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ИЗВЕСТИЯ
ВЫСОКИХ ТЕХНОЛОГИЙ

BULLETIN
OF HIGH TECHNOLOGY

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2025

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Տեղեկագիրը հրատարակվում է Ակադեմիկոս Ի.Վ.Եղիազարովի ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտի, Հիդրավլիկական հետազոտությունների հայկական ազգային ասոցիացիայի, Երևանի կապի միջոցների գիտահետազոտական ինստիտուտի և Շուշիի տեխնոլոգիական համալսարանի կողմից: Հիմնադրվել է 2016թ.: Լույս է տեսնում տարեկան 4 անգամ:

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APPLICATION OF POLYMER-MINERAL MATERIAL «PMM» FOR CREATION OF WATERPROOFING LAYER DURING CONSERVATION OF TAILINGS: DEVELOPMENT OF INSTALLATION TECHNOLOGIES AND LABORATORY RESEARCH

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Abstract

It is recommended to waterproof the surface of the mothballed tailings storage facility by directly applying the polymer-mineral material "PMM" or a composite created on its basis. During laboratory research, an effective composition of the waterproofing layer was determined and two technologies for its installation were developed.

E.V.Avanesyan, V.R.Grigoryan, D.H.Grigoryan, H.V.Tokmajyan

APPLICATION OF POLYMER-MINERAL MATERIAL «PMM» FOR CREATION OF WATERPROOFING LAYER DURING CONSERVATION OF TAILINGS: DEVELOPMENT OF INSTALLATION TECHNOLOGIES AND LABORATORY RESEARCH

Laboratory studies show that when creating an anti-filtration composite using sandy-loamy soil, the required amount of «PMM» filler is significantly lower than when using ordinary soil.

Keywords: recreation, urban environment, tailings storage facilities, waterproofing.

Introduction

The service life of tailings storage facilities may be relatively short, but the waste will be stored for an extended period. Conservation of a tailings storage facility involves stopping the supply of processed ore waste for storage and maintaining the facility in a safe, pollution-preventing condition for an indefinite period. The area of the conserved tailings storage facility may be used for agricultural or other purposes. Conservation measures may include dismantling infrastructure, reclamation, landscaping, and using the storage facility and adjacent lands for national economic development. After completion of conservation measures and implementation of the necessary design solutions for conservation, the tailings storage facility is transferred to a long-term maintenance and monitoring mode. During the post-conservation period, responsibility for the tailings storage facility may be transferred from the owner to the local administration. Operation of the tailings storage facility should ensure the creation of a sustainable, safe, and low-maintenance facility that does not pose long-term safety risks or environmental impacts for future generations [1].

A large number of works are devoted to the impact of tailings storage facilities on the environment [2–4].

A mothballed tailings storage facility located at a distance of 2 km from populated areas, in accordance with the safety regulations for the operation of tailings, sludge and hydraulic waste disposal facilities of the Russian Federation, must be fenced along the perimeter with a prefabricated reinforced concrete fence, at least 2 m high. If a mothballed tailings storage facility is located more than 2 km from populated areas, it is permissible to construct a fence along its perimeter from two rows of barbed wire on reinforced concrete posts [5].

This approach is unacceptable for the conservation of tailings ponds in Armenia, since the flat areas of mountainous zones remain unused.

The primary objective of tailings storage facility conservation should be to ensure long-term stability of the physical and chemical state, as well as environmental and social conditions, and to maintain the storage facility in a trouble-free condition for a reasonable period. The key objectives are [1]:

- Reclamation and storage should not require any ongoing maintenance or costs beyond normal land-use requirements;
- The tailings storage facility, after conservation, should not pose an unacceptable risk to human health and safety;
- The tailings storage facility, after conservation, should not pose an unacceptable risk to the environment;

- Conservation of the storage facility area should allow for the use of the storage facility area for agriculture or other purposes.

Based on a combination of factors, the optimal approach to reclamation (preservation) is sanitary and hygienic, which includes the following measures [6]:

- Site planning with the installation of an anti-seepage element;
- Restoration of previously removed fertile soil layer;
- Removal of contaminated soil.

The use of polymer-mineral materials “PMM” will allow the construction of environmentally friendly modern tailings storage facilities, as well as the safe use of areas where waste has been buried [7, 8].

To utilize former tailings dumps for agricultural purposes, before covering them with a layer of soil suitable for sowing, some researchers propose preparing a sarcophagus 7-10 cm thick by mixing 30 g of polymer-mineral material (PMM) with 1 kg of soil and compacting it. This will prevent chemicals hazardous to human health from penetrating upward from the tailings dump, as well as prevent water from precipitation and irrigation from penetrating into the tailings dump layer and spreading into the surrounding environment. When applying the proposed technology, it is important to consider that polymer-mineral material (PMM) can decompose in the aggressive environment of the tailings dump, so the impact of the PMM on the latter must be studied [7].

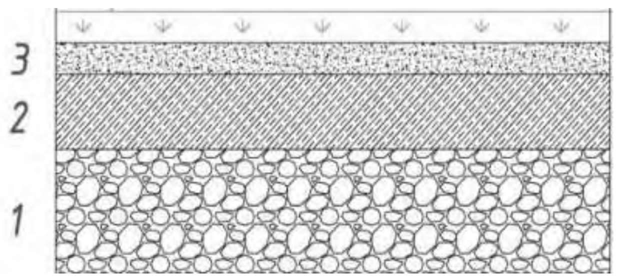

Fig. 1 Technology for reclamation of the tailings surface
1-tail, 2-loam (h=0.5m), 3-soil

The technology for reclaiming the surface of a tailings storage facility developed in [6] is shown in Fig. 1 and includes:

- Leveling the surface of the deposited tailings with soil from overburden waste dumps (rocks) to stabilize the surface, grading toward the drainage ditch; backfilling with loamy soil to create an anti-seepage element, grading it 0.5 m thick;
- Laying a fertile soil layer.

Landscape pollution with heavy metals is a serious problem because it negatively impacts soil characteristics and limits its productive and vital functions. Heavy metals are considered a key environmental pollutant due to their stability and bioaccumulative potential; their accumulation leads to negative consequences for ecological systems. Metal waste contributes to the leaching of metallic substances into water bodies, appears in dangerous quantities in food products, and impacts the biodiversity of ecosystems [7].

Until the restoration of natural vegetation on the reclaimed site, close to the natural ecosystem, it is proposed to carry out mountain-ecological monitoring [9].

However, it is obvious that without laying a waterproofing layer on the waste dumps, it is impossible to prevent dangerous filtration processes that could hinder the use of the protected waste dump area for agricultural, recreational and other purposes.

E.V.Avanesyan, V.R.Grigoryan, D.H.Grigoryan, H.V.Tokmajyan

APPLICATION OF POLYMER-MINERAL MATERIAL «PMM» FOR CREATION OF WATERPROOFING LAYER DURING CONSERVATION OF TAILINGS: DEVELOPMENT OF INSTALLATION TECHNOLOGIES AND LABORATORY RESEARCH

Water use opportunities are declining not only due to global economic and population growth, but also due to the pollution of water resources and their subsequent withdrawal from economic circulation. As a result, the environmental challenge of preserving and efficiently using water resources is becoming increasingly pressing. Currently, not only the concept of economic capital is used, but the existence of closely interconnected and interdependent economic, socio-political, and environmental capitals for the well-being of human society is emphasized [7, 10, 11].

Conflict Setting

The conservation of tailings storage facilities is a serious issue for many countries. The aim of this study is to conduct research into the creation of a waterproofing layer on the surface of tailings storage facilities using polymer-mineral material (PMM) and the development of installation technologies.

Research Results

Below is a description of the technologies for creating and installing a waterproofing layer for tailings dams using the polymer-mineral suspension "PMM" (hereinafter also referred to as PMM) and an analysis of laboratory test results.

Two technologies for creating and installing a waterproofing layer have been developed, based on the results of laboratory tests conducted in Yerevan and Moscow.

Analysis of laboratory test results for the waterproofing layer, conducted at the Institute of Mechanics of Moscow State University and the I.V. Yegiazarov Institute of Water Problems and Hydraulic Engineering, suggests conducting field studies on a small section of the tailings dam. The development and installation of a waterproofing layer on the surface of the tailings dam as part of a pilot project (preliminary testing of the impervious lining of a tailings dam covering an area of approximately 1,500-3,000 square meters) will allow us to verify the reliability of the waterproofing layer, refine its installation technology, and evaluate the cost of each proposed option.

Samples of enrichment waste provided by the Department of Environmental Protection and Subsoil Inspection of the Republic of Armenia, soil used during the reclamation of the tailings storage facility, sandy loam soil, ordinary soil and polymer-mineral material "PMM" were used for the tests.

A modified version of the "PMM" material was used during testing. Its physical and technical characteristics are presented below:

- The density of the dry fraction of the PMM material with a particle size of up to 1 mm is 1 kg/l;
- Inert (according to preliminary tests) to aggressive environments and non-polar liquids;
- Frost-resistant during operation. Frost resistance is between that of sandy and sandy-loamy soils;
- Chemical resistance to aggressive environments (sulfate and acid resistance) – stable in the pH range of 4-12;

- Stable when laid on slopes with a ratio of 1:3;
- Resistance of the waterproofing layer to groundwater – resistant to erosion at speeds of up to 5 m/s.

Description of the first technology for conducting laboratory tests:

1. A composite mixture of polymer-mineral material "PMM" and soil is laid on the pre-leveled surface of the mothballed tailings dam and then compacted with a rammer. The soil must be as uniform as possible.
2. To ensure the integrity of the waterproofing layer, a layer of soil (without PMM) 7-10 cm thick (soil, sandy loam soil or other material) is placed on top, which is compacted with a rammer.
3. The resulting surface is slowly covered with water using sprinkling until the water reaches the top of the test tube (a layer of water 10-15 cm thick is formed).
4. Every day, depending on the degree of absorption, water is added to the test tube until it reaches the top of the test tube.

To obtain composite waterproofing layers, laboratory tests were conducted with various types and masses of soil, with different ratios of the use of the "PMM" material.

The aggressive tailings material was placed in a transparent plastic cylindrical tube with a diameter of d=0.225 m with holes in the bottom and compacted.

Experiment N1

1. Experiment start: November 2, 2025.
2. Soil type: inorganic material with a predominance of quartz sand, containing a limited amount of aluminosilicate and carbonate mixtures (hereinafter referred to as soil). Soil type: inorganic material with a predominance of quartz sand, containing a limited amount of aluminosilicate and carbonate mixtures (hereinafter referred to as soil).[1]
3. The mass of the soil is 4 kg.
4. The amount of "PMM" material is 280 g (based on 7 kg/m^2).
5. The total mass of the test tube at maximum saturation with water is 14.85 kg - 12/04/2025.
6. Water absorption level at maximum saturation - 100%: 12/04/2025 Water absorption level at maximum saturation - 100%: 12/04/2025.
7. A weak filtration flow is observed through the holes in the bottom of the test tube (slight wetting of the bottom. No measurable yield is observed). A weak filtration flow is observed through the holes in the bottom of the test tube (slight wetting of the bottom. No measurable yield is observed).
8. The onset of the filtration phenomenon through the holes in the bottom of the test tube: 12/04/2025.
9. Termination of the filtration phenomenon through the holes in the bottom of the test tube: 12/13/2025.

[1] Soil characteristics are given after the description of the experiments.

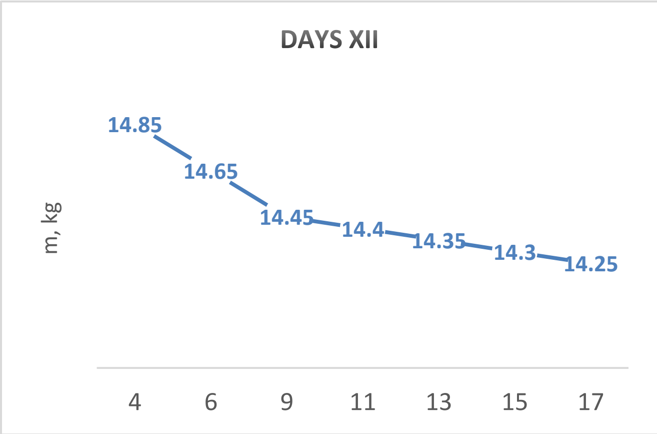

Fig.2 Evaporation losses after opening the lid for the baseline data of experiment N1

10. The decrease in the total mass of the test tube with an open lid by days from the start of filtration through the holes in the bottom of the test tube (12/04/2025) is shown in Fig. 2.

Experiment N2

1. Experiment start: November 2, 2025.

2. Soil type: sandy loam soil used for reclamation of tailings ponds. Soil type: sandy loam soil used for reclamation of tailings ponds.
3. The mass of the soil is 4 kg.
4. The amount of "PMM" material is 280 g (based on 7 kg/m^2).
5. The total mass of the test tube at maximum saturation with water is 14.7 kg - 12/04/2025.
6. Water absorption level at maximum saturation- 60%: 12/04/2025.
7. There is no filtration through the holes in the bottom of the test tube (the tail material is completely dry).
8. On December 14, 2025, the lid of the test tube was opened to study the evaporation process.

Fig. 3 Experiment N2, Point 6

Experiment N3

1. Experiment start: November 11, 2025.
2. Soil type: sandy loam (Fig. 4, right).[2]
3. The mass of the soil is 4 kg.
4. The amount of "PMM" material is 320 g (based on 8 kg/m^2).
5. The total mass of the test tube at maximum saturation with water is 14.85 kg - 12/04/2025.
6. Water absorption level at maximum saturation - 60%: 12/04/2025.

[2] Soil characteristics are given after the description of the experiments.

7. There is no filtration through the holes in the bottom of the test tube (the tail material is completely dry).

Experiment N4

1. Experiment start: November 11, 2025.
2. Soil type: Sandy loam soil used for reclamation of tailings ponds (Fig. 4, right).
3. The mass of the soil is 4 kg.
4. The amount of "PMM" material is 320 g (based on 8 kg/m^2).
5. The total mass of the test tube at maximum saturation with water is 15 kg -12/04/2025.
6. Water absorption level at maximum saturation – 50-55 %: 12/04/2025.
7. There is no filtration through the holes in the bottom of the test tube (the tail material is completely dry).

Fig. 4. Experiment 3, point 6: left & Experiment 4, point 6: right

Experiment N5

1. Experiment start: November 17, 2025.
2. Soil type: Sandy loam soil used for reclamation of tailings ponds.
3. The mass of the soil is 3 kg.
4. The amount of "PMM" material is 320 g (based on 8 kg/m^2).
5. The total mass of the test tube at maximum saturation with water is 14.05 kg -12/04/2025.
6. Water absorption level at maximum saturation – 50 %, Fig.5: 12/04/2025.
7. There is no filtration through the holes in the bottom of the test tube (the tail material is completely dry).

Fig. 5 Experiment N5, Point 6

Experiment N6

1. Experiment start: November 17, 2025.
2. Soil type: inorganic material with a predominance of quartz sand, containing a limited amount of aluminosilicate and carbonate mixtures (hereinafter referred to as soil). Soil type: inorganic material with a predominance of quartz sand, containing a limited amount of aluminosilicate and carbonate mixtures (hereinafter referred to as soil).[3]

3. The mass of the soil is 3 kg.
4. The amount of "PMM" material is 320 g (based on 8 kg/m^2).
5. The total mass of the test tube at maximum saturation with water is 14.75 kg -12/14/2025.
6. Water absorption level at maximum saturation – 100 %, Fig.6: 12/14/2025.
7. The onset of the filtration phenomenon through the holes in the bottom of the test tube: 12/14/2025.
8. The increase in the total mass of the test tube when additional water is absorbed with the lid closed over in Fig. 7.

Fig. 6 Experiment N6, Point 6

Experiment N7

1. Experiment start: November 22, 2025.
2. Soil type: inorganic material with a predominance of quartz sand, containing a limited amount of aluminosilicate and carbonate mixtures (hereinafter referred to as soil). Soil type: inorganic material with a predominance of quartz sand, containing a limited amount of aluminosilicate and carbonate mixtures (hereinafter referred to as soil).[4]
3. The mass of the soil is 3 kg.
4. The amount of "PMM" material is 360 g (based on 9 kg/m^2).
5. The total mass of the test tube at maximum saturation with water is 13.8 kg - 12/14/2025.
6. Water absorption level at maximum saturation – 100 %: 12/14/2025.
7. Slight filtration flow from the holes in the bottom of the test tube (slight wetting of the bottom. No measurable flow is observed).

Experiment N8

1. Experiment start: November 22, 2025.
2. Soil type: inorganic material with a predominance of quartz sand, containing a limited amount of aluminosilicate and carbonate mixtures (hereinafter referred to as soil). Soil

[3] Soil characteristics are given after the description of the experiments.
[4] Soil characteristics are given after the description of the experiments.

type: inorganic material with a predominance of quartz sand, containing a limited amount of aluminosilicate and carbonate mixtures (hereinafter referred to as soil).[5]

3. The mass of the soil is 3 kg.
4. The amount of "PMM" material is 400 g (based on 10 kg/m^2).
5. The total mass of the test tube at maximum saturation with water is 13.4 kg - 11/22/2025.
6. The total mass of the test tube at maximum saturation with water is 14.45 kg - 12/14/2025 (Fig.8).
7. Water absorption level at maximum saturation – 100 %: 12/14/2025.
8. Slight filtration flow from the holes in the bottom of the test tube (slight wetting of the bottom. No measurable flow is observed).
9. Filtration through the holes in the bottom of the test tube stops.

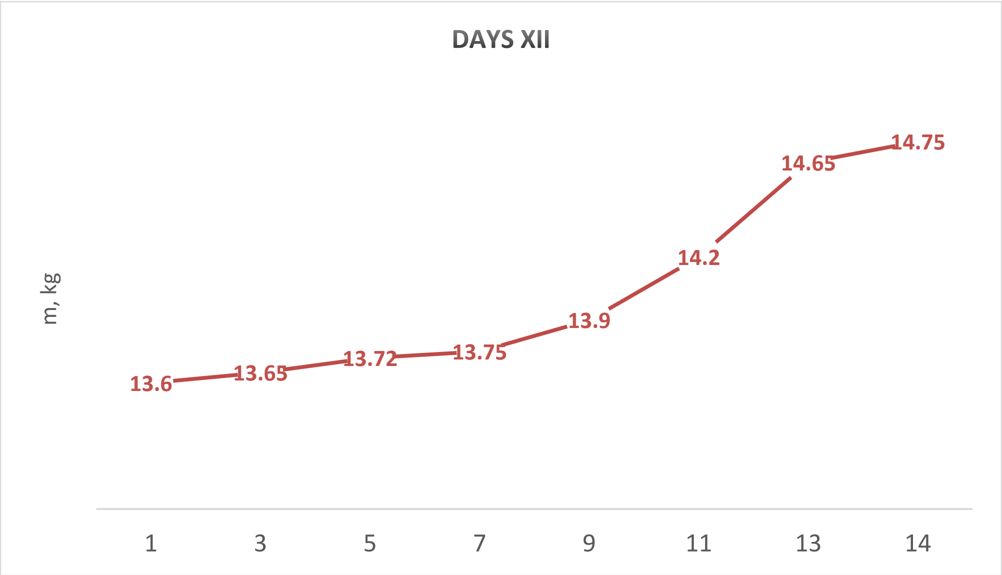

Fig. 7 Increase in total test tube mass due to absorption of additional water for baseline data of experiment N6

Description of the second technology for the purpose of conducting laboratory research:

1. A leveling layer of sandy loam soil at least 3 cm thick is laid and compacted with a rammer.

2. A layer of "PMM" material several millimeters thick (5 to 7 mm) is laid on top of the compacted sandy loam soil and compacted with a rammer.

3. To protect it from mechanical damage during operation, it is covered with a protective layer of sandy loam soil (up to 10 cm) and compacted with a rammer.

[5] Soil characteristics are given after the description of the experiments.

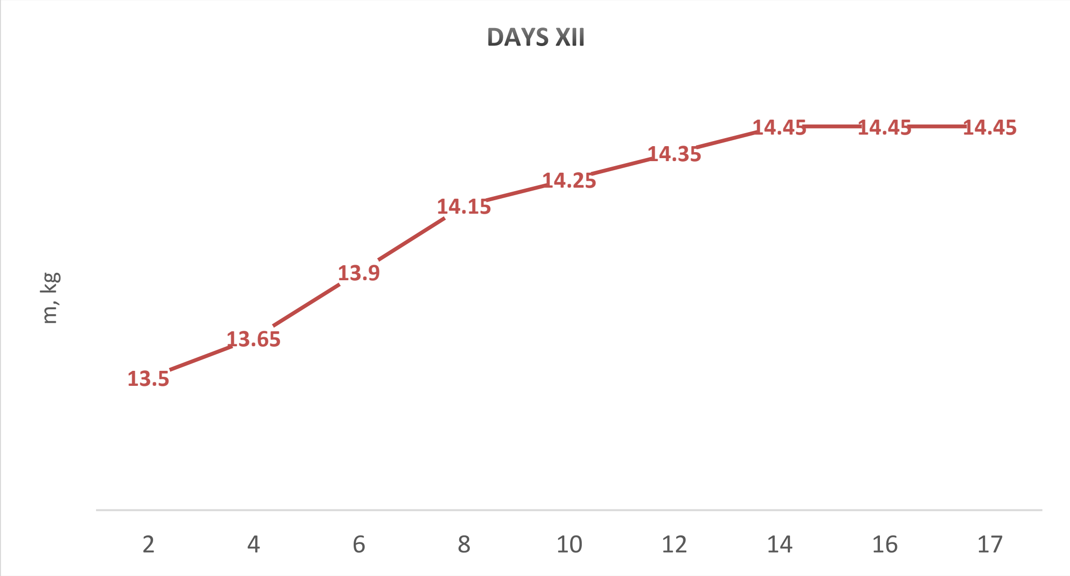

Fig. 8 Increase in total test tube mass due to absorption of additional water for baseline data of experiment N8

Experiment N9 (Technology 2: PMM with a separate layer)

1. Experiment start: December 14, 2025.
2. Soil type: sandy loam.
3. The mass of soil below and above the «PMM» layer is 4 kg.
4. The amount of PMM material (without mixing with soil) was 360 g (estimated value: 9 kg/m2) (Fig. 9).
5. The total mass of the test tube, 13.25 kg, remained constant from the beginning of the experiment (12/14/2025).

Fig. 9 Experiment N9, Point 4

Experiment N10 (Technology 2: PMM with a separate layer)

1. Experiment start: December 17, 2025.
2. Soil type: sandy loam.
3. The mass of soil below and above the «PMM» layer is 4 kg.
4. The amount of PMM material (without mixing with soil) was 280 g (estimated value: 7 kg/m2)
5. The total mass of the test tube, 13.65 kg, remained constant from the beginning of the experiment (12/17/2025) (Fig. 10).

Fig. 10 Experiment N10, Point 5

Experiment N11 (Water from under the tail)

1. Experiment start: December 14, 2025.
2. Soil type: sandy loam.
3. The mass of the soil is 3 kg.
4. The amount of "PMM" material is 360 g (based on 9 kg/m^2).
5. Additional added soil mass without PMM - 2.5 kg.
6. Water is added to the top of the test tube and it is turned upside down.
7. The added soil settles to the bottom of the test tube after 3-4 hours.
8. The composite does not allow the water to rise (Fig. 11).

Fig. 11 Experiment N11, Point 8

Soil characteristics

A) Natural sandy soil.

FTIR spectroscopic analysis results show that the sample under study is characterized by a predominantly sandy (quartz) composition. The most intense absorption band in the spectrum is observed in the 1100–1000 cm^{-1} range, which corresponds to asymmetric stretching vibrations of Si–O–Si bonds and is the main parameter characteristic of quartz sand.

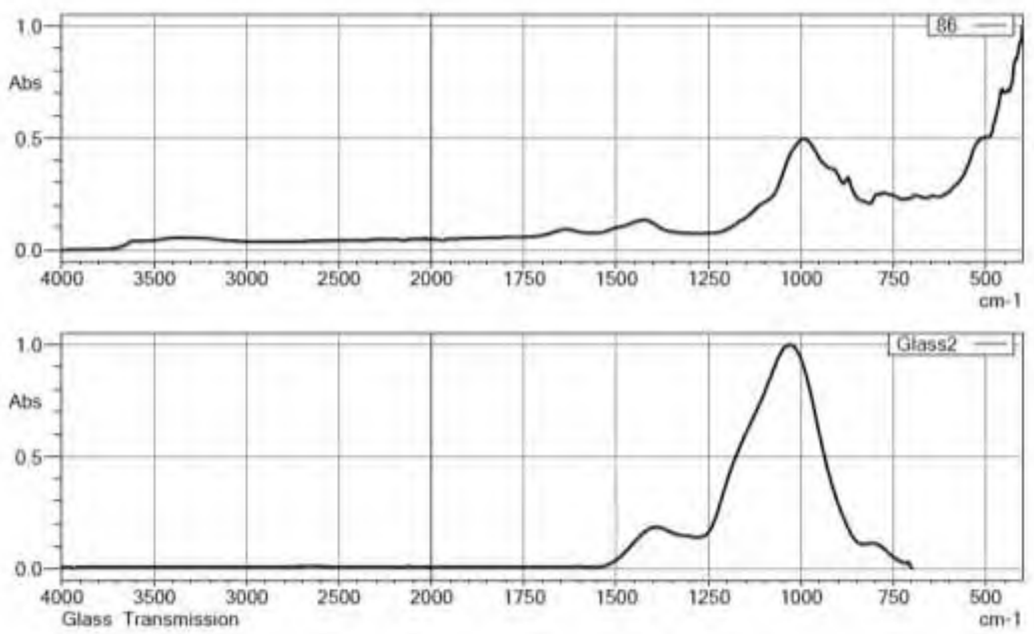

Fig. 12 IR-Fourier analysis of soil

The absorptions recorded in the ranges of 800–780 cm⁻¹ and 470–450 cm⁻¹ are associated with the symmetric Si–O–Si stretching vibrations and Si–O bending vibrations, respectively, further confirming the presence of a SiO_2-rich well-formed silicate structure.

Weak absorption bands observed in the 3600–3200 cm^{-1} and around 1630 cm^{-1} ranges are due to the presence of surface hydroxyl groups and physically adsorbed water, which is typical of sand and quartz materials. A weak band detected in the 1450–1400 cm^{-1} range may indicate the presence of small amounts of carbonate impurities. Very weak C–H vibrations observed in the 2950–2850 cm^{-1} range indicate a negligible content of organic components in the sample.

The study results show that the sample is an inorganic material dominated by quartz sand (Fig. 12), containing limited amounts of aluminosilicate and carbonate impurities. This composition is typical of natural sandy soils and ensures the chemical stability of the material.

B) Sandy loam soil.

Analysis shows that the soil is clayey in nature, rich in kaolinite or similar aluminous clays, and dominated by the silicate/quartz fraction. According to data obtained from the soil extract, the environment is close to neutral, and the electrical conductivity is also low, indicating a relatively low content of dissolved salts (Table 1, Fig. 13). For initial field studies, it is recommended to use sandy loam taken from reserves near the tailings dump as the soil.

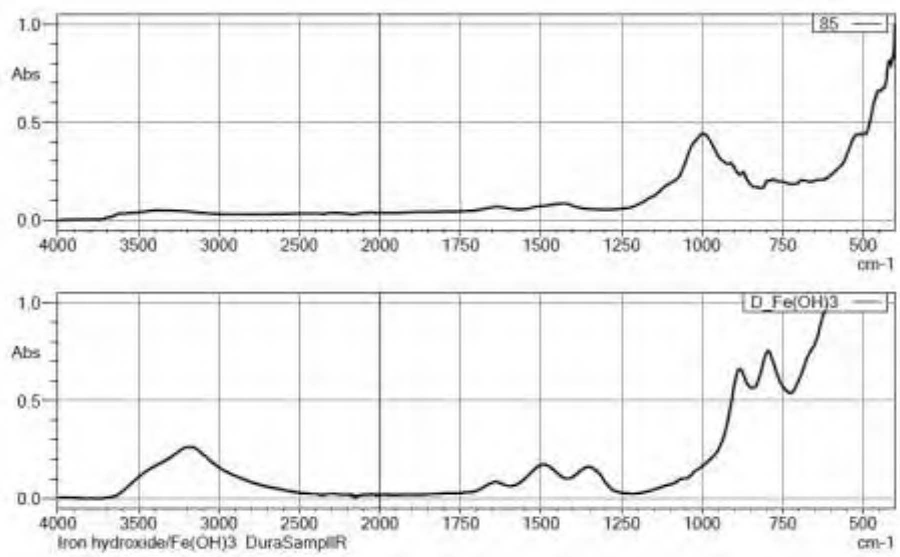

Fig. 13 IR-Fourier analysis of sandy loam soil

Table 1

Sample	Electrical conductivity, µm/cm Water analyzer HACH LANGE HQ 14d	pH Water analyzer HACH LANGE HQ 14d
1	595	8.18

Laboratory tests at the Institute of Mechanics of Lomonosov Moscow State University.

For laboratory testing, PMM material was added to the waterproofing layer at various doses (from 7 to 10 kilograms of PMM per square meter in 1-kilogram increments).

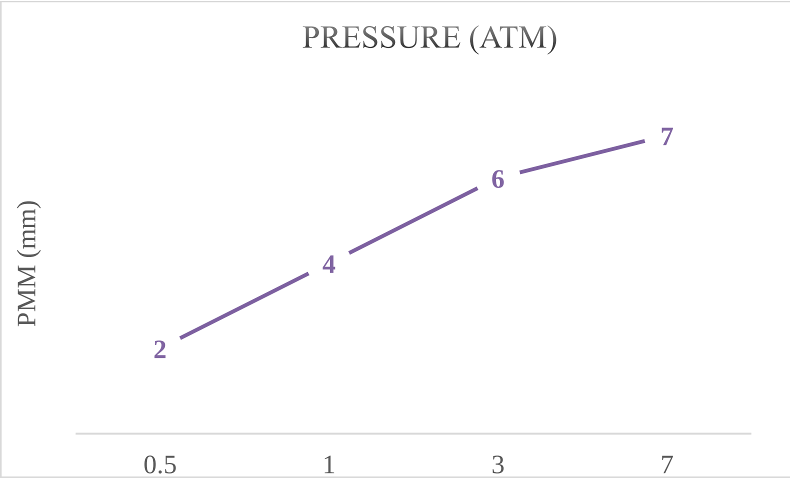

Fig. 14 Dependence of the thickness of the PMM material on the applied pressure at which the liquid begins to flow out of the bottom of the testing device.

The composite manufactured using PMM was placed on an experimental device, which was subjected to a water column pressure ranging from 0.25 to 30 meters (Figs. 14 and 15).

Composites prepared in various combinations were tested, with a PMM suspension weight of 7-10 kg per square meter of surface area.

Depending on the installation method and the amount of PMM used in the waterproofing layer, the amount of water leaking from the holes in the bottom of the container was determined over time. As a result of laboratory testing, a waterproofing layer using PMM material was created that was capable of withstanding high water column pressure over a long period.

