrix} -\lambda_1 & 0 & \lambda_3 Q_{13} \\ \lambda_1 Q_{21} & -\lambda_2 & 0 \\ \lambda_1 Q_{31} & \lambda_2 Q_{32} & -\lambda_3 \end{vmatrix}, \quad (30)$$

где $\lambda_i$ – интенсивность завершения этапа i;

$Q_{ij}$ – вероятность выбора перехода из этапа i в этап j.

В отличие от линейных моделей, где процесс завершается на этапе получения результата, предложенная модель предполагает, что злоумышленник анализирует итоги успешной атаки (рефлексия) и использует полученную информацию для формулировки целей следующей атаки. Согласно теории вероятностей, вероятность совместного осуществления цепи зависимых событий равна произведению вероятностей перехода между каждым соседним состоянием [25, 28]. Соответственно, математически это представляется как цепь последовательных событий, где переход к следующему этапу возможен только при успешном завершении предыдущего:

$$P_{cycle} = p_{61} \cdot p_{12} \cdot p_{23} \cdot p_{34} \cdot p_{45} \cdot p_{56}, \quad (31)$$

где $P_{cycle}$ – вероятность полного цикла атаки с последующей итерацией.

Формула (31) представляет полный цикл социоинженерной атаки. Индексы в обозначении соответствуют номерам этапов модели (1-6). Множитель обозначает вероятность успешного перехода с этапа на этап.

Ключевым параметром, который обеспечивает цикличность модели, выступает коэффициент $p_{61}$, обозначающий вероятность возврата от этапа завершения атаки к этапу формулировки цели новой итерации; он отражает решение злоумышленника не завершать деятельность окончательно, а на основе рефлексии и анализа успеха или неудачи сформулировать новую цель для повторной атаки, что принципиально отличает предложенную модель от классических линейных схем.

Стационарное распределение вероятностей нахождения системы в каждом состоянии вычисляется как решение системы уравнений:

$$\rho = \pi \cdot P, \quad (32)$$

где $\pi = (\pi_1, \pi_2, \dots, \pi_6)$ – вектор стационарных вероятностей;

$P$ – матрица переходных вероятностей размером 6×6.

При условии нормировки:

$$\sum_{i=1}^{6} \pi_i = 1, \quad (33)$$

где $\pi_i$ – стационарная вероятность нахождения на этапе i.

Данная формализация подтверждает итеративную природу модели, где злоумышленник может многократно проходить цикл с корректировкой стратегии на основе накопленного опыта. Для оценки рисков на каждом этапе применяется базовая формула анализа рисков информационной безопасности:

$$R = P_{threat} \cdot P_{vulnerability} \cdot Impact, \quad (34)$$

где $R$ – риск (в условных единицах ущерба);

$P_{threat}$ – вероятность возникновения угрозы;

$P_{vulnerability}$ – вероятность использования уязвимости;

$Impact$ – величина потенциального ущерба.

Формула может быть детализирована с учетом эффективности защитных мер:

$$R = P_{threat} \cdot P_{vulnerability} - \big(1 - E_{prevent}\big) \cdot Impact \cdot \big(1 - E_{mitigate}\big), \quad (35)$$

где $E_{prevent}$ – эффективность мер, предотвращающих уязвимость;

$E_{mitigate}$ – эффективность мер, снижающих последствия.

Общий риск для всей атаки вычисляется как сумма рисков по всем этапам:

$$R_{total} = \sum_{i=1}^{6} R_i, \quad (36)$$

где $R_i$ – риск на каждом i-ом этапе атаки.

На основании приведенных математических формулировок формируется пошаговый алгоритм. На этапе инициализации параметров модели задаются начальные значения матрицы переходных вероятностей P, устанавливаются пороги θ, γ, τ для критериев качества, доверия и перехода, инициализируется виктимная модель жертвы $V_{victim}$. При формулировке цели вычисляется функция полезности $U_{attacker}(C, J)$ по формуле (9), формируется первичный портрет цели $P_0(j)$ по формуле (10), жертвы ранжируются по убыванию полезности. На этапе рекогносцировки инициализируется счетчик

итераций k = 0, выполняется сбор данных по формуле (11), вычисляется качество данных $Quality(D)$ по формуле (12). Если $Quality \geq \theta$, k увеличивается на 1 и повторяется сбор, иначе переходится к верификации.

При подготовке атаки верифицируются данные по условию (14). Если доля верифицированных данных меньше ρ, осуществляется возврат к этапу рекогносцировки, иначе вычисляется оптимальный вектор атаки по формуле (16) и генерируется сценарий коммуникации по формуле (19). На этапе инициации контакта вычисляется $TrustScore$ по формуле (23). Если $TrustScore < \tau$, адаптируется сценарий и повторяется попытка, иначе переходится к этапу эксплуатации. При эксплуатации вычисляется вероятность целевого действия по формуле (24), оценивается успешность по формуле (25). При неудаче применяется адаптивная коррекция по формуле (26).

На этапе завершения атаки обновляются параметры модели злоумышленника по формулам (27) и (28), вычисляется вероятность успешного завершения по формуле (29). Если доступны новые цели, осуществляется возврат к этапу формулировки цели с обновленными параметрами $\Theta_{t+1}$. Проверка условия сходимости осуществляется вычислением изменения функции потерь $\Delta L = |L_t - L_{t-1}|$. Если $\Delta L < \varepsilon$, алгоритм завершен, иначе увеличивается счетчик итераций и осуществляется переход к этапу формулировки цели. Условие сходимости алгоритма:

$$\lim_{t\to\infty} \Delta L = 0, \qquad (37)$$

что гарантирует стабилизацию модели злоумышленника и достижение оптимальной стратегии атаки.

Таким образом, нами представлено математическое обоснование шестиэтапной концептуальной модели жизненного цикла социоинженерной атаки. Атака представлена как ориентированный граф с вероятностными переходами, что позволяет описать адаптивную природу современных угроз. Циклическая природа модели доказана через стационарное распределение вероятностей марковской цепи, где $p_{61} > 0$ обеспечивает возможность многократных итераций. Разработан пошаговый алгоритм с условием сходимости, гарантирующим стабилизацию модели злоумышленника и достижение оптимальной стратегии атаки.

**Заключение**

Проведенное исследование подтвердило, что в условиях глобальной цифровизации и геополитической нестабильности социальная инженерия остается наиболее критическим вектором киберугроз. Анализ эмпирических данных за первое полугодие 2025 года свидетельствует о доминировании методов манипуляции человеческим фактором: 97% таргетированных атак на организации и 93% атак на частных лиц реализуются посредством методов социальной инженерии. Ключевым трендом эволюции угроз стал переход к технологиям искусственного интеллекта (Deepfake, LLM-фишинг, автоматизированная верификация данных и другие).

Установлено, что существующие модели проведения атак утратили релевантность, поскольку не учитывают «адаптивную природу» современных злоумышленников, игнорируют этап автоматизированной верификации данных и не отражают комплексной взаимосвязи (обучение атакующего на основе обратной связи). В ответ на выявленные ограничения в работе разработана и обоснована шестиэтапная концептуальная модель цикла социоинженерной атаки. Модель прошла процедуру математической формализации с использованием аппарата теории вероятностей, марковских процессов и нечеткой логики. На основе математического обоснования построена блок-схема алгоритма реализации модели, отражающая все логические переходы, условия сходимости и итерационные циклы.

Практическая значимость работы заключается в возможности использования предложенной модели в качестве новых теоретических решений для разработки систем защиты информации. Ключевое преимущество таких систем – способность идентифицировать критические точки разрыва в цикле атаки, в том числе на ранних стадиях. Реализация предложенной методики точечного противодействия на уровне отдельных субъектов или организаций позволяет трансформировать техническую защиту (киберзащиту): устранение последствий инцидентов к упреждающему прерыванию атак на каждой из фаз жизненного цикла. Кроме того, это позволит актуализировать обучающие программы для пользователей с учётом психологических аспектов принятия решений.

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# REASONS FOR BUSINESSMEN, MANAGERS AND EMPLOYEES OF WESTERN AND RUSSIAN ORGANIZATIONS TO DEAL WITH QUALITY MANAGEMENT OF PRODUCTS AND/OR SERVICES

**Ponomarev S.**
*Tambov State Technical Universyty, Russian Federation*
**Mishchenko S.**
*Tambov State Technical Universyty, Russian Federation*
**Ponomareva E.**
*Equinor ASA, Bergen, Norway*
https://doi.org/10.5281/zenodo.19292677

**Abstract**

The article discusses the main and additional reasons that motivate both foreign and domestic businessmen to focus on quality management issues, the main stages of the product life cycle, the impact of successful quality management on product costs, the law of tenfold increase in costs to overcome quality management failures, the iceberg law, the social consequences of improving quality, and information about the certification of quality management systems in accordance with the international ISO9001 standard for the beginning of 2025.

**Keywords:** quality management, manufacturer market, consumer market, consumer satisfaction, product competitiveness, cost, consequences of quality improvement, certification of quality management systems.

*For successful product and/or service quality management,*
*all processes (works) must be completed correctly the first time and completed exactly on schedule*
*S.V. Ponomarev*

## Introduction

Many firms, companies and industrial enterprises of foreign countries, widely use quality management systems (QMS), made according to the requirements of international standards ISO 9000 series, for the management of production and support processes [1 - 3]. Unfortunately, the number of companies in the Russian Federation that have implemented a quality management system remains relatively small. You may be wondering, "Why do foreign businesspeople and then Russian entrepreneurs feel the need to engage in quality management?" Let's explore the answer to this question.

## 1. The initial reasons that prompted foreign businessmen to engage closely quality management issues

### 1.1. Main characteristics of the consumer market

Let's consider the situation that developed in Western Europe and Japan immediately after the end of World War II [1-3]. As in the former Soviet Union, a significant number of cities, towns, and industrial enterprises in these countries were in a state of devastation. Significant efforts and financial resources were required to overcome the post-war crisis.

It can be said that the situation in Western European countries and Japan in the 1940s and 1950s was similar to that in the former Soviet Union at the same time. From an economic perspective, during this period, the markets were dominated by producers and sellers, and there were so-called "producer markets" in all countries, where consumers purchased everything offered by sellers.

The same situation was the case in the former Soviet Union until 1991. The majority of the population had cash, but due to the shortage of goods at that time, it was difficult to buy anything with this money. In order to buy a TV, furniture, or a car, it was necessary to register in a specialized store in advance (several years in advance) and then wait for a long time for your turn to buy the ordered goods.

Under these conditions, businessmen and manufacturers had no need to worry about the quality of their products. In a shortage-driven economy, the price of goods was determined as follows [1-3].

Price = Production costs + Desired profit. (1.1)

For the reasons listed above, in Western European countries from 1946 to 1955 and in the former Soviet Union until 1991, manufacturers and sellers had the ability to set their own prices and achieve the desired profits. In this context, reducing design and production costs was not a primary concern for manufacturers, as the market allowed them to maintain prices at their desired levels.

### 1.2. The role of Deming's seminar in realizing the need to engage in product quality management [1 - 6]

In 1947, the so-called Marshall Plan was developed and implemented in the United States. According to this plan, the United States provided commodity loans to Germany, Japan, England, France, Spain, and other countries in order to help them recover from the aftermath of World War II. This included the deployment of specialists (metallurgists, chemists, engineers, etc.) to assist in the reconstruction of their economies.

As part of the Marshall Plan, E. W. Deming (1900-1993), the now widely known patriarch (guru) of quality, was sent to Japan to assist in the restoration of the electrical industry. Before the war and during World War II, Deming was engaged in research on the problems of statistical control and quality management of military products in the United States. After the end of the Second World War, he began to offer businessmen and top managers of American firms and enterprises with a proposal: "Let's start applying the experience of

product quality management and technological processes accumulated at defense enterprises during the war, at enterprises producing goods for the population." American business owners listened to him politely, smiled, but did not hear, because the goods produced at their enterprises were perfectly bought and without any quality management.

It should be noted that when providing assistance to someone, many sponsors prefer to give away something that is not the most valuable thing they have. Based on this, it can be assumed that in 1947, the leaders of the U.S. government agencies who sent Deming to help Japan did not consider his knowledge of methods and tools for product quality control and management to be valuable for the United States.

During his stay in Japan, while helping to restore the country's electrical industry, E.W. Deming, as a true scientist, could not help but talk about the results of his scientific research in the field of quality control and management. In 1950, he organized a seminar for the executives of 45 of Japan's largest companies. At this seminar, he told them about the possibilities of using product quality control and management to improve their competitiveness. At the end of the seminar, he said the following [1-6]: "Listen to me, and in five years, you will be competing with the West. Keep listening until the West asks for protection from you." These words turned out to be prophetic. In the early 60s of the twentieth century. Japan came to the forefront in the world, and after a while the whole world began to talk about the Japanese miracle, admiring it to the present day [1-6].

In the mid-60s of the twentieth century, owners and managers (managers) of enterprises, firms and companies in countries such as England, France, Germany, Italy, and the United States found that their products were being displaced (not only from the markets of Africa, Asia, and South America, but also from their own domestic markets) significantly higher-quality and less expensive Japanese goods. After studying the reasons for the situation that developed in 1964-1969, Western European and American businessmen realized the importance and necessity of addressing quality issues, which are an integral part of improving consumer satisfaction and product competitiveness.

### 1.3. Consumer satisfaction and product competitiveness

**The concept of customer satisfaction.**

Simplified, "consumer satisfaction" can be represented by the expression (1.2) as a function that depends on the following indicators [2, 4, 5, 6]:

$$Y = f(K, C, E, S, I, N, G, Ps, ...), \quad (1.2)$$

where Y is customer satisfaction; f is a function that determines the dependence of Y on the product characteristics listed below: K is quality; C is price; E is operating costs during service life; S is service life; I is the image of the manufacturer; N is reliability; G is warranty obligations and term their actions; Ps – availability of after-sales service, etc.

The last formula (provided that the values of C, I, N, G, and Ps are approximately the same for all types of products under consideration) can be simplified to the following form:

$$Y = K/(C+E) \quad (1.3)$$

and if the operating costs E are also approximately the same, then even to the following form:

$$Y = K/C \ . \quad (1.4)$$

From the simplified formulas considered, it is seen that in order to increase the satisfaction of consumers Y, it is necessary to increase the quality K of products and reduce the price C and operating costs E. It is obvious that the service life S, the image I of the company, the reliability N of products, the warranty obligations G and the level of after-sales service Ps should be increased. Note that the satisfaction of the consumer with the product - is the consumer's view on the product that he has already purchased or is going to buy.

**The concept of product competitiveness.**

Along with the concept discussed above, the term "product competitiveness" is often used, which can be simplified [2, 4, 5, 6] in the form of (1.5)

$$\mathcal{K} = F(K, C, E, S, I, N, G, Ps, ...) \approx \frac{K}{C+E} \approx \frac{K}{C}, \quad (1.5)$$

where F is a function (slightly different from the function f) that determines the dependence of product competitiveness on indicators-characteristics K, C, E, S, I, N, G, Ps, etc., already discussed above. Product competitiveness $\mathcal{K}$ is the view of the owners (shareholders) of an organization on the products produced (by this organization).

If consumers are satisfied with the products they have purchased, and they tell their relatives, friends, colleagues, and neighbors about their admiration for the excellent products they have bought, then it is safe to say that these products have a high level of competitiveness.

Thus, product competitiveness $\mathcal{K}$ and consumer satisfaction Y are quite similar concepts that represent interrelated perceptions of products:

- either by the managers and owners of the product-producing organization;
- or by the consumers who purchase the products.

From the simplified definition of the concept of "competitiveness" considered, it is seen that the competitiveness $\mathcal{K}$ can be increased either by increasing the quality of K, or by reducing the price of C. It is even better if, simultaneously with increasing the quality of products, its price will be reduced. In our opinion, the successful conquest of the English, French, German, Italian, and American domestic markets by Japanese goods in the second half of the 1960s was due to the fact that Japanese goods were of significantly higher quality (compared to Western European and American goods) at a significantly lower price.

Thus, American and Western European businessmen and industrialists came to realize the need to focus on quality after Japanese firms demonstrated *the power of Deming's teachings*, which had previously been overlooked by American government officials and businessmen.

### 1.4. Requirements of the modern "consumer market"

Starting in the second half of the 1960s, business conditions began to change. As a result, in the 1980s and 1990s, the old formula for successful business had

to be transformed [2, 4, 5, 6] into the modern formula (1.6)

Profit = Price – Production Costs. (1.6)

The modern market has quickly reduced the price of goods and forced manufacturers to reorient themselves to meet the needs and requirements of consumers, and the market, which was once a "producer market," has now transformed into a "consumer market." The transition from a "producer market" to a modern "consumer market" in the former Soviet Union is discussed in the book [7].

In today's "consumer market," the success of manufacturers depends on their ability to respond quickly and effectively to consumer demands. This speed determines which manufacturers and business owners are leaders and which are failures. The success of manufacturers hinges on their ability to achieve a well-defined goal that minimizes production costs while ensuring high-quality products at affordable prices for consumers [2, 4, 5, 6].

The most effective quality work model that contributes to increasing the competitiveness of products and the company is "Total Quality Management" (TQM), which is translated into Russian as "All-encompassing Quality Management". If a competitor is able to implement TQM as a quality work model or, at least, a quality management system faster than you, they will have a competitive speed, which means that the distance between them and you will begin to increase. The more you delay and wait, the more you will fall behind your competitor [1, 2, 4, 5].

The most effective way to increase the competitiveness of your company and its products is to be able to quickly manage the quality of your products in response to changing consumer demands, while minimizing the cost of ensuring that quality. According to the formula (1.6) for successful business, the current profit of an organization is the result of skillfully managing the quality of its products while minimizing the cost of designing and producing them.

### 1.5. The impact of successful quality management on production costs

Let's assume that there are two factories in a certain city that produce the same product. The first factory has a very successful process management system and produces high-quality products. However, the second factory pays less attention to process management, resulting in lower-quality products compared to the first factory.

Please think about this and answer the following question: Which of these two factories will have a higher production cost – the first or the second?

In previous years, it was often said that the cost of production would be higher at the first plant that successfully managed its quality. This answer is incorrect. To illustrate the incorrectness of this answer, consider the data in Table 1 below.

From table 1 it is seen that at the first and second plant launched in production the same amount of raw materials (materials, parts and components), sufficient for production of 1000000 pieces of finished products.

**Table 1.**

**Comparison of the impact of quality management results on production costs at two factories**

| Characteristics of the plant | Raw materials and materials for product production, units | Produced products, units | Rejected products, units | Cost of production |
|---|---|---|---|---|
| Factory with high quality products | 1 000 000 | 999 997 | 3 | low |
| Factory with low quality products | 1 000 000 | 800 000 | 200 000 | high |

The first plant, which successfully manages its processes and produces high-quality products, produces 999,997 units. (units) of products that meet the requirements, and a very small number of products (2-3 pcs.) are rejected by quality control inspectors. At the second plant (which does not manage the quality of production processes well), only 800,000 usable (high-quality) products are produced from the same number of raw materials (materials, parts, components) instead of 1,000,000. units of products turn out to be non-compliant (rejected) when their quality is checked by the plant's quality Control committee.

If not all 200,000 pieces of rejected products are final defects, i.e. some of these 200,000 low-quality products workers will be able to correct (re-make), then the plant will have to spend additional funds:

- to pay for additional quantities of raw materials (materials, spare parts, parts, components) used in the re-make (correct) of non-conforming units of products;
- for the payment of electricity consumed during the correction (alteration) of defective products;
- for the payment of labor costs for workers engaged in the correction (alteration) of these non-conforming products, etc.

All costs to produce defective products, recognized as final marriage, as well as the additional costs listed above, the plant will be forced to contribute to the cost of compliance with the requirements (good) products. If after such comments to ask: "At which of the considered factories the cost of production will be higher?" – it becomes obvious that production costs are higher at facilities where quality management is ineffective, and vice versa, the cost of production is lower at plants where quality is managed successfully.