During the tests, the mass of the PMM material was changed in steps of 1 kg from 5 kg/m^2 (0.5 cm of compacted material PMM) to 10 kg/m^2 (1 cm of compacted material PMM).

Experiment N12 (Technology 2)

A 3-cm-thick layer of sandy loam is laid on compacted soil 7 cm thick, followed by a 0.6-cm-thick layer of PMM material, followed by a 5-7-cm-thick layer of sandy loam material. With this layering sequence, the system can withstand a water column of 30 meters.

However, if the sandy clay layer is not laid on compacted soil 7 cm thick, and then a 0.6-cm-thick layer of PMM material is immediately laid on top of it, followed by a 5-7-cm-thick layer of sandy loam material, water will begin to leak within a week under a water column of 15 meters at a rate of no more than one drop per day. However, over time, the leakage rate may increase, and the waterproofing layer will become highly permeable.

Therefore, to ensure the effectiveness of the waterproofing layer, it is recommended to level the compacted soil base with a layer of sandy-loamy material at least 3 cm thick before laying the compacted layer of PMM material.

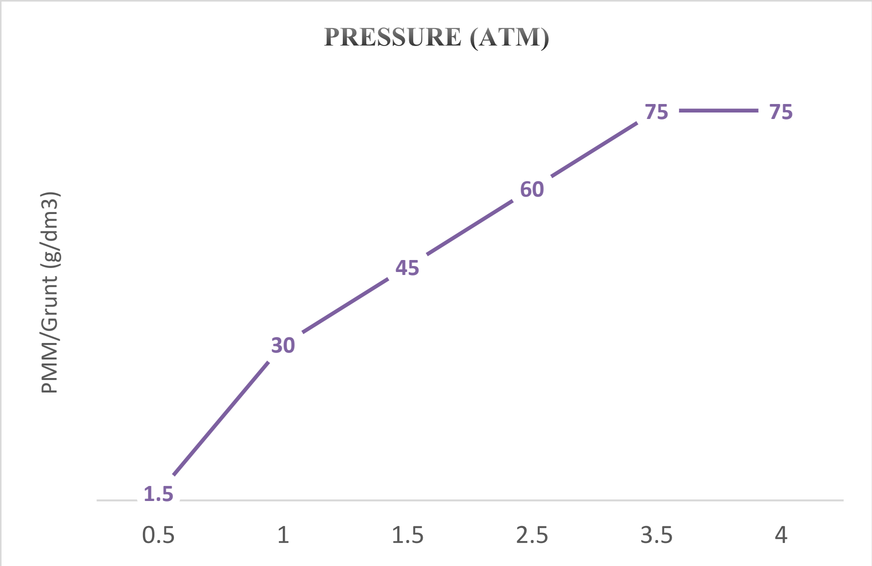

Fig. 15. Dependence of the magnitude of the applied pressure and the characteristics of the composite with different ratios of soil and PMM material, at which the liquid begins to flow out of the bottom of the test device

Experiment N13 (Technology 1)

A 7 cm thick layer of compacted soil is placed at the bottom of the test tube, followed by a 3 cm thick layer of sandy clay. A 7 cm thick compacted waterproofing layer consisting of a mixture of 65 g of PMM per 1 kg of soil is then placed on top, which, after compaction with a rammer, turns into a 5 cm thick layer. Using a mixture of 65 g of PMM aggregate per kg of soil, the protective layer will withstand a water column of 30 m.

PMM materials should be stored in covered warehouses protected from moisture. They do not release toxic compounds into the air or water, do not pollute the environment, and are environmentally safe.

The development and installation of a waterproofing layer on the surface of the tailings dam as part of a pilot project (full-scale testing on a tailings dam covering approximately 3,000 square meters) will allow us to verify the reliability of the waterproofing layer and improve its installation technologies, as well as estimate the labor costs for each of the recommended options.

Conclusion

1. It is recommended to cover the surface of recycled waste dumps by directly applying a layer of "PMM" or using a composite created with its application.
2. Laboratory tests show that when creating an anti-filtration composite, in the case of using sand-loamy soil, the amount of the required mass of the "PMM" material is much smaller and more effective.

3. The first stage of natural tests is recommended to be carried out on the area of landfills of recycled waste of 1500-3000 m^2, of which 80% - according to technology № 1 and 20% - according to technology № 2.
4. At the first stage of tests, it is recommended to use reclaimed sand-loam soil.
5. In the case of using technology No. 1, it is recommended to use 8 kg/m^2 of composite in a ratio of 1:10 with soil.
6. In case of technology No. 2 effectively use 8-9 kg/m^2 material "PMM".

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ՊՈԼԻՄԵՐԱՀԱՆՔԱՅԻՆ «PMM» ՍՈՐՈՒՆԻ ԿԻՐԱՌՄԱՄԲ ՀԻԴՐՈՄԵԿՈՒՍԻՉ ՇԵՐՏ ԿՈՆՍԵՐՎԱՑՎԱԾ ՊՈՉԱՄԲԱՐՆԵՐԻ ՀԱՄԱՐ. ՏԵԽՆՈԼՈԳԻԱՆԵՐԻ ՄՇԱԿՈՒՄ ԵՎ ԼԱԲՈՐԱՏՈՐ ՀԵՏԱԶՈՏՈՒԹՅՈՒՆՆԵՐ

Է.Վ. Ավանեսյան[1], **Վ.Ռ.Գրիգորյան**[2], **Դ.Հ.Գրիգորյան**[1], **Հ.Վ. Թոքմաջյան**[2]
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[2]*Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ*

Կոնսերվացված պոչամբարների մակերևույթն առաջարկվում է ջրամեկուսացնել «PMM» սորունի անմիջական տեղադրման կամ դրա կիրառմաբ ստեղված կոմպոզիտի միջոցով: Լաբորատոր հետազոտությունների ընթացքում որոշվել է ջրամեկուսիչ շերտի արդյունավետ բաղադրակազմը և մշակվել է դրա տեղադրման երկու տեխնոլոգիա: Լաբորատոր փորձարկումները ցույց են տալիս, որ հակաֆիլտրացիոն կոմպոզիտ ստեղծելիս, ավազակավային գրունտի օգտագործման դեպքում, «PMM» սորունի անհրաժեշտ չափաքաքանակը զգալիորեն ցածր է, քան սովորական հողերի օգտագործման դեպքում:

Բանալի բառեր. ռեկրեացիա, քաղաքային միջավայր, պոչամբար, ջրամեկուսացում:

ПРИМЕНЕНИЕ ПОЛИМЕРНО-МИНЕРАЛЬНОГО МАТЕРИАЛА «ПММ» ДЛЯ СОЗДАНИЯ ГИДРОИЗОЛЯЦИОННОГО СЛОЯ ПРИ КОНСЕРВАЦИИ ХВОСТОХРАНИЛИЩ: РАЗРАБОТКА ТЕХНОЛОГИЙ УКЛАДКИ И ЛАБОРАТОРНЫЕ ИССЛЕДОВАНИЯ

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Рекомендуется гидроизолировать поверхность законсервированного хвостохранилища путем непосредственного нанесения полимерно-минерального материала «PMM» или композита, созданного на его основе. В ходе лабораторных

E.V.Avanesyan, V.R.Grigoryan, D.H.Grigoryan, H.V.Tokmajyan

APPLICATION OF POLYMER-MINERAL MATERIAL «PMM» FOR CREATION OF WATERPROOFING LAYER DURING CONSERVATION OF TAILINGS: DEVELOPMENT OF INSTALLATION TECHNOLOGIES AND LABORATORY RESEARCH

исследований был определен эффективный состав гидроизоляционного слоя и разработаны две технологии его укладки.

Лабораторные исследования показывают, что при создании антифильтрационного композита с использованием песчано-суглинистого грунта, необходимое количество наполнителя «ПММ» значительно меньше, чем при использовании обычной почвы.

Ключевые слова: рекреация, городская среда, хвостохранилище, гидроизоляция.

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ALGORITHM FOR CALCULATION AND OPTIMIZATION OF SEDIMENTATION BASIN STRUCTURES FOR SMALL HYDROPOWER PLANTS

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Abstract

The paper addresses the optimization of geometric and cost parameters of sedimentation basins for small hydropower plants (SHPPs) operating on mountainous rivers. It is shown that widely used design solutions with variable geometry of sedimentation chambers are often due to the lack of a comprehensive methodology for the coordinated calculation of all elements of the structure and are not always economically optimal.

A systematic approach to the design of SHPP sedimentation basins is proposed, based on maintaining design flow velocities and using a constant chamber width. Based on a generalized analysis of calculation results for various values of discharge, chamber width, and captured particle sizes, a parametric model of the volume of monolithic reinforced concrete of the sedimentation basin is obtained in the form of a power-law function of the main governing factors.

The paper substantiates the selection of the maximum allowable particle size based on physical principles of abrasive erosion and the concept of hydraulic sedimentation velocity. A comparative analysis of different methods for calculating hydraulic sedimentation velocity (Stokes, Goncharov, Arkhangelsky, Rubey, Ferguson–Church) is performed for particle sizes typical of mountain rivers.

To assess capital costs, an aggregated cost model is developed that relates the construction cost of the sedimentation basin to the volume of reinforced concrete and a regional cost index for 1 m³ of monolithic reinforced concrete.

The results of the study can be used in the design and techno-economic justification of SHPP sedimentation basins, as well as in the development of unified methodologies for the optimal selection of their geometric parameters taking into account hydraulic and economic factors.

S.G.Gabayan

ALGORITHM FOR CALCULATION AND OPTIMIZATION OF SEDIMENTATION BASIN STRUCTURES FOR SMALL HYDROPOWER PLANTS

Keywords: SHPP sedimentation basins, sediments, turbine types, hydraulic particle size, geometric optimization, suspended sediment sedimentation, construction cost, techno-economic optimization.

Methodological Reasons for the Use of Sedimentation Basins with Variable Geometry and Limitations of Existing SHPP Design Approaches

The design of sedimentation basins for small hydropower plants (SHPPs), especially in mountain river environments, is traditionally carried out using separate calculation methods for individual structural elements, integrated into a water intake structure. In practice, solutions with variable sedimentation basin widths along the length of the structure are quite common, despite their structural complexity and, as a rule, increased cost. Analysis shows that the main reason for the prevalence of such solutions is not their cost effectiveness, but the lack of an integrated methodology for the "package" calculation of a sedimentation basin as a single integrated hydraulic and technological system.

In a broad engineering sense, an SHPP sedimentation basin represents a sequence of interconnected elements, including a coarse trash screen, a supply channel, a sedimentation chamber with dead volume for sediment accumulation, a flushing unit, a fine trash screen, as well as a pressure chamber and a diversion inlet pipe. Each of these elements has its own calculation method based on local hydraulic criteria: permissible velocities, pressure losses, and sedimentation or flushing conditions.

At the same time, the parameters of these elements are interconnected through water flow, levels, and the characteristic flow cross-section. A particularly important connecting parameter is the width of the structure, which directly determines flow velocities in all zones of the sedimentation basin. A constant width ensures consistency of hydraulic conditions: velocities in front of the screens, in the sedimentation chamber, and in the diversion inlet zone are within the same scale range and can be matched within one-dimensional calculation models.

In the absence of an integrated methodology, the designer is forced to solve the problem sequentially, element by element. As a result, the requirements of various components often prove contradictory: the velocities acceptable for screen operation are too high for effective sedimentation; the minimum velocity requirements in the sedimentation chamber conflict with the washing requirements; and the requirements for a uniform velocity field in the pressure chamber are incompatible with the transient operation of the washing unit. In the absence of a formalized procedure for reconciling these requirements, the structure's geometry begins to perform a compensating function.

It is precisely in this situation that solutions with variable widths, diffuser and confusor sections, and additional buffer zones emerge in practice. Geometric "uncoupling" of the elements allows for the local satisfaction of the requirements of each node, but leads to the formation of extended transition sections, in which the flow is spatial, significantly non-unidimensional. For such zones, classical one-dimensional hydraulic models become inapplicable, and the sedimentation efficiency cannot be accurately estimated by calculation.

From an engineering perspective, transition sections typically cannot be fully included in the effective sedimentation length of a sedimentation basin. To ensure a given sediment collection rate, the designer is forced to increase the overall geometric length of the structure by the length of the inlet and outlet transitions. This inevitably leads to increased excavation and concrete work, more complex structural components, an increased number of joints and connections, and higher capital costs.

An additional consequence of using variable geometry is increased operational risks. Recirculation zones and localized flow accelerations often form in expansion and contraction zones, contributing to uneven sediment accumulation and deteriorating flushing conditions. As a result, the structure becomes more sensitive to hydraulic fluctuations and requires additional maintenance measures.

An important factor is the complication of construction of transition sections due to the complexity of their geometry.

Thus, the widespread use of variable-width sedimentation basins in small hydroelectric power station projects is primarily due to the methodological limitations of existing approaches focused on element-by-element calculations. The lack of a unified "package" methodology that takes into account the mutual influence of all sedimentation basin elements forces designers to resort to geometric complications as a means of compensating for inconsistent design requirements.

From a methodological perspective, a more rigorous and economically sound approach is one in which the entire sedimentation basin complex is considered as a single hydraulic-technological system with a minimum number of characteristic parameters. Using a constant width along the main sedimentation section allows for the design of the screens, sedimentation chamber, flushing unit, and pressure chamber to be integrated into a single system, reducing the length of transition zones and increasing the transparency of technical and economic optimization.

Implementing such an approach requires the development of an integrated calculation methodology in which the sedimentation basin's geometric parameters are selected not in isolation, but as part of a coordinated solution that ensures the required sediment collection efficiency at minimal net costs. The lack of such methods is currently one of the key reasons for suboptimal design solutions in small hydropower plant projects.

Literature Review and Analysis of Existing Approaches

Classical works on the theory of particle sedimentation in a flow [1,2] laid the foundation for calculation methods used to select the dimensions of sedimentation basins. Subsequently, these approaches were further developed in studies devoted to hydraulic structures and sediment-related problems (Morris [3]; Garde, Raju [4]).

Practical guidelines for the design of small hydropower plants [5,6] contain recommendations on structural layouts and permissible hydraulic parameters; however, the calculation of individual elements are performed separately.

Economic aspects of SHPP design and the assessment of construction costs are considered in the reports of NVE [7] and USBR [8], where the cost of sedimentation basins is determined through the volumes of construction works. At the same time, the mutual influence of sedimentation basin elements is not analyzed in these sources.

In the national engineering school, a significant contribution to the development of calculation methodologies for hydraulic structures was made by the works of G.I. Zhuravlev and V.I. Gubin. In Zhuravlev's textbook "Hydraulic Structures" [9], approaches to the calculation of intake and sedimentation structures are systematized, including requirements for velocity regimes, layout, and structural elements. At the same time, the calculation of sedimentation basins is considered predominantly on an element-by-element basis, without a formalized procedure for coordinating the parameters of all units within a single system.

The works of V.I. Gubin devoted to the design and operation of hydraulic structures on rivers with high sediment loads [10] emphasize the importance of considering actual hydraulic conditions and operational factors. They note that transition zones and sections with unsteady flows often fail to achieve the design efficiency and require additional sizing margins, which indirectly confirms the advisability of minimizing variable geometry when designing SHPP sedimentation basins.

Thus, the existing literature confirms that the absence of an integral calculation methodology leads to fragmented design solutions and the widespread use of sedimentation basins with variable geometry.

Description of the Calculation Model

To solve the stated problem, a program was developed in the VBA environment. The program makes it possible to perform the following tasks:

1. Based on the initial hydrological and morphometric data, to model the type of the river longitudinal profile and its thermal regime. On this basis, to assess the probable water temperature at the cross-section of the designed water intake.
2. Modeling the location of the designed sedimentation basin based on a given longitudinal profile and two transverse cross-sections, in order to assess excavation volumes and bank protection works.
3. Determine, based on the given pressure and type of installed turbine, the recommended clearances of the fine trash rack and the maximum diameter of particles passed through the turbine and determine the hydraulic size.
4. Determining the main dimensions of the pressure chamber to prevent vortex formation, rationally positioning the pressure pipe confusor, and ensuring sufficient volume to prevent the turbine from operating in an unstable condition. Determining the minimum possible width of the sedimentation basin based on the placement of the pressure diversion confusor.
5. Calculation of the plan area of the sedimentation basin. Determination of the optimal value of Bsedm, at which the minimum total construction cost of the sedimentation basin is achieved. Determination of the optimal length of the sedimentation basin.
6. Based on the obtained width, calculation of the fine trash rack for operation at maximum discharge and under winter conditions, taking into account the normatively permissible clogging.

7. The design depth of the filled sedimentation basin is coordinated with the height of the dividing wall, and, based on flushing conditions, the slope and water depths at the beginning and at the end of the sediment-filled sedimentation basin are determined.
8. An acceptable flushing frequency of the sedimentation basin during the flood period is specified for the given project, on the basis of which the depth of the dead storage chamber of the sedimentation basin is determined.
9. The bottom elevation of the inlet channel is tied to the elevation of the maximum filling of the sedimentation basin dead storage volume. To ensure independence of the calculation of the coarse trash rack from the parameters of the sedimentation chamber, a supporting wall is installed under the rack. The coarse trash rack, like the fine one, is calculated for operation at maximum discharge and under winter conditions, taking into account the normatively permissible clogging. The height of the supporting wall for the coarse trash rack is determined by comparison.

The block diagram of the program for calculating the sedimentation basin is shown in Fig. 1.

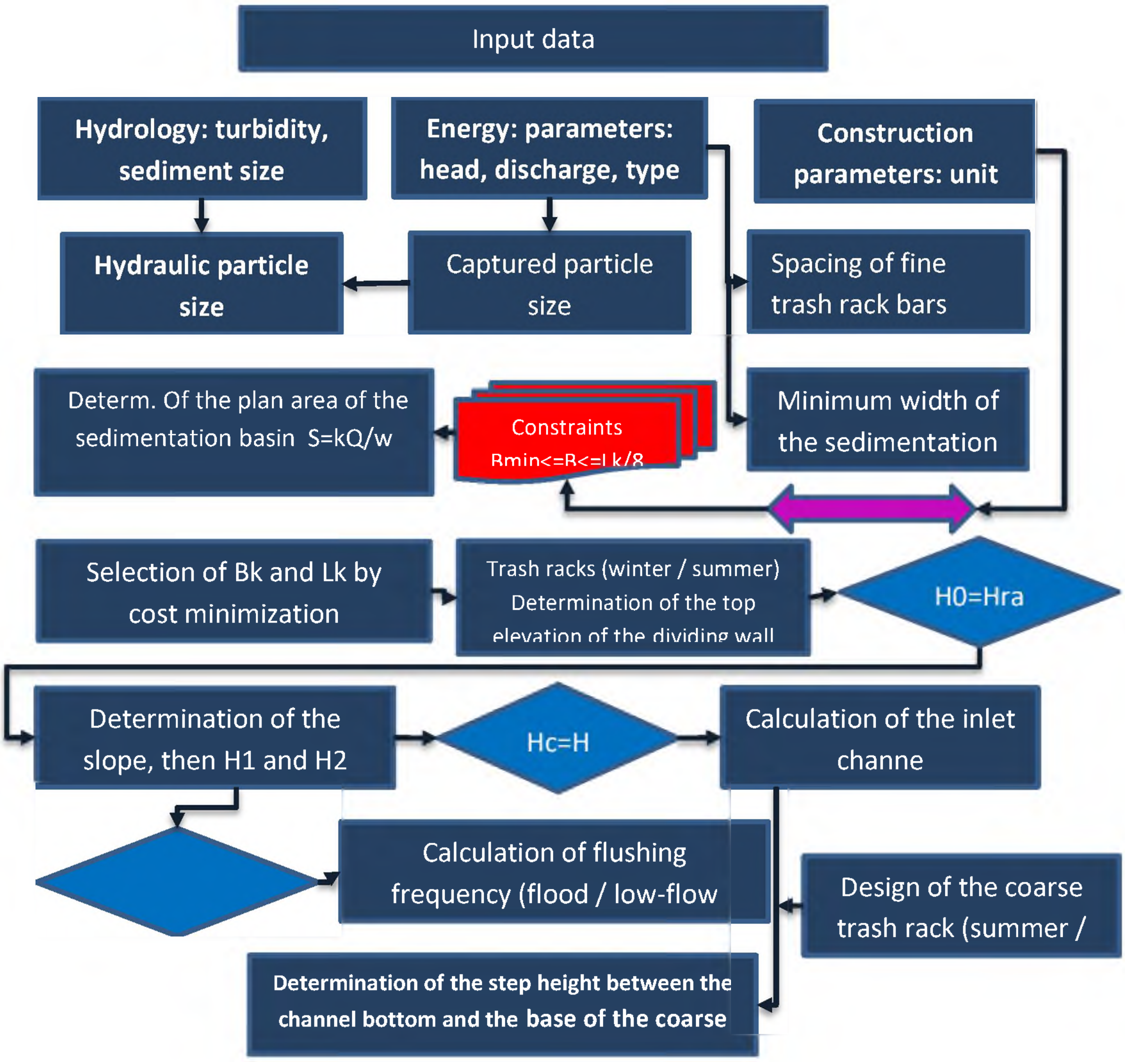

Fig. 1 The block diagram of the program for calculating the sedimentation basin is shown in

On the Methodology for Determining the Hydraulic Particle Size

During the program's development, questions arose about the methodology for selecting the maximum diameter of sediment particles passing through the turbine and determining the hydraulic particle size. Questions also arose regarding the hydraulic particle size determination, due to significant discrepancies in different literature sources. Meanwhile, these factors are key to ensuring the correct operation of the sedimentation basin and protecting the unit from the abrasive impact of sediments (Fig. 2).

Fig. 2 Wear of the Crossflow turbine runner as a result of the ingress of large sediment particles

The maximum permissible particle size allowed to pass through small hydroelectric power plant (SHPP) turbines is determined to prevent abrasive and cavitation-abrasive wear of flow path components, ensure the equipment's estimated service life, and comply with turbine manufacturer warranty conditions.

The intensity of abrasive wear of turbine components can be represented in a generalized form by the following relationship:

$$E \sim C_s \cdot d^n \cdot v^m, \quad (1)$$

where: Cs- is the concentration of solid particles, d is the characteristic particle size, v is the relative velocity of interaction of particles with the surface, n≈1–2 and m≈2–3 are empirical exponents. From this relationship it follows that an increase in particle size has a more significant effect on wear than an increase in their concentration, which necessitates strict limitation of the maximum permissible particle size.

The main factors in selecting the maximum permissible particle size are the turbine type, the design head of the plant, as well as the granulometric composition and mineralogy of the sediments [15–17]. The sensitivity of turbines to the abrasive impact of sediments varies significantly depending on their type.

High-head Pelton turbines are characterized by high jet velocities and the greatest sensitivity to sandy particles. For these turbines d_{max} value in the range of 0.15–0.30 mm is recommended.

Francis turbines have a more complex flow passage at relatively low flow velocities. Permissible values of dmax are on the order of 0.30–0.60 mm. However, for high-head turbines this value may decrease to 0.15 mm.

Crossflow turbines are distinguished by the relative simplicity of the flow passage and the absence of narrow channels, which makes them less sensitive to sediments compared to Francis turbines. For Crossflow turbines, it is recommended to take d_{max} within the range of 0.30–0.80 mm.

Kaplan turbines are low-head turbines and are practically not used in the construction of small hydropower plants in mountainous regions.

However, in practice, the permissible particle diameter is specified by the manufacturer and stipulated in the warranty obligations for the supply of SHPP equipment, and therefore is decisive in the selection of the diameter of particles to be settled. Based on this, drawing on experience in SHPP design in Armenia, Georgia, and Kyrgyzstan, as well as on discussions with leading European manufacturers of units for small hydropower plants, we have compiled an indicative table of permissible particle diameter values for different turbine types at various head ranges (tab. 1).

As can be seen from Table 1, for SHPPs constructed on mountainous rivers, the range of permissible particle sizes is 0.1–0.8 mm, which corresponds to fine and medium sand, for which the process of free sedimentation occurs in the transitional region between laminar and turbulent flow regimes.

In the calculation of sedimentation basins for SHPPs, the main parameter considering for the size of the captured particles is their hydraulic size.

Various methodologies based on different physical assumptions are used to assess the hydraulic particle size of sandy particles. These methodologies can generally be divided into three groups: analytical, semi-empirical, and experimental methods.

The particle size itself is not directly used in hydraulic calculations. The key design parameter is the hydraulic particle size ω(d), which represents the velocity of free sedimentation of a particle in still water. The design value of the maximum permissible particle size dmax is adopted in such a way that the following condition is satisfied:

$$\omega(d_{max}) \geq Vsedm, \quad (2)$$

where: Vsedm- the characteristic flow velocity in the sedimentation basin. Fulfillment of this condition ensures reliable sedimentation of the hazardous sediment fraction before the water enters the turbine.

Table 1

Maximum permissible particle sizes allowed to pass through turbines

Head, m	Maximum particle size, mm			Name/Country
	Francis	Crossflow	Pelton	
25	0.5	0.8		Bila Tserkva / Ukraine
50	0.4	0.6		Chirukhi, Sanalia / Georgia
100	0.3	0.5		Ishkhanasar / Armenia
150	0.25	0.4		Jyrgalan / Kyrgyzstan
200	0.2	0.3	0.25	Turgen / Kyrgyzstan
300	0.2		0.2	Amberd / Armenia
500	0.2		0.2	Tush Ashu 1,2 / Kyrgyzstan
750	0.1		0.2	Bozuchuk, Dzhergez / Kyrgyzstan
1000			0.2	Informative

Table 2

Hydraulic particle size determined by various calculation methods

d, mm	Hydraulic particle size ω\omegaω, mm/s				
	Stokes	Goncharov	Arkhangelsky	Rubey	Ferguson–Church
0.05	2.2		1.6	2.2	2.1
0.1	9.0	6.63	6.10	8.4	7.5
0.15	20.2	14.90	11.69	16.7	14.9
0.2	35.9	20.42	17.80	25.3	23.2
0.25	56.0	26.02	24.60	33.2	31.8
0.3	80.7	31.62	32.15	40.3	40.4
0.35	109.9		40.4	46.7	48.6
0.4	143.5	42.92	48.40	52.4	56.5
0.45	181.6			57.7	64.0
0.5	224.2	54.02	63.32	62.5	71.1
0.55	271.3			67.0	77.9
0.6	322.8	65.22	79.05	71.2	84.3
0.65	378.9			75.1	90.4
0.7	439.4		93.9	78.9	96.2
0.75	504.4		100.7	82.4	101.8
0.8	573.9		106.9	85.8	107.1

To assess the applicability of the studied methods and to select the most optimal one for the investigated particle size range, calculations were performed using various methodologies and their comparative analysis was carried out. The calculation results are presented in tab. 2 and fig. 3.

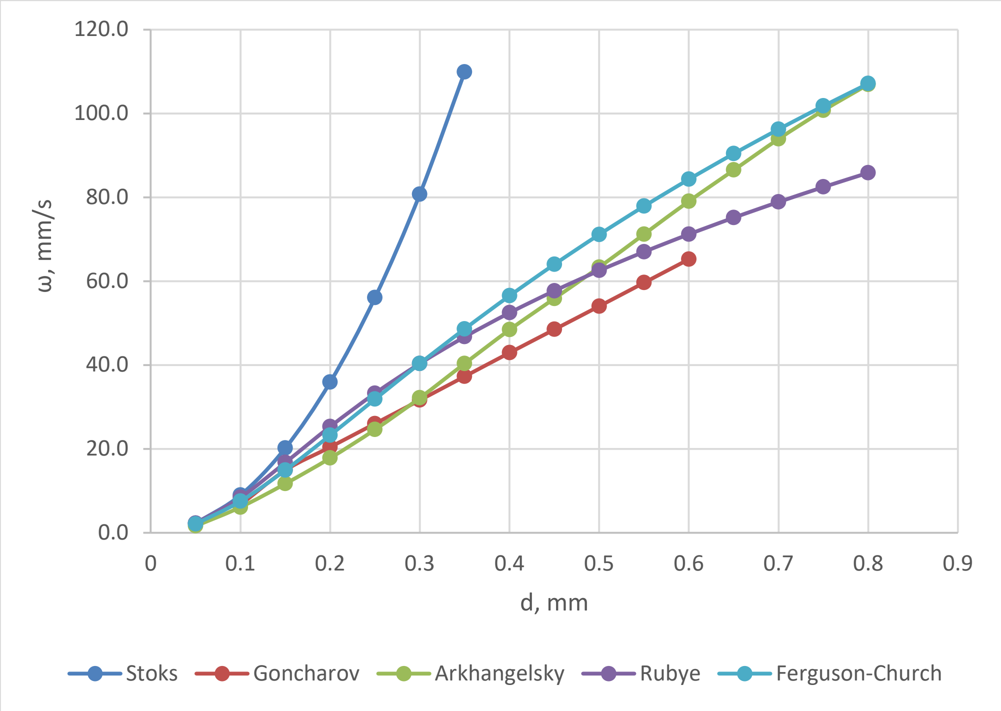

Fig. 3 Graphs of changes in hydraulic size from particle size, calculated using various methods

Stoks's formula [19] is based on a purely analytical solution for laminar flow. The classical Stoks's formula for determining the hydraulic particle size is valid only under laminar sedimentation conditions:

$$Re\_p = \omega \cdot d / \nu < 1, \quad (3)$$

For sandy particles in the size range characteristic of mountainous rivers (Re = 5–200), this condition is not satisfied, which makes the Stoks's formula inapplicable for substantiating dmax and necessitates the use of transitional and universal relationships.

In the works of B.V. Arkhangelsky and V.N. Goncharov [9,11], the hydraulic size is considered as a function determined by particle size, relative density, and water viscosity at different temperatures. As can be seen from Figure 1, calculations using Goncharov's method yield somewhat lower results compared to other calculation methods.

Rubey's formula [12] is widely used in engineering practice due to its simplicity and satisfactory accuracy for sandy particles. As can be seen from the performed calculations, it yields underestimated results for particle sizes above 0.5 mm. The calculation concepts of these methods assume a spherical shape of particles.

The Ferguson–Cherch formula [13] essentially develops the approaches incorporated in the above-mentioned methods and additionally introduces a correction accounting for particle shape and roughness. This formula provides the most physically substantiated description of sedimentation and shows good agreement with experimental data. A number of sources note that calculations using this methodology exhibit the highest agreement with experimental results (<5%).

S.G.Gabayan

ALGORITHM FOR CALCULATION AND OPTIMIZATION OF SEDIMENTATION BASIN STRUCTURES FOR SMALL HYDROPOWER PLANTS

Based on the conducted studies, for the calculation of sedimentation basins of small hydropower plants constructed on mountainous rivers, it is recommended to determine the hydraulic particle size using the Ferguson–Cherch method, as the most accurate within the given range of sedimentation particle sizes.