Quality management specialists, factory owners, managers, specialists, and workers are well aware that successful quality management results not only in high-quality products, but also in reduced production costs. As a result, the first factory can sell its products at a lower price than the second factory.

As a result, the competitiveness $К \approx \frac{К}{Ц}$ of the first factory's products is higher than the competitiveness of the second factory's products. If the owners, managers,

employees, and workers of the second factory fail to implement quality management tools and techniques [1-6], profits will decrease, and the second factory may eventually go bankrupt and be closed.

Thus, the following are the initial reasons that prompted entrepreneurs and businessmen in England, France, Germany, Italy, the United States, and other developed countries to pay serious attention to the problems of ensuring and improving the quality of their enterprises, firms, and companies [2-6]:

- the displacement of Western goods by Japanese goods (which had significantly higher quality at significantly lower prices) in the second half of the 1960s;

- the high effectiveness of Deming's teachings on methods and tools for controlling and managing product quality, demonstrated by Japanese entrepreneurs to Western businessmen, who previously viewed quality management as a "poor" problem handled by "poor" specialists [1-6];

- the economic benefits of successful quality management, which, by improving the quality and reducing the cost of products, can increase customer satisfaction Y and product competitiveness $\mathcal{K}$ .

In the 1970s, Western business owners and managers quickly realized that quality management was not a "poor" problem, but for a long time, quality specialists were still treated as "poor" people [1-6]. In the 1980s and 1990s, the vast majority of entrepreneurs and businesspeople in foreign countries came to fully understand the importance of quality and recognize the significant contribution of quality specialists to improving the competitiveness of products and ensuring the survival of companies in today's consumer market.

## 2. Additional reasons that motivate foreign and Russian businessmen to deal with quality management issues

### 2.1. The main enlarged stages of the product life cycle

Consider the main enlarged stages of the product life cycle [1 - 5], schematically presented in Fig. 1.

The first stage of the product life cycle begins long before the appearance of a prototype or model of this product. The marketing department should be responsible for carrying out the stage "Planning production and development of product requirements" at enterprises. This department conducts market research, i.e. studies the market, establishes the preferences and expectations of potential consumers, and then prepares proposals for the top management of the enterprise on which types of products should be designed and prepared for production, and which types of products should be modernized in order to meet the changing needs of the market. In the case of a decision to produce new products, the main result of this first stage is the development of requirements (technical specifications) for the products and the issuance of a task to the design department.

At the second stage, "Product Design and Development", designers and technologists translate product requirements into the language of drawings and technological instructions, according to which the production facilities of the enterprise will have to produce high-quality and competitive products.

The second stage is completed after testing the prototypes of the designed products, confirming that the designed products meet the requirements for their quality, and obtaining convincing evidence of the economic feasibility of producing new products.

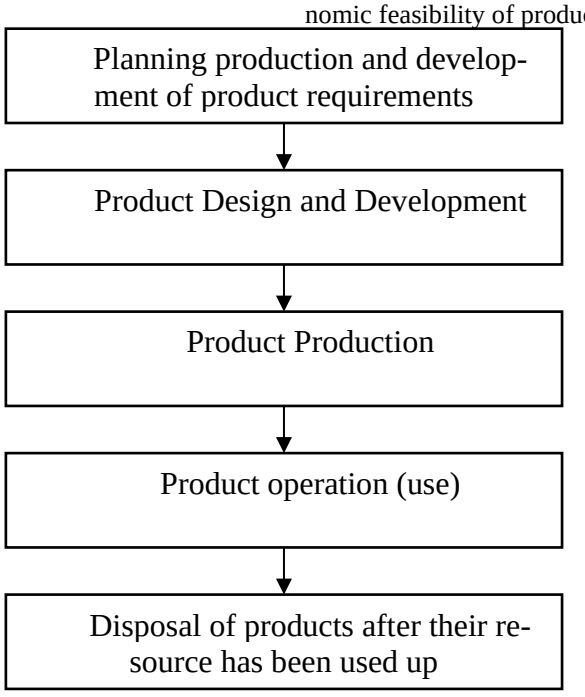


*Fig. 1. Main enlarged stages of the product life cycle*

The third stage, "Product Production," begins with the procurement of necessary materials, components, machines, equipment, and control tools, as well as the training and retraining of workers and employees, if necessary. Once these tasks are completed, the company can begin producing new products. The result of this stage is the production of mass-produced products, which are first sent to the technical control department, then to the warehouse, and finally to consumers.

The content of the fourth stage, "Product operation (use)", is clear from its name. At this stage, the manufacturer should assist the consumer in installing and commissioning their products or at least provide clear instructions on how to install and use the products.

At the first, second, third, and fourth stages, the international ISO 9000 series standards consider products to be intentional and intended for consumers. Product quality management at these stages must comply with the requirements of the ISO 9000 series standards.

At the fifth stage, "Disposal of products after their resource has been used up," the international ISO 9000 series standards consider products to be unintended. At this stage, the management of the disposal of unintended products (the conversion of products into waste, as defined by the 2015 edition of the ISO 9000 series standards) should be based on the international ISO 14000 series standards, which define the requirements for environmental quality management systems.

You may have a question: "At what stage of the product life cycle should product quality management begin?" Some students answer this question by saying that product quality management should begin at the production stage, while others say that it should begin at the design and development stage. Some students and more experienced professionals argue that product quality management should begin immediately during the first stage, during the planning and development of requirements for new (future) products.

### 2.2. The law of the tenfold increase in cost for overcoming failures when transitioning to the next stage of the product life

The need to address product quality management issues from the earliest stages of the product's life cycle is illustrated by the law of tenfold increase in the cost of overcoming failures in achieving the established quality. This law [1-6] is graphically represented in Figure 2.

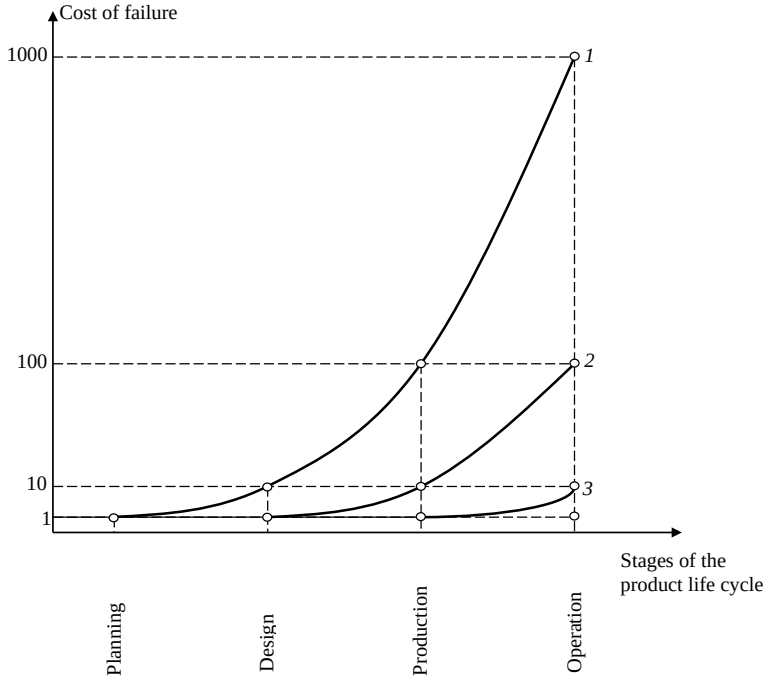


*Fig. 2. The law of tenfold increase in the cost of overcoming failures in achieving the established quality [1 - 6]*

Let's assume that during the planning of production and the development of requirements for a new product, an error was made in determining the value and/or tolerance range of one of the quality characteristics. If this error is detected at the same stage, its correction is usually not very expensive. Let's consider the cost of correcting this error at the first stage as a single unit, for example, it could be the cost of re-issuing (reprinting and re-approval) the established requirements (technical specifications) for the product.

Let's assume that this error was not detected at the first stage, but was discovered at the next stage, "Product Design and Development." Based on the global experience of quality management professionals, it is estimated that correcting this error (made at the first stage) during the second stage would cost approximately 10 times more (in addition to changing the established product requirements, several existing drawings and process instructions would need to be revised).

If an error made at the first stage is not detected at the second stage, but is only detected at the third stage, "Product Production," then its correction will cost 10 times more, i.e., 100 units (the first batch or part of it may be rejected).

The greatest costs of overcoming failures that occurred in the first stage will take place if the error is first detected in the fourth stage "Operation (use) of products". It is believed that in this case, the costs of overcoming failures will again increase by about 10 times. In this case, the manufacturer will have to send its representatives on business trips to consumers to eliminate defects, often have to recall products for reworking or repair, sometimes replace defective products with new ones.

The above ideas about a tenfold increase in the cost of overcoming failures during the transition from the first stage of the life cycle to subsequent stages are illustrated in Fig. 2 by Line 1.

If an error occurs at the second stage "Product design and development", then the law of a tenfold increase in the cost of overcoming failures (see Fig. 2) can be represented by line 2.

When an error occurs in the third stage, "Product Production", the law of tenfold increase in the cost of overcoming failures can be represented by line 3 in Figure 2.

Note: Lines 1, 2, and 3 in Figure 1.2 start from points with a value of one conventional unit. It is important to note that the values of this conventional unit may vary for each of these lines.

Let's consider an example that illustrates the law of tenfold increase in the cost of overcoming failures [2-6].

As you may know, in the summer of 2000, a Concorde aircraft crashed at Le Bourget Airport near Paris. In November 2001, it was announced that test flights (without passengers) would begin between Europe and North America.

The investigations conducted showed that the cause of the plane crash was a metal part that was on the airport's runway. When the Concorde plane was taking off, this part damaged the tire of the plane's wheel, and a piece of the tire (about the size of a brick) detached from the wheel due to centrifugal force and was thrown upward at high speed, damaging the fuel tank and causing a fire that killed all the passengers and crew members.