Development of a Methodology for Rapid Assessment of the Construction Cost of Sedimentation Basins in Different Countries

To determine the impact of selecting the main dimensions on the construction cost of sedimentation basins, a series of calculations was carried out for various values of these parameters. The calculations were performed for real facilities designed in Armenia, Kyrgyzstan, Georgia, and Kazakhstan.

To reduce the influence of regional unit costs of materials and works, the following assumptions were adopted:

The construction cost was determined excluding VAT;

In addition to prices, it was decided to compare the volumes of the main types of works involved in the construction of sedimentation basins;

To exclude the influence of terrain configuration on cost, in all projects the terrain relief was conditionally assumed to be 1 m below the top of the sedimentation basin walls.

An analysis of the pricing structure for sedimentation basin construction shows that approximately 75% of the cost of a sedimentation basin is formed by the cost of placed concrete, and 17% by the cost of reinforcement. Consequently, the volume of placed reinforced concrete can be considered representative for assessing the construction cost of a sedimentation basin. To determine this relationship, calculations were performed using the developed program, with unit rates adopted for different countries.

To assess the construction cost of sedimentation basins for small hydropower plants, a linear relationship between the construction cost of the structure and the volume of monolithic reinforced concrete was identified:

$$P = A \cdot Vb + B, \tag{4}$$

where: P is the construction cost, thousand USD; Vb is the volume of monolithic reinforced concrete, m^3;

A is the unit cost proportional to the volume of reinforced concrete; B is a conditionally constant value reflecting costs for auxiliary elements (trash racks, flushing units, local reinforcements, construction organization).

The coefficients A and B depend on the regional price level for monolithic reinforced concrete and construction works.

The coefficients A and B, obtained through calculations performed using unit rates for different countries, are presented in tab. 3.

Further, the concept is based on the hypothesis of proportionality between the construction cost of a sedimentation basin and the unit cost of placed reinforced concrete, where concrete + reinforcement + works + transportation and machinery are integrally taken into account.

Analysis of information obtained from various sources made it possible to index the cost of 1 m³ of placed reinforced concrete for the countries under study (tab. 3).

Table 3

Some parameters for the systematization of sedimentation basin costs by country

Country	A	B	Price of 1m3 reinforsconcrete $	
Kazakhstan	0.35	14.6	150	
Uzbekistan	0.36	14.8	153	.02
Kyrgyzstan	0.39	15.8	165	.1
Georgia	0.48	19.6	202.5	.35
Armenia	0.53	21.5	223.5	.49

To account for regional differences, a relative cost index K is introduced, equal to the ratio of the cost of 1 m³ of monolithic reinforced concrete in the country under consideration to the baseline value (K=1.0) for the country with the lowest unit cost (Kazakhstan).

To obtain a universal cost model, a linear approximation of the coefficients A and B as functions of the index K was performed using the least squares method.

As a result, the following relationships were obtained:

$$A(K) = 0.3645 \cdot K - 0.0125,$$

$$B(K) = 14.32 \cdot K + 0.19, \qquad (5)$$

The quality of the approximation was assessed using the coefficient of determination R^2. For the coefficient A(K), a value of R^2 = 0.9997 was obtained, and for the coefficient B(K), R^2 = 0.9991.

Substituting the obtained expressions, A(K) and B(K) into equation (4) and taking into account that the base value is K=150, a universal model for estimating the construction cost of an SHPP sedimentation basin is obtained:

$$P = (2.43C_x - 12.52)V_{bx} + (95{,}45C_x + 193.7), \qquad (6)$$

where: C_x и V_{bx} accordingly, the cost of 1 m³ of placed monolithic concrete and the total volume of concrete works for the construction of the sedimentation basin in the country under consideration.

This formula makes it possible to:

estimate the construction cost of a sedimentation basin for a known volume of reinforced concrete;

perform a comparative techno-economic analysis of construction costs in different countries without reference to regional parameters.

Scope of applicability and limitations of the model

The proposed model is valid under the following conditions:

the structural scheme of the sedimentation basin corresponds to typical monolithic solutions and is designed with a constant width along its entire length;

the construction technology is comparable (monolithic reinforced concrete, standard reinforcement and formwork);

the cost of 1 m³ of monolithic reinforced concrete is determined uniformly (including materials, works, and overhead costs);

the technological levels of the countries under study in the field of construction are comparable.

Development of recommendations for optimizing the dimensions of sedimentation basins

In calculation methodologies of sedimentation basins, it is proposed to assign certain parameters of the sedimentation basin based on design experience (for example, Havg [10] or B [11]) and then to determine the remaining parameters of the sedimentation basin. The specified literature does not provide any recommendations for selecting economically optimal dimensions of sedimentation basins; instead, it is only recommended to perform several calculations with different initial parameters in order to select an optimal option.

An attempt was made to systematize the selection of the main parameters of the sedimentation basin in order to minimize its construction cost by generalizing the results of numerous calculations and comparing their outcomes. The calculations were performed using the developed program for comprehensive analysis of sedimentation basin parameters with a constant width.

It has been theoretically substantiated that, for a given discharge and hydraulic size (and, consequently, the size of the captured particles), the plan area of the sedimentation chamber is constant.

A series of calculations performed for various combinations of design discharge, diameter of captured particles, and sedimentation basin width, under identical structural assumptions and with preserved flow velocities (Fig. 4), made it possible to develop recommendations for the optimized selection of the main dimensions of the sedimentation basin.

The volume of concrete placed in the structures of the sedimentation basin as a whole (Vb) can be expressed by a power-law model of the following form:

$$V_b = C \cdot Q^{\alpha} \cdot B^{-n} \cdot d^{-m}, \quad (7)$$

where: Vb -is the volume of concrete of the sedimentation basin, m³; Q is the design discharge, m³/s; B- is the basin width, m; d- is the size of the captured particles, mm.

By means of regression analysis, the coefficients of the equation were obtained. Thus, under the adopted approach to the structural design of the sedimentation basin, equation (7) can be written in the following form:

$$V_b = C \cdot Q^{1.01} \cdot B^{-0.74} \cdot d^{-1.06}\ , \quad (7a)$$

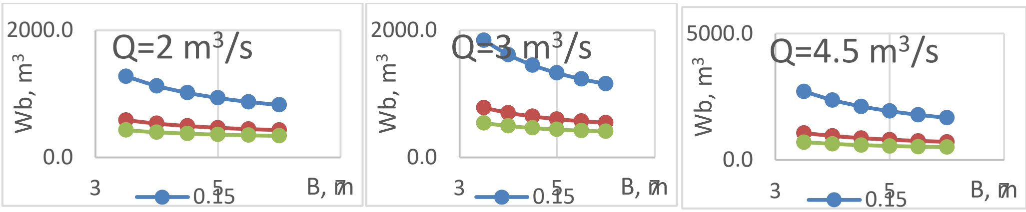

Fig. 4 Dependence of the volume of sedimentation basin concrete on the sedimentation basin width, the diameter of retained particles, at various design discharges

Analysis and physical interpretation of the obtained coefficients make it possible to draw the following **conclusions:**

The proximity of the α coefficient to 1 indicates that the volume of concrete placed in the sedimentation basin is practically linearly proportional to the design discharge of the SHPP. This is also theoretically confirmed by the linear dependence of the plan area of the sedimentation basin on the design discharge.

An increase in the width of the sedimentation basin has an effective influence on reducing the volume of placed concrete. However, it should be taken into account that excessive widening of the sedimentation basin may lead to a violation of flow linearity and a violation of the hydraulic laws adopted as the basis for the calculations. Based on this, it is considered necessary to adhere to the ratio L/B≈8, as recommended in a number of fundamental sources [1,6,10].

The influence of particle size increases sharply as the size of the captured particles decreases.

The obtained relationship is characterized by a coefficient of determination R2=0.98.

Limitations. The calculations were performed for a conditional object, and the task was set to minimize the influence of secondary factors on the comparability of the calculated options. Therefore, the construction site for the sedimentation basin was assumed to be horizontal, at the level of the full depth of the sedimentation basin. Within the considered range of parameters, the optimum is achieved at the upper boundary of the permissible width values.

In real calculations, the transverse slope of the bank where the sedimentation basin is planned to be constructed should be taken into account. This factor can lead to a significant increase in cost due to an increase in earthwork volumes. In the presence of additional constraints (relief, bank protection, site conditions), the optimum may shift inward within the range. Optimization of the L/BL/BL/B ratio in such cases is possible through direct calculation using the “Optimum Sedimentation Basin” program, with the input of the terrain relief into the program in the form of longitudinal and transverse terrain cross-sections.

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ՓՈՔՐ ՀԻԴՐՈԷԼԵԿՏՐԱԿԱՅԱՆՆԵՐՈՒՄ ՊԱՐԶԱՐԱՆՆԵՐԻ ՀԱՇՎԱՐԿԻ ԵՎ ՕՊՏԻՄԱԼԱՑՄԱՆ ԱԼԳՈՐԻԹՄԸ

Ս.Գ.Գաբայան
Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ

Հոդվածում ուսումնասիրվում են լեռնային հոսանքների վրա գործող փոքր հիդրոէլեկտրակայանների (ՓՀԷԿ) պարզարանների երկրաչափական և ծախսային պարամետրերի օպտիմալացման խնդիրները: Ցույց է տրվում, որ փոփոխական նստվածքային խցիկի երկրաչափությամբ լայնորեն կիրառվող նախագծային լուծումները հաճախ պայմանավորված են բոլոր կառուցվածքային տարրերի համակարգված հաշվարկման համար համապարփակ մեթոդաբանության բացակայությամբ և միշտ չէ, որ տնտեսապես օպտիմալ են:

S.G.Gabayan

ALGORITHM FOR CALCULATION AND OPTIMIZATION OF SEDIMENTATION BASIN STRUCTURES FOR SMALL HYDROPOWER PLANTS

Առաջարկվում է ՓՀԷԿ-երի պարզարանների նախագծման համակարգային մոտեցում, որը հիմնված է հոսքի արագության պահպանման և խցիկի լայնության հաստատուն մնալու վրա:

Հոդվածում հիմնավորվում է առավելագույն թույլատրելի մասնիկի չափի ընտրությունը: Ներկայացվում է լեռնային գետերին բնորոշ մասնիկների չափերի համար նստվածքային արագության հաշվարկման տարբեր մեթոդների (Սթոքս, Գոնչարով, Արխանգելսկի, Ռուբի, Ֆերգյուսոն-Չըրչ) համեմատական վերլուծություն:

Ուսումնասիրության արդյունքները կարող են օգտագործվել փոքր հիդրոէլեկտրակայանների նախագծման գործընթացում:

Բանալի բառեր. պարզարան, ջրաբերուկ, տուրբինի տեսակ, հիդրավլիկական խոշորություն, երկրաչափական օպտիմալացում, կախված պինդ մասնիկների նստեցում, շինարարության արժեք, տեխնիկական և տնտեսական օպտիմալացում.

АЛГОРИТМ РАСЧЕТА И ОПТИМИЗАЦИЯ КОНСТРУКЦИЙ ОТСТОЙНИКОВ МАЛЫХ ГЭС

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В статье рассмотрены вопросы оптимизации геометрических и стоимостных параметров отстойников малых гидроэлектростанций (МГЭС), эксплуатируемых на горных водотоках. Показано, что широко применяемые проектные решения с переменной геометрией отстойных камер зачастую обусловлены отсутствием комплексной методики согласованного расчёта всех элементов сооружения и не всегда являются экономически оптимальными.

Предложен системный подход к проектированию отстойников МГЭС, основанный на сохранении расчётных скоростей потока и использовании постоянной ширины камеры.

В статье обосновывается выбор максимально допустимого размера частиц на основе физических принципов абразивной эрозии и концепции гидравлической скорости осаждения. Проведен сравнительный анализ различных методов расчета гидравлической скорости осаждения (Стокса, Гончарова, Архангельского, Руби, Фергюсона-Черча) для размеров частиц, характерных для горных рек.

На основе обобщения результатов расчётов для различных значений расхода, ширины камеры и размеров улавливаемых частиц получена параметрическая модель объёма монолитного железобетона отстойника в виде степенной функции от основных определяющих факторов. Для оценки капитальных затрат разработана укрупнённая стоимостная модель, связывающая стоимость строительства отстойника с объёмом железобетона и региональным индексом стоимости 1 м³ монолитного железобетона.

Результаты работы могут быть использованы при проектировании и технико-экономическом обосновании отстойников МГЭС, а также при разработке унифицированных методик оптимального выбора их геометрических параметров с учётом гидравлических и экономических факторов.

Ключевые слова: отстойники МГЭС, наносы, тип турбин, гидравлическая крупность, геометрическая оптимизация, осаждение взвешенных частиц, стоимость строительства, технико-экономическая оптимизация.

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SURFACE-MODIFIED PUMICE FOR EFFICIENT REMOVAL OF OILY POLLUTANTS

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Abstract

Wastewater treatment has become a growing environmental challenge due to rapid urbanization and industrial development. Conventional physical, chemical, and biological treatment methods often suffer from high operational costs and generate secondary pollutants. Among alternative approaches, adsorption using natural materials has emerged as an effective and environmentally friendly solution owing to its high efficiency, low cost, and minimal secondary contamination.

Car washing stations generate large volumes of oily wastewater containing petroleum hydrocarbons, detergents, suspended solids, surfactants, and trace heavy metals. If discharged without proper treatment, these effluents can pose serious risks to aquatic ecosystems and soil quality, potentially exceeding permissible discharge standards.

In this study, pumice obtained from the Irind mine was investigated as a natural adsorbent for treating car wash wastewater. To enhance its performance, the pumice surface was modified with polysiloxane, a widely studied biomaterial known for its chemical stability. The modified pumice exhibited a 40% increase in adsorption efficiency compared to the unmodified material, demonstrating its potential as an effective and low-cost adsorbent for treating oily wastewater.

Keywords: basins, car washing station; pumice; surface modification; adsorption; wastewater treatment.

Introduction

The Car wash facilities are among the major sources of dispersed oily wastewater, and the contamination of water resources by petroleum hydrocarbons has become a global environmental concern requiring urgent attention. During vehicle washing operations, motor oil, petrol, grease, lubricants, and detergent residues are released into wastewater streams [1]. If discharged without proper treatment, these contaminants can infiltrate soils, damage aquatic ecosystems, reduce oxygen transfer, form oil films on surface waters, and impair the performance of municipal wastewater treatment plants (WWTPs).

Car wash wastewater is characterized by its complex and highly variable composition, which depends on factors such as vehicle condition, washing techniques, detergents used, operational frequency, and the quantity of debris removed [2]. Rapid urbanization has significantly increased the volume of wastewater generated, prompting regulatory authorities to impose stricter discharge limits on sewage. Consequently, there is a growing interest in developing economical and environmentally friendly treatment methods for car wash effluents [3].

Car wash wastewater typically contains detergents, phosphates, oils, surfactants, suspended solids, and heavy metals [4]. Surfactants, which are widely used in cleaning agents, promote foam formation and contribute to eutrophication in receiving water bodies, leading to increased pH, oxygen depletion, and deterioration of aquatic ecosystems [5]. The presence of hydrocarbons, organic matter, and heavy metals further intensifies environmental and public health risks [6].

Conventional treatment of car wash wastewater often involves multistage processes. Primary treatments, such as sedimentation and oil–water separation, are effective for removing large particles and free-floating oils [7]. Secondary treatment methods, including coagulation–flocculation and advanced oxidation processes (AOPs), are used to reduce the organic load and turbidity. For example, coagulants such as ferric chloride and aluminum sulfate destabilize colloidal particles, facilitating their removal; however, these processes require precise chemical dosing and generate secondary sludge and by-products [8]. Ozonation, an advanced oxidation technique, is effective for degrading organic contaminants; however, it is associated with high energy consumption and operational costs [9].

Adsorption is a widely applied and efficient method for treating oily wastewater because of its simplicity, low operational cost, and high removal efficiency. The physical interactions, such as van der Waals forces, hydrophobic interactions, hydrogen bonding, polarity effects, steric interactions, dipole-induced dipole interactions, and π–π interactions [10,11]. In this process, sorbate molecules accumulate on the external surface and within the pores of the adsorbent without penetrating its internal structure [12].

Oil adsorption generally proceeds through three main stages: dispersion of oil molecules onto the adsorbent surface, entrapment of oil within the porous framework via capillary action, and agglomeration of oil droplets within the rough and porous structure of the material [13]. Compared with conventional treatment methods, adsorption offers advantages such as low capital investment, operational simplicity, and flexibility. Although activated carbon is widely used as an effective adsorbent, its high cost and regeneration requirements limit its large-scale applications [14]. Therefore, alternative low-cost and efficient natural materials such as pumice are being increasingly explored.

In this study, pumice obtained from the Irind mine was modified with a polysiloxane solution to enhance its oil adsorption capacity for the treatment of car wash wastewater.

1. Materials and Methods

1.1 Irind mine pumice

The Republic of Armenia leads the world in terms of nonmetallic mineral diversity and abundance. The country has almost every type of mineral rock known globally. Light rocks (tuffs, perlite, pumice-stone, zeolite, scoria, etc.) are the most significant mountainous rocks formed by volcanic processes in Armenia.

Irind is located in the Talin region. It is 46 km from the regional center. The village has perlite and pumice resources of industrial importance. In the Republic of Armenia, pumices are divided into two types according to their physical and mechanical characteristics: Ani type and lithoid pumices [14, 15].

One type of Ani pumice was sourced from the Irind mine. This pumice primarily consists of non-crystalline (amorphous) glass particles, plagioclase, pyroxene, mineral crystals, and fragments of ancient lava. Its porosity ranges from 35% to 44%, and it typically appears yellowish, occasionally exhibiting a yellow-brown or pink-yellow hue. The thermal insulating properties of pumice are notably high. It has a bulk density of 0.3–0.6 g/cm3 [16].

Studies have shown that the pumice is composed of aluminosilicates in which the amount of alkaline oxides is: SiO2 -61.54 %, MgO - 1.13%, TiO2 - 1.00%, Fe2O3 - 3.99%, K2O +Na2O - 8.18 %, Al2O3 - 16.58%, and CaO is 3.78 %.

Table 1

Chemical composition of Irind mine pumice (wt. %)

Oxide	Content (wt%)
SiO2	61.54
MgO	1.13
TiO2	1.00
Fe2O3	3.99
K2O +Na2O	8.18
Al2O3	16.58
CaO	3.78

The examination of the pumice by X-ray diffractometry has shown that it is a volcanic rock and is composed of cristobalite and coesite.

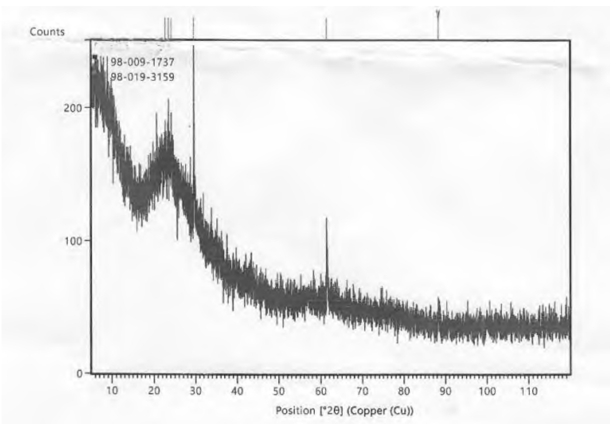

Fig.1 X-ray Diffraction (XRD) analysis of pumice

Coesite and cristobalite are high-pressure polymorphs of silica, silicon dioxide (SiO2). They have the same composition but possess a different crystal structure [14].

1.2. Polysiloxane

Polysiloxanes are among the most extensively studied and utilized biomaterials owing to their inherent stability and biocompatibility. Their hydrophobicity, low surface tension, and heat stability render polysiloxanes ideal for manufacturing catheters and other medical devices [17,18]. In the laboratories of the chemical industry, polysiloxane is used as a mold release agent, lubricant, plasticizer, emulsifier, or defoaming agent. Many of these applications are made possible by the very low surface tension of polysiloxanes [19,20]. The chemical structure of polysiloxane is presented in Fig.2.

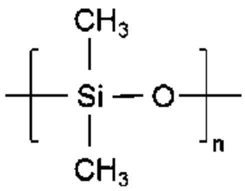

Fig.2 Chemical structure of polysiloxane

1.3. Wastewater

Car wash wastewater typically contains a complex mixture of physical, chemical, and biological pollutants. The most frequently reported contaminants include diesel and gasoline fractions, motor oils, lubricants, greases, and polycyclic aromatic hydrocarbons (PAHs). These compounds are predominantly hydrophobic and tend to form stable films or emulsions in water, making their removal particularly challenging using conventional treatment methods.

1.4. Surface modification

Before use and modification, pumice was washed several times with distilled water to remove any impurities and dried at a temperature of 40±10 °C. For chemical treatment using an acid solution, pumice was immersed and stirred in HCl 1 M for 3 h and washed using distilled water, then dried at 1300C for 3 h.
The optimum concentration of the modifier was 15% of the mass of the pumice; the ratio of the water to the solvent was 1:25. The emulsion of polysiloxane was added, thoroughly mixed, and dried at T = 60 ºC for 8 hours until a complete hydrophobic effect occurs.

Conflict Setting

The rapid growth of car washing stations has led to increased discharge of oily wastewater, posing serious environmental risks when inadequately treated. While effective, conventional treatment methods are often too costly and complex for small-scale facilities. This creates a conflict between environmental protection requirements and economic feasibility, highlighting the need for low-cost and efficient solutions such as surface-modified natural adsorbents.

Research Results

2. Results and discussion

2.1. FTIR investigation of polysiloxane modified pumice

Fig.3 shows the Fourier transform infrared (FTIR) spectrum of pumice before and after modification with polysiloxane.

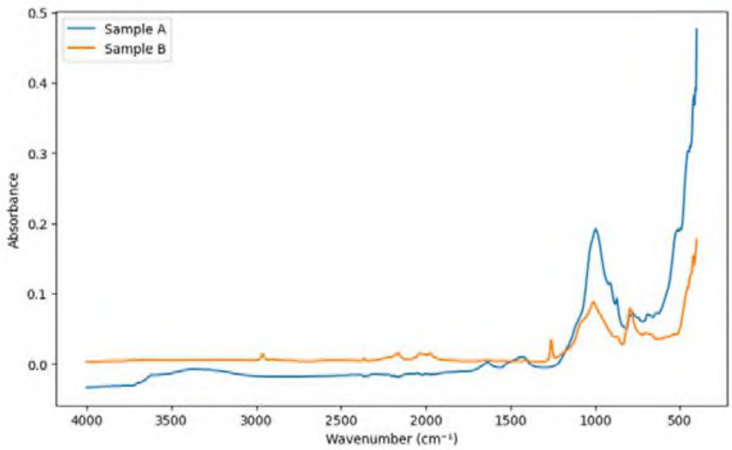

Fig.3 FTIR analysis of pumice
Sample A is the spectrum before modification
Sample B is the spectrum after modification

The FTIR spectrum of the pumice sample reveals characteristic absorption bands confirming surface modification with polysiloxane. The absorption peak observed at approximately 1260 cm^{-1} is attributed to the Si–CH_3 bending vibration, indicating the presence of methyl (C–H) groups. The strong absorption band in the region of ~1100 cm^{-1} corresponds to Si–O–Si stretching vibrations, which are characteristic of siloxane linkages. In addition, stretching vibrations detected at around ~2960 cm^{-1} are assigned to C–H stretching modes of methyl groups. The presence of these characteristic bands confirms that the surface of the pumice has been successfully modified with organic polysiloxane compounds, in agreement with previous studies [21].

Fig 4. Standard laboratory cylindrical flask for filtration

The study for water purification was carried out in standard laboratory cylindrical flasks with volumes of 150 ml. Based on the existing dimensions of these mini-filters (diameter and loading height), the speed of free-flow filtration was regulated using a valve located at the bottom. The average results of filtration speeds (1.5–3.0 mm/s) for the retention of petroleum products were observed.

2.2. Effects of contact time

To attain equilibrium throughout the batch process, the contact time and oil removal were regulated, as shown in Figure 4. Oil removal increased with longer contact times. Due to adsorbent surface modification, adsorption occurred on the surface between the first (20–30) and last (40–60) minutes of the experiment.

2.3. Concentration determination

Oil concentrations before and after adsorption were measured using a UV-Vis Spectrophotometer (Cary-60). The wavelength of 250.0 nm–1 corresponds to the maximum absorbance of the oil on the pumice. After modification by polysiloxane, the absorbance increased by 40% compared with unmodified pumice (Fig. 5).

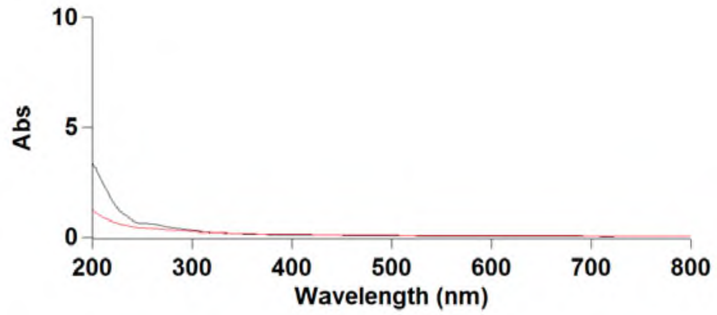

Fig 5. UV-Vis spectrophotometric analysis

Conclusion

This study demonstrated the potential of pumice obtained from the Irind mine as a low-cost and effective adsorbent for the treatment of oily wastewater generated by car washing stations. XRD analysis confirmed the predominantly amorphous aluminosilicate structure of the pumice, which is favorable for adsorption processes. FTIR spectroscopy verified the successful surface modification of pumice with polysiloxane through the appearance of characteristic Si–CH_3, Si–O–Si, and C–H functional groups, indicating the introduction of hydrophobic organic moieties.

Surface modification enhanced the adsorption performance of the pumice. The polysiloxane-modified pumice exhibited approximately **40% higher oil adsorption efficiency** compared with the unmodified material, which can be attributed to increased hydrophobicity and improved affinity toward nonpolar organic contaminants present in car wash wastewater. The adsorption mechanism is primarily governed by hydrophobic interactions between the modified pumice surface and petroleum-based pollutants.

The results highlight that polysiloxane-modified pumice is a promising, environmentally friendly, and economical adsorbent for oily wastewater treatment. Its natural abundance, simple modification process, and improved adsorption efficiency make it suitable for practical applications in car wash wastewater treatment systems.

Future studies should focus on regeneration, reuse potential, and performance evaluation under continuous-flow conditions.

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M.A. Kalantaryan, A.K. Harutyunyan
SURFACE-MODIFIED PUMICE FOR
EFFICIENT REMOVAL OF OILY POLLUTANTS

ՊԵՄԶԱՅԻ ՄԱԿԵՐևՈՒՅԹԻ ՄՈԴԻՖԻԿԱՑՈՒՄԸ և ԴՐԱ ԿԻՐԱՌՈՒՄԸ ՋՐԵՐԻՑ ՔՍՈՒՔԱՅՈՒՂԵՐԻ ՀԵՌԱՑՄԱՆ ԳՈՐԾԸՆԹԱՑՈՒՄ

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Կեղտաջրերի մաքրումը դարձել է բնապահպանական խնդիր՝ պայմանավորված քաղաքաշինության և արդյունաբերական զարգացման հետ: Ֆիզիկական, քիմիական և կենսաբանական մաքրման մեթոդները հաճախ բնութագրվում են շահագործման բարձր ծախսերով և երկրորդային աղտոտիչների առաջացմամբ: Այլընտրանքային մոտեցումների շարքում բնական նյութերով ադսորբցիոն գործընթացը դիտարկվում է որպես արդյունավետ և շրջակա միջավայրի համար անվտանգ լուծում՝ շնորհիվ բարձր արդյունավետության, ցածր արժեքի և երկրորդային աղտոտման նվազագույն մակարդակի:

Ավտոլվացման կայանները արտադրում են մեծ քանակությամբ յուղային կեղտաջրեր, որոնք պարունակում են նավթային ածխաջրածիններ, լվացող միջոցներ, կախյալ մասնիկներ, մակերևութաակտիվ նյութեր և աննշան քանակությամբ ծանր մետաղներ: Առանց համապատասխան մաքրման շրջակա միջավայր արտանետվելու դեպքում նման կեղտաջրերը կարող են լուրջ վտանգ ներկայացնել ջրային էկոհամակարգերի և հողի որակի համար՝ հաճախ գերազանցելով սահմանային թույլատրելի կոնցենտրացիաները:

Սույն աշխատանքում Իրինդի հանքավայրի պեմզան ուսումնասիրվել է որպես բնական ադսորբենտ ավտոլվացման կեղտաջրերի մաքրման համար: Դրա արդյունավետությունը բարձրացնելու նպատակով պեմզայի մակերեսը մոդիֆիկացվել է պոլիսիլոքսանով՝ քիմիական կայունությամբ հայտնի և լայնորեն ուսումնասիրված կենսանյութով: Մոդիֆիկացված պեմզան ցուցաբերել է ադսորբցիոն ունակությանմոտ 40 % աճ՝ համեմատած չմոդիֆիկացված նյութի հետ, ինչը հաստատում է դրա կիրառելիությունը որպես արդյունավետ և ցածրարժեք ադսորբենտ յուղային կեղտաջրերի մաքրման համար:

Բանալի բառեր. ավտոլվացման կայան; պեմզա; մակերեսի մոդիֆիկացում; ադսորբցիա; կեղտաջրերի մաքրում:

МОДИФИКАЦИЯ ПОВЕРХНОСТИ ПЕМЗЫ И ЕЁ ПРИМЕНЕНИЕ ДЛЯ УДАЛЕНИЯ СМАЗОЧНЫХ МАСЕЛ ИЗ ВОДНЫХ СРЕД

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Очистка сточных вод стала одной из нарастающих экологических проблем, обусловленных быстрым процессом урбанизации и развитием промышленности. Физические, химические и биологические методы очистки часто характеризуются высокими эксплуатационными затратами и образованием вторичных загрязняющих веществ. Среди альтернативных подходов адсорбция с использованием природных материалов

M.A. Kalantaryan, A.K. Harutyunyan

SURFACE-MODIFIED PUMICE FOR EFFICIENT REMOVAL OF OILY POLLUTANTS

рассматривается как эффективное и экологически безопасное решение благодаря высокой эффективности, низкой стоимости и минимальному вторичному загрязнению.

Автомоечные станции образуют значительные количества маслосодержащих сточных вод, включающих нефтяные углеводороды, моющие средства, взвешенные частицы, поверхностно-активные вещества и малые количества тяжелых металлов. При сбросе без надлежащей очистки стоки могут представлять серьезную угрозу для водных экосистем и качества почв, зачастую превышая предельно-допустимые концентрации.

В настоящем исследовании пемза, добытая на месторождении Иринд, была изучена в качестве природного адсорбента для очистки сточных вод автомоек. Для повышения ее адсорбционных свойств поверхность пемзы была модифицирована полисилоксаном — широко исследуемым биоматериалом, известным своей химической стабильностью. Модифицированная пемза продемонстрировала увеличение адсорбционной эффективности на 40 % по сравнению с немодифицированным материалом, что подтверждает ее потенциал в качестве эффективного и низкозатратного адсорбента для очистки маслосодержащих сточных вод.