From the point of view of the law under consideration of a tenfold increase in the cost of overcoming failures, at the planning stage of the production of the Concorde aircraft, the possibility that a piece of the aircraft wheel tire could damage the fuel tank and cause a catastrophe was not taken into account. If at the planning stage such a possibility had been taken into account (for example, in the form of a requirement to place fuel tanks out of reach of objects thrown by the aircraft wheel or special protection of fuel tanks from mechanical damage), then the elimination of this error would cost one conventional unit (perhaps 1000 – 5000 dollars). According to the law in question, the cost of correcting this error at later stages of the Concorde's life cycle would have been as follows:

- during design: (10,000 to 50,000) dollars;
- during production: (100,000 to 500,000) dollars;
- during operation: (1 to 5 million) dollars.

However, this error was not detected by experts in any of the first three stages of the Concorde's life cycle, and it manifested itself in the fourth stage of operation as a sudden failure that led to a plane crash and loss of life.

After the crash, all Concorde planes in service were grounded, and experts conducted investigations to determine the cause of the crash. Then, new requirements for ensuring flight safety on Concorde aircraft were developed, and after the planning phase, design work was carried out and necessary changes were made to the aircraft's design. Subsequently, Concorde aircraft were upgraded at aircraft factories, and finally, in late autumn 2002, the first flights (without passengers) were conducted on these aircraft.

From the above, it is clear that the mistake made in the first stage of the Concorde aircraft's life cycle, which manifested itself in the fourth stage of "Product Operation (Use)," was extremely costly for the airlines that operated these supersonic aircraft. The lost profits (the aircraft were not carrying passengers for approximately 1.5 years, resulting in no revenue for the airlines) were likely in the millions, if not billions, of dollars. In addition, airlines had to spend money on upgrading their aircraft. In the case of the Concorde, it can be assumed that there was a twenty- or even thirty-fold increase in the cost of overcoming failures during the transition from one stage of the product lifecycle to the next.

### 2.3. The Iceberg Law

Another additional reason that motivates Western and Russian entrepreneurs to deal with quality issues is the so-called "iceberg" law (Fig. 3), which determines [1-6] the way information about an enterprise's failures to achieve the established quality is disseminated among consumers and potential customers of its products.

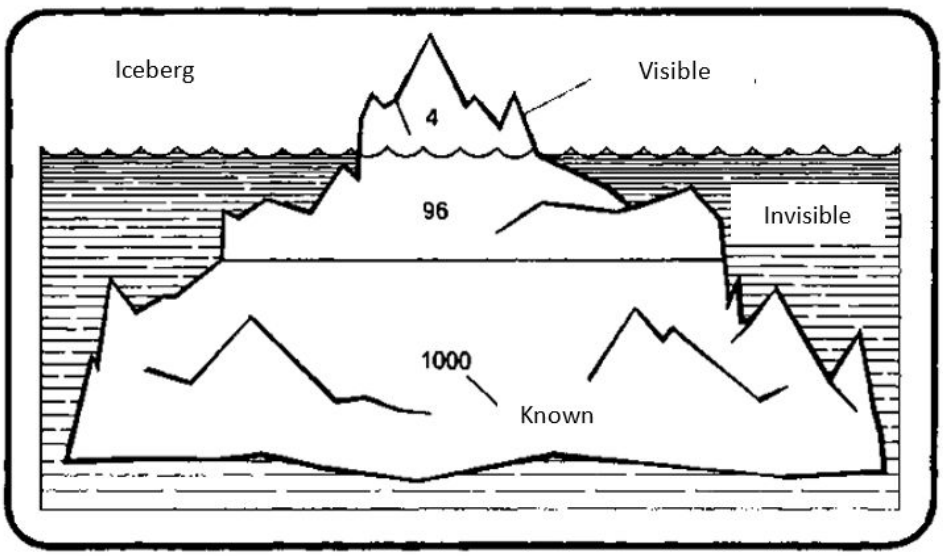


*Fig. 3. Graphical illustration of the iceberg law [1-6]*

Let's assume that during the quality control of products, 100 units of defective products were not detected by the technical control department and were sent to consumers. Based on the experience of Western quality management experts, it is estimated that on average, only four out of 100 dissatisfied consumers will file a complaint or make a claim with the manufacturer (supplier). Therefore, the visible part of the "iceberg" typically includes an average of only four percent of the total number of defective products that reach consumers. The remaining 96% of dissatisfied consumers (the invisible part of the "iceberg") usually do not report any defects to the manufacturer. However, global experience shows that each dissatisfied consumer reports that they have received defective products to an average of 10 or more potential consumers or customers. According to literature, this information about quality failures is sometimes shared by each dissatisfied consumer with up to 30 potential consumers or customers. Thus, when 4 complaints are received by the manufacturer, according to the law of the "iceberg" on average, it can be assumed that 100 units of defective products have penetrated to consumers, and it can be confidently stated that unsatisfied consumers reported the low quality of products to approximately 1000 - 3000 potential consumers and customers. This means that the manufacturer has lost approximately 1000 - 3000 new orders for its products.

If we recall the example of the Concorde plane crash discussed above, it is clear that the failure to achieve the quality of this aircraft was brought to the attention of hundreds of millions of people around the world by the media. From the perspective of the iceberg principle, this means [1-6] that hundreds of thousands, or even millions, of potential passengers who could have purchased tickets for these aircraft may have given up on their plans and opted for conventional subsonic jet aircraft instead. It can be argued that the airlines that owned Concorde aircraft suffered significant losses due to the decline in ticket sales for supersonic flights. In April 2003, several airlines that operated Concorde aircraft announced the discontinuation of regular flights between Paris and New York due to their unprofitability. Currently, Concorde flights have been completely discontinued, and the remaining aircraft are housed in aviation museums.

Thus, the following are additional reasons that encourage foreign and Russian entrepreneurs to deal with quality management issues [1-6]:

- the desire to increase the competitiveness of their products by reducing the costs of ensuring their quality (remember the law of tenfold increase in costs), which forces the management of enterprises, firms, and companies to start improving the quality of their products from the first stage of the product life cycle;

- the desire not to lose the company's image (remember the "iceberg" law) also motivates businesses, firms, and companies to pay the utmost attention to ensuring and improving product quality.

**3. Social consequences of quality improvement [1 - 6]**

Let's say that one of the factories in the city of Ensk has managed to significantly improve the quality of its products. As a result, the standard of living of not only the employees of this factory but also other residents of the city has significantly improved. These so-called social consequences of quality improvement are commonly illustrated using the "Deming value response" [2-6], as shown in Figure 4.

Improving product quality (Fig. 4) leads to reduced production costs (product costs) due to:

1) reducing the number of errors made by workers during production processes, as "all processes are performed correctly the first time and on time";

2) reducing the number of rework and corrections of non-conforming products;

3) reducing the number of delays and downtime;

4) improving the use of materials (raw materials, parts, and components) and time, as there is no need to rework or correct non-conforming products.

As a result of all of the above, productivity will increase (the number of products produced will increase) and the cost of production will decrease. By reducing the cost of production, the price of the product can be lowered. As a result, consumers will start to buy this higher-quality product, which is also sold at a lower price. This will lead to increased customer satisfaction Y and, at the same time, increased product competitiveness $\mathcal{K}$. All of this will allow the factory (enterprise) that has improved the quality of its products to retain, expand, and capture more and more sectors of its market.

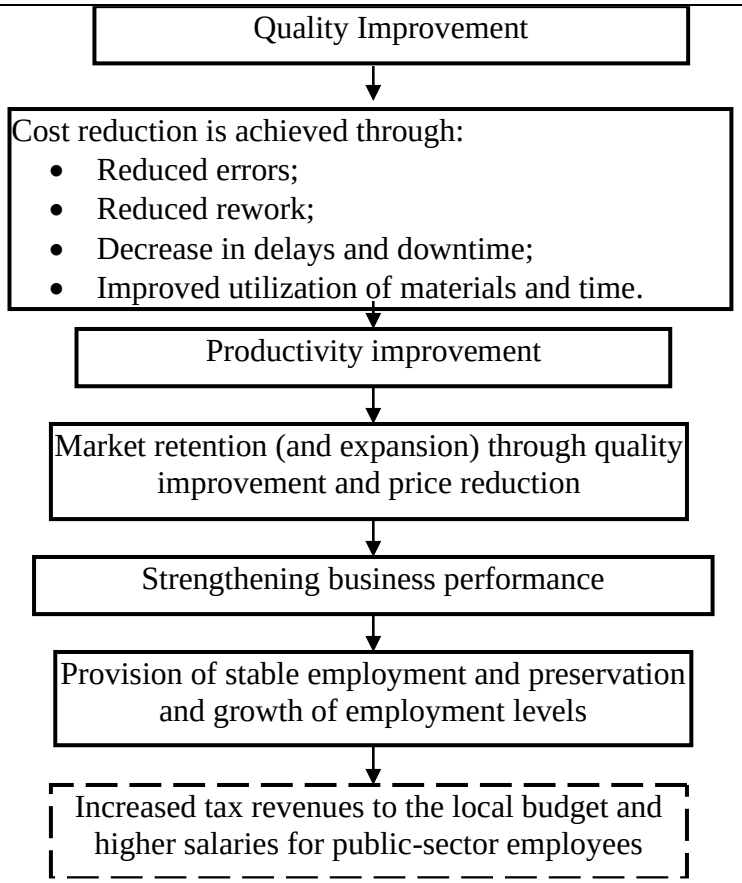


*Fig. 4. Deming's Chain Reaction*

Holding (capturing) the market by improving quality and reducing prices can significantly strengthen a business (business activity). By increasing profits, it is possible to purchase new machines, equipment, and production lines, as well as expand the production and sales of products. This, in turn, leads to additional profit growth.

As the business grows and profits increase, the factory will need more workers and employees. All the factory's employees will have stable employment, and their children and grandchildren also could find well-paying jobs at the factory due to the increased number of job opportunities. This is an important aspect of the social impact of improving the factory's product quality.

The six steps (phases, stages) of the Deming chain reaction can be supplemented with a seventh stage, which is depicted in Figure 1.4 as a dotted rectangle.

Increased product sales, strengthened business, increased factory profits, and increased salaries for workers and employees will lead to increased taxes in the local city budget. As a result, the city government will be able to increase the salaries of public sector employees (teachers, doctors, nurses, and paramedics) paid from the municipal budget, and purchase equipment for schools and hospitals in the city. This second component of the social consequences of improving the quality of products at a factory located in a city is very important. As a result of the increase in public sector employees' salaries, the workers and employees of a successful factory will also benefit, as they and their families will receive better medical care, and their children and grandchildren will have access to schools equipped with modern computers and educational technology. Teachers, doctors, nurses, and other public employees will receive higher salaries and be able to perform their work better.

Western businessmen, entrepreneurs, and company executives have long understood that relationships with employees and workers should be based on the principles of social responsibility, which help to maintain a high level of employee satisfaction. This issue is currently receiving a lot of attention. The international standards of the SA 18000 series provide recommendations for ensuring the necessary level of social satisfaction among workers and employees.

The social consequences of quality improvement discussed in this section illustrate the fact that successful quality management is not only aimed at:

- improving quality; reducing costs;
- increasing customer satisfaction;
- increasing product competitiveness;

but also at increasing social satisfaction:

- of the organization's workers and employees;
- of the local community.

**4. Information about the certification of quality management systems in accordance with the requirements of the international ISO9001 standard at the beginning of 2025**

Article [8] provides information about the results of certification of quality management systems according to ISO 9001 requirements (from The ISO Survey 2024 report) as of the beginning of 2025.

| | **Number of certificates/Number of sites** |
|---|---|
| People's Republic of China | 651831/999266 |
| Italy | 101426/157890 |
| India | 95007/116890 |
| Germany | 45983/104193 |
| Great Britain | 32988/55589 |
| United States of America | 28783/47463 |
| Russian Federation | 1804/2303 |

When comparing the data on quality management system certification in the People's Republic of China and the Russian Federation (presented above), it becomes clear why consumer goods (mobile phones, shirts, T-shirts, underwear, socks, trousers, etc.) produced in China by companies with certified quality management systems are widely available in public stores in the United States, France, Germany, and other countries. The fact is that these products are of high quality and have a relatively low price, which makes them highly competitive (refer to Section 1.5. The Impact of Successful Quality Management on Product Costs).

Due to the fact that there are very few companies in the Russian Federation that have certified their quality management systems, it is understandable why there are few products from Russian companies in public stores in the United States, France, Germany, and other countries. Based on the above, it can be concluded that the future successful development of the Russian Federation's economy is closely linked to the implementation and widespread use of quality management systems in organizations and enterprises in our country. In this regard, I would like to recall the words of the Russian philosopher Ivan Alexandrovich Ilyin: "**…the Russian people have only one way out and one salvation - a return to quality and its culture**", as stated in his article "Salvation in Quality," published in 1928 in the journal "Russian Bell." [9]

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# A PROBABILISTIC MODEL FOR PREDICTING TRAFFIC ACCIDENTS BASED ON THE PARAMETERS OF THE THREE-DIMENSIONAL GEOMETRY OF THE ROAD PROFILE

**Baghdasaryan I.**
*Junior member of the Institute of Applied Problems of Physics, National Academy of Sciences of Armenia, Yerevan, Armenia*
**Barseghyan A.**
*Department of Economics and Law, National University of Architecture and Construction of Armenia, Yerevan, Armenia*
https://doi.org/10.5281/zenodo.19292681

**Abstract**

The article proposes a probabilistic model for assessing the risk of road accidents on sections of highways with three-dimensional pedestrian markings. The aim of the study is to develop an approach to quantifying the risk of an accident based on the parameters of the spatial geometry of the road profile and traffic conditions. The model is based on the integration of methods of three-dimensional geometric modeling of road infrastructure, analysis of curve radii, longitudinal and transverse slopes, visibility zones and statistical forecasting of accidents using logistic regression. The model also takes into account external factors, including the speed of vehicles, weather conditions, and time of day. To form a vector of features, key parameters of the road infrastructure were identified, the impact of which on the probability of accidents was assessed using weighting coefficients. The results show that small curve radii, significant longitudinal slopes and limited visibility range have the greatest impact on the risk of an accident. The practical significance of the study lies in the possibility of using the developed model in analyzing the safety of road infrastructure and identifying potentially dangerous sections of highways. The use of three-dimensional pedestrian markings can help reduce the speed of movement and increase the attention of drivers, which is confirmed by the results of the analysis.

**Keywords**: 3D marking, road geometry, logistic regression, binary classification, accident risk, spatial modeling, road safety, integral risk

## 1. Introduction

Road traffic accidents remain one of the main causes of injuries and deaths on the roads in many countries of the world. Improving road safety is one of the most important tasks of transport engineering and road infrastructure management [11]. One of the key factors in accidents is failure to observe safe driving speeds on sections of roads with complex geometries, including sharp turns, longitudinal slopes and limited visibility. In recent years, special attention has been paid to the development of new methods to improve road safety. One of the modern solutions is the use of three-dimensional (3D) pedestrian markings that create a visual effect of a three-dimensional obstacle on the surface of the roadway [1]. Such solutions are aimed at attracting the attention of drivers and reducing the speed of vehicles on potentially dangerous sections of the road.

The issues of forecasting road accidents are actively being investigated in transportation engineering. Statistical methods, including logistic regression models, are widely used to analyze the probability of accidents [2,7,8]. These models make it possible to quantify the impact of various factors, such as road geometry, speed, weather conditions and visibility conditions, on the likelihood of an accident [4].

Modern research also actively uses machine learning methods to analyze accidents and identify dangerous sections of the road network [5,10,14,15,16]. The use of such methods makes it possible to take into account the complex interrelationships between the parameters of the road infrastructure and the characteristics of the traffic flow [3, 12]. In addition, the use of three-dimensional models of road infrastructure makes it possible to more accurately take into account the spatial geometry of the road, including slopes, curve radii and visibility zones, which helps to more accurately identify potentially dangerous sections of the road network. In recent years, accident forecasting models based on machine learning and big data analysis have been actively developing [15,16].

With the increasing intensity of traffic flows and the increasing complexity of the road infrastructure, the development of methods for predicting road accidents based on the analysis of geometric road parameters and behavioral factors of drivers is becoming particularly relevant. Modern modeling methods allow us to take into account the complex relationships between the characteristics of the road environment, traffic conditions and the likelihood of accidents. In this regard, the use of three-dimensional models of road infrastructure and statistical analysis methods opens up new opportunities for a more accurate assessment of the risk of accidents and the development of effective measures to improve road safety.

«Recent advances in integrating 3D road modeling with statistical and machine learning approaches enable more precise risk prediction. These methods consider not only geometric parameters but also dynamic traffic and environmental factors, improving safety planning and infrastructure design.».

*The purpose of this study is to develop a probabilistic model for quantifying the risk of road accidents on road sections with three-dimensional pedestrian markings based on the parameters of the spatial geometry of the road profile.*

## 2. Research methodology

### 2.1 Mathematical model of accident probability

Statistical analysis of accidents using 3D technologies makes it possible to more accurately reproduce the spatial characteristics of the road infrastructure and simulate the trajectory of a vehicle. Unlike traditional two-dimensional analysis schemes, three-dimensional models allow you to take into account the slopes of the road surface, the radii of curves and visibility zones, which significantly increases the accuracy of assessing the risk of accidents.

The mathematical model is based on the description of vehicle motion as a complex motion of a solid body in three-dimensional space. The model is based on statistical analysis and machine learning methods, which are widely used to predict accidents on highways [3, 12].

**1.2.Calculation of stopping and stopping distance**

The braking distance of a car on a section of road with a longitudinal slope is determined by the expression:

$$S = \frac{v^2}{(2g(f \pm Sin\ \alpha)} \quad (1)$$

Where **S** is the stopping distance, m;

**v** is the speed of the car, m\s;

**g = 9.81** m\s$^2$ – acceleration of gravity

**f** is the coefficient of wheel adhesion to the road (dimensionless);

$\alpha$ - the longitudinal slope of the road (rad or hail);

The « + » sign is used for lifting;

« - » the sign is used for descent.

The longitudinal slope of the road is automatically calculated for each point of the vehicle's trajectory, displayed from the position of the camera (the driver's eye or virtual camera), the coordinates of the marking point on the road, as well as from the direction of movement. Therefore, $\alpha$ it is the angle between the line of sight and the road plane, or the angle between the direction of travel and the vector to the marking point.

The probability of a traffic accident occurring on the road section under consideration is determined using a logistic regression model, which is one of the most common binary classification methods in accident analysis tasks [2,7,8].

The probability of an accident on a section of road P is determined using logistic regression:

$$P = \sigma(W \cdot G + b) = \frac{1}{1+e^{-(W \cdot G + b)}} \quad (2)$$

where P is the probability of an accident on a road section (0-1);

σ - sigmoid function

$\mathbf{G = [R, \alpha, \beta, S_{vis}, V, W_{weather}, W^{time}]^T}$ - is the vector of site features;

$\mathbf{W = [w_R, w_\alpha, w_\beta, w_S, w_V, w_{weather}, w^{time}]}$ - vector of weights reflecting the influence of each feature;

**b** is the bias (the baseline probability level under neutral conditions).

The stopping distance (SD) is considered a critical, as well as the main aspect of road safety, and, as a result, ignorance of the principle of safe distance provokes the cause of one in three accidents in large cities [5]. When assessing the probability of an accident risk, special attention is paid to the stopping distance of the vehicle. It includes the driver's reaction distance, the delay time for the start of braking, and the braking distance itself until it comes to a complete stop. Ignorance or underestimation of a safe stopping route is one of the key causes of accidents on the roads, especially in areas with limited visibility, steep slopes or a small radius of curves.

A correct assessment of the stopping distance allows you to take into account how much time and distance the driver needs to safely respond to a potential danger. Combined with factors such as speed, curve radii, and road slopes, it is possible to predict the risk of an accident on specific road sections much more accurately.

Thus, taking into account the braking distance in the model enhances its practical value and makes it possible to more effectively identify potentially dangerous areas on the highway where the use of safety measures, such as 3D markings, would be most justified.

$$S_{ocm} = S_p + S_c + S_t \quad (3)$$

The SD is the length of the route from the point of danger detection to the final cessation of movement, as well as the distance to the start of braking $t_p$, the delay time of braking, and the braking distance St (formula 3).