***Ключевые слова*:** автомоечная станция; пемза; модификация поверхности; адсорбция; очистка сточных вод.

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OPTIMIZING PARALLEL OPERATION OF AGGREGATES EQUIPPED WITH «CROSSFLOW» TURBINES

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Abstract

The paper addresses the issue of optimizing the parallel operation of two identical hydropower aggregates equipped with Crossflow turbines under variable water flow conditions. The objective of the study is to determine the optimal distribution of the plant total flow between the aggregates that maximizes the capacity at a given flow rate. The optimization is formulated using the method of Lagrange multipliers, with the objective function proportional to the hydraulic capacity under constant head conditions.

It is shown that when the plant flow does not exceed the nominal flow of one aggregate, the maximum capacity is achieved by operating only one turbine, and no dispatching control is required. In the range of parallel operation of two aggregates, a nontrivial optimization problem arises. Numerical analysis based on manufacturer performance curves of Crossflow turbines demonstrates that the maximum total capacity in this operating zone is achieved when the flow is evenly distributed between the two aggregates. The reduction in efficiency observed for strongly asymmetric flow distributions is explained by the sharp decrease in turbine efficiency at low relative flows, which is characteristic of Crossflow turbines.

The obtained results provide a theoretical justification for practical operating rules of small hydropower plants with Crossflow turbines and can be applied in the design and operation of control systems for such facilities.

Keywords: crossflow turbine, small hydropower plant (SHPP), parallel operation, flow distribution, efficiency optimization, Lagrange multipliers, operating regimes.

Introduction

Installation of one aggregate at SHPP supplying the grid with generated electricity is the most economically optimal option. Therefore, aggregates equipped with Crossflow turbines have proven themselves in the construction of small hydropower plants on high-mountain rivers due to their stable efficiency over a wide range of flow rate fluctuations and their low starting threshold, which is only 5-6% of the design flow.

The runoff of high-mountain rivers in arid regions is generally characterized by large fluctuations between flood and low-flow periods. Therefore, to rationally cover the range of flow variations, even when Crossflow turbines are installed, it is sometimes necessary to install two or more aggregates.

S.G.Gabayan

OPTIMIZING PARALLEL OPERATION OF AGGREGATES EQUIPPED WITH CROSSFLOW TURBINES

When installing more than one aggregate, to ensure maximum plant efficiency, arises the issue of optimal distribution of flow among the turbines.

An issue of flow distribution between aggregates is the category of optimal load/water distribution between hydroaggregates and is solved using constrained optimization methods. However, Crossflow turbines are characterized by a specific form of partial efficiency and control, so the direct application of general recommendations requires adaptation and verification using real characteristics.

Let us consider the case of two aggregates installed at SHPP. Then, the total capacity of the plant, assuming a constant design head, is expressed by the relationship:

$$N(q_1 q_2) = gH[q_1\eta_1(q_1) + q_2\eta_2(q_2)], \quad (1)$$

Where: q_1, q_2-are the flows through the first and second aggregates, respectively, H – is the design head of the plant, $\eta_1(q_1), \eta_2(q_2)$ – are the efficiencies of the first and second aggregates. The flows of the aggregates are constrained by the following relationship:

$$q_1+q_2=Q, \quad (2)$$

where:Q – is the plant flow at the current moment.

To account for the total flow limitation, the Lagrange multiplier method is used. Let us introduce the Lagrange function [1–4]:

$$L\ (q_1,q_2,\lambda)=gH[q_1\eta_1(q_1)+q_2\eta_2(q_2)]+\lambda(Q-q_1-q_2), \quad (3)$$

Where λ - Lagrange multiplier, which has the dimensions of capacity for per unit flow rate.

The necessary condition for an extremum is that the partial derivatives of the Lagrange function with respect to the variables $q_1$and q_2 are equal to zero:

$$\frac{\partial L}{\partial q_1} = gH\left[\eta_1(q_1) + q_1\frac{d\eta_1}{dq_1}\right] - \lambda = 0,$$

$$\frac{\partial L}{\partial q_2} = gH\left[\eta_2(q_2) + q_2\frac{d\eta_2}{dq_2}\right] - \lambda = 0, \quad (4)$$

By eliminating the Lagrange multiplier λ, the key equation for optimal flow distribution is obtained:

$$\eta_1(q_1)+q_1\eta_1'(q_1)=\eta_2(q_2)+q_2\eta_2'(q_2), \quad (5)$$

This relationship is a necessary condition for an interior optimum and is valid for arbitrary efficiency characteristics of the aggregates.

Let us consider a particular, but practically the most important case, when both hydropower aggregates are identical in terms of their energy characteristics. This is the most common design solution, as it ensures interchangeability of spare parts between the aggregates. In this case, relationship (6) can be written in the following form:

$$N(q_1 q_2) = gH[q_{1i}\eta_{1i}(q_{1i}) + (Q - q_{1i})\eta_{2i}(Q - q_{1i})] \rightarrow \max, \quad (6)$$

Moreover, the range of variation of the values q_i is as follows:

$$q_1 \le q_{1i} \le Q; \;\; 0 \le q_{2i} \le q_2,$$

Considering that the design head of the plant is constant for each i-th value of Q_i, the problem reduces to solving the following relationship:

$$F(q_{1,}q_2) = [q_{1i}\eta_{1i}(q_{1i}) + (Q - q_{1i})\eta_{2i}(Q - q_{1i})] \rightarrow \max \;, \quad (7)$$

The literature presents numerous examples of efficiency curves for Crossflow turbines, which very often do not correspond to each other [5,6]. These discrepancies arise because the authors identify Banki turbines with modern Crossflow turbines equipped with a dual regulation system.

In order to avoid such errors, the efficiency curves used in this study are based on passport data (guaranteed by the manufacturer) from more than 30 different projects, covering a wide range of design flows and heads. The technical characteristics of aggregate components with different parameters were analyzed [7], and as a result of the study it was found that high-quality Crossflow turbines, although differing in nominal efficiency, exhibit similar characteristics in terms of the dynamics of efficiency reduction with changing flow. This makes it possible to unify the efficiency curves $\eta = f(h)$, by introducing a virtual efficiency equal to:

$$\eta_v = \frac{\eta_i}{\eta_n}, \quad (8)$$

Where: η_v, η_n – are the virtual and nominal efficiencies of the aggregate, respectively.

Figure 1 presents the values of the virtual efficiency of anaggregate equipped with a Crossflow turbine and of its individual components.

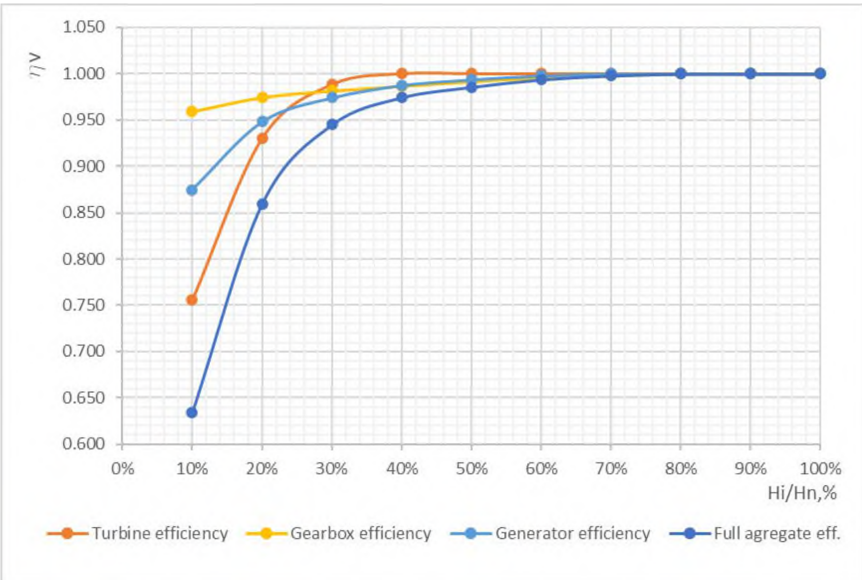

Fig. 1 Virtual efficiency of anaggregate equipped with a Crossflowturbine and its individual components

The design features of the aggregate, including the type of guide vanes and its operating modes, are not explicitly considered in the subsequent analysis, since their influence has already been taken into account in the experimental dependence of efficiency on flow.

The studies have shown that the curves of variation of the virtual efficiency values are well approximated by a sixth-degree polynomial. Table 1 presents the coefficients of the polynomial approximations of the virtual efficiency curves of the aggregate as a whole and of its individual components.

As can be seen from Fig. 1, in contrast to other types of turbines (for example, Francis turbines [5]), the efficiency curve of an aggregate equipped with a Crossflow turbine exhibits a continuously increasing character.

It follows that, when the plant flow fluctuates within the range $0 \leq Q \leq q_1$, the maximum power capacity is achieved exclusively by operating a single unit, and there is no need for dispatching control of the station.

A program for the numerical solution of relationship (7) was developed in the VBA environment. The calculation results obtained for a plant with two aggregates are presented in Fig. 2.

Table 1

Coefficients of the sixth-degree polynomial for anaggregate equipped with a Crossflow turbine and its components.

K of polynomial	Aggregate	Turbine	Gearbox	Generator
A0	0.115059	0.335271	0.921054	0.691226
A1	7.400958	6.055544	0.574933	2.720816
A2	-26.76362	-22.3743	-2.45923	-11.0335
A3	51.79591	43.0003	5.96336	24.56213
A4	-55.66332	-45.4277	-7.79015	-30.4424
A5	31.3024	25.06336	5.136381	19.61107
A6	-7.187377	-5.65245	-1.34637	-5.10938
R^2	**1**	**1**	**0.9998**	**0.9999**

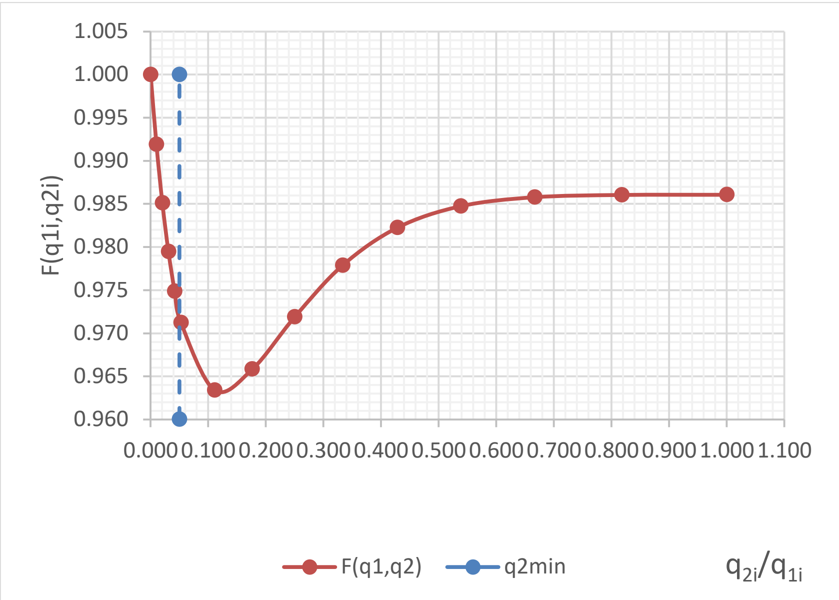

Fig.2 Dependence of F(q1, q2) on the ratio q2i/q1i)

As can be seen from Fig. 2, the target function sharply begins to decrease at small values of the ratio q2i/q1i and reaches its minimum value a$q_{2i}/q_{1i} \simeq 0.125$. Further, the value of $F(q_{1,}q_2)$ begins to increase and reaches its maximum value at $q_{2i}/q_{1i} = 1$.
Taking into account the minimum starting flow of Crossflow turbines, equal to 5%, it can be concluded that in the flow range $q_1 \leq Q_i \leq Q$ is necessary to equalize the turbine flows, which provides the maximum possible capacity of SHPP.

Thus, for 0≤Q≤q1 the optimal operating regime is realized with the operation of a single aggregate, whereas in the rang q1≤Q≤2q1 the optimization problem becomes nontrivial, and the maximum capacity is achieved with an even distribution of flows between the aggregates.
Efficiency curves of the plant with and without dispatching control were constructed by the authors (Fig. 3).

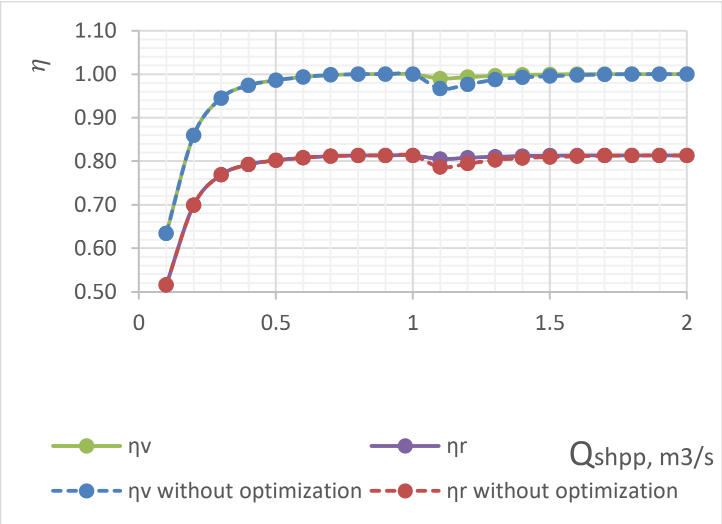

Fig. 3 Efficiency curves of the plant with two aggregates with and without dispatch control

The analysis of the calculation results shows that, due to the stable efficiency of Crossflow turbines, the influence of the absence of dispatch control during parallel operation of aggregates is relatively small compared to other types of turbines.

The calculations have shown that, when two identical aggregates are installed, the absence of dispatch control has the greatest effect in the flow range $q_1 \leq Q_i \leq 1.5Q$. In this range, the maximum efficiency drop reaches 2.3% at a flow of approximately $Q \simeq 1.1q$. Beyond this range, the influence of dispatching control practically does not affect the total capacity of the plant.

Limitations: All solutions presented above are obtained for Crossflow turbines equipped with a two-section guide apparatus and cannot be applied to other design configurations.

1. The developments are carried out for aggregates equipped with a gearbox. In the absence of a gearbox, it is recommended to recalculate the polynomial coefficients and to set the gearbox efficiency value $\eta_{gb} = 1$ in the gearbox efficiency term.
2. The obtained solutions are not applicable to aggregates operating at heads below 40 m, where Crossflow turbines operate in a reaction mode.

Conclusion

1. When the plant flow fluctuates within the nominal flow of a single aggregate, the maximum capacity of a SHPP is achieved by operating one aggregate, and dispatch control is not required.

2. When the total plant flow exceeds the nominal flow of one aggregate, a zone of parallel operation of two aggregates arises, in which the problem of optimal flow distribution becomes essential.
3. Based on the analysis of the energy characteristics of the aggregates and the application of constrained optimization methods, it has been obtained that for identical aggregates the optimal operating regime in the parallel operation zone corresponds to an even distribution of flow between the aggregates.
4. Numerical analysis of the functional proportional to the plant capacity has confirmed the presence of a maximum of the total capacity at equal flows through the aggregates, which is clearly demonstrated by graphical dependencies.
5. The obtained results make it possible to substantiate a practical operating rule for SHPP with Crossflow turbines: when transitioning to the parallel operation of aggregates, it is advisable to ensure an even distribution of water flow in order to achieve the maximum total capacity of the plant.

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OPTIMIZING PARALLEL OPERATION OF AGGREGATES EQUIPPED WITH CROSSFLOW TURBINES

«CROSSFLOW» ՏՈՒՐԲԻՆԱՅԻՆ ԱԳՐԵԳԱՏՆԵՐԻ ԶՈՒԳԱՀԵՌ ԱՇԽԱՏԱՆՔԻ ՕՊՏԻՄԱԼԱՑՈՒՄ

Ս.Գ.Գաբայան

Ակադեմիկոս Ի.Վ. Եղիազարովի անվան ջրային հիմնահարցերի և հիդրոտեխնիկայի ինստիտուտ

Հոդվածում ուսումնասիրվում է փոքր հիդրոէլեկտրակայանի Crossflow տուրբիններով համալրված երկու նման հիդրոագրեգատների զուգահեռ աշխատանքի օպտիմալացման խնդիրը՝ ջրի փոփոխվող հոսքի պայմաններում: Հետազոտության նպատակն է որոշել կայանի ընդհանուր հոսքի այնպիսի բաշխում, որը տվյալ հոսքի դեպքում կապահովի առավելագույն հզորություն: Օպտիմալացման խնդիրը ձևակերպվում է Լագրանժի բազմապատկիչների մեթոդի կիրառմամբ, որտեղ նպատակային ֆունկցիան համեմատական է հիդրավլիկական հզորությանը՝ հաստատուն ճնշման պայմաններում:

Ցույց է տրվում, որ կայանի այն հոսքի դեպքում, որը չի գերազանցում մեկ ագրեգատի անվանական հոսքը, առավելագույն հզորությունը ստացվում է մեկ ագրեգատի աշխատանքի պայմաններում, և չի պահանջվում հսկողություն կամ կառավարում: Երկու ագրեգատների համատեղ աշխատանքի տիրույթում առաջանում է ոչ տրիվիալ օպտիմալացման խնդիր: Crossflow տուրբինների արտադրողի տեխնիկական բնութագրերի վրա հիմնված թվային վերլուծությունը ցույց է տալիս, որ տվյալ տիրույթում առավելագույն ընդհանուր հզորությունը ապահովվում է հոսքի հավասար բաշխման դեպքում: Արդյունավետության նվազումը հոսքի խիստ անհավասար բաշխման ժամանակ պայմանավորված է Crossflow տուրբիններին բնորոշ՝ փոքր հարաբերական հոսքերի դեպքում օգտակար գործողության գործակցի կտրուկ անկմամբ:

Ստացված արդյունքները հնարավորություն են տալիս տեսականորեն հիմնավորել փոքր հիդրոէլեկտրակայանների գործնական շահագործման ռեժիմները և կարող են կիրառվել նման կայանների նախագծման և կառավարման գործընթացներում:

Բանալի բառեր. Crossflow տուրբին, փոքր հիդրոէլեկտրակայան, ագրեգատների զուգահեռ աշխատանք, հոսքի բաշխում, հզորության օպտիմալացում, Լագրանժի մեթոդ, շահագործման ռեժիմներ

Оптимизация параллельной работы агрегатов, оснащенных турбинами «CROSSFLOW»

С.Г.Габаян

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В работе рассматривается задача оптимизации параллельной работы двух идентичных гидроагрегатов, оснащённых турбинами Кроссфлоу, при переменном расходе воды на МГЭС. Целью исследования является определение рационального распределения суммарного расхода станции между агрегатами, обеспечивающего максимальную вырабатываемую мощность при заданном расходе. Задача оптимизации формулируется с

S.G.Gabayan

OPTIMIZING PARALLEL OPERATION OF AGGREGATES EQUIPPED WITH CROSSFLOW TURBINES

использованием метода множителей Лагранжа, при этом целевая функция пропорциональна гидравлической мощности при постоянном напоре.
Показано, что при расходе станции, не превышающем номинальный расход одного агрегата, максимальная мощность достигается при работе одного агрегата и необходимость диспетчеризации отсутствует. В диапазоне совместной работы двух агрегатов возникает нетривиальная задача оптимального распределения расхода. Численный анализ, выполненный на основе паспортных характеристик турбин Кроссфлоу, показывает, что в данной зоне максимальная суммарная мощность достигается при равномерном распределении расхода между агрегатами. Снижение эффективности при существенно неравномерном распределении расхода обусловлено резким падением коэффициента полезного действия турбины в области малых относительных расходов.
Полученные результаты позволяют теоретически обосновать практические режимы эксплуатации малых гидроэлектростанций с турбинами Кроссфлоу и могут быть использованы при проектировании и управлении такими объектами.

***Ключевые слова*:** турбина Кроссфлоу, малая гидроэлектростанция, параллельная работа агрегатов, распределение расхода, оптимизация мощности, метод Лагранжа, эксплуатационные режимы.

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Abstract

The aim of this study was to develop a production technology for fermented dairy products with reduced lactose content enriched with oat flakes. For this purpose, finely milled oat flakes were selected, and their optimal dosage was determined to be 3%. The optimal sugar concentration in the product was set at 5%. The sensory properties and titratable acidity of yogurt were investigated. Microbiological parameters of yogurt samples were comparatively evaluated, particularly with respect to coliforms, yeasts, and molds.

The results of the study demonstrated that the number of the above-mentioned microorganisms, as well as the sensory and chemical indicators of the experimental samples, complied with the requirements established by CU TR 033/2013 “On Safety of Milk and Dairy Products”.

The production of this product will contribute to the diversification of fermented dairy assortments and provide consumers with a nutritious and beneficial food.

Keywords: yogurt, lactose hydrolysis, oat flakes, sensory properties, microbiological indicators.

Introduction

In recent years, the development of functional and alternative dairy products has become a major focus in food science and nutrition. Conventional dairy products are rich in essential nutrients such as proteins, calcium, and bioactive peptides. However, for individuals suffering from lactose intolerance or cow’s milk protein allergies, their consumption can lead to discomfort and dietary limitations. Therefore, an increasing number of studies have been directed toward the development of low-lactose and lactose-free products, demonstrating their growing role in modern nutrition [1, 2]. Alongside the demand for lactose-free foods, there has been increasing consumer interest in plant-based alternatives. Among various cereals, oats (Avena sativa) have received considerable attention. Researchers have shown that oats contain β-glucans, polyphenols, and proteins that not only improve the nutritional quality of the diet but also exert cholesterol-lowering and prebiotic effects [3]. Furthermore, it has been demonstrated that the incorporation of oats in fermented dairy-like products enhances satiety and supports cardiovascular health, highlighting their role as a promising functional ingredient [4].

Fermentation itself plays a critical role in improving the quality of cereal-based dairy alternatives. Several studies have reported that fermentation with lactic acid bacteria not only increases the bioavailability of nutrients but also improves texture, flavor, and product stability [6]. Moreover, it has been shown that selecting specific probiotic strains of *Lactobacillus* and *Bifidobacterium* can optimize both the sensory characteristics and the functional potential of oat-based yogurts [6].

Recent investigations have also explored the enrichment of oat-based yogurts with functional additives such as chia seeds, flaxseed, or honey. These studies have demonstrated improvements in antioxidant capacity, rheological behavior, and consumer acceptability, further emphasizing the multifunctional potential of cereal-based dairy alternatives [7].

Taken together, the current body of research highlights that the integration of oats into low-lactose or lactose-free fermented dairy products not only addresses the nutritional needs of lactose-intolerant populations but also responds to global consumer trends toward sustainable, plant-based, and health-promoting foods.

Conflict Setting

The growing prevalence of lactose intolerance and the increasing consumer demand for functional, nutritionally enhanced foods create a technological challenge in the dairy industry. Conventional fermented dairy products contain lactose and lack plant-derived bioactive components, which limits their suitability for individuals with hypolactasia and reduces functional diversity within the product range.

Therefore, the central problem addressed in this study is the development of a technologically feasible method for producing a fermented dairy product with reduced lactose content, while simultaneously enhancing its nutritional and functional value through the incorporation of finely milled oat flakes. The challenge lies in determining the optimal parameters of enzymatic lactose hydrolysis, defining the appropriate dosage of oat flakes that ensures desirable sensory and physicochemical properties, and establishing compliance with microbiological safety standards.

Using principles of dairy technology, enzymology, and food microbiology, this work aims to formulate a scientifically grounded production scheme that ensures stable product quality, consumer acceptability, and safety, thereby expanding the assortment of functional fermented dairy products.

Materials and methods

The experiments were carried out at the Department of Processing Technologies of Animal Products, Armenian National Agrarian University. Yogurt was produced according to the traditional technology [8].

To induce milk coagulation, a direct-vat-set (DVS) lyophilized starter culture YF-L811 (Chr. Hansen, Denmark), containing *Streptococcus thermophilus* and *Lactobacillus delbrueckii subsp. bulgaricus*, was added [9]. For the preparation of a low-lactose fermented dairy product, raw cow's milk was used. Enzymatic hydrolysis of lactose was performed with the Ha-lactase 5200 preparation (Chr. Hansen, Denmark), produced by deep fermentation of *Kluyveromyces lactis* on a vegetable substrate [10, 11]. Ha-lactase is a neutral lactase with an optimal pH of 6.0–7.0.

The lactose content of milk was determined refractometrically using an IRF-464 refractometer, and the degree of hydrolysis was calculated [12]. The milk used for yogurt production contained 1% fat, titratable acidity of 18°T, density of 1029.2 g/dm^3, and 9.4% dry matter.

Oat flakes (2–4 mm, ground) were added to the milk prior to pasteurization. Sugar and cinnamon were added to improve sensory properties [13].

Titratable acidity of milk and yogurt was measured titrimetrically according to GOST (State Standard of the Russian Federation) 3624 [14]. Milk and dairy products — Titratable acidity determination method. Interstate Council for Standardization, Metrology and Certification], dry matter content by drying (GOST 3626-73 1973). Milk and dairy products — Methods for determination of dry matter content. Interstate Council for Standardization, Metrology and Certification, fat content by the Gerber acid method (GOST 5867-90 1990). Milk and dairy products — Methods for determination of fat content by the Gerber method. Interstate Council for Standardization, Metrology and Certification, and density using a hydrometer (GOST 3625-84. 1984). Milk and dairy products — Methods for determination of density. Sensory evaluation of yogurt samples was conducted using a 5-point hedonic scale [15].

Microbiological parameters were assessed by determining coliform bacteria (GOST 9225), ISO 4832:2006. (2006). Microbiology of food and animal feeding stuffs — Horizontal method for the enumeration of coliforms — Colony-count technique. International Organization for Standardization, yeasts, and molds (GOST 10444.12), ISO 6611:2004. Milk and milk products — Enumeration of colony-forming units of yeasts and/or moulds — Colony-count technique at 25 °C. International Organization for Standardization].

To determine the optimal hydrolysis parameters, the degree of lactose hydrolysis was studied depending on enzyme concentration, hydrolysis temperature, and duration. For enzyme concentration (0.02%, 0.05%, and 0.1%) and temperature dependency, hydrolysis was conducted for 4 h at 20–50 °C. For time-dependency, milk was incubated at 38 ± 1 °C with enzyme concentrations of 0.02%, 0.05%, and 0.1%, while maintaining a constant temperature [16].

Research Results

At the initial stage of the study, the optimal parameters for lactose hydrolysis were determined. Considering that lactic acid bacteria present in fermented milk products ferment approximately 30% of lactose—equivalent to about 1.6 g per 100 g of product—it is advisable, when preparing milk mixtures intended for individuals with hypolactasia, to reduce the residual lactose content from 5.33% to 3.04–3.52%.

Based on the above, the aim was to decrease the initial lactose content in milk by 40–50% through enzymatic hydrolysis.

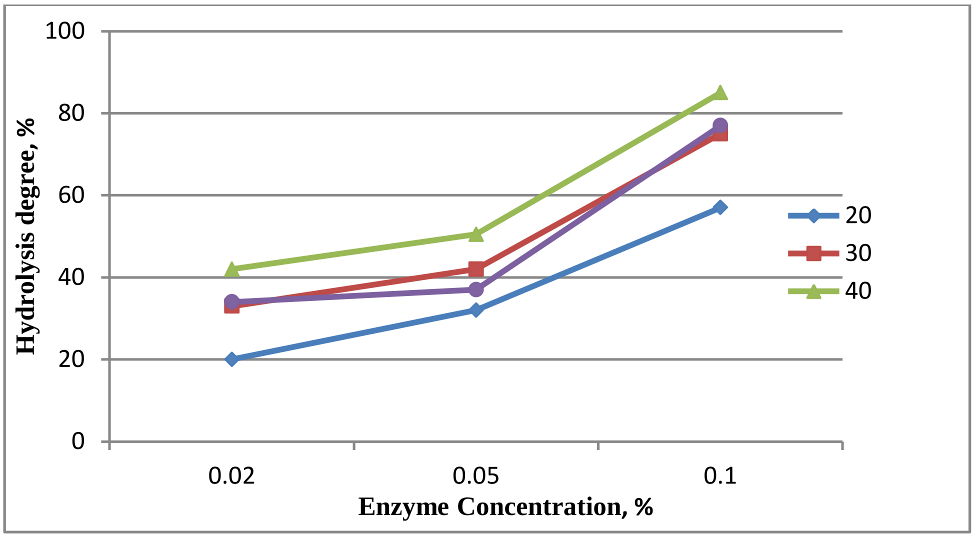

Fig. 1 Dependence of lactose hydrolysis degree on temperature and enzyme concentration

As shown in Figure 1, increasing the temperature from 20 °C to 40 °C leads to a rise in the degree of lactose hydrolysis, while a further increase up to 50 °C causes a noticeable decline. The degree of hydrolysis was 40–50% at 20 °C with 0.067–0.085% enzyme concentration; 30 °C with 0.042–0.06%; 40 °C with 0.02–0.05%; and 50 °C with 0.053–0.067%, respectively.

For the "Ha-lactase" enzyme, the optimal temperature range was determined to be 35–45 °C. Denaturation began above 50 °C, with complete inactivation observed at 72 °C.

Considering the enzyme characteristics and experimental data, the optimal hydrolysis temperature was set at 38 ± 1 °C.

According to Figure 2, with an enzyme concentration of 0.02%, the degree of lactose hydrolysis reached 40% after 3 h and did not exceed 50% even after 5 h. At 0.05% concentration, 40% hydrolysis was achieved after 1.5–2 h, and 50% after 4 h. When the enzyme concentration was increased to 0.1%, 50% of lactose was hydrolyzed within 1 h.

Thus, at 38 ± 1 °C, 40–50% hydrolysis of lactose occurred within 2–4 h at 0.02–0.05% enzyme concentration, and within 1 h at 0.1%. Since the hydrolysis degree increases with both enzyme concentration and reaction time, regulating these parameters allows achieving the desired hydrolysis level, which is essential for reducing the production cost of the final product.

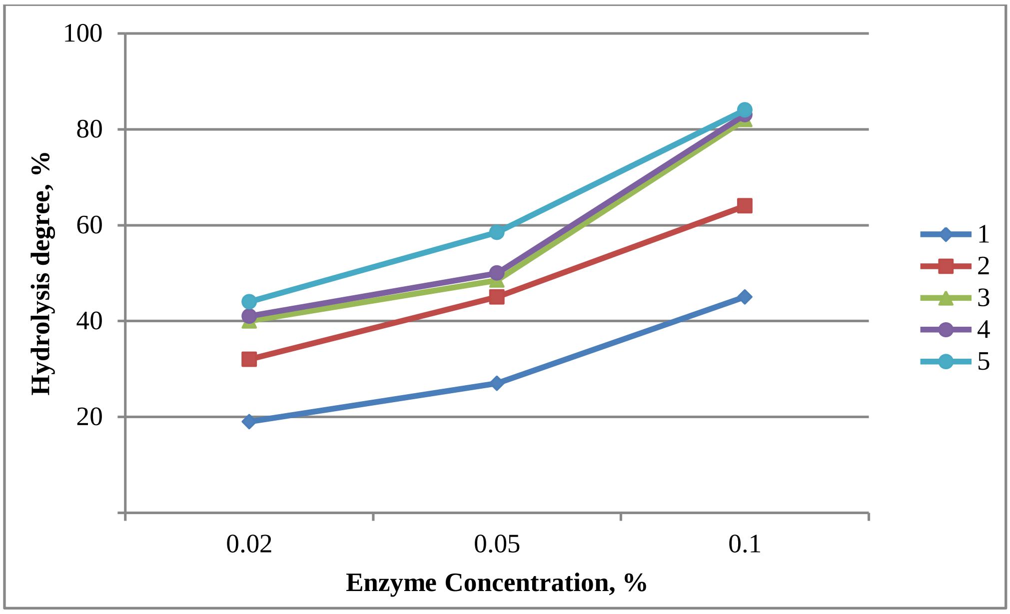

Fig. 2 Dependence of lactose hydrolysis degree on process duration and enzyme concentration

Based on the obtained data, the optimal parameters for achieving the required residual lactose concentration were defined as follows: enzyme concentration – 0.05%; process duration – 3 ± 0.1 h; temperature – 38 ± 1 °C.

The sensory and physicochemical characteristics of yogurt samples prepared with different amounts of oat flakes are presented in Figure 3.

According to Figure 3, the samples containing 2–3% oat flakes received the highest sensory scores. These yogurts had a mild lactic aroma and taste, complemented by a pleasant or moderately pronounced cereal note. The texture was homogeneous, dense or moderately thick, without syneresis, and the distribution of oat particles was uniform. The color was milky white to pale yellow, with evenly dispersed light brown inclusions.

As the amount of oat flakes increased, the flavor and aroma became more pronounced, the consistency thicker and pasty, and the color turned more yellowish. With lower amounts of oat flakes, the consistency was comparatively less dense. The addition of oats improved yogurt consistency and prevented whey separation during storage.

The choice of stabilizers for fermented milk products is closely related to the rheological and sensory characteristics of texture. However, the effect of stabilizers on the biological value of the product is rarely assessed.

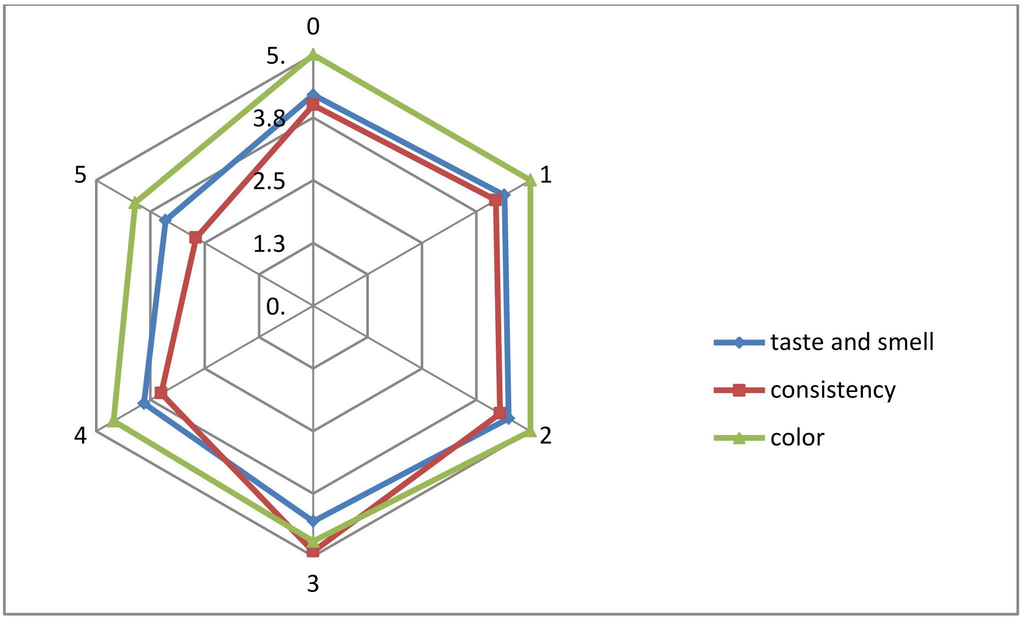

Fig. 3 Sensory and physicochemical evaluation of yogurt samples with different oat flake contents

According to previous studies, stabilizers with optimal functional properties may reduce the biological value of yogurt by up to 12%. In contrast, the addition of oat flakes not only improves texture stability but also enhances the biological value of the product, serving as a natural source of bioactive compounds such as dietary fibers, microelements, and vitamins.

The titratable acidity of all yogurt variants remained within acceptable limits, ranging from 76 °T to 88 °T.

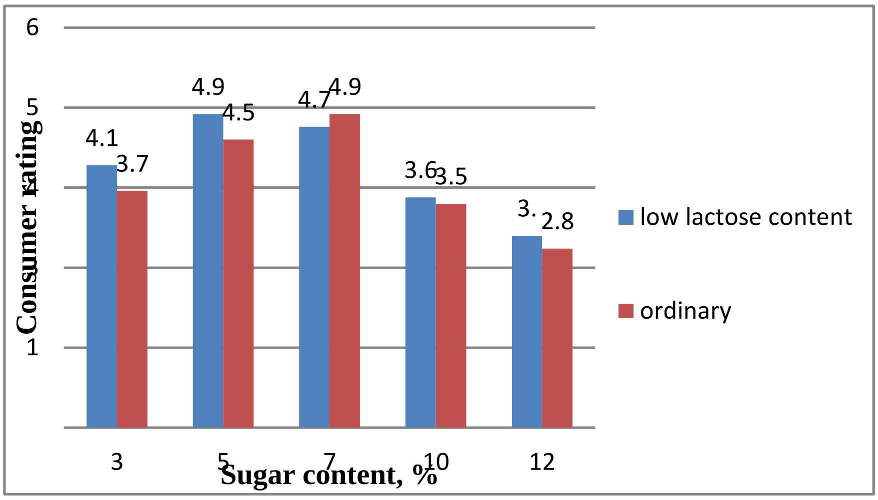

Fig. 4 Consumer evaluation of fermented milk products with different sugar contents

Lactase hydrolyzes lactose into glucose and galactose, thereby making the yogurt suitable for individuals with lactose intolerance. Moreover, the hydrolysis of lactose increases the product's sweetness due to the formation of glucose and galactose. Thus, with the addition of 5% sucrose, the yogurt acquired a pleasant sweet taste, while higher concentrations resulted in an excessively sweet flavor.

An essential indicator of food safety is the absence of pathogenic microflora. Therefore, determining the composition and quantity of microorganisms in the final product is a critical preventive measure.

The microbial parameters of yogurt—including E. coli, yeasts, molds, *Staphylococcus aureus, Salmonella* spp., and lactic acid bacteria—must comply with the requirements of the Eurasian Technical Regulation "On Safety of Milk and Dairy Products" (TR CU 033/2013). The viable count of lactic acid bacteria should not be less than 1×10^7 CFU/g during the storage period (TR CU 033/2013).

The results of the microbiological analysis are presented in tab.1.

Table 1

Microbiological indicators of yogurt

Product	Microbiological indicator	Permissible level	Exsperimental result
Fermented milk product (Shelf life > 72 h)	Lactic acid bacteria, min.	1×10^7	1×10^7
	Coliforms (per 0,01 g/cm^3)	Not allowed	Not detected
	Yeasts (CFU/cm^3, max.)	50	-
	Molds (CFU/cm^3, max.)	50	-

The obtained results (Table 1) show that the microbial content of the experimental samples fully complies with the safety standards established by TR CU 033/2013 "On Safety of Milk and Dairy Products".

Conclusion

A technology for producing low-lactose fermented milk with added oat flakes was developed. The optimal parameters for lactose hydrolysis using the "Ha-lactase 5200" enzyme preparation were established: temperature – 38 ± 1 °C; duration – 3 ± 0.5 h; enzyme concentration – 0.05 ± 0.01%.

Oat flakes were selected as the cereal additive, with an optimal addition level of 3%. Due to partial lactose conversion during hydrolysis, the optimal sucrose content in the formulation was determined to be 5%. To enhance the flavor and aroma of the product, 0.01% cinnamon was added.

Microbiological analysis (for molds, yeasts, coliforms, and lactic acid bacteria) confirmed that the product meets the safety requirements of TR CU 033/2013.

Fermented milk products are known for their dietary, therapeutic, and preventive properties. The inclusion of oat flakes improves the consistency and increases the biological value of yogurt owing to their natural content of biologically active compounds (dietary fibers, trace elements, vitamins, etc.), without posing any health risks. The production of such combined functional products expands the range of fermented dairy products and contributes to providing consumers with nutritionally beneficial foods.

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G.A. Hakhoyan, I.H. Melkonyan, K.S. Stepanyan, A.H. Grigoryan

DEVELOPMENT OF A TECHNOLOGY FOR A NOVEL FERMENTED DAIRY PRODUCT WITH OAT FLAKES AND REDUCED LACTOSE CONTENT

ՎԱՐՍԱԿԻ ՓԱԹԻԼՆԵՐՈՎ ԵՎ ԼԱԿՏՈԶԻ ՑԱԾՐ ՊԱՐՈՒՆԱԿՈՒԹՅԱՄԲ ՄԱԿԱՐԴՎԱԾ ԿԱԹՆԱՄԹԵՐՔԻ ՆՈՐ ՏԵԽՆՈԼՈԳԻԱՅԻ ՄՇԱԿՈՒՄ

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Այս ուսումնասիրության նպատակն էր մշակել ֆերմենտացված կաթնամթերքի արտադրության տեխնոլոգիա՝ լակտոզի նվազեցված պարունակությամբ, հարստացված վարսակի փաթիլներով: Ընտրվել են մանրացված վարսակի փաթիլներ և որոշվել է դրանց օպտիմալ չափաքանակը՝ 3%: Արտադրանքում շաքարի օպտիմալ կոնցենտրացիան կազմել է 5%: Ուսումնասիրվել են յոգուրտի օրգանոլեպտիկ հատկությունները և տիտրվող թթվայնությունը: Կատարվել է յոգուրտի նմուշների մանրէաբանական պարամետրերի համեմատական գնահատում, մասնավորապես՝ կոլիֆորմների, խմորիչների և բորբոսների պարունակության համար:

Ուսումնասիրության արդյունքները ցույց են տվել, որ այս միկրոօրգանիզմների քանակը, ինչպես նաև փորձարկվող նմուշների օրգանոլեպտիկ և քիմիական պարամետրերը համապատասխանում են «Կաթի և կաթնամթերքի անվտանգության մասին» ՄՄՏԿ 033/2013 պահանջներին:

Այս արտադրանքի արտադրությունը կնպաստի ընդլայնել ֆերմենտացված կաթնամթերքի տեսականին և սպառողներին կապահովի սննդարար և առողջարար սննդամթերքով:

Բանալի բառեր. յոգուրտ, լակտոզի հիդրոլիզ, վարսակի փաթիլներ, օրգանոլեպտիկ հատկություններ, մանրէաբանական ցուցանիշներ:

Разработка технологии нового ферментированного молочного продукта с овсяными хлопьями и пониженным содержанием лактозы

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Целью данного исследования было разработать технологию производства ферментированных молочных продуктов с пониженным содержанием лактозы, обогащённых овсяными хлопьями. Для этого были выбраны тонко измельчённые овсяные хлопья, оптимальная дозировка которых составила 3%. Оптимальная концентрация сахара в продукте была установлена на уровне 5%. Были исследованы органолептические свойства и титруемая кислотность йогурта. Проведена сравнительная оценка микробиологических показателей образцов йогурта, в частности содержания колиформных бактерий, дрожжей и плесневых грибов.

G.A. Hakhoyan, I.H. Melkonyan, K.S. Stepanyan, A.H. Grigoryan

DEVELOPMENT OF A TECHNOLOGY FOR A NOVEL FERMENTED DAIRY PRODUCT WITH OAT FLAKES AND REDUCED LACTOSE CONTENT

Результаты исследования показали, что количество указанных микроорганизмов, а также органолептические и химические показатели опытных образцов соответствуют требованиям ТР ТС 033/2013 "О безопасности молока и молочной продукции".

Производство данного продукта способствует расширению ассортимента ферментированных молочных изделий и обеспечивает потребителей питательным и полезным продуктом питания.

***Ключевые слова*:** йогурт, гидролиз лактозы, овсяные хлопья, органолептические свойства, микробиологические показатели.

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COMPARATIVE ANALYSIS OF ARMENIA AND GEORGIA'S EXPORT STRUCTURE AND COMPETITIVENESS (ON THE EXAMPLE OF THE MAIN COMMODITY GROUPS)

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Abstract

This study analyzes the dynamics of Armenia's and Georgia's foreign trade structures through the lens of Comparative Competitive Advantage (CCA) across the years 2020–2024. Focusing on the top ten product groups with the highest CCA indicators, the research highlights key differences in the export profiles of the two countries. Armenia's trade is characterized by a strong and consistent competitive advantage in a limited number of resource-based sectors, particularly ores, slag and ash, as well as processed agricultural goods such as alcoholic beverages and tobacco. In contrast, Georgia shows signs of increasing diversification and adaptability in its export structure, with notable improvements in the competitiveness of value-added goods such as animal and vegetable fats and oils, textiles, and footwear. The findings suggest that while Armenia maintains depth and stability in specific sectors, Georgia demonstrates broader flexibility and emerging strengths across various industries. This comparative perspective offers valuable insights into the evolving nature of trade specialization and competitiveness in the South Caucasus region.

Keywords: Comparative Competitive Advantage (CCA), foreign trade, Armenia, Georgia, export structure, trade specialization, economic competitiveness, South Caucasus, product groups, trade analysis**.**

Introduction

Foreign trade remains a vital instrument in the economic development and integration of countries, particularly for small, open economies such as those of Armenia and Georgia.

These post-Soviet South Caucasian nations have undergone significant structural transformations in their trade patterns over the past two decades, striving to enhance export competitiveness, diversify their trade portfolios, and strengthen their positions in the global economy. Amid global economic fluctuations, regional instability, and shifting trade alliances, identifying sectors with comparative competitive advantage (CCA) is critical for developing sustainable trade policies and boosting national economic performance.

The theory of comparative advantage suggests that countries should specialize in producing and exporting goods for which they have the lowest opportunity cost relative to other nations. However, this theoretical premise must be contextualized within modern global trade dynamics, where value chains, technological intensity, and market access determine competitiveness. Therefore, empirical assessments such as the CCA index provide practical insights into the real-world trade performance of individual product groups. By analyzing trade flows through this lens, policymakers can identify priority sectors and address inefficiencies in foreign trade structures.

This paper focuses on examining and comparing the foreign trade performance of Armenia and Georgia by analyzing the CCA indicators of product groups from 2010 to 2024. In doing so, it explores both the best-performing and worst-performing sectors based on their relative trade balances. The analysis reveals the degree of specialization, structural shifts, and emerging trends in each country's export and import composition. For Armenia, particular strengths are found in the export of mineral products, ores, precious metals, alcoholic beverages, and tobacco, while Georgia's competitive edge lies in precious metals, fats and oils, and select industrial products. At the same time, both countries demonstrate significant trade deficits in machinery, chemical products, and various manufactured goods—highlighting critical gaps in industrial capacity and value-added production.

By comparing the trade structures and CCA trends of these two economies, the study not only maps sectoral strengths and weaknesses but also contributes to broader discussions on regional integration, trade-driven growth, and economic security in the South Caucasus. This work also aims to offer practical recommendations for improving trade policy, enhancing competitiveness, and fostering sustainable export development in both Armenia and Georgia.

The analysis of foreign trade structures and export competitiveness is firmly grounded in both classical and modern international trade theory. A substantial body of literature emphasizes the role of gravity models as a fundamental empirical tool for explaining bilateral trade flows. Shengelia [1] provides a structured overview of gravity-model applications, highlighting their relevance for evaluating trade intensity and forecasting international trade relations. Complementing this approach, Sartania [2] examines the driving forces behind Georgia's economic integration with the European Union, emphasizing the importance of foreign trade liberalization, institutional convergence, and regulatory alignment.

Building on gravity-based approaches, Shengelia [1] and related studies demonstrate that trade flows in small open economies are influenced not only by economic size and distance but also by policy orientation and institutional quality. In this context, Charaia [3] analyzes China–Georgia economic relations within the Belt and Road Initiative, stressing the role of infrastructure development and trade facilitation in strengthening bilateral cooperation.

Abesadze [4] further explores Georgia's post-independence growth trajectory, underlining the increasing importance of foreign trade and structural reforms in supporting long-term economic development.

A parallel strand of the literature focuses on export diversification as a key determinant of economic resilience and growth. Hesse [5] argues that diversification reduces vulnerability to commodity price shocks, particularly in developing and transition economies. Imbs and Wacziarg [6] propose a dynamic, U-shaped relationship between diversification and income levels, suggesting that economies diversify at early stages of development and re-specialize as they mature.

Earlier empirical work by Love [7] demonstrates that export concentration is associated with higher earnings instability, while diversified export structures contribute to more stable growth paths. Gourdon [8] provides further empirical evidence that both product and market diversification are positively associated with higher growth rates and economic resilience. Cadot, Carrère, and Strauss-Kahn [9] distinguish between extensive diversification (new products) and intensive diversification (expansion of existing products into new markets), showing that both dimensions enhance export performance.

The role of public policy in promoting diversification is emphasized by Lederman and Maloney [10], who highlight infrastructure development, trade facilitation, and trade agreements as critical enablers of export diversification. Rodrik [11] argues that industrial policy can play a constructive role in overcoming coordination failures and fostering new competitive sectors, while later contributions [12] stress the importance of pragmatic and context-specific policy design. However, Agosin [13] notes that diversification efforts face significant constraints, including limited access to finance, technology, and skilled labor, as well as high entry costs and regulatory barriers in international markets.

Innovation-oriented perspectives on diversification are explored by Klinger and Lederman [14], who link export diversification to entrepreneurial discovery and experimentation with new products. Korea's development experience, analyzed by Kim and Lin [15], illustrates how strategic industrial policy, investment in human capital, and technological upgrading can transform an economy from primary production to high-value-added exports.More recent contributions emphasize not only diversification but also export sophistication. Hidalgo et al. [16] introduce the concept of the "product space," arguing that countries with more complex and diversified export baskets are better positioned for sustained growth. Hausmann, Hwang, and Rodrik [17] reinforce this argument by demonstrating that the composition and quality of exports significantly influence long-term economic growth outcomes. Overall, the literature suggests that export competitiveness is shaped by a combination of structural factors, diversification strategies, institutional quality, and policy interventions. This theoretical foundation provides a robust basis for applying the Comparative Competitive Advantage (CCA) framework to analyze and compare the export structures of Armenia and Georgia.

Conflict Setting

Armenia and Georgia face a strategic conflict between maintaining existing competitive strengths and pursuing broader export diversification. Armenia's exports are concentrated in a few resource-based sectors, offering stability but limiting flexibility in response to global market fluctuations. Conversely, Georgia shows increasing diversification and competitiveness in value-added goods, but this approach carries risks associated with overextension and volatility in emerging sectors. This tension creates a policy and economic setting where decisions must balance depth in established industries with flexibility to exploit new trade opportunities, highlighting the need for informed, data-driven strategies based on Comparative Competitive Advantage (CCA) analysis.

Research Results

Foreign trade diversification research involves a combination of qualitative and quantitative methods to comprehensively analyze the extent, determinants, and effects of trade diversification.

Analysis of statistical series of export and import of product groups (sections) was used in the study: methods of induction and deduction, approaches of scientific abstraction. The authors put the theory of comparative advantages as the basis of the policy of development of export and import diversification possibilities and ways of product groups (sections). The point is that according to that theory, it is possible to assess (quantify) the degree of specialization of export and import of product groups (sections) and therefore trade circulation. Such an approach with foreign and mutual trade partner countries makes it possible to choose the best partner (partners) in the region and the global economy, based on the mutual benefit (efficiency) of the process, according to which the comparative advantage coefficients of product groups (sections) are the basis of these calculations, and the calculations are carried out based on available and published rich statistical information on foreign and mutual trade. The CCAs of a product group (section) is calculated from the export of the commodity group (section) - import of the commodity group (section) / their export + import. In the form of a formula, it is expressed as follows:

$$\textbf{CCA of the product group (section)}. = \frac{\textbf{Product group (section) E} - \textbf{Product group (section) I}}{\textbf{Product group (section)E} + \textbf{Product group (section) I}},$$

where: the product group (section) E- is the country's export volume, and the product group (section) I – is the country's import volume.

The magnitude of CCAs varies in the range [-1,+1]. According to that, the greater the CCAs, the higher the expediency of foreign trade. This criterion was adopted by the authors as a predictor of diversification of foreign and mutual trade.

The data for Armenia were collected from the official publications of the Statistical Committee of the Republic of Armenia, including the "Statistical Yearbook of Armenia" and monthly reports on the socio-economic situation. The data for Georgia were obtained from the External Trade Portal of the National Statistics Office of Georgia (Geostat). In addition to the CCA calculation, each product group's share in total exports and imports was computed to analyze structural significance. Based on these indicators, the study identifies the top ten product groups with the highest and lowest CCA values for both countries, providing insights into export diversification, specialization, and vulnerability to external shocks.The analysis was conducted using Microsoft Excel for data cleaning, aggregation. Descriptive statistics and trend analysis were used to interpret the results across years and product categories.

Analysis

Table 1 shows the volumes and structure of RA exports and imports by product categories in 2022-2023, thousand dollars.

Table 1

Volumes and structure of RA export and import by product categories in 2022-2023, thousand dollar [18][19]

Product section	Export			Import			Specific gravity, %			
	2022 January-December	2023 January - December	growth rate, %	2022 January-December	2023 January - December	growth rate, %	export 2022	export 2023	import 2022	import 2023
Total	**5,419,064.5**	**8,415,155.1**	**155.3**	**8,775,859.2**	**12,307,957.0**	**140.2**	100.0	100.0	100.0	100.0
including:										
live animals and animal products	170,832.5	98,189.9	57.5	261,145.7	248,349.3	95.1	3.2	1.2	3.0	2.0
products of plant origin	225,944.0	182,576.3	80.8	421,935.1	356,687.0	84.5	4.2	2.2	4.8	2.9
animal and vegetable oils and fats	7,516.5	1,526.6	20.3	105,646.0	66,255.6	62.7	0.1	0.0	1.2	0.5
prepared food products	882,197.1	885,061.9	100.3	579,422.2	617,800.4	106.6	16.3	10.5	6.6	5.0
mineral products	1,027,520.8	887,650.7	86.4	1,196,064.5	1,113,167.0	93.1	19.0	10.5	13.6	9.0
products of chemical and allied industries	83,491.5	120,940.5	144.9	588,239.6	622,775.8	105.9	1.5	1.4	6.7	5.1
plastics and articles thereof, rubber and rubber articles	63,111.5	66,443.4	105.3	327,685.5	351,811.6	107.4	1.2	0.8	3.7	2.9
leather raw materials, leather, fur, and articles made from them	11,130.5	21,988.4	197.6	28,444.1	42,344.0	148.9	0.2	0.3	0.3	0.3
wood and wood products	4,726.6	9,353.0	197.9	93,977.9	88,373.5	94.0	0.1	0.1	1.1	0.7
paper and paper products	6,742.2	4,771.2	70.8	137,730.2	147,545.8	107.1	0.1	0.1	1.6	1.2
textile items	224,409.9	357,657.2	159.4	397,899.9	648,713.9	163.0	4.1	4.3	4.5	5.3
footwear, hats, umbrellas	12,640.8	41,456.5	3.3 times	76,689.9	116,616.9	152.1	0.2	0.5	0.9	0.9
things made of stone, plaster, cement	37,247.2	37,209.3	99.9	160,974.4	174,657.5	108.5	0.7	0.4	1.8	1.4
precious and semi-precious stones, precious metals, and articles thereof	989,410.8	3,211,869.9	3.2 times	691,595.9	2,302,882.6	3.3 times	18.3	38.2	7.9	18.7
base metals and articles made from them	460,401.4	452,236.7	98.2	624,041.4	602,692.5	96.6	8.5	5.4	7.1	4.9
machines, equipment, and mechanisms	718,756.0	1,290,921.6	179.6	1,728,318.9	2,459,173.6	142.3	13.3	15.3	19.7	20.0
land, air, and water vehicles	332,562.0	548,276.8	164.9	957,936.9	1,832,380.6	191.3	6.1	6.5	10.9	14.9
devices and apparatus	117,571.1	142,955.8	121.6	196,927.5	265,833.7	135.0	2.2	1.7	2.2	2.2
various industrial products	39,519.5	53,315.9	134.9	191,855.2	243,560.7	127.0	0.7	0.6	2.2	2.0
works of art	3,332.7	753.5	22.6	9,328.4	6,334.9	67.9	0.1	0.0	0.1	0.1

Note: These and the following tables were compiled and calculated by the authors.

From the data in Table 1, it follows that the volume of exports to RA in 2023 increased by 155.3% compared to the previous year, and imports increased by 140.2%, respectively. Such a high rate of growth of export and import is mainly due to the Russian-Ukrainian conflict, as a result of which RA's re-export to the Russian Federation has increased significantly.

Table 2

Volumes and Structure of Georgia's Export and Import by Product Categories in 2023–2024, thousand USD [20]

Product section	**Export 2023 (thsd USD)**	**Export 2024 (thsd USD)**	**Import 2023 (thsd USD)**	**Import 2024 (thsd USD)**	**Export growth rate (%)**	**Import growth rate (%)**	**Export share 2023 (%)**	**Export share 2024 (%)**	**Import share 2023 (%)**	**Import share 2024 (%)**
Live animals and animal products	182071.9	158600.2	446326.1	458329.4	87.1	102.7	3.0	2.4	2.9	2.7
Products of plant origin	264414.8	324332.3	430050.6	486164.4	122.7	113.0	4.3	4.9	2.8	2.9
Animal or vegetable fats and oils	21813.94	25267.82	88153.31	97407.6	115.8	110.5	0.4	0.4	0.6	0.6
Prepared food products	968550.6	1171606	1053212	1155379	121.0	109.7	15.9	17.9	6.8	6.8
Mineral products	719750.9	491033.2	2161457	2164519	68.2	100.1	11.8	7.5	13.9	12.8
Products of chemical and allied industries	432189.1	423025.9	1398865	1534361	97.9	109.7	7.1	6.5	9.0	9.1
Plastics and articles thereof, rubber and rubber articles	86053.13	67754.62	601099.8	620322.6	78.7	103.2	1.4	1.0	3.9	3.7
Leather, fur, and related products	3589.93	3441.89	36164.88	39565.42	95.9	109.4	0.1	0.1	0.2	0.2
Wood and wood products	41881.09	48030.94	211596.5	224035.5	114.7	105.9	0.7	0.7	1.4	1.3
Paper and paper products	40861.48	57568.09	194830.9	208468.5	140.9	107.0	0.7	0.9	1.3	1.2
Textile items	231407.7	247242.5	596273.5	663037.4	106.8	111.2	3.8	3.8	3.8	3.9
Footwear, hats, umbrellas	7074.38	6708.21	126794.6	143725	94.8	113.4	0.1	0.1	0.8	0.8
Stone, plaster, cement items	16470.88	20758.34	347199.4	336906.8	126.0	97.0	0.3	0.3	2.2	2.0
Precious and semi-precious stones, metals	95405.37	109215.6	15837.8	18699.33	114.5	118.1	1.6	1.7	0.1	0.1
Base metals and products	326660.4	475727.2	1122532	1381393	145.6	123.1	5.4	7.3	7.2	8.2
Machines and equipment	259694.2	254433.7	2152043	2373585	98.0	110.3	4.3	3.9	13.8	14.0
Vehicles (land, air, water)	2272665	2559511	3917832	4316954	112.6	110.2	37.4	39.0	25.2	25.5
Devices and apparatus	85300.17	79502.46	218603.1	232968.2	93.2	106.6	1.4	1.2	1.4	1.4
Various industrial products	25466.12	34006.22	448969.2	454748.9	133.5	101.3	0.4	0.5	2.9	2.7
Works of art	441.06	355.33	798.96	2417.54	80.6	302.6	0.0	0.0	0.0	0.0
Total	6081762	6558122	15568639	16912988	2148.6	2364.9	100.0	100.0	100.0	100.0

The share of precious and semi-precious stones, precious metals, and their articles has the largest share of RA product groups (sections) - 38.2% in 2023, the share of machines, equipment, and mechanisms - 15.3%, ground, ready-made food products - 10.5%, for air and water vehicles - 6.5%. The divisions of other product groups are not large, which implies that the diversification of divisions of the mentioned product groups is not related to certain difficulties and the period of assimilation of new markets. Import volumes of the mentioned product groups also have the largest specific weight, which also confirms the previous statement.

The analysis of Armenia's and Georgia's foreign trade for the periods 2022–2023 and 2023–2024 respectively reveals several strategic and structural differences. In both countries, the total volumes of exports and imports have undergone significant changes, while also exhibiting important distinctions in their commodity composition.

In 2023, Armenia's export volume reached approximately USD 8.4 billion, marking a 155.3% increase compared to the previous year. Import volume stood at over USD 12.3 billion, showing a 140.2% growth. In contrast, Georgia's exports in 2024 amounted to around USD 6.6 billion, a modest increase of 7.8%, while imports reached approximately USD 16.9 billion, growing by 8.6%. Thus, Armenia's export growth was significantly more rapid and intensive, especially in high-value product groups.

At the level of product composition, important differences emerge. In Armenia's export structure, precious metals and articles made thereof dominated in 2023, accounting for 38.2% of total exports. In Georgia, however, similar goods represented only 1.7% of total exports. This discrepancy is attributed not only to external demand but also to Armenia's re-export strategy and its orientation toward specific foreign markets.

Conversely, transport equipment, particularly motor vehicles, play a dominant role in Georgia's export structure, comprising 39% of total exports in 2024. This reflects Georgia's function as a regional hub for vehicle import and re-export. Imports of transport equipment were also substantial, accounting for 25.5% of total imports—highlighting both domestic consumption and re-export activity.

In Armenia, machinery and equipment (15.3%) and prepared food products (10.5%) were among the most important exported categories after precious metals. In Georgia, machinery and equipment accounted for just 3.9% of exports, while prepared food products were more significant at 17.9%. These figures suggest that Armenia is more intensively engaged in the manufacturing and processing industry, whereas Georgia has stronger positioning in agro-processing sectors.

Regarding mineral products, both countries showed a decline in export shares. In Armenia, their share dropped from 19% in 2022 to 10.5% in 2023. In Georgia, the decline was from 11.8% in 2023 to 7.5% in 2024. This is partially attributable to global raw material price fluctuations and declining demand in international markets.