**2. Risk factors and mathematical model.**

**3.1. The influence of bias**

The following indicators are used to assess the influence of the geometric parameters of the road: radius of the curve of the road; longitudinal slope; transverse slope; range of visibility; speed of movement; weather conditions; time of day.

The use of logistic models makes it possible to quantify the impact of various factors of road infrastructure and traffic conditions on the likelihood of emergency situations [4.10].

The linear combination of features used in the sigmoid function, i.e. the total weighted risk indicator will take the following form:

$$\mathbf{Z = W \cdot G + b} = \sum_{i=1}^{m} wigi + b \quad (4)$$

where **m** is the number of features in the vector G;

**Z** - indicates the overall threat level at the site; as Z increases, the probability of an accident increases.

Formulas are used to assess the influence of individual road geometry factors:

a) the effect of the longitudinal slope on the braking distance

$$\mathbf{K_{slope} = 1 + a \cdot |\alpha|^b} \quad (5)$$

where **a** and **b** are empirical constants.

b) the effect of the radius of the curve:

$$\mathbf{K_{curve} = \{c/R\},} \text{ при } \mathbf{R<Rmin} \quad (6)$$

where **c** is the coefficient of influence of the curve;

$\mathbf{R_{min}}$ is the minimum safe radius.

**2.2.The impact of visibility**

The effect of visibility using the inverse dependence of the sigmoid:

$$K_{vis} = \frac{1}{1+\exp(k \cdot (Sfact - Sstop)} \quad (7)$$

where $\mathbf{S_{fact}}$ is the actual visibility, m;

$\mathbf{S_{stop}}$ - stopping distance, m;

**k** is the steepness coefficient (the greater the k, the sudden jump in the risk of RTA).

The essence of the formula is as follows

- with $S_{fact} \ll S_{stop}$, then $K_{vis} \approx 1$ is a high risk;

- with $S_{fact} \gg S_{stop}$, then $K_{vis} \approx 0$ is a low risk.

The technique consistently reproduces the justified risk of an accident.

**2.3. The influence of the curve radius**

When exposed to the radius of the curve, an exponential dependence (pattern of change) is applied, which smoothly increases the risk when the radius of the curve decreases as follows:

$$\mathbf{K_{curve} = \exp\left(-\frac{R}{R_0}\right)} \quad (8)$$

Where **R** – is the radius of the curve, m;

**$R_0$ –** is the characteristic radius (empirical constant) at which the risk is the considered moderate,

**$K_{curve}$ -** increases at $R_1$, for very small curve radii.

The exponential formula is simple, easy to understand, and effective for creating models.

**2.4. Integral risk model**

The total integral risk, taking into account geometric and external factors, has the form:

$$\mathbf{R_{total} = P \cdot K_{slope} \cdot K_{curve} \cdot K_{vis}} \quad (9)$$

This is what the final stage of the accident probability looks like, taking into account the synergistic effect.

Thus, the model takes into account the influence of road geometry, visibility, speed, and external factors, allowing you to quantify the probability of an accident on each road section.

3D zebra pedestrian markings are a type of road marking that creates the illusion of a three-dimensional obstacle due to graphic techniques that form the effect of a bulge on a flat surface of the roadway. This visual effect is based on the mechanisms of optical perception and is aimed at increasing the attention of drivers and reducing the speed of vehicles. The driver's consciousness captures the differences between "chiaroscuro", three-dimensionality and modeling as a space. When depicting zebra stripes with "chiaroscuro" and displacement, the driver fixes them as an obstacle on the road. This representation is based on the mechanisms of binocular and monocular depth perception, as well as the processing of light and shadow by the visual cortex. If the car driver notices reality in 3D, i.e. perceives depth, it should be taken into account that binocular vision provides a fusion reflex (merging two images into one) [3]. In this sense, the driver's mental abilities are understood to combine images into a single whole [7]. Binocular vision, unlike monocular vision, gives a person the opportunity to navigate normally in space. With monocular vision, complete loss of functioning of one eye, severe strabismus, amblyopia ("lazy eye") or the consequences of injuries (operations) [4]. Whereas binocular vision creates a three-dimensional image, monocular vision forms a plane, i.e. a 2D picture. If the mind captures a possible danger, then the orientation reflex is activated, attention is increased, then the driver automatically reduces speed. The whole process is associated with the work of emotional reactions and an instant threat monitoring system.

If there are strange objects on the roadway on motorways, then they concentrate more intensely here, they are easier to fix, and they occasionally improve concentration. Such a study is called the novelty effect, and it is scientifically based in the field of behavioral psychology and transportation safety.

The review analysis allows you to mathematically substantiate the distance at which the driver noticed the obstacle from afar. The software simulates viewing areas from the point of view of the car driver to the elements of road construction. In 3D markup, the integrated risk management system (ERM) on highways is considered a comprehensive digital plan with geometric data, as well as with characteristics and probabilistic safety indicators.

To assess the impact of individual road infrastructure factors on the probability of an accident, feature vectors G and corresponding weighting coefficients W were determined (Table 1). To quantify the risk of road accidents on the road sections under consideration, the key parameters forming the feature vector G and the corresponding weighting coefficients W were determined.

Each factor characterizes a specific aspect of the road infrastructure or traffic conditions and affects the likelihood of an accident. Thus, *the radius of the curve (R)* reflects the curvature of the road section - reducing the radius increases the risk of accidents. *The longitudinal slope (α)* shows the effect of ascents and descents on braking distance and driving dynamics, while *the transverse slope (β)* has a more moderate effect. *The range of visibility ($S_{vis}$)* is critically important for a timely driver response: reducing it increases the risk of a collision. *The speed of movement (V)* directly increases the probability of an accident, and *weather conditions ($W_{weather}$)* and *time of day ($W_{time}$)* modify the risk of an accident, taking into account the influence of the external environment and visibility.

**Table 1.**

**The main indicators of the factors are vectors of features and weighting coefficients**

| **Names** | **Symbols** | **Measures of quantities** | **Weight, $w_i$** | **Notes** |
|---|---|---|---|---|
| Radius of the curve | R | m | 0.45 | Reducing the radius leads to an increase in danger |
| Longitudinal slope | A | rad | 0.60 | Steep descent increases the risk |
| Lateral slope | B | rad | 0.25 | Light impact |
| Range of visibility | $S_{vis}$ | m | - 0.50 | Keeping a distance reduces the risk of an accident |
| The speed of movement | V | m\s | 0.55 | As the speed increases, the threat increases |
| Weather conditions | $W_{weather}$ | Immeasurable | 0.35 | Precipitation increases the risk |
| Time of day | $W_{time}$ | immeasurable | 0.20 | At night, the probability of an accident is slightly higher |

All indicators and their numerical values are presented in Table 1. Analysis of this table makes it possible to understand which factor has the greatest impact on the risk of an accident and how their combined impact forms an integral indicator of danger on a road section.

The proposed model reflects the cumulative effect of location, i.e. the synergetic effect of territorial circumstances (combining a steep curve with a steeply sloping descent), which cannot be said about traditional 2D schemes.

**3. Features of visual perception of 3D markup**

The effectiveness of three-dimensional pedestrian markings is related to the peculiarities of human visual perception. The illusion of a three-dimensional obstacle is formed through the use of chiaroscuro effects, perspective distortions, and lane shifts that create the visual effect of a bulge on a flat road surface [1,9,13].

The driver's binocular vision makes it possible to estimate the depth of space and the distance to objects, which increases the accuracy of orientation on the road [6, 13]. When perceiving 3D markings, the orientation reflex is activated, attention is increased, and the driver automatically reduces the speed of movement. In addition, psychological effects such as the novelty effect enhance the driver's concentration: an unusual visual element on the road instantly attracts attention and improves concentration. This is especially important in areas with limited visibility or complex road geometry.

Combined with an analysis of the geometric parameters of the road and an assessment of external factors (speed, weather conditions, time of day), taking into account the driver's visual perception makes the accident risk assessment model more accurate and practical. Thus, the integration of 3D markings into the risk forecasting system allows not only to identify potentially dangerous sections of the road, but also to take into account the behavioral aspect of the driver when assessing the likelihood of accidents.

**4. Conclusion**

As a result of the conducted research, a probabilistic model for assessing the risk of road accidents on sections of highways with three-dimensional pedestrian markings has been developed. The proposed approach is based on the integration of methods of three-dimensional geometric modeling of road infrastructure and statistical analysis using logistic regression**.**

The analysis showed that the combined effect of the geometric characteristics of the road and external factors forms a synergistic effect that significantly affects the likelihood of road accidents. In particular, the combination of small radii of curvature, significant longitudinal slopes, and limited visibility leads to a marked increase in the integral risk level.

The use of three-dimensional modeling makes it possible to more accurately take into account the spatial structure of the road profile and identify potentially dangerous sections of the road network. This significantly expands the analytical capabilities compared to traditional two-dimensional analysis methods.

The results obtained confirm the prospects of integrating statistical analysis, machine learning, and three-dimensional modeling methods to develop intelligent traffic safety systems.

The proposed model can be used in analyzing the safety of individual sections of highways, as well as in intelligent road infrastructure management systems. The results obtained can serve as a basis for developing practical recommendations on the placement of road infrastructure elements, including the use of three-dimensional pedestrian markings on potentially dangerous road sections. Further research may be aimed at expanding the set of model factors and using machine learning methods to improve the accuracy of predicting traffic accidents.

The proposed probabilistic model can be integrated into intelligent transportation systems to support real-time risk assessment and guide strategic placement of 3D pedestrian markings. Future work may focus on expanding the set of environmental and behavioral factors to enhance predictive accuracy.

**Discussion of the results**

An analysis of the results shows that the geometric parameters of the road and the speed of vehicles have the greatest impact on the likelihood of road accidents. At the same time, the combined effect of several factors forms a synergistic effect, in which the risk level increases significantly more than with the isolated influence of each individual parameter.

The synergistic effect of multiple risk factors indicates that interventions targeting combined geometric and environmental risks are more effective than isolated measures. Furthermore, incorporating behavioral aspects of drivers into predictive models enhances the accuracy of traffic safety assessments.

**Scientific novelty and practical significance of the research**

*The scientific novelty* of the research lies in the development of a probabilistic model for predicting road accidents, taking into account the parameters of the three-dimensional geometry of the road profile, visibility factors and external traffic conditions. The proposed approach makes it possible to integrate several critical risk factors into a single model, which provides a more accurate assessment of the probability of an accident compared to traditional methods.

*The practical significance* of the work is shown in the possibility of using the model in analyzing the safety of road infrastructure, identifying potentially dangerous areas and developing recommendations for the use of 3D pedestrian markings to increase driver attention and reduce speed.

**Contribution of the authors**

**Irina Baghdasaryan** – research concept, methodology development, mathematical modeling, writing the initial text of the article.

**Angela Barseghyan** – data analysis, visualization of results, editing and scientific review of the text.

**Conflict of interests**.

The authors declare that there is no conflict of interest.

**List of abbreviations**

3D - three- dimensional;

Traffic accident - a traffic accident;

ERM - risk management system;

Svis - range of visibility;

R is the radius of the curve;

V is the speed of movement.

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# ENVIRONMENTAL FACTORS INFLUENCING THE DEVELOPMENT OF GEO-ECOLOGICAL MONITORING OF THE RESTORATION OF LAND USED FOR TRANSPORT INFRASTRUCTURE

**Mamonov K.**
*D. Sc. (Econ.), Prof., head of department,*
*department of land administration and geographic information systems*
*O.M. Beketov National University of Urban Economy in Kharkiv*
http://orcid.org/0000-0002-0797-2609
**Teliura N.**
*Cand. Sc. (Tech.), Associate Professor, Department of Chemistry and Integrated Technologies*
*O. M. Beketov National University of Urban Economy in Kharkiv*
https://orcid.org/0000-0003-0732-7789
**Viatkin R.**
*Cand. Sc. (Tech.), associate professor,*
*department of land administration and geoinformation systems*
*O.M. Beketov National University of Urban Economy in Kharkiv*
https://orcid.org/0000-0001-8807-9988
**Frolov V.**
*Cand. Sc. (Tech.), assistant*
*of the department of land administration and geographic information systems*
*O.M. Beketov National University of Urban Economy in Kharkiv*
https://orcid.org/0000-0001-8045-3963
https://doi.org/10.5281/zenodo.19400206

**Abstract**

It has been demonstrated that the development and implementation of geo-ecological monitoring of the restoration of transport infrastructure land, taking into account the influence of environmental factors, is a pressing issue.

The theoretical approaches outline the directions and characteristics of the development and application of elements of geo-ecological monitoring of the restoration of transport infrastructure land. However, issues regarding the development of a comprehensive system for geo-ecological monitoring of the restoration of transport infrastructure land, taking into account the influence of environmental factors in particular, remain unresolved.

The research objective of identifying the environmental factors applicable to geo-ecological monitoring of the restoration of transport infrastructure land has been achieved.

The environmental factors influencing the development of geo-ecological monitoring of the restoration of transport infrastructure land have been identified. This enables the construction of a multi-level system of indicators, the development of an assessment method, and the establishment of a quantitative basis for making informed decisions.

The identified factors provide opportunities to determine attribute information for geoinformation and mathematical modelling, forecasting changes, and developing technology for establishing geo-ecological monitoring of land restoration for transport infrastructure.

**Keywords:** environmental factors, land restoration, geo-ecological monitoring, transport infrastructure, environmental monitoring, geoinformation systems.

**Introduction.** The transformational processes currently taking place within the land relations system are characterised by a decline in the efficiency of land use and in the spatial provision of territorial units; an imbalance in stakeholder relations is evident, and opportunities for applying modern technologies to enhance land use are diminishing. These processes are exacerbated by the conduct of aggressive military operations. It should be noted that as a result of Russia's invasion, Ukraine's infrastructure has suffered direct losses amounting to $170 billion. Losses to transport infrastructure are estimated at $38.5 billion, including:

– 26,000 km of motorways damaged or destroyed, amounting to $28.3 billion;
– rail transport – $4.3 billion;
– port infrastructure – $0.85 billion;
– the aviation sector – $2 billion;
– 260,000 vehicles were destroyed or damaged, with total direct losses amounting to $2.2 billion [1].

The consequences of the aggression included the destruction of transport infrastructure, disruption of logistics links, increased economic losses and a decline in passenger numbers, as well as a reduction in investment and attractiveness.

In this process, the issue of identifying and defining environmental factors for the establishment of geo-ecological monitoring of the restoration of transport infrastructure land is of particular relevance. To substantiate these environmental factors, the relevant regulatory framework is applied: the Forest Code of Ukraine of 21 January 1994 № 3852-XII, the Subsurface Code of Ukraine of 27 July 1994 № 132/94-VR, the Water and Land Codes of Ukraine of 6 June 1995 № 213/95-VR, the Laws of Ukraine «On Waste Management» of 20 June 1992 № 2320-IX, «On the Legal Regime of the Territory Affected by Radioactive Contamination as a Result of the Chernobyl Disaster» of 27 February 1991

№ 791a-XII, «On the Protection of the Natural Environment» of 25 June 1991 № 1264-XII, «On the Nature Reserve Fund of Ukraine» of 16 June 1992 № 2456-XII, «On the Protection of Atmospheric Air» of 16 October 1992 № 2707-XII, «On a Moratorium on Clear-Cutting on Mountain Slopes in the Fir and Beech Forests of the Carpathian Region» of 10 February 2000 № 1436-III, «On Game Management and Hunting» of 22 February 2000 № 1478-III, «On High-Risk Facilities» (№ 2245), «On the Animal Kingdom» of 13 December 2001 № 2894-III, «On the Red Book of Ukraine» dated 7 February 2002 № 3055-III, «On Land Protection» dated 19 June 2003 № 962-IV, «On State Control over the Use and Protection of Land» dated 19 June 2003 № 963-IV, «On State Registration of Real Rights to Immovable Property and Encumbrances Thereon» of 1 July 2004 № 1952-IV, «On the Basic Principles of State Supervision (Control) in the Sphere of Economic Activity» of 5 April 2007 № 877-V, «On Environmental Impact Assessment» (Law № 2059), «On Strategic Environmental Assessment» dated 20 March 2018 № 2354-VIII. At the same time, the development and implementation of geo-ecological monitoring of the restoration of land used for transport infrastructure, taking into account the impact of environmental factors, remains a pressing issue.

**Justification of existing theoretical approaches.** Existing scientific studies present theoretical approaches to defining geo-ecological monitoring. At the same time, the development and implementation of geo-ecological monitoring of land restoration for transport infrastructure require further refinement.

Issues relating to the implementation of environmental monitoring are prominent in scientific research [2–4]. Modern geoinformation systems are used to develop and implement geo-ecological monitoring; their characteristics are set out in [5–7]. The areas and characteristics of the development and implementation of geo-ecological monitoring are outlined in the following works [8, 9].

The proposed environmental monitoring system consists of the following structural components (Table 1).

Table 1

Components of environmental monitoring [10]

| Structural elements | Specification |
|---|---|
| The operation of the state environmental monitoring system | The Law of Ukraine «On the Protection of the Natural Environment» (Articles 20 and 22) provides for the establishment of a State Environmental Monitoring System (SEM) and the monitoring of the state of the natural environment and levels of pollution. These functions are entrusted to the Ministry of the Environment and other central executive bodies, which are entities of the State Environmental Monitoring System, as well as enterprises, institutions and organisations whose activities cause or may cause deterioration of the environment. The main principles of the State Environmental Monitoring System (SEM) are set out in Resolution № 391 of the Cabinet of Ministers of Ukraine dated 30 March 1998 «On the Approval of the Regulations on the State Environmental Monitoring System». Currently, within the State Environmental Monitoring System (SEM), the functions and tasks of observation and information provision are carried out by eight entities of the monitoring system: the Ministry of the Environment, the Ministry of Emergencies, the Ministry of Health, the Ministry of Agrarian Policy, the Ministry of Housing and Communal Services, the State Water Management Agency, the State Forestry Committee, and the State Land Committee. Each of the SES entities monitors those environmental components specified in the Regulations on the State Environmental Monitoring System and in the procedures and regulations on state monitoring of individual environmental components. The State Environmental Monitoring System operates at three levels, organised on a territorial basis: the national level, covering priority areas and monitoring tasks across the whole country; the regional level, covering priority areas and tasks within a specific territorial region; the local level, covering priority areas and monitoring tasks within specific territories subject to increased anthropogenic pressure. |
| Air quality monitoring | The State Hydrometeorological Service (SHS) monitors atmospheric air pollution in 53 cities across Ukraine at 162 fixed monitoring stations, two mobile monitoring posts and two transboundary transport stations. Observations are also carried out on the chemical composition of atmospheric precipitation and on the acidity of precipitation. The mandatory air quality monitoring programme covers seven pollutants: particulate matter, nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$), carbon monoxide, formaldehyde ($H_2CO$), lead and benzo(a)pyrene. Some stations monitor additional pollutants. Analyses are carried out to determine the presence of pollutants in precipitation and snow cover. |

| | |
|---|---|
| Monitoring of inland water quality | The State Hydrometeorological Service (SHS) monitors the hydrochemical status of water at 151 water bodies and conducts hydrobiological observations at 45 water bodies. Data is collected on 46 parameters, enabling the assessment of water chemistry, biogenic parameters, the presence of suspended solids and organic matter, major pollutants, heavy metals and pesticides. Monitoring of chronic water toxicity is carried out at 8 water bodies. Indicators of radioactive contamination of surface waters are determined. The State Environmental Inspectorate (Ministry of Environment) takes water samples and collects data on 60 measured parameters. |
| Monitoring of coastal waters | The State Hydrometeorological Service (MNS) operates a coastal water monitoring network comprising monitoring stations at wastewater discharge points and research stations located in the coastal areas of the Black and Azov Seas. At the existing stations, measurements are taken of between 16 and 26 hydrochemical parameters of the water and bottom sediments. |
| Soil monitoring | The State Hydrometeorological Service (SHS) monitors soil contamination of agricultural land by pesticides and heavy metals in populated areas. Samples are taken once every five years; samples for heavy metals in the towns of Kostiantynivka and Mariupol are taken annually. The State Environmental Inspectorate (Ministry of Environment) carries out sampling at industrial sites across the country. The total number of parameters measured is 27. |
| Monitoring of biodiversity indicators | Due to limited budgetary funding, monitoring is carried out only for species of commercial interest (trees, fish, game). Enterprises under the State Forestry Committee monitor forest vegetation in 24 regions of the country. Assessments are carried out of biomass and damage caused to it by biotic and abiotic factors; game fauna and biodiversity; and radiological measurements. Some studies are carried out with international assistance or within the framework of international programmes. |
| Radiation monitoring | The State Hydrometeorological Service (SHS) monitors atmospheric radioactive contamination by taking daily measurements of gamma radiation exposure doses (GRE), the deposition of radioactive particles from the atmosphere, and the concentration of radioactive aerosols in the air. Measurements of radioactive contamination in surface waters are carried out at eight water bodies. Near nuclear power stations, the State Hydrometeorological Service measures radioactive contamination of surface waters with caesium-137 and soil contamination. |