In terms of import structure, both countries are heavily dependent on machinery, equipment, chemical products, and mineral resources. This indicates a shared reliance on high-tech goods and production inputs. Georgia's import volumes remained large and displayed a relatively diversified structure.

In conclusion, Armenia's export system in 2023 demonstrated dynamic growth, particularly in high-value commodities, although it remains concentrated around a limited number of product groups, which introduces certain vulnerabilities. Georgia's export structure is more balanced, while both economies continue to exhibit high external dependency in import flows, especially in machinery and transport sectors.

Table 3 shows the RA foreign trade CCAs by product groups (sections) for 2010-2023, in descending order of indicators for 2023.

Table 3

RA foreign trade CCAs by product groups (sections) in 2010-2023, in descending order of 2023 indicators [18][19]

Product groups	2010	2015	2018	2019	2020	2021	2022	2023
prepared food products	-0.405	-0.028	0.161	0.189	0.172	0.179	0.207	0.178
precious and semi-precious stones, precious metals, and articles thereof	-0.085	0.269	0.034	0.167	0.440	0.145	0.177	0.165
mineral products	-0.421	-0.165	-0.054	-0.045	0.043	0.024	-0.076	-0.113
base metals and articles made from them	-0.051	-0.049	-0.068	-0.139	-0.223	-0.035	-0.151	-0.143
Total	-0.578	-0.373	-0.346	-0.352	-0.287	-0.279	-0.236	-0.188
textile items	-0.895	-0.333	-0.171	-0.287	-0.295	-0.243	-0.279	-0.289
devices and apparatus	-0.809	-0.498	-0.383	-0.121	-0.293	-0.565	-0.252	-0.301
machines, equipment, and mechanisms	-0.912	-0.928	-0.911	-0.902	-0.908	-0.876	-0.413	-0.312
leather raw materials, leather, fur, and articles made from them	-0.620	-0.285	-0.279	-0.473	-0.496	-0.609	-0.437	-0.316
products of plant origin	-0.862	-0.680	-0.399	-0.369	-0.305	-0.216	-0.303	-0.323
live animals and animal products	-0.626	-0.391	-0.445	-0.490	-0.254	-0.218	-0.209	-0.433
footwear, hats, umbrellas	-0.915	-0.877	-0.855	-0.918	-0.875	-0.854	-0.717	-0.475
land, air, and water vehicles	-0.967	-0.897	-0.865	-0.920	-0.868	-0.776	-0.485	-0.539
various industrial products	-0.954	-0.695	-0.684	-0.819	-0.777	-0.833	-0.658	-0.641
things made of stone, plaster, cement	-0.672	-0.707	-0.591	-0.712	-0.646	-0.687	-0.624	-0.649
products of chemical and allied industries	-0.935	-0.903	-0.866	-0.878	-0.868	-0.833	-0.751	-0.675
plastics and articles thereof, rubber and rubber articles	-0.811	-0.848	-0.867	-0.879	-0.853	-0.845	-0.677	-0.682
works of art	-0.330	0.299	0.553	-0.294	0.300	0.568	-0.474	-0.787
wood and wood products	-0.974	-0.941	-0.934	-0.967	-0.978	-0.970	-0.904	-0.809
paper and paper products	-0.980	-0.952	-0.971	-0.972	-0.972	-0.962	-0.907	-0.937
animal and vegetable oils and fats	-0.999	-0.997	-0.997	-0.998	-0.997	-0.998	-0.867	-0.955

From the data in Table 3, it follows that the state of RA's foreign trade in 2010-2023 has improved, as the CCAs had a decreasing trend, from -0.578 in 2010 to 2023: -0.289. According to this, in recent years, they have had positive CCAs: prepared food products, precious and semi-precious stones, precious metals, and articles thereof. The CCAs of the remaining product groups (sections) had a negative value, which once again proves the problem of renewing the RA export policy and finding new markets.

Of considerable practical interest is the picture of the 10 product groups with the highest CCAs and 10 product groups with the lowest CCAs of the RA product groups.

Table 4 presents Georgia's foreign trade Comparative Competitive Advantage (CCA) indicators by product groups (sections) for the years 2010, 2015, 2019, 2020, 2021, 2022, 2023, and 2024, ranked in descending order based on 2024 CCA values.

The analysis of Armenia's and Georgia's foreign trade structures based on Comparative Competitive Advantage (CCA) indicators between 2010 and 2024 allows us to identify fundamental differences in their export profiles, trade dynamics, and competitiveness.

Table 4

Georgia's foreign trade CCAs by product groups (sections) in 2010, 2015, 2019, 2020, 2021, 2022, 2023, 2024, in descending order of 2024 indicators [20]

Product section	2010	2015	2019	2020	2021	2022	2023	2024
Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes	-0.302	-0.609	-0.347	-0.156	-0.171	-0.065	-0.367	0.79
Natural or cultured pearls, precious or semi-precious stones, precious metals, metals clad with precious metal and articles thereof; imitation jewellery; coin	0.297	0.278	0.702	-0.057	-0.648	-0.409	0.535	0.656
Special classification provisions; Goods not intended for economic activity	0.322	-0.908	0.319	-0.877	0.597	0.657	0.005	0.58
Footwear, headgear, umbrellas, sun umbrellas, walking-sticks, seat-sticks, whips, riding-crops and parts thereof; prepared feathers and articles made therewith; artificial flowers; articles of human hair	-0.281	-0.431	-0.353	-0.813	-0.989	-0.466	-0.132	0.458
Pulp of wood or of other fibrous cellulosic material; recovered (waste and scrap) paper or paperboard; paper and paperboard and articles thereof	-0.437	0.031	-0.834	-0.944	-0.969	0.314	-0.414	0.327
Plastics and articles thereof; rubber and articles thereof	-0.356	0.847	-0.316	0.612	-0.685	-0.198	-0.245	0.251
Textiles and textile articles	-0.04	-0.305	-0.317	-0.622	0.379	0.639	-0.517	0.242
Machinery and mechanical appliances; electrical equipment; parts thereof; sound recorders and reproducers, television image and sound recorders and reproducers, and parts and accessories of such articles	-0.577	0.186	-0.467	-0.384	-0.185	-0.342	0.309	0.159
Wood and articles of wood; wood charcoal; cork and articles of cork; manufactures of straw, of esparto or of other plaiting materials; basketware and wickerwork	-0.216	-0.605	-0.211	0.129	0.039	0.037	0.141	-0.131
Works of art, collectors pieces and antiques	0.455	-0.149	-0.747	0.891	-0.423	0.484	-0.467	-0.131
Raw hides and skins, leather, fur skins and articles thereof; saddlery and harness; travel goods, handbags and similar containers; articles of animal gut (other than silk-worm gut)	0.399	0.579	0.118	-0.127	-0.765	0.31	0.046	-0.137
Vegetable products	-0.349	0.057	-0.35	-0.362	-0.15	0.049	0.862	-0.196
Vehicles, aircraft, vessels and associated transport equipment	-0.852	0.925	-0.575	-0.916	-0.304	-0.917	0.258	-0.228
Base metals and articles of base metal	-0.791	-0.268	0.166	-0.468	-0.157	-0.546	0.058	-0.273
Prepared foodstuffs; beverages, spirits and vinegar; tobacco and manufactured tobacco substitutes	0.818	-0.27	-0.812	-0.729	-0.169	-0.547	0.426	-0.323
Live animals; animal products	-0.004	0.655	-0.203	-0.005	-0.3	-0.555	-0.786	-0.394
Mineral products	0.23	-0.61	0.029	0.037	0.121	0.158	0.63	-0.505
Swords, cutlasses and similar arms and parts, scabbards and sheaths therefor	-0.206	-0.174	0.191	0.188	-0.25	0.006	-0.755	-0.64
Optical, photographic, cinematographic, measuring, checking, precision, medical or surgical instruments and apparatus; clocks and watches; musical instruments; parts and accessories thereof	-0.289	-0.28	-0.734	0.192	-0.403	0.39	0.154	-0.789
Products of the chemical or allied industries	-0.212	0.53	-0.613	0.227	-0.041	0.284	0.633	-0.889

Articles of stone, plaster, cement, asbestos, mica or similar materials; ceramic products; glass and glassware	-0.345	-0.972	-0.119	-0.657	-0.379	-0.239	0.299	-0.958
Miscellaneous manufactured articles	0.051	-0.167	-0.738	0.241	0.916	-0.122	-0.124	-0.971
Total	-2.685	-1.66	-6.211	-4.6	-4.936	-1.078	0.549	-3.102

In the case of Armenia, the product groups with positive CCA values in 2023 are limited.

The highest-ranking groups are prepared food products and precious metals and stones, with CCA values of 0.178 and 0.165, respectively. These groups also hold significant shares in Armenia's export structure, which suggests some level of export competitiveness, albeit with a high concentration in a few sectors.

On the other hand, Georgia in 2024 demonstrated significantly different results. The highest CCA value was recorded for the group of animal or vegetable fats and oils at 0.79. Other high-performing groups include precious metals (0.656) and goods not intended for economic activity (0.58), although the latter has limited economic importance. These figures indicate that Georgia's foreign trade is largely driven by re-exports, and the high competitiveness scores in certain product groups may not be backed by strong domestic production bases.

Among mid-level product groups, Armenia's mineral products show some progress. In 2023, their CCA was -0.113, which, despite being negative, indicates gradual improvement compared to earlier years.

Machinery and mechanical appliances also show a shift from strongly negative to near-neutral positions, reflecting some structural stabilization.

A similar trend can be observed in Georgia, where product groups such as plastics and rubber, textiles, and technical equipment reported neutral or slightly positive CCA values. This could point to a gradual activation of processing and light manufacturing industries.

When examining product groups with low competitiveness, both countries still face challenges. In Armenia, the CCA values remain strongly negative for sectors such as transport vehicles, paper, wood products, textiles, and vegetable oils and fats. For instance, the 2023 CCA for the latter was as low as -0.955.

In Georgia, similar concerns are seen in the chemical industry, vehicles, and base metals. Notably, sectors with significant import volumes, such as transport equipment, continue to show negative competitiveness indicators, underlining a reliance on foreign supply.

Looking at total CCA indicators, Armenia shows gradual improvement. Its aggregate CCA score in 2023 was -0.188, compared to -0.578 in 2010, reflecting some positive shifts in export competitiveness. In contrast, Georgia registered a positive total CCA of 0.549 in 2023, but this dropped drastically to -3.102 in 2024. This sharp decline suggests a serious imbalance that may stem from structural shifts in export composition, a surge in imports, or methodological changes. It highlights the fragility of trade equilibrium in the Georgian context.

Table 5

RA exports and imports by product groups, their structure, and the 10 product groups with the best indicators of CCAs in 2020-2022 (calculated for 2022 in descending order of CCAs) [18][19]

Place	Product Group	2020		2021		2022		CCA		
		Exports (1,000 US dollars)	Imports (1000 US dollars)	Exports (1000 US dollars)	Imports (1000 US dollars)	Exports (1000 US dollars)	Imports (1000 US dollars)	**2020**	**2021**	**2022**
	Total	2,536,974.1	4,564,032.3	3,015,987.2	5,362,209.0	5,419,064.5	8,775,859.2	-0.285	-0.280	-0.236
1	Ores, slag and ash	733,415.9	2,852.2	923,205.7	2,274.7	922,281.7	3,154.1	0.992	0.995	0.993
	% in total	28.91	0.06	30.61	0.04	17.02	0.04			
2	Tin and articles thereof	-	314.0	1,906.1	147.1	1,759.8	81.0	-	0.857	0.912
	% in total	-	9.27	3.01	1.53	1.47	0.38			
3	Fish and crustaceans, mollusks, and other aquatic invertebrates	49,692.0	3,386.8	63,367.1	9,632.4	119,501.6	21,571.5	0.872	0.736	0.694
	% in total	1.96	0.07	2.10	0.18	2.21	0.25			
4	Alcoholic and non-alcoholic and vinegar	240,572.1	34,607.7	291,792.4	55,916.3	364,595.1	68,236.0	0.748	0.678	0.685
	% in total	9.48	0.76	9.67	1.04	6.73	0.78			
5	Tobacco and manufactured tobacco substitutes	256,544.2	127,106.3	249,793.1	89,240.9	344,464.1	88,664.1	0.337	0.474	0.591
	% in total	10.11	2.78	8.28	1.66	6.36	1.01			
6	Live animals	15,579.9	7,016.9	23,268.0	8,136.3	17,531.9	8,046.9	0.379	0.482	0.371
	% in total	0.61	0.15	0.77	0.15	0.32	0.09			
7	Pulp of wood or other fibrous cellulosic material; waste and scrap of paper or paperboard	0.0	42.8	174.3	53.9	129.8	60.5	-1.000	0.528	0.364
	% in total	0.00	0.00	0.00	0.00	0.00	0.00			
8	Preparations of vegetables, fruit, nuts, or other parts of plants	33,997.0	23,968.5	43,372.1	30,083.1	84,493.4	46,568.8	0.173	0.181	0.289
	% in total	1.34	0.53	1.44	0.56	1.56	0.53			
9	Edible vegetables and certain roots and tubers	46,793.2	18,686.0	72,737.9	23,485.0	73,629.8	41,517.3	0.429	0.512	0.279
	% in total	1.84	0.41	2.41	0.44	1.36	0.47			
10	Copper and articles thereof	13,039.0	6,522.7	20,561.1	8,420.1	20,713.0	12,755.9	0.333	0.419	0.238
	% in total	0.51	0.14	0.68	0.16	0.38	0.15			

Table 6

Georgia's Exports and Imports by Product Groups, Their Structure, and the 10 Product Groups with the Best Indicators of CCA in 2022–2024 (Ranked by 2024 CCA in Descending Order) [20]

Place	Product Group	Export 2022	Import 2022	Export 2023	Import 2023	Export 2024	Import 2024	CCA 2022	CCA 2023	CCA 2024
1	Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes	22303.01	127119.4	21813.94	88153.31	25267.82	97407.6	-0.867	-0.604	0.790
	% in total	2.81	3.43	2.75	2.17	3.07	2.2			
2	Natural or cultured pearls, precious or semi-precious stones, precious metals, metals clad with precious metal and articles thereof; imitation jewellery; coin	103508	9403.21	95405.37	15837.8	109215.6	18699.33	0.833	0.714	0.656
	% in total	13.04	0.25	12.04	0.39	13.29	0.42			
3	Special classification provisions; Goods not intended for economic activity	4713.9	27550.29	4648.86	34952.2	2238.06	34675.98	-0.707	-0.765	0.580
	% in total	0.59	0.74	0.59	0.86	0.27	0.78			
4	Footwear, headgear, umbrellas, sun umbrellas, walking-sticks, seat-sticks, whips, riding-crops and parts thereof; prepared feathers and articles made therewith; artificial flowers; articles of human hair	10829.5	107225.5	7074.38	126794.6	6708.21	143725	-0.814	-0.893	0.458
	% in total	1.36	2.89	0.89	3.12	0.82	3.25			
5	Pulp of wood or of other fibrous cellulosic material; recovered (waste and scrap) paper or paperboard; paper and paperboard and articles thereof	35163.93	198863.4	40861.48	194830.9	57568.09	208468.5	-0.699	-0.653	0.327
	% in total	4.43	5.37	5.16	4.8	7	4.71			
6	Textiles and textile articles	240368.3	541380.2	231407.7	596273.5	247242.5	663037.4	-0.385	-0.44	0.242
	% in total	30.28	14.61	29.2	14.69	30.08	14.99			
7	Machinery and mechanical appliances; electrical equipment; parts thereof; sound recorders and reproducers, television image and sound recorders and reproducers, and parts and accessories of such articles	250316.8	1870604	259694.2	2152043	254433.7	2373585	-0.788	-0.784	0.159
	% in total	31.53	50.49	32.77	53.04	30.96	53.66			
8	Plastics and articles thereof; rubber and articles thereof	89890.79	597090.7	86053.13	601099.8	67754.62	620322.6	-0.738	-0.749	0.251
	% in total	11.32	16.11	10.86	14.81	8.24	14.02			
9	Raw hides and skins, leather, fur skins and articles thereof; saddlery and harness; travel goods,	3669.98	27648.17	3589.93	36164.88	3441.89	39565.42	-0.765	-0.818	-0.137

	handbags and similar containers; articles of animal gut (other than silk-worm gut)									
	% in total	0.46	0.75	0.45	0.89	0.42	0.89			
10	Wood and articles of wood; wood charcoal; cork and articles of cork; manufactures of straw, of esparto or of other plaiting materials; basketware and wickerwork	33115.91	198374.9	41881.09	211596.5	48030.94	224035.5	-0.713	-0.669	-0.131
	% in total	4.17	5.35	5.29	5.21	5.84	5.06			

Table 7

RA exports and imports by product groups, their structure, and the 10 product groups with the worst indicators of CCAs in 2020-2022 (calculated for 2022 in descending order of CCAs) [18][19]

Key Contrasts

Criteria	Armenia	Georgia
Most Competitive Sector	Ores, slag and ash (CCA 0.993)	Animal/vegetable oils (CCA 0.790)
Nature of Top Exports	Resource-based, alcohol, fish	Mixed: processed food, chemicals, footwear
Shift in CCA Trend	Stable high CCAs	Steep improvements in 2024
Manufactured Goods	Limited competitiveness	Growing competitiveness

Place	Product Group	2020		2021		2022		CCA		
		Exports (1000 US dollars)	Imports (1000 US dollars)	Exports (1000 US dollars)	Imports (1000 US dollars)	Exports (1000 US dollars)	Imports (1000 US dollars)	**2020**	**2021**	**2022**
	Total	2,536,974.1	4,564,032.3	3,015,987.2	5,362,209.0	5,419,064.5	8,775,859.2	-0.285	-0.280	-0.236
87	Meat and edible meat offals	143.7	57,170.2	286.1	81,995.3	1,787.6	104,680.4	-0.995	-0.993	-0.966
	% in total	0.01	1.25	0.01	1.53	0.03	1.19			
88	Chemical filaments	316.0	23,177.3	164.2	30,458.9	556.7	35,133.7	-0.973	-0.989	-0.969
	% in total	0.01	0.51	0.01	0.57	0.01	0.40			

89	Products of the milling industry; malt; starches; inulin and other	368.2	17,473.3	392.3	13,014.6	295.5	24,321.8	-0.959	-0.941	-0.976
	% in total	0.01	0.38	0.01	0.24	0.01	0.28			
90	Explosives; matches; certain combustible preparations	31.6	2,201.7	19.1	2,331.1	21.0	2,392.2	-0.972	-0.984	-0.983
	% in total	0.00	0.05	0.00	0.04	0.00	0.03			
91	Special woven fabrics; tufted textile fabrics; lace; tapestries; trimmings; embroidery	95.4	7,283.7	38.6	7,811.7	95.3	11,611.4	-0.974	-0.990	-0.984
	% in total	0.00	0.16	0.00	0.15	0.00	0.13			
92	Vegetable textile material; paper yarn and wove	-	1,083.1	22.6	789.0	1.9	246.0	-	-0.944	-0.985
	% in total	-	0.02	0.00	0.01	0.00	0.00			
93	Zinc and articles thereof	0.3	167.1	-	313.9	5.4	1,020.6	-0.996	-	-0.989
	% in total	0.00	0.00	-	0.01	0.00	0.01			
94	Lacs, gums, resins, and other vegetable saps and extracts	17.9	7,576.4	9.0	9,798.8	70.5	13,339.1	-0.995	-0.998	-0.989
	% in total	0.00	0.17	0.00	0.18	0.00	0.15			
95	Cereals	45.9	96,915.3	601.6	89,534.8	749.1	149,495.9	-0.999	-0.987	-0.990
	% in total	0.00	2.12	0.02	1.67	0.01	1.70			
96	Fertilisers	8.2	24,193.7	0.0	21,053.9	67.9	40,867.5	-0.999	-1.000	-0.997
	% in total	0.00	0.53	0.00	0.39	0.00	0.47			

Armenia demonstrates strong and stable competitive advantages in a few key export sectors, especially ores, slag and ash, with consistently high CCA values above 0.99 in 2020–2022. Other high-performing sectors include tin products, fish and seafood, alcoholic beverages, and tobacco products.

These are mainly based on natural resources and agro-processing.

The dominance of these sectors suggests a more concentrated export structure.

Georgia, in contrast, shows a more dynamic export structure. Some product groups that had negative CCA values in 2022, such as animal and vegetable fats and oils and footwear and accessories, significantly improved by 2024. Georgia's precious metals, special classification goods, and textiles also emerged as areas of growing competitiveness. This reflects a diversification trend and adaptive capacity in external trade.

Key Insights

- Armenia's export advantage is concentrated in natural resources and traditional agro-industries.
- Georgia shows growing competitiveness across a wider range of sectors, with significant improvements in value-added exports.
- Armenia relies on stable advantages, while Georgia reflects flexibility and structural adaptation in foreign trade.

This suggests that while Armenia benefits from depth in specific sectors, Georgia is developing broader, more flexible trade strengths.

It follows from Table 5 that RA exports and imports CCAs for 2020-2022 had a negative magnitude, although a decrease in that magnitude was observed. All other product groups in the table had a positive value in 2020-2022. This circumstance means that all the mentioned product groups have the maximum export potential and it is necessary to promote their export.

It follows from Table 4 that all the given product groups are significantly dependent on import volumes, which implies that it is necessary to look for more efficient and profitable partners for new import markets.

Table 8

Georgia's Exports and Imports by Product Groups, Their Structure, and the 10 Product Groups with the Worst CCA Indicators in 2022–2024 (Ranked by 2024 CCA in Ascending Order) [20]

Place	Product Group	Export 2022	Import 2022	Export 2023	Import 2023	Export 2024	Import 2024	CCA 2022	CCA 2023	CCA 2024
1	Miscellaneous manufactured articles	732293.2	936614.2	2171633.9	2785545.5	56119.3	3838139.0	-0.122	-0.124	-0.971
	% in total	2.3	2.19	6.91	7.86	0.21	9.79			
2	Articles of stone, plaster, cement, asbestos, mica or similar materials; ceramic products; glass and glassware	2390648.3	3891948.8	2017423.0	1088608.3	39168.1	1844825.0	-0.239	0.299	-0.958
	% in total	7.5	9.1	6.42	3.07	0.15	4.71			
3	Products of the chemical or allied industries	997299.3	556232.1	1636470.0	367516.1	182225.8	3111856.2	0.284	0.633	-0.889
	% in total	3.13	1.3	5.21	1.04	0.69	7.94			
4	Optical, photographic, cinematographic, measuring, checking, precision, medical or surgical instruments and apparatus; clocks and watches; musical instruments; parts and accessories thereof	760921.3	333594.5	2497129.0	1830000.9	145301.6	1234172.3	0.390	0.154	-0.789

	% in total	2.39	0.78	7.94	5.16	0.55	3.15			
5	Swords, cutlasses and similar arms and parts, scabbards and sheaths therefor	1653832.1	1634892.3	382126.3	2736292.5	507991.3	2314396.4	0.006	-0.755	-0.640
	% in total	5.19	3.82	1.22	7.72	1.93	5.91			
6	Mineral products	2036356.6	1480652.6	1440069.9	327293.1	1023886.4	3116994.6	0.158	0.630	-0.505
	% in total	6.39	3.46	4.58	0.92	3.89	7.95			
7	Live animals; animal products	1123342.2	3927499.3	347330.4	2905121.5	318311.8	732792.3	-0.555	-0.786	-0.394
	% in total	3.52	9.18	1.1	8.2	1.21	1.87			
8	Prepared foodstuffs; beverages, spirits and vinegar; tobacco and manufactured tobacco substitutes	750618.0	2561495.3	1481273.2	596317.1	1427060.8	2791019.0	-0.547	0.426	-0.323
	% in total	2.36	5.99	4.71	1.68	5.42	7.12			
9	Base metals and articles of base metal	1065399.1	3627156.4	259564.9	230943.5	1827676.5	3201185.6	-0.546	0.058	-0.273
	% in total	3.34	8.48	0.83	0.65	6.95	8.17			
10	Vehicles, aircraft, vessels and associated transport equipment	57791.1	1339249.2	1788460.8	1055851.4	1307381.1	2080152.2	-0.917	0.258	-0.228
	% in total	0.18	3.13	5.69	2.98	4.97	5.31			

Cross-Country Comparison

Criterion	Armenia (2020–2022)	Georgia (2022–2024)
Most persistent low CCA group	Meat and cereals	Misc. manufactured goods, chemicals
Level of diversification in low CCA groups	Concentrated in food, agri, chemicals	Broader: includes industrial, transport, and tech products
Export share of worst performers	Extremely low (often <0.05%)	Some groups over 5%, though with large deficits
Import dependency	Heavy and consistent	More volatile, with periodic competitiveness
Policy implication	Need for structural development in agriculture and industry	Focus on sustaining competitive sectors, reduce volatility

A comparison of the foreign trade structures of Armenia and Georgia reveals both common challenges and distinct differences stemming from their production capacities, competitiveness levels, and economic structures.

In Armenia, from 2020 to 2022, the product groups with the lowest CCA (Comparative Competitive Advantage) indicators were mostly concentrated in agricultural, food, and chemical sectors. For example, meat and edible meat offal consistently had extremely negative CCA values, nearing -1, indicating almost complete import dependency. Similar patterns are observed in cereals, fertilizers, and technical textiles, which show negligible export volumes and CCA values close to -1, demonstrating Armenia's lack of export competitiveness in these groups. Their share in total exports rarely exceeds 0.01%, while imports for these categories remain significant.

In contrast, Georgia's data from 2022 to 2024 shows a more dynamic but unstable trend. Some product groups that had positive or neutral CCA values in previous years experienced sharp declines in 2024. For instance, the "miscellaneous manufactured articles" group saw a dramatic drop in export volume and a significant increase in imports, causing the

CCA to plunge to nearly -1. Similar cases are observed in chemical products and precision instruments, which had positive CCA values in 2022–2023 but ranked among the weakest by 2024.

At the same time, several product groups in Georgia, despite having negative CCA values-accounted for a significant share of total exports (above 5%), indicating a broader but often vulnerable export base. This suggests that Georgia benefits from a relatively more diversified export structure, but with greater volatility and exposure to market fluctuations, reflecting either unstable demand or limitations in maintaining competitiveness.

Overall, Armenia faces long-term structural issues related to limited production capacity and low competitiveness, particularly in key food and industrial sectors. Georgia’s challenges are more associated with sharp shifts in export-import balances and a lack of consistency, even in product groups with considerable export volumes.

For both countries, strategic responses are necessary: in Armenia, this includes boosting domestic production and reducing dependency on imports, while in Georgia, the focus should be on enhancing the stability of export sectors and more effective management of import flows.

Conclusion

This study examined the export and import structures of Armenia and Georgia through the lens of Comparative Competitive Advantage (CCA), focusing on the product groups with the best and worst trade performance between 2020 and 2024. The results underscore significant differences and emerging patterns in the trade specialization of the two South Caucasus countries, shaped by both structural factors and economic policy directions.

Armenia's strongest trade positions lie in a few highly concentrated sectors, most notably ores, precious metals, alcoholic beverages, and tobacco products, which consistently show strong positive CCA indicators. However, this narrow specialization also points to vulnerability, as the country remains highly dependent on a limited set of raw material exports with limited value addition. Conversely, sectors such as fertilizers, cereals, meat, and chemical filaments continue to display deep and persistent comparative disadvantages, reflecting structural weaknesses in agricultural processing and industrial capacity.

Georgia, on the other hand, demonstrates a more dynamic shift in certain product categories, with a marked improvement in CCA indicators for vegetable oils, precious metals, and textile-related products in recent years. However, similar to Armenia, Georgia shows chronic negative CCA values in machinery, vehicles, plastics, and chemical products—highlighting its heavy dependence on imports in key industrial sectors.

The analysis also revealed that both countries face a significant trade deficit in high-tech and capital-intensive goods, while their competitive advantages are mostly limited to natural resources and low to medium-processed products. These trends emphasize the need for targeted industrial policies, investment in technology, and export diversification strategies.

In conclusion, while Armenia and Georgia have made progress in building comparative advantage in specific sectors, their overall foreign trade patterns remain highly imbalanced and vulnerable to external shocks. Strengthening regional cooperation, investing in value-added production, and fostering innovation and infrastructure development will be essential to improving their long-term trade competitiveness and economic resilience.

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ՀԱՅԱՍՏԱՆԻ ԵՎ ՎՐԱՍՏԱՆԻ ԱՐՏԱՀԱՆՄԱՆ ԿԱՌՈՒՑՎԱԾՔԻ ԵՎ ՄՐՑՈՒՆԱԿՈՒԹՅԱՆ ՀԱՄԵՄԱՏԱԿԱՆ ՎԵՐԼՈՒԾՈՒԹՅՈՒՆ (ՀԻՄՆԱԿԱՆ ԱՊՐԱՆՔԱՅԻՆ ԽՄԲԵՐԻ ՕՐԻՆԱԿՈՎ)

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Սույն ուսումնասիրությունը վերլուծում է Հայաստանի և Վրաստանի արտաքին առևտրի կառուցվածքների դինամիկան՝ հիմնված համեմատական մրցակցային առավելության (ՀՄԱ) ցուցիչների վրա 2020–2024 թթ. ընթացքում: Ուսումնասիրվել են տասն առավել բարձր ՀՄԱ ունեցող ապրանքային խմբերը՝ բացահայտելով երկու երկրների արտահանման կառուցվածքների հիմնական տարբերությունները: Հայաստանի առևտուրը բնութագրվում է սահմանափակ թվով ռեսուրսային ուղղվածություն ունեցող ոլորտներում՝ մասնավորապես հանքաքարերի, շլակների և մոխրի, ինչպես նաև վերամշակված գյուղատնտեսական ապրանքների (ալկոհոլային խմիչքներ, ծխախոտ) արտահանման կայուն և բարձր մրցակցային առավելությամբ: Ի տարբերություն Հայաստանի՝ Վրաստանը ցուցաբերում է աճող դիվերսիֆիկացիայի և հարմարվողականության միտում՝ արտահանման կառուցվածքում նկատվում է ավելացված արժեքով ապրանքների մրցունակության աճ, ինչպիսիք են կենդանական և բուսական ճարպերն ու յուղերը, տեքստիլը և կոշիկները: Վերլուծության արդյունքները վկայում են, որ Հայաստանը պահպանում է խորություն և կայունություն մի շարք ընտրված ոլորտներում, մինչդեռ Վրաստանը ցուցաբերում է ավելի լայն ճկունություն և նոր զարգացող ուժեղ կողմեր տարբեր արդյունաբերական ճյուղերում: Այս համեմատական դիտանկյունը արժեքավոր պատկերացումներ է տալիս Հարավային Կովկասի տարածաշրջանում առևտրային մասնագիտացման և մրցունակության զարգացման ընթացքի վերաբերյալ:

M.A. Markosyan, J. Cen

COMPARATIVE ANALYSIS OF ARMENIA AND GEORGIA'S EXPORT STRUCTURE AND COMPETITIVENESS (ON THE EXAMPLE OF THE MAIN COMMODITY GROUPS)

Բանալի բառեր. համեմատական մրցակցային առավելություն (ՀՄԱ), արտաքին առևտուր, Հայաստան, Վրաստան, արտահանման կառուցվածք, առևտրային մասնագիտացում, տնտեսական մրցունակություն, Հարավային Կովկաս, ապրանքային խմբեր, առևտրի վերլուծություն:

СРАВНИТЕЛЬНЫЙ АНАЛИЗ СТРУКТУРЫ ЭКСПОРТА И КОНКУРЕНТОСПОСОБНОСТИ АРМЕНИИ И ГРУЗИИ (НА ПРИМЕРЕ ОСНОВНЫХ ТОВАРНЫХ ГРУПП)

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В данном исследовании анализируется динамика внешнеторговых структур Армении и Грузии с точки зрения сравнительного конкурентного преимущества (СКП) в период с 2020 по 2024 годы. Основное внимание уделено десяти товарным группам с наивысшими показателями СКП, что позволяет выявить ключевые различия в экспортных профилях двух стран. Экспорт Армении характеризуется выраженным и устойчивым конкурентным преимуществом в ограниченном числе отраслей, основанных на природных ресурсах, в частности, руды, шлак и зола, а также переработанные сельскохозяйственные товары, такие как алкогольные напитки и табачные изделия. В противоположность этому, Грузия демонстрирует признаки растущей диверсификации и адаптивности экспортной структуры, с заметным улучшением конкурентоспособности товаров с добавленной стоимостью — животных и растительных жиров и масел, текстиля и обуви. Результаты исследования свидетельствуют о том, что в то время как Армения сохраняет глубину и стабильность в определённых секторах, Грузия проявляет более широкую гибкость и формирующиеся конкурентные преимущества в различных отраслях. Такой сравнительный подход предоставляет ценные сведения о развитии торговой специализации и конкурентоспособности в регионе Южного Кавказа.