The theoretical approaches outline the main directions and characteristics of the development and application of geo-ecological monitoring elements for the restoration of transport infrastructure land. However, questions remain unresolved regarding the development of a comprehensive system for the geo-ecological monitoring of transport infrastructure land restoration, particularly in view of the influence of environmental factors.

**The aim of the study** is to identify the environmental factors used for geo-ecological monitoring of the restoration of transport infrastructure land.

**Main section.** In the context of the development of land relations and ensuring the functioning of transport infrastructure, resolving issues related to the implementation of environmental and safety measures is of particular importance. In recent years, fluctuating trends have been observed in the capital investment index for environmental protection (Fig. 1).

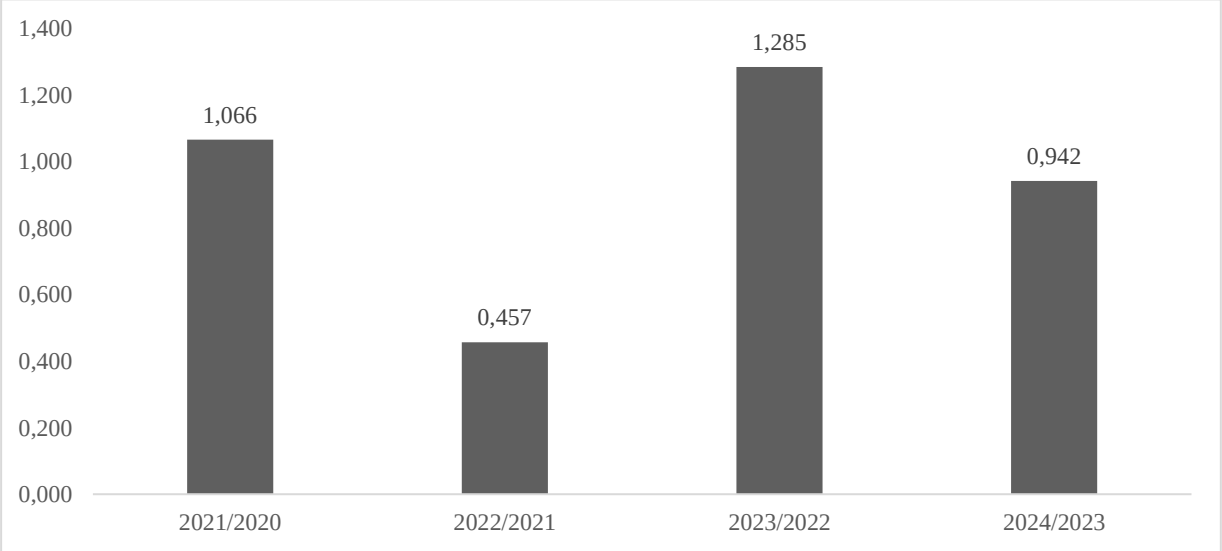


*Fig. 1. Trend in the index of capital investment in environmental protection, relative units, according to [11]*

In particular, in 2021, compared with 2020 (the 'pre-war' period), there was an increase in capital investment in environmental protection. This indicates positive developments in the implementation of environmental policy. In 2022, as a result of Russia's aggression, a significant decline in this indicator was observed. This is the lowest value for the period under review. In 2023, compared to the previous year, there is a certain 'adaptation' to existing conditions, with capital investment in environmental protection increasing by 28.5%. In the subsequent period under review, this indicator fell by 5.8%.

The trend in the current environmental protection investment index is shown in Figure 2.

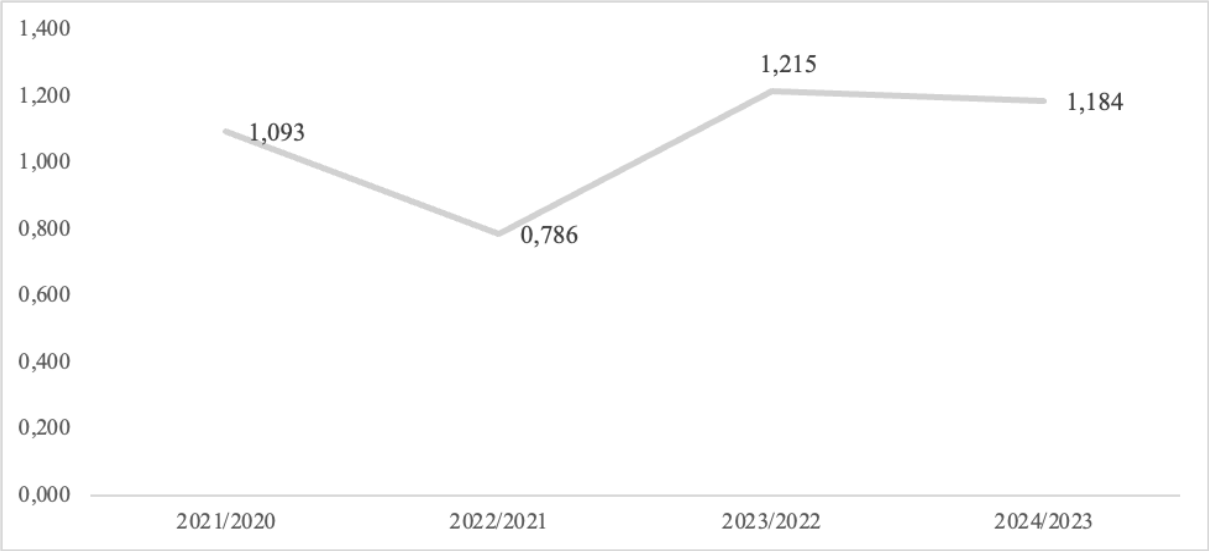


*Fig. 2. Trend in the index of current investment in environmental protection, relative units [11]*

Ambiguous trends were observed in the volume of current investment in environmental protection over the period under review, with periods of growth alternating with periods of decline. The sharpest drop in this indicator occurred in 2022.

A selection of local environmental indicators was carried out to assess the development and use of geo-ecological monitoring of transport infrastructure land restoration:

– conducting a financial assessment of the implementation of climate change adaptation measures ($RTIL_{21}^{1}$);

– index of changes in the ratio of treated to generated waste by region ($RTIL_{22}^{1}$);

– index of changes in generated waste relative to regional area ($RTIL_{23}^{1}$);

– index of changes in emissions of pollutants and carbon dioxide into the atmosphere ($RTIL_{24}^{1}$);

– index of changes in capital investment in environmental protection ($RTIL_{25}^{1}$);

– index of changes in current investment in environmental protection ($RTIL_{26}^{1}$);

– level of application of geographic information systems in the environmental monitoring system ($RTIL_{27}^{1}$);

– levels of preservation of the climate system in a state that prevents an increase in risks to human health and well-being and the natural environment ($RTIL_{28}^{1}$);

– Ukraine's achievement of the Sustainable Development Goals (SDGs) adopted at the United Nations Sustainable Development Summit in 2015 ($RTIL_{29}^{1}$);

– promoting balanced (sustainable) development by achieving a balance between the components of development (economic, environmental, social) and focusing on the priorities of balanced (sustainable) development ($RTIL_{210}^{1}$);

– integrating environmental requirements during the drafting and approval of national planning documents, as well as sectoral, regional and local development documents, and in the decision-making process regarding the implementation of planned activities at facilities that may have a significant impact on the environment ($RTIL_{211}^{1}$);

– fostering cross-sectoral partnerships and engaging stakeholders ($RTIL_{212}^{1}$);

– ensuring environmental safety and maintaining ecological balance within Ukraine, and improving environmental safety levels in the exclusion zone ($RTIL_{213}^{1}$);

– ensuring the inevitability of liability for breaches of environmental legislation ($RTIL_{214}^{1}$);

– improving the system of natural resource registers and state statistical reporting on the use of natural resources and environmental pollution ($RTIL_{215}^{1}$);

– stimulating the development of waste management infrastructure ($RTIL_{216}^{1}$);

– stimulating the renewal of worn-out fixed assets in industrial and transport infrastructure and housing and communal services facilities through direct state subsidies, cheaper loans, partial compensation of interest rates on loans, etc. ($RTIL_{217}^{1}$);

– introducing environmental accounting to assess the effectiveness of policy and management ($RTIL_{218}^{1}$).

**Conclusions.** Thus, the environmental factors influencing the development of geo-ecological monitoring of land restoration for transport infrastructure have been identified. This enables the construction of a multi-level system of indicators, the development of an assessment method, and the establishment of a quantitative basis for informed decision-making.

The identified factors make it possible to determine attribute information for geoinformation and mathematical modelling, forecasting changes, and developing technology for establishing geo-ecological monitoring of the restoration of transport infrastructure land.

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№177/2026

**Norwegian Journal of development of the International Science**

ISSN 3453-9875

It was established in November 2016 with support from the Norwegian Academy of Science.

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