Ключевые слова: сравнительное конкурентное преимущество (СКП), внешняя торговля, Армения, Грузия, структура экспорта, торговая специализация, экономическая конкурентоспособность, Южный Кавказ, товарные группы, торговый анализ.

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SUPERVISING BANKS DIGITAL TRANSFORMATION: THE SABBMDT MODEL BASED ON THE ECB DIGITALISATION ASSESSMENT FRAMEWORK

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Abstract

This study aims to enhance the supervisory assessment system of banks' digital transformation (DT), given its nascent nature. To elevate the current state-of-the-art assessment system to the level of a scientific model, the study applies theory-building methodology and the bricolage technique.

The scientific novelty of the study is the resulting SABBMDT model, which represents three main improvements over its predecessor, the European Central Bank's (ECB) digitalisation assessment system. First, the ECB's system has been enriched with the findings of the literature review on key success factors of banks' DT. Second, the model became more parsimonious after combining the original 14 criteria into the model's 7 components. Third, the study identifies and explains potential interlinkages among the model's components.

The study's main limitations include the non-systematic nature of the conducted intermediary literature review, the limitations of the bricolage technique, and the rapid pace of DT demanding continuous refinement for the model, as well as judgment-based decisions applied to criteria combinations and interlinkage identification.

Accordingly, future research should include a systematic literature review on key success factors for DT, as well as exploring potential ways to justify the criteria combination and interlinkage identification scientifically.

Keywords: Banking supervision, Digital transformation, ECB, SREP, business model sustainability.

Introduction

Technological innovations are reshaping economic activities and the banking sector is no exception. In recent years, the convergence of finance and technologies (fintech) has led to services, such as the ones offered by Apple Pay, Google Pay, WeChat, Bunq or Revolut, which have become an integral part of daily life. To maintain and enhance their competitive position in the market, banks are increasingly undergoing digital transformation (DT). DT typically occurs across the entire bank, although customers mainly observe the front-office changes. Banking institutions' DT includes, for example, customers' credit risk assessment through machine learning and alternative data [1] (e.g., could be customers' digital footprint [2]), use of scalable computational capabilities through cloud service providers [3].

Banks' DT strategies, allocated resources and managerial capabilities differ; as a result, some banks may be lagging behind their peers. Particularly, according to a quantitative study, it is small and capital-deficient banks that are more likely to lag behind in the DT race emphasizing the need to allocate adequate resources for DT [4]. It is worth noting that a bank's DT would not necessarily result in a competitive advantage but rather aims to keep pace with the new "market standard", consistent with the Resource-based view (RBV) theory. Although Beccalli's "profitability paradox" is still relevant [5] (the positive linkage of IT (~DT) investments to the bank profitability has not yet been proven empirically), another study found that successful DT at banks improves cost-efficiency since the medium term [6]. Thus, it is important to manage banks' DT efficiently, as the digital divide between banks can lead to significant business implications.

The management of banks' DT takes place at both the bank level and the supervisory level (central bank or a separate supervisory authority), with supervision focusing on the overall financial stability. This study focuses on DT management from the central bank perspective. Generally, central banks manage the banking sector's risks through regulation and supervision. In this regard, banks' DT is more suitable for supervision. In recent years, most high-level supervisory policy documents have highlighted the need for DT supervision. For example, the Basel core principles' updated document (in 2024) mentions digitalisation as a potentially significant risk for banks that can materialize over a longer-term horizon and therefore needs proper risk management processes in place [6]. In addition, a working paper from the Bank of International Settlements mentions that digitalisation in finance gives rise to strategic (business model), operational and financial stability risks [3]. This suggests that strategic risk is the primary transmission channel of digitalisation risks to banks, while operational and financial stability risks (mostly) follow it. Consequently, the DT assessment can inform subsequent operational risk assessment. Finally, the consultation paper on the revised SREP (Supervisory Review and Evaluation Process) guidelines states that digitalisation should be assessed to evaluate the impact on the banks' business strategy, execution capabilities, cost control and revenue generation under business model assessment [7]. Moreover, regarding digitalisation's impact on other SREP pillars, DT assessment insights should be considered when assessing liquidity needs in the short and medium term [7].

Within the SREP methodology, supervisory assessment of banks' DT fits best within business model (BM) sustainability assessment [8]. SREP guidelines have been widely used (especially in Europe) since their introduction in 2014. Supervisors use SREP guidelines to assess banks' risks, which results in scores per risk and, ultimately, the bank's overall score. SREP guidelines include four main pillars: business model, governance and risk management, risks to capital (i.e., credit, market, operational risks), and risks to funding and liquidity. Each pillar's weight in the overall SREP score can be divided equally (25%) or differentiated: for instance, the Central Bank of Brazil gives 40% weight to BM assessment [9]. Each banking risk is typically divided into two parts: risk level, which includes the quantitative measures, and the risk control, which assesses the governance (management) practices around the given risk. Each part typically involves three phases and is scored from one to four (one indicating low risk and 4 indicating high risk). Phase 1 includes data collection and preliminary assessment without assigning any score to the assessed risk. Phase 2 provides an automated, anchoring score based on predetermined thresholds of selected ratios that reflect most risk areas. During Phase 3, the supervisor conducts an in-depth analysis and assigns the final score, which may deviate from Phase 2's automated score within a restricted range. Regarding the BM assessment, it is divided into the assessment of BM viability (≤1y) and BM sustainability (>1y). Additionally, the SREP guidelines mention that business model (BM) sustainability assessment should also consider potential changes in the banks' operating environment [10]. In this context, fintech developments constitute a large-scale change in the banks' business environment. Moreover, since DT is a major cost and (future) revenue driver, as well as part of the European Central Bank's (ECB) 3-year supervisory priorities since 2020 [11], DT is well-suited for BM sustainability assessment.

Currently, the most transparent and advanced assessment system for banks' DT supervision has been published by the ECB in May 2024 and consists of 14 criteria covering DT management practices (risk control) [12]. Risk level assessment is less relevant for DT, since it is hard to find sector-wide, comparable DT metrics and such measures tend to reflect past performance without considering forward-looking information. Not surprisingly, since the ECB is a leader in SREP assessments, the proposed digitalisation assessment system is intended to be integrated into the SREP framework. ECB notes that the current model is not a definitive assessment model but one that will be improved over time, particularly through the addition of profitability indicators of banks' DT projects [13]. While the ultimate responsibility of strategic planning and implementation lies within the bank's board, the banking supervisor should assess its potential risks and raise those questions to the bank's management [10]. Unlike other supervisory authorities that do not disclose digitalisation assessment criteria (apparently due to confidentiality reasons), the ECB's publication serves as supervisory expectations and provides a common ground for dialogue between banks and supervisors. Moreover, a principle-based approach in the supervision of banks' DT is preferable to prescriptive rules, given the rapid pace of fintech developments [14]. To develop the digitalisation assessment criteria, the ECB has made substantial efforts in terms of DT assessment in the last few years, as DT was also among the ECB's supervisory priorities. First, in 2022, the ECB conducted a horizontal assessment (survey) among the European Union's 105 biggest banks to gather market intelligence. Next, in 2022-23, the ECB conducted 21 on-site visits and reviewed its previous DT assessment. Finally, in May 2024, the ECB published its 14 assessment criteria.

Our previous study examined two criteria of the ECB's system and enhanced them by integrating additional tools and insights [15]. In particular, the prior study shows that the recommended SWOT analysis can be further enhanced with other analysis tools, such as

PESTEL, Porter's Five Forces model, and Analytic Hierarchy Process (AHS) [15]. The study also suggested defining "digital strategy" to clarify the supervisory expectations and align with academic terminology [15]. In conclusion, the study proposed a comprehensive refinement of the ECB's system. Also, scientific enhancement can make the current ECB assessment system more grounded for further supervisory actions. In other words, scientific rationale is capable of lowering banks' resistance to new supervisory requirements, which may lead to further supervisory actions (e.g., additional capital requirement as a Pillar 2 add-on). Thus, the gap we identify is that the ECB's system may omit DT-related literature review insights because the ECB framework does not state that the system also considers DT-related academic literature. Moreover, the current system appears too complex to produce a single overall DT score, as it includes 14 criteria, and is better suited to being divided across the SREP pillars. Finally, the ECB system presents the criteria largely as standalone elements rather than interconnected ones.

To make the supervisory assessment system more grounded and rigorous, given the abovementioned gap analysis, this study suggests several improvements. First of all, we take the ECB assessment criteria as an initial point, given its current state-of-the-art nature and aim to enhance it scientifically. The identified main gaps include the absence of scientific findings in the development of the current assessment system and the fact, that the system does not specify how these criteria are related. In addition, the current assessment is largely based on gathered market intelligence, but does not broadly consider the academic insights, which could add value.

This paper is structured in the following order. The Conflict setting section articulates the research motivation and objectives. The subsequent Literature review section identifies the key success factors of banks' DT. In the "Methodology" section, we describe all the methodological steps and logic used to develop the resulting model. Next, in the "Results" section, we present the resulting model, focusing primarily on the model's improvements over its predecessor and on interlinkages among the model's components. After that, in the "Discussion" section, we present the developed model's contribution to the literature. In the end, we conclude by mentioning the study's limitations and by proposing further research areas.

Conflict Setting

This study aims to develop a scientifically grounded model for supervisory assessment of banks' business model digital transformations (hereafter, SABBMDT), which can be integrated within the SREP framework. Specifically, the paper's suggested improvements are threefold compared to its predecessor: the resulting model incorporates insights from academic and grey literature, the assessment model becomes more parsimonious, and highlights potential linkages among the model's components.

Literature review of DT key success factors

To incorporate insights from the literature into the ECB assessment system, we first conduct a literature review on key success factors (KSFs) of digital transformations, focusing on the banking sector. The literature review is summarized below with the concept matrix logic suggested by Webster and Watson [16]. For simplicity, we represent the identified opposite of banks' challenges as KSFs as well.

The five selected publications consist of three academic papers and two publications from consulting firms. The first academic paper investigates the DT challenges of a European bank [17]. The second paper highlights seven key factors affecting banks' DT through a textual analysis of questionnaires completed by 604 bank employees [18]. The third paper looks into essential components of a successful DT strategy using examples from three non-bank companies [19]. We also include relevant publications from McKinsey and Deloitte [20] [21]. Below we list and elaborate on the KSFs that were identified during our literature review.

We have grouped the observed KSFs into three main groups, namely Strategic Management, Employees and Technology. The remaining important elements have been attributed to the Other category. This arbitrary grouping has an objective to position the KSFs among themselves.

The first seven KSFs come together to make the Strategic Management group. The KSF 1 suggests that having a clear understanding of the DT framework and ensuring its alignment with business strategy helps to achieve successful DT [17] [19] [20] [21]. In addition, it encourages to have roadmap (action plan) and a strategy that is centered around customers. The KSF 2 highlights the importance of top management support [17]. The KSF 3 demands to recognize data as the organization's top priority asset as well as to have an optimal data architecture, and data governance policies and tools to derive insights from the data [19] [21]. Next, the KSF 4 relates to the flexible and innovation-driven working environment by smoothing the organization chart and investing in change management [17] [21]. Such bank-wide changes have the potential to lower the organizational level for decision-making, thus, bringing the customer feedback closer to the decision-making process and encouraging data-driven decisions. The KSF 5 suggests clearly defining the scope of responsibility for the implementation of DT: for instance, the bank can have a team of high-level management as the DT responsible body (instead of one person), as well as a supervisory body (or a committee) [17] [18] [20] [21]. The KSF 6 underlines the significance of having KPI (key performance indicators) systems in place to evaluate DT progress [20] [21]. Finally, the KSF 7 stresses the importance of ensuring effective communication in the workplace as a key driver for successful DT [18].

The next group of KSFs – Employees – consists of the KSF 8 and the KSF 9. To begin with, the KSF 8 suggests recruiting specialists with technical knowledge, as in-house developments are crucial for successful DT, as opposed to the outsourcing of the technical tasks [20] [17]. KSF 9 highlights the importance of developing and trigger employees' ability to sense and materialize opportunities. Additionally, it underlines the importance of the Chief Data Officer (CDO), which can catalyze considerable changes when assigned properly defined responsibilities [17] [19].

The KSF 10 and the KSF 11 make up the third group, named Technology. The KSF 10 demands ensuring interoperability between existing systems and reviewing business processes

[17] [19] [20]. The APIs (application programming interfaces) may play a crucial role in this regard. Regarding the KSF 11, it encourages providing the necessary technical tools and managing employees' expectations [18].

As mentioned above, all the remaining important elements have been combined under the KSF 12, which does not fall under previous categories, but forms a new one – Other. It includes leadership, project management skills, cooperation with experienced companies in DT and having not very slow changes [20] [17] [21] [19].

Finally, juxtaposing the ECB's assessment system with the literature review on KSFs of banks' DT aims to develop a comprehensive framework in which additional insights from the literature are integrated, while overlapping points support the robustness of the ECB framework and diverging points require reconsideration.

Methodology

It is worth mentioning that our study adopts a relativist ontology and a social constructionist epistemology as the study's philosophical assumptions. According to relativism, there is no single reality or truth; instead, multiple perspectives exist, because different observers may have different viewpoints [22]. This is consistent with our study because the desired model is to be used by banking supervisors to assess a bank's DT. Secondly, regarding the epistemology, our research adheres to social constructionism. This also fits the nature of our study area - the interpretation of the overall governance around banks' DT, which can be described with words rather than with numbers and tested by questions rather than by hypotheses.

First, to address the mentioned gaps between the ECB assessment system and scientific model characteristics, we apply the methodological steps of theory-building in management studies, which have been summarized by Shepherd and Suddaby [23]. While some management scientists have broadly defined the most important principles for theory qualification (e.g., Bacharach mentions falsifiability and utility as key criteria [24]), the boundary after which the work can be considered as a theory is not clear [25].

The same is also true for models in management studies. In contrast to theories, models represent less robust concepts that aim to measure and analyze some areas to support decision making rather than explaining the relationship between constructs. For instance, Porter's Five Forces model helps analyze a product's market to assess its competition pressure and potential profit rather than explaining the interplay among the model's five forces. In short, we justify the use of theory-building methodology for a model, given that theory-building approaches typically apply stricter evaluation criteria than model development.

According to Shepherd's and Suddaby's literature review of theory building in management science, the theory-building approach includes five key elements: conflict, character, setting, sequence, and plot and arc [23]. The conflict (challenging the value of an existing system) has been discussed in the introduction. Next, to distinguish our model from other frameworks in management research, we name it SABBMDT, which stands for Supervisory Assessment Model for Banks' Business Model's Digital Transformation.

Regarding time, we acknowledge that the developed model will require periodic updates as new insights emerge.

From the spatial perspective, even though our model is designed to function universally, it builds upon the ECB's system designed for the SREP framework. Hence, it fits better to the SREP adopted countries. Finally, we apply the bricolage technique, combining the starting ECB assessment system with a literature review on key success factors of banks' DT. The bricolage technique aims to combine various existing concepts from sufficiently diverse sources in a sensible way to create a theory. In our study, we acknowledge the immense work behind the ECB's assessment system; thus, we rely on it instead of starting from scratch. Next, we aim to combine it with sufficiently diverse sources. It should be noted that both the ECB's system and our intended model aim to assess how successful a bank's DT will be from a forward-looking perspective.

Hence, their criteria essentially describe the KSF of banks' DT. Thus, we conclude that a literature review on KSF of banks' DT would generate important insights for integrating the literature into the model. Given the absence of such a literature review, we conduct it as an intermediary step for our study. For the literature review, we include grey literature, in particular, relevant publications of reputable consulting firms, given the lack of relevant academic sources.

The conducted literature review on KSFs of banks' DT partly draws on the methodological steps suggested by Annarelli et al. [26], and builds upon five relevant sources. Our inclusion criteria for choosing academic papers were to be in English, to appear in "Web of Science" (ensuring high-quality content), and to be relevant for the banks' DT (based on the author's judgement). The literature review has been summarized with the logic of the concept matrix following Webster and Watson [16], and its main points are compared against and combined with the initial ECB assessment system.

For simplicity, the opposites of banks' challenges are represented as KSF. Finally, juxtaposing the ECB's assessment system with the literature review on KSFs of banks' DT aims to develop a comprehensive model, where the literature review's additional insights are integrated into the model, while overlapping points support the ECB framework and suggest areas for refinement.

Second, to make our model more parsimonious, we use scientific abstraction and combine the original 14 assessment criteria into the SABBMDT model's 7 components. Usually, when invited to improve things, people systematically default to searching for additive transformations, and consequently overlook subtractive transformations, unless reminded firmly about the latter [27].

Subtractive transformations can also help to make the model more parsimonious. As Bacharach states, the theory's purpose of a theory is to organize parsimoniously and communicate clearly [24]. To decrease the complexity of the ECB's system, we rearrange the criteria, resulting in model components' reduction. This rearrangement considers that SABBMDT is designed for BM sustainability assessment integration, contrary to its predecessor (divided across BM, governance (SREP's 2^{nd} element) and risk management (SREP's 3^{rd} element)) [12]. Here, scientific abstraction does not remove the initial criteria, but makes the model's components more compact. This approach can be interpreted as shifting complexity to the lower levels of assessment. This makes the model parsimonious while allowing expandability when needed.

During this process, three components of the SABBMDT model retained the original criteria, while the other four components hosted two original criteria and the last component combined five of them. By default, such combinations lower the combined criteria's weight in contrast to non-combined ones (non-combined criteria's weight increases from 1/14 to 1/7, while combined ones' weight either stays the same or decreases depending on how many initial criteria were combined). However, since the SREP framework takes into account the stringency of discovered shortcomings, a serious shortcoming can still materially affect the final score regardless of combinations.

Third, we explore and articulate the SABBMDT model's components' interlinkages as part of model development and in line with SREP. Although models are not always expected to explain (or prove empirically) the relationships among the model's components, the identification of interlinkages and their interplay is crucial. Moreover, the guidelines of SREP support the idea of making use of interlinkages by stating that the outcome of the BM assessment should support the assessment of all other elements of the SREP [28]. In the current study, however, we focus on interlinkages within the model rather than interlinkages across all SREP elements. We present the linkages in a matrix form with directional arrows.

Research Results

In this section, we juxtapose the intermediary literature review with the ECB assessment system to include important missing elements, then present the SABBMDT model's components and lastly, present and explain the interlinkages among the model's components. The resulting SABBMDT model's high-level structure is presented in Table 1, where the first column exhibits the seven components of the model, while the second and third columns show, respectively, the underlying ECB criteria and the main additions stemming from DT KSF's literature review. We did not observe any contradicting points against the ECB model. Meanwhile, many KSFs from the literature review align with the original ECB assessment system proving the latter's robustness. The color-coding of the second column is according to the ECB's criteria, divided into 3 groups: business model and strategy (bleached almond), governance (peach bud) and risk management (pale blue).

The intersections between the literature review insights and the ECB's system are discussed in the descriptions below. Since the original ECB's system is approximately 16 pages long, we will not reproduce it here. Instead, we will mention the resulting SABBMDT model's each component, the ECB criteria on which they are based and the key implications from the combination of the ECB's system with the literature review's KSFs (i.e., additions, contradictions and consistence). For the first component, we incorporate findings from our previous research.

The SABBMDT model's first component is "Business environment analysis and banks' digital maturity" and is based on the ECB's "Business environment" criterion. ECB explains that it is based on both external factor analysis and internal capability assessment; hence, we add digital maturity in the title to emphasize its equal importance. Moreover, KSF 10 highlights the importance of reviewing existing business processes and assessing the interoperability of current systems for the internal capability assessment.

The second component, “DT strategy formulation and definition” combines the ECB criteria “digital strategy formulation and definition” and “data governance framework”. The combination is justified because the DT strategy should be both customer-centric and data-centric (KSF 3).

Table 1

SABBMDT model, underlying the ECB’s digitalisation assessment criteria and main additions based on the conducted literature review

SABBMDT model components	ECB’s digitalisation assessment criteria (May 2024)	Additions based on the literature review on KSFs of banks’ DT and previous research
1. Business environment and bank’s digital maturity	1. Business environment	1. Integration of PESTEL, AHS, and Porter's Five Forces [15] 2. Business process review and check on existing systems’ interoperability (KSF 1)
2. Digital Transformation (DT) strategy formulation and definition	2. Digital strategy formulation and definition	3. Chief Data Officer with clearly defined responsibilities (KSF 9) 4. Having a Roadmap (KSF 1) 5. Top Management support (KSF 2) 6. Cooperation with DT experienced companies and not very slow changes (KSF 12)
	12. Data governance framework	
3. Execution Capabilities	3. Execution Capabilities	7. Recruitment of technical knowledge staff instead of outsourcing (KSF 8)
4. KPI system	4. KPI system	-
5. Coordinating and Communicating of DT strategy implementation	5. Coordination and steering of digital initiatives	1. Investment needs in corporate culture change to develop the DT mindset (KSF 4) 2. Develop and trigger employees' ability to sense and materialize opportunities (KSF 9) 3. Leadership (KSF 12)
	9. Digitalisation risk culture	
4. Monitoring and Reporting	6. Monitoring and Reporting	-
	7. The management body in its supervisory function/non-executives’ capacity to challenge	
5. Involvement of internal control functions	8. Internal control functions’ involvement in decision-making on digitalisation	-
	10. Assessment of critical dependencies	
	11. Risk identification	
	13. Risk modelling	
	14. Update of the risk appetite framework, the risk management framework and key risk indicators	

In terms of alignment, KSF 1's requirement for the DT strategy to be aligned with the business strategy matches the ECB's explanation. In addition, KSF 9 suggests that having a CDO with clear responsibilities is important for successful DT. Moreover, KSF 1 recommends that the DT strategy should have a defined roadmap, and KSF 2 adds the importance of top management support, which can be added to the second component, given that DT starts from the strategy formulation. Lastly, KSF 12 suggests that the DT strategy should avoid overly slow changes and cooperation with companies that have successful DT experience.

The third component, "Execution capabilities" builds upon the ECB's eponymous criterion. KSF 5 highlights the importance of rationalized and justified cost planning, given that DT expenses tend to surpass initial levels, which supports the ECB's suggestion to have a cost-benefit analysis as a rationale for budgeting the costs. Moreover, conducting a cost-benefit analysis for DT projects will help identify more profitable projects and facilitate the prioritization process.

Such cost planning should, in principle, include the remuneration of staff with technical knowledge, who, according to KSF 8, are recommended to be recruited rather than outsourced. Additionally, a clear allocation of resources can be observed through the separation of Information Technology (IT) and DT budgets. Such a distinction can signify that the bank has a clear view on cost planning as IT expenses tend to be "to-run" costs, while DT requires "to-change" costs.

Next, the fourth component, "KPI system" largely relies on the ECB's criterion with the same name. It aligns with KSF 6. Moreover, it serves as a bridge between DT strategy formulation, execution, monitoring and reporting; therefore, it is no surprise that this particular component is highly linked with other components (discussed later in the section).

The fifth component "Coordination and communication of DT strategy implementation" builds upon ECB's criteria "coordination and steering of digital initiatives" and "digitalisation risk culture".

Regarding this component, the literature review focuses on changes in corporate culture. First, KSF 4 highlights the importance of investments changing the corporate culture to develop a DT mindset and to make the organizational structure flatter to push the decision-making to lower levels, where decisions would be supported by data. KSF 7 is in line with the ECB's elaboration on the importance of effective communication. At the same time, KSF 9 suggests that corporate culture should encourage employees to sense and materialize opportunities (innovations). Moreover, according to KSF 11, the bank should manage employees' expectations and equip them with the necessary technical tools. Lastly, KSF 12 highlights the importance of leadership and project management skills, which are relevant for the coordination of DT.

The last two components do not intersect with the literature review, but do combine in seven original criteria at once. In particular, the sixth component "Monitoring and Reporting" combines the ECB's "Monitoring and Reporting" and "The management body in its supervisory function/non-executives' capacity to challenge" criteria. And finally, the seventh component “Involvement of internal control functions” combines the internal control function-related five criteria (see Table 1).

These combinations are justified given their overall purpose: the challenging follows the reporting and monitoring procedure, while the remaining criteria directly assess the internal control functions’ participation in a bank’s DT. Even though such a combination might decrease the contribution of internal control assessment to the overall DT score, this approach is justified for two reasons.

Table 2

The interlinkages within the SABBMDT model

	1	2	3	4	5	6	7
1							
2	↓ DT objectives						
3	↓ The rationale for a cost-benefit analysis	Bringing rationale for innovative projects ↑					
4		↓ KPIs and remuneration policies					
5				Involvement in KPI development ↕			
6		↓ data governance policies	↓ clearly defined budget and projects	↕ to include the KPI system	↓ assigning responsibilities		
7		identification of DT risk ↑		Involvement of KRIs ↕			

First, SABBMDT is integrated into the BM sustainability assessment and should be broadly aligned with the performance of risk management functions, which is assessed in more depth under the SREP elements “corporate governance” and “risks to capital”. Second, depending on the severity of the identified issues, the supervisor can always adjust the component’s weight in the overall DT score.

Finally, after the integration of literature review insights in the model and making it parsimonious, we explore the interlinkages of the model's components. The latter are depicted in Table 2, where the "down" arrow means that an issue in the header row translates into (influences) the intersecting row's component. An arrow "up" means that the given row's component influences the header row's component.

In some cases, where components are likely to influence each other, we use two-sided arrows. For simplicity, we write the components' order number (consistent with Table 1's ordering) instead of their names. It is to be noted that the presented interlinkages do not include the influence of DT assessment on overall SREP elements and do not comprise an exhaustive list of all potential linkages, but an attempt to capture the most prominent linkages through reasoning.

First, shortcomings in the first component are likely to cause problems for the second and the third components. This is because the DT strategy and cost-benefit analysis largely rely on the business environment analysis and the bank's internal capabilities. Next, the issues in the second component, "DT strategy formulation and definition" will carry over to the KPI system (component 4) and related remuneration policies, as the KPI system should be entirely based on and interconnected with the strategy. Moreover, the data governance policies are likely to influence the monitoring and reporting capabilities of the bank (component 6). At the same time, the robustness of cost-benefit analysis influences prioritization and, therefore, the coherence of the DT strategy. Also, the DT risk identification assessed under component 7 influences the formulation of the DT strategy (component 2). Third, issues in DT projects' operational plans (component 3) will negatively affect the monitoring and reporting (component 6). Regarding the KPI system (component 4), it is closely linked to both DT strategy coordination (component 5), monitoring and reporting (component 6), as well as risk indicators (component 7), where the first two use the progress or profitability tracking KPIs, while the third one provides additional measures from a DT risk perspective. Lastly, DT strategy coordination influences the Monitoring procedure by assigning reporting responsibilities.

Discussion

In this study, we enhance the existing state-of-the-art supervisory assessment system of banks' DT by applying the steps and principles of theory-building methodology in management studies. We aim to extend the academic discussion around the supervision of banks' DT started by our prior study, considering its importance, evolving nature of the topic (DT), as well as the applied scientific technique (bricolage).

This study's main contribution to the literature is the SABBMDT model, which is scientifically more grounded than its predecessor. First, we apply the theory-building methodology proposed by Shepherd and Suddaby and enhance the existing assessment system with an intermediary literature review on KSFs of banks' DT using the bricolage technique. Second, we make the model more parsimonious by combining the original ECB assessment criteria into the model's components, thus lowering the model's high-level complexity. Third, we articulate potential linkages among the model's components.

This study has three main limitations. The main limitation concerns the conducted intermediary literature review. Ideally, the model enhancement would require a systematic literature review on the topic; however, given the study's primary interest, the conducted literature review was deemed sufficient for the purpose of the study. Nevertheless, we can notice that the conducted literature review didn't cover all components of the model, indicating areas for further improvement. The second limitation is due to the applied bricolage technique, which does not produce a definitive model. In addition, the rapid pace of fintech developments requires continuous updating. Finally, the third limitation concerns the judgment-based changes applied to the model and the exploration of interlinkages among the model's components, because the criteria grouping and the identification of interlinkages were conducted by a single researcher.

Conclusion

This study contributes to enhancing the supervisory assessment of banks' DT. More specifically, the study explores the key success factors and challenges during banks' DT and incorporates them into the existing state-of-the-art assessment system suggested by the ECB. Given the importance of the topic and the fast-changing nature of fintech developments, future research is needed to refine the model.

Therefore, we propose the following research agenda. First, given the growing importance of DT, we suggest conducting a systematic literature review on key success factors and/or challenges of digital transformation, which can later be applied to different sectors, including the banking sector. Second, we propose exploring ways to provide a more rigorous justification for the grouping of assessment criteria into model components, as well as the identification and explanation of interlinkages among the model's components.

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SUPERVISING BANKS DIGITAL TRANSFORMATION: THE SABBMDT MODEL BASED ON THE ECB DIGITALISATION ASSESSMENT FRAMEWORK

ԲԱՆԿԵՐԻ ԹՎԱՅԻՆ ՓՈԽԱԿԵՐՊՄԱՆ ՎԵՐԱՀՍԿՈՂՈՒԹՅՈՒՆ. ԵԿԲ-Ի ԹՎԱՅՆԱՑՄԱՆ ԳՆԱՀԱՏՄԱՆ ՉԱՓԱՆԻՇՆԵՐԻ ՎՐԱ ՀԻՄՆՎԱԾ ԲԲՄԹՓՎԳ ՄՈԴԵԼԸ

Հ.Հ. Մանուկյան

ՀՀ պետական կառավարման ակադեմիա

Տվյալ հետազոտությունը նպատակ ունի բարելավել բանկերի թվային փոխակերպման (ԹՓ) վերահսկողական գնահատման համակարգը՝ հաշվի առնելով վերջինիս նոր բնույթը: Առկա ամենաառաջադեմ գնահատման համակարգը գիտական մոդելի վերածելու նպատակով կիրառվել են տեսության մշակման մեթոդաբանություն և բրիկոլաժի տեխնիկա:

Հետազոտության գիտական նորույթը ստացված ԲԲՄԹՓՎԳ մոդելն է, որը ենթադրում է երեք հիմնական բարելավումներ Եվրոպական կենտրոնական բանկի՝ (ԵԿԲ) թվայնացման գնահատման համակարգի նկատմամբ: Նախ, ԵԿԲ-ի գնահատման համակարգը հարստացվել է բանկերի ԹՓ հաջողության գործոնների գրականության ակնարկի բացահայտումներով: Այնուհետև մոդելի բարդությունը նվազեցվել է՝ սկզբնական 14 չափանիշները մոդելի յոթ բաղադրիչներում ներառելու միջոցով: Վերջում բացահայտվում և մեկնաբանվում են մոդելի բաղադրիչների միջև հնարավոր կապերը:

Հետազոտության հիմնական սահմանափակումները պայմանավորված են իրականացված միջանկյալ գրականության ակնարկի ոչ համակարգային լինելով, կիրառված բրիլոկաժի տեխնիկայի սահմանափակումներով, ուսումնասիրվող ԹՓ ոլորտի արագ փոփոխվող բնույթով, ինչպես նաև մոդելի պարզեցման և կապերի բացահայտման դատողական մոտեցմամբ: Հետևաբար, որպես ապագա հետազոտական ուղղություններ առաջարկվում են ԹՓ գործընթացների հաջողության գործոնների շուրջ համակարգային գրականության ակնարկի իրականացումը, ինչպես նաև մոդելի տարրերի միավորումների և կապերի բացահայտման՝ գիտականորեն հիմնավոր մեթոդական քայլերի ուսումնասիրությունը:

Բանալի բառեր. բանկային վերահսկողություն, թվային փոխակերպում, ԵԿԲ, SREP, բիզնես մոդելի կայունություն:

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SUPERVISING BANKS DIGITAL TRANSFORMATION: THE SABBMDT MODEL BASED ON THE ECB DIGITALISATION ASSESSMENT FRAMEWORK

НАДЗОР ЗА ЦИФРОВОЙ ТРАНСФОРМАЦИЕЙ БАНКОВ: МОДЕЛЬ SABBMDT, ОСНОВАННАЯ НА СИСТЕМЕ ОЦЕНКИ ЦИФРОВИЗАЦИИ ЕЦБ

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Целью настоящего исследования является совершенствование системы надзорной оценки цифровой трансформации банков с учетом ее новизны. Для того чтобы поднять существующую систему оценки до уровня научной модели, в исследовании применяется методология построения теории и метод бриколажа.

Научная новизна исследования заключается в полученной модели SABBMDT, которая представляет собой три основных улучшения по сравнению со своей предшественницей - системой оценки цифровизации Европейского центрального банка (ЕЦБ). Во-первых, система ЕЦБ была обогащена результатами обзора литературы по ключевым факторам успеха цифровой трансформации банков. Во-вторых, модель стала более лаконичной после объединения исходных 14 критериев в 7 компонентов модели. В-третьих, исследование выявляет и объясняет потенциальные взаимосвязи между компонентами модели.

Основные ограничения исследования включают несистематический характер проведенного промежуточного обзора литературы, ограничения метода бриколажа и быстрые темпы цифровой трансформации, требующие постоянного совершенствования модели, а также принятие решений на основе экспертной оценки при сочетании критериев и выявлении взаимосвязей. Таким образом, будущие исследования должны включать систематический обзор литературы по ключевым факторам успеха цифровой трансформации, а также изучение потенциальных способов научного обоснования сочетания критериев и выявления взаимосвязей.

Ключевые слова: банковский надзор, цифровая трансформация, ЕЦБ, SREP, устойчивость бизнес-модели.

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IMPROVING THE EFFICIENCY OF SUPERVISORY ACTIVITIES IN THE BANKING SECTOR THROUGH THE IMPLEMENTATION OF INFORMATION TECHNOLOGY AND ARTIFICIAL INTELLIGENCE

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Abstract

In the context of rapid digitalization and the emergence of new financial technologies in the market, the effectiveness of supervisory activities is becoming a critical task for the central banks (CBs) of the countries that emerged from the former Soviet Union.

This study proposes a concept for the digital transformation of supervision using SupTech (Supervisory Technology) – a technological solution aimed at enhancing analytical potential and automating business processes.

Based on an analysis of the current supervisory structure for the Central Bank of the Republic of Uzbekistan, the most problematic aspects (low automation, fragmentation of information systems (IS), and high reliance on manual labor) were identified, which are characteristic of many other central banks in the CIS countries. Strategic development directions were also identified based on international practices and the concept of data-centric supervision. The proposed practical solution includes the development of a SupTech platform with an integrated liquidity stress testing module [1-4].

The architecture of the proposed platform covers the entire data processing cycle: from collection, integration, and quality assurance to modeling and visualization of the obtained results.

To address the identified issues in the supervisory activities of the Central Bank, modern tools and technologies are used: MinIO, PostgreSQL, Apache Airflow, Prophet, Random Forest, XGBoost, Grafana, Prometheus, and WhyLogs [5-8].

The developed model predicts the LCR indicator, assesses the risks of regulatory violations, and generates management reports in the required format. High reliability, transparency, and compliance with compliance requirements are ensured. Visualization and automatic notifications support the prompt response of supervisory units.

The implementation of SupTech will improve the quality and accuracy of supervision, reduce decision-making time, enhance regulatory responsiveness, and increase trust in the country's financial system. The developed concept offers a technological foundation for the transition from reactive to risk-based and predictive supervision, consistent with international standards and the challenges of the digital economy [9, 10].

Keywords: automation of supervisory activities, bank liquidity, supervision, SupTech.

Introduction

The modern banking sector of former Soviet Union countries faces the need to transform supervisory mechanisms in the context of economic digitalization and the emergence of new financial technologies based on information technology (IT). Central banks in CIS countries strive to build a reliable, sustainable, and innovative financial system.

However, the effectiveness of supervision is often limited by low levels of automation, fragmented IT infrastructure, and a high burden on manual business processes. This study aims to develop a concept for the implementation of SupTech – a set of technologies that improve the efficiency and analytical capacity of central bank supervisory activities [9].

The procedures used in this study include an analysis of the current IT environment of the Central Bank of the Republic of Uzbekistan, the architecture of the SupTech platform, the development of a liquidity stress testing model, and an assessment of its applicability [1].

The result is a comprehensive technological solution covering the entire supervisory data processing cycle—from collection to visualization and management decision-making.

At the current stage, the development of the banking sector has become particularly relevant for the CIS countries due to the transition to a market economy in the early 1990s, characterized by the transformation of existing and the emergence of new lending institutions, without which the successful accumulation, redistribution, and use of funds in the country's circulation is impossible.

Credit institutions play a crucial role in the development of an effectively functioning national financial market, redistributing the money supply to meet the demand for cash, a fundamental factor in the growth of a market economy.

The Central Bank ensures the development of a modern and reliable financial sector in the country, facilitating the transition to a more developed economy based on the service and manufacturing sectors, and achieving sustainable growth.

Today, in a rapidly changing environment, achieving the reliability of a country's financial system without strong and innovative supervisory capacity is not easy. To ensure financial stability and protect the interests of depositors, creditors, and shareholders, the Central Bank acts as a supervisory authority. The Central Bank's supervisory activities include verifying the compliance of credit institutions' decisions and actions with laws regulating banking activities and Central Bank regulations.

The Central Bank's supervisory functions are established in the Law "On Banks and Banking Activities" and are carried out by the Banking Supervision Committee.

The Central Bank's goal is to create conditions to prevent financial instability in commercial banks and to monitor their compliance with established requirements.

The purpose of the Central Bank's supervisory activities is to maintain the stability of the country's banking system, protect the interests of depositors and creditors, ensure the effective functioning of the financial market, and ensure financial security [10].

The Central Bank's supervisory powers include:

- mandatory rules for banks regarding the conduct of banking operations, accounting, and statistical reporting, as well as the preparation of annual reports;
- mandatory rules for microcredit organizations regarding the conduct of financial operations, accounting, and reporting;

- mandatory rules for pawnshops and credit bureaus regarding the conduct of their activities and operations.

The Central Bank has the right to:

- receive and verify reports and other documents from banks, microcredit organizations, pawnshops, and credit bureaus, request and receive information on their activities, including transactions;
- demand clarification on the information received;
- inspect the activities of banks and microcredit organizations, their branches, and affiliated entities, as well as the activities of pawnshops and credit bureaus, and apply sanctions to violators;
- establish requirements for internal audit of banks and credit bureaus;
- establish requirements for classifying the quality of banks' assets and creating adequate reserves to cover potential asset losses;
- determine the conditions and procedure for writing off bad assets;
- send banks, microcredit organizations, pawnshops, and credit bureaus binding orders to eliminate any violations identified in their activities;
- request and receive information on the financial position and reputation of bank shareholders in the event that they acquire a portion of the authorized capital exceeding the amount established by law;
- impose qualification requirements on the managers, board members, and chief accountants of banks and their branches, and the heads of executive bodies of microcredit organizations and credit bureaus.

The implementation of recent reforms in the financial sector of the Republic of Uzbekistan was extremely significant and effectively marked the beginning of a new era on the path to the development of a reliable and competitive financial sector. In light of these transformations, it is expected that financial institutions will increasingly change their business models and diversify their financial services. Technological innovation is also driving significant transformations in the financial services industry. At the same time, the COVID-19 pandemic has presented additional challenges for financial sector participants in response to social distancing measures. In this context, effective supervision is one of the conditions and factors for ensuring transparency and stability in the financial sector.

Analysis of Existing Problems

External environmental factors include the growth of new market players, the increasing complexity of business models, the changing risk landscape, new regulatory requirements, rising consumer and investor expectations, and compliance with industry standards.

Key internal factors include:

- increased complexity of data analysis due to the lack of specialized tools, limited primarily to descriptive analytics (what happened) versus predictive (what might happen) and prescriptive analytics (how to avoid or optimize it);
- low productivity and low reliability of reporting processes (timeliness of information receipt and high effort required to obtain it);
- low data quality (insufficient completeness, integrity, timeliness, accuracy, consistency/uniformity), lack of standardization and consistency in data collection (e.g., different formats – printed, Excel, PDF files;
- different data transmission channels – email, reporting applications);
- increased efforts to organize data preparation (manual checks, manual aggregation, dealing with high error rates, etc.);
- the need for human resources with a mixed skill profile, both in their core professions and in IT, to better assess the new risks posed by IT-enabled financing business models.

The regulator and financial market participants are implementing IT in many areas of their activities, both to improve the efficiency of internal procedures and for digital interactions with each other. Rational use of IT reduces time and costs, improves the quality of services provided, ensures efficient interaction, and reduces risks.

Within the framework of the use of modern IT by the regulator and supervised organizations, two areas can be distinguished – SupTech and RegTech [9].

SupTech (Supervisory Technology) – technologies used by the regulator to improve the effectiveness of control and supervision of the activities of financial market participants.

RegTech (Regulatory Technology) – technologies used by financial organizations to improve the effectiveness of compliance with the regulator's requirements.

The objectives of implementing SupTech solutions are:

- improving the quality of data analytics by optimizing data collection, storage, and processing;
- increasing the efficiency and speed of risk identification in financial institutions;
- freeing up employee time to address issues requiring professional (motivated) judgment and expertise.

The objectives of implementing RegTech solutions are:

- automation and standardization of business processes related to ensuring and fulfilling regulatory requirements;
- reducing risks and costs, increasing the accuracy of compliance with regulatory requirements;
- increasing the speed of fraud detection and response.

As regulatory reporting challenges continue to worsen, central banks are increasingly adapting their internal systems to provide more effective supervisory capabilities, in particular by implementing solutions in the field of regulatory and supervisory technologies.

SupTech – supervisory technologies – is the use of technological innovations by supervisory authorities to improve the efficiency of supervisory activities. SupTech encompasses technologies and solutions that enable regulators to improve efficiency and reorganize internal supervisory processes to align them with the digital transformation of the financial sector, process data faster and in larger volumes, automate business processes, analyze key risks, and identify trends.

International experience shows that SupTech is becoming a strategic priority for an increasing number of supervisory authorities, as it helps streamline administrative processes, reduce supervisory costs, improve decision-making, minimize risks, and maintain financial stability.

The use of SupTech solutions by supervisory authorities has a positive impact on the activities of supervised organizations, as it reduces the workload of supervisory authorities, improves reporting processes, helps reduce compliance costs, etc.

Possible technologies used may include:

- data collection, processing, and storage technologies;
- artificial intelligence;
- natural language processing;
- data visualization technologies;
- robotics;
- cloud services;
- platform solutions. The objective of this work is to develop a concept and justify the need for an innovative solution to improve the efficiency of the Central Bank's supervisory activities.

Objectives:

- Analysis of existing problems in supervisory activities;

- Justification of the need to implement an information system into the Central Bank's supervisory business processes;
- Conduct research and develop a design solution based on agreed-upon business requirements;
- Define technical requirements for the developed information system and its components;
- Work plan, schedule, and Gantt chart for the development and implementation of the information system;
- Evaluation of the effectiveness of the developed system.

The relevance of this work is linked to the Central Bank's ability to achieve its strategic goals of creating a robust financial system based on inclusiveness, innovation, efficiency, and sustainable economic growth through the transformation of oversight using IT.

It is believed that artificial intelligence and machine learning can significantly improve the capabilities of human intelligence in descriptive, diagnostic, predictive, and prescriptive analysis. Examples of use include identifying patterns in business performance in terms of liquidity and profitability, which enables more proactive regulatory intervention.

The main areas of application for SupTech solutions are:

- risk analysis and management;
- improving financial market access procedures;
- identifying illegal activities in the financial market;
- improving information exchange with financial institutions and other entities;
- implementing a data-centric approach;
- automating the supervision of financial market participants;
- improving the efficiency of the Central Bank's handling of appeals from individuals and legal entities.

A practical solution is to develop a digital office concept based on workflow management, case management, and collaboration platforms.

Let's list the main stages of implementing an information system to automate the Central Bank's supervisory business processes:

- Analysis of the supervisory authority's readiness for the information system implementation;
- Assessment of the existing infrastructure;
- Formation of a project team;
- Development of an implementation business plan, specifying timelines, required resources, and considering personnel training needs;
- Implementation and testing of the solution, its installation, configuration, and integration with existing information systems;
- Maintenance and servicing throughout the lifecycle after its commissioning.

Methodology

The key categories of the study are:

Supervision — the process of monitoring financial institutions to ensure their resilience and compliance with regulatory requirements;

SupTech — the use of modern digital technologies (machine learning, ETL pipelines, visualization) for automation and analytics in supervisory practice;

Data-centric supervision — an approach focused on the use of primary, granular data rather than aggregated reporting;

Stress testing — a method for assessing the resilience of financial institutions to market and behavioral shocks.

The study is applied in nature and is based on an engineering and analytical approach. The following basic tools were used:

- Analysis of current regulatory practices of the Central Bank;
- Development of a SupTech platform architecture with data integration, modeling, and visualization modules;
- Construction of a liquidity stress testing model using the Prophet, Random Forest, and XGBoost algorithms;
- Data quality testing using Great Expectations;
- Organization of monitoring and visualization through Prometheus and Grafana.

The choice of tools for automating supervisory business processes was driven by their scalability, open source nature, and successful use in banking practices in other countries.

Research Results

Thus, thanks to the development, implementation, and commercialization of the information system for automating the Central Bank's supervisory activities, we have achieved the following results:

- a multi-level architecture for the SupTech platform with a liquidity stress testing module was developed;
- a 30-day LCR forecast and a five-month deposit outflow scenario were implemented;
- target accuracy indicators were achieved: RMSE < 0.005, AUC > 0.90;
- automatic notification of deviations and regulatory violations was configured;
- API channels for transmitting calculations and reports were implemented;
- incident logging, model retraining, and internal audit were organized.

It is worth noting that SupTech can dramatically improve the efficiency of supervision, reduce dependence on manual data processing, and ensure earlier risk identification. The developed solution complies with international standards (Basel III, ISO 27001, NIST CSF) and successfully replicates approaches tested by many regulators in developed countries [1].

Compared to the traditional oversight model, SupTech provides a more comprehensive and timely risk picture, enables the implementation of target and stress scenarios, and the development of informed oversight measures.

Conclusions

The study demonstrated that the introduction of SupTech into the Central Bank's supervisory practices can serve as a catalyst for the transition to proactive and analytically sound regulation.

The developed system for stress testing the capital liquidity of commercial banks represents a practice-oriented solution capable of enhancing the resilience of the financial sector, transparency, and accuracy of supervision, and also creating a foundation for the further implementation of risk management information systems.

The results obtained in the study are applicable to regulators in various countries interested in the digitalization of supervision.

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ԲԱՆԿԱՅԻՆ ՈԼՈՐՏՈՒՄ ՎԵՐԱՀՍԿՈՂ ԳՈՐԾՈՒՆԵՈՒԹՅԱՆ ԱՐԴՅՈՒՆԱՎԵՏՈՒԹՅԱՆ ԲԱՐՁՐԱՑՈՒՄ՝ ՏԵՂԵԿԱՏՎԱԿԱՆ ՏԵԽՆՈԼՈԳԻԱՆԵՐԻ և ԱՐՀԵՍՏԱԿԱՆ ԲԱՆԱԿԱՆՈՒԹՅԱՆ ՆԵՐԴՐՄԱՆ ՄԻՋՈՑՈՎ

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Արագընթաց թվայնացման և ֆինանսական նոր տեխնոլոգիաների շուկա մուտք գործելու պայմաններում վերահսկող գործունեության արդյունավետությունը դառնում է կենսական կարևորության խնդիր նախկին ԽՍՀՄ տարածքում ձևավորված երկրների Կենտրոնական բանկերի (ԿԲ) համար: Սույն հետազոտության շրջանակում առաջարկվում է վերահսկողության թվային տրանսֆորմացիայի հայեցակարգ՝ SupTech (Supervisory Technology) տեխնոլոգիական լուծման կիրառմամբ, որը նպատակ ունի բարձրացնել վերլուծական ներուժը և ավտոմատացնել բիզնես գործընթացները: Ուզբեկստանի Հանրապետության Կենտրոնական բանկի վերահսկողության գործող կառուցվածքի վերլուծության հիման վրա բացահայտվել են մի շարք խնդրահարույց ասպեկտներ՝ ավտոմատացման ցածր մակարդակ, տեղեկատվական համակարգերի (ՏՀ) ֆրագմենտացվածություն, ձեռքի աշխատանքի նկատմամբ բարձր կախվածություն, որոնք բնորոշ են նաև ԱՊՀ երկրների բազմաթիվ Կենտրոնական բանկերին: Միաժամանակ սահմանվել են զարգացման ռազմավարական ուղղություններ՝ հիմնված միջազգային փորձի և տվյալակենտրոն վերահսկողության (data-centric supervision) հայեցակարգի վրա: Առաջարկվող գործնական լուծումը ներառում է SupTech հարթակի մշակումը՝ ներկառուցված իրացվելիության սթրես-թեստավորման մոդուլով [1–4]:
Առաջարկվող հարթակի ճարտարապետությունը ընդգրկում է տվյալների մշակման ամբողջական ցիկլը՝ հավաքագրումից, ինտեգրումից և որակի վերահսկումից մինչև մոդելավորում և ստացված արդյունքների վիզուալացում:
Բացահայտված վերահսկող խնդիրների լուծման համար կիրառվում են ժամանակակից գործիքներ և տեխնոլոգիաներ՝ MinIO, PostgreSQL, Apache Airflow, Prophet, Random Forest, XGBoost, Grafana, Prometheus և WhyLogs [5–8]:
Մշակված մոդելը կանխատեսում է LCR ցուցանիշը, գնահատում է նորմատիվների խախտման ռիսկերը և ձևավորում է կառավարչական հաշվետվություններ անհրաժեշտ ձևաչափով: Ապահովվում են բարձր հուսալիություն, թափանցիկություն և

համապատասխանություն կոմպլայենսի պահանջներին: Վիզուալիզացիան և ավտոմատ ծանուցումները նպաստում են վերահսկող ստորաբաժանումների օպերատիվ արձագանքին: SupTech-ի ներդրումը կբարձրացնի վերահսկողության որակը և ճշգրտությունը, կնվազեցնի որոշումների ընդունման ժամանակը, կուժեղացնի կարգավորողի ակտիվությունը և կբարձրացնի վստահությունը երկրի ֆինանսական համակարգի նկատմամբ: Մշակված հայեցակարգը առաջարկում է տեխնոլոգիական հիմք՝ անցում կատարելու ռեակտիվ վերահսկողությունից դեպի ռիսկակենտրոն և կանխատեսողական վերահսկողություն, որը համապատասխանում է միջազգային չափանիշներին և թվային տնտեսության մարտահրավերներին [9, 10]:

Բանալի բառեր. վերահսկող գործունեության ավտոմատացում, բանկերի իրացվելիություն, վերահսկողություն, SupTech:

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ НАДЗОРНОЙ ДЕЯТЕЛЬНОСТИ В БАНКОВСКОЙ СФЕРЕ ЗА СЧЁТ ВНЕДРЕНИЯ ИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ И ИСКУСТВЕННОГО ИНТЕЛЛЕКТА

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В условиях стремительной цифровизации и появления новых финансовых технологий на рынке эффективность надзорной деятельности становится критически важной задачей для Центрального банка (ЦБ) стран, образовавшихся из бывшего СССР.

В рамках настоящего исследования предлагается концепция цифровой трансформации надзора с использованием SupTech (Supervisory Technology) — технологического решения, направленного на повышение аналитического потенциала и автоматизацию бизнес-процессов.

На основе проведенного анализа текущей структуры надзора для ЦБ Республики Узбекистан, выявлены наиболее проблемные аспекты (низкий уровень автоматизации, фрагментация информационных систем (ИС), высокая зависимость от ручного труда), которые характерны и многим другим ЦБ стран СНГ, а также определены стратегические направления развития на основе международных практик и концепции data-centric supervision. Предложенное практическое решение включает разработку SupTech-платформы со встроенным модулем стресс-тестирования ликвидности [1- 4].

Архитектура предлагаемой платформы охватывает весь цикл обработки данных: от сбора, интеграции, проверки качества до моделирования и визуализации полученных результатов.

A. A. Vartanyan, A.M. kizi Kenjeeva

IMPROVING THE EFFICIENCY OF SUPERVISORY ACTIVITIES IN THE BANKING SECTOR THROUGH THE IMPLEMENTATION OF INFORMATION TECHNOLOGY AND ARTIFICIAL INTELLIGENCE

Для решения выявленных проблем по надзорной деятельности ЦБ используются современные инструменты и технологии: MinIO, PostgreSQL, Apache Airflow, Prophet, Random Forest, XGBoost, Grafana, Prometheus и WhyLogs [5- 8].

Разработанная модель прогнозирует показатель LCR, оценивает риски нарушения нормативов и формирует управленческие отчёты в необходимом формате. Обеспечены высокая надёжность, прозрачность и соответствие требованиям комплаенса. Визуализация и автоматические уведомления поддерживают оперативную реакцию надзорных подразделений.

Внедрение SupTech повысит качество и точность надзора, сократит время принятия решений, повысит активность регулятора и доверие к финансовой системе страны. Разработанная концепция предлагает технологическую основу для перехода от реактивного к риск-ориентированному и предиктивному надзору, соответствующему международным стандартам и вызовам цифровой экономики [9, 10].

Ключевые слова: автоматизация надзорной деятельности, ликвидность банков, надзор,
SupTech

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RESEARCH OF MODEL FOR INCREASE LEARNING SPEED OF A NEURAL NETWORK IN THE WINDOWS OPERATING SYSTEM

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Abstract

The paper presents the effect of the processor time quantum size on the training speed of neural network. The Windows Server 2019 operating system was chosen as the operating environment, where the training speed of the neural network was analyzed with various system settings. A convolutional neural network was used as the object of research.To speed up the training of the neural network, a method based on the use of automatic command merging and a decrease in the processor time quantum size was used. The obtained results allow optimizing the training processes of neural networks in multitasking environments, ensuring an increase in the overall performance of the system. An analysis of the relationship between the parameters of planning computing resources and the training speed was carried out, and recommendations for optimizing systems taking into account the specifics of neural networks were proposed.

Keywords: batching, clockers, hyperparameter, convolutional neural network, failover cluster, operating environment, processor time quantum.

Introduction

The performance of neural network training heavily depends on the hardware. However, in addition to the architectural solutions of the equipment - the number of CPU (Central Processing Unit) and GPU (Graphics Processing Unit), the type and volume of long-term HDD/SSD (Hard Disk Drive, HDD/Solid-State Drive, SSD) and short-term (Random Access Memory, RAM) data storage devices, the transfer rate of the system bus, a parameter that often remains outside the attention of researchers of systems using machine learning (ML) - the quantum of processor time[1] - has a significant impact on the speed and stability of training. The processor time quantum is especially important in situations where the processor resources are divided between several tasks, such as when training a neural network under conditions of limited access to dedicated computing nodes. In such a case, the length of the processor time quantum determines how often the training task will have access to the processor and how smoothly sequential computations will be processed. If the time quantum is too small, the processor will frequently switch between tasks, creating

[1] Processor time quantum - this parameter defines the minimum time interval during which the processor allocates resources to perform a specific task.

additional load on the system due to context switches. This may lead to decreased performance and increased training time of the neural network. On the other hand, too large a time quantum may cause delays in processing I/O tasks. Thus, proper configuration of the processor time quantum becomes critical for optimal use of computing resources. For different operating environments, the value of the processor time quantum is different.

The values of the processor time quantum for the Windows operating systems (OS) that served as the platform for this research presented in Tab. 1 [1-3].

Table 1

The value of the quantum of processor time for Windows operating systems

Operating system	Quantum of time processor (ms)	Note
Windows 7	15–30	Depends on power mode. The scheduler is focused on the balance of interactivity and performance.
Windows 10	15–30	Uses a scheduler with dynamic quantum management. The interval changes depending on the system activity.
Windows 11	15–30	Similar to Windows 10, optimized for new processors and hybrid architectures.
Windows Server 2012, 2016	120	Optimized for server tasks with minimal context switching frequency.
Windows Server 2019	120	Expanded support for containers and cloud solutions, optimization for long-term calculations.
Windows Server 2022	120	Security and performance improvements for large server workloads.

When training neural networks on computers united in clusters, it is important to correctly configure the processor time quantum depending on both the type of neural network being trained and its parameters/hyperparameters[2].

A pressing task is to determine the optimal time quantum value to increase the learning/response speed in parallel computations, such as distributed training of a neural network (networks) on several nodes. Researchers in ML systems offer various solutions to this problem [6-9] each of which has certain limitations. However, the method of accelerating the training of neural networks by changing the automatic combination of commands (batching[3]) with a parallel change in the quantum of the processor has not been considered.

The novelty of the research lies in the application of methods for changing the batching size and the parameters of the quantum of the processor to increase the speed of training of a convolutional neural network.

Conflict Setting

It is necessary to obtain the optimal value of the processor time quantum for a given operating system when training a neural network.

[2] Hyperparameters of a neural network are parameters of a ML model that are set before training begins. Hyperparameters, unlike parameters, are unchanged during the training process [4, 5].

[3] Batching (ML) is changing multiple weights in different layers of neural networks with one command.

Discussion

By changing the values of the processor time quantum for a given OS, as well as modifying the batching value for the convolutional neural network code, obtain the most effective value for the learning speed.

Boundary condition

- at a given point in time, only one neural network is trained,
- training was carried out based on only the CPU, on computers united in a cluster.

Experimental procedures

A computing cluster[4] (Fig. 1) consisting of 12+1 computers was deployed under Windows Server 2019 Standard (build 17763). The Failover cluster [10] and Hyper-V [11] roles are activated and configured in the OS. The computing cluster is configured using the SAN (Storage Area Network, SAN) architecture.

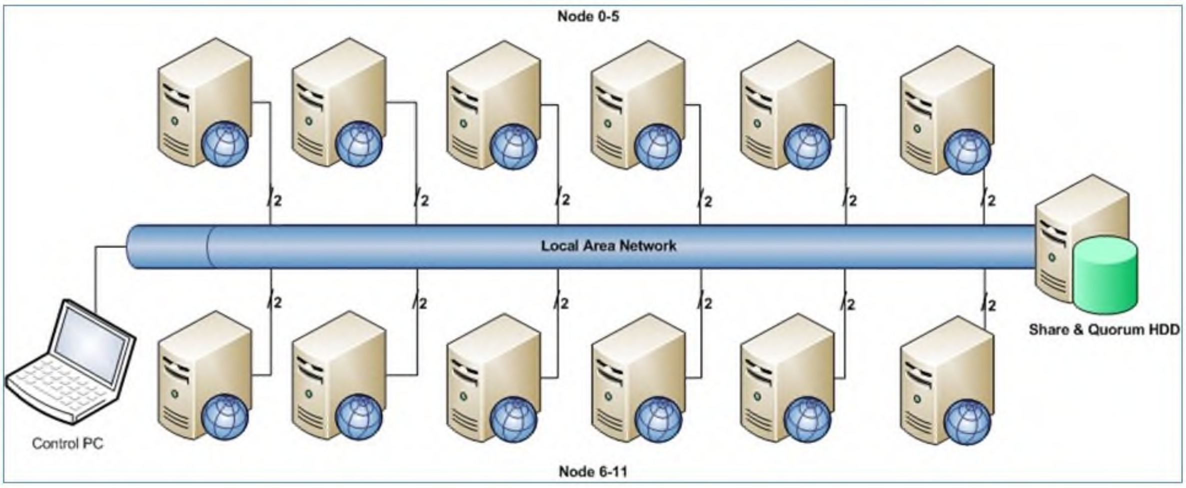

Fig. 1 Diagram of the computing cluster

The computers are connected two local networks (control and data transmission) using two network interfaces. A common storage is implemented on a separate computer and a quorum disk is activated. The OS has Tensor Flow software [12] installed, in which a convolutional neural network is deployed. The processor time quantum was changed according to the description presented in [13]. The control of the change in the quantum of processor time for the Windows OS was carried out by the *Clockres* software [14, 15].

Research was carried out with different values of the hyperparameters of the convolutional neural network. Fig. 2 show the modified values of the processor time quantum for the Windows Server 2019 OS used in the research.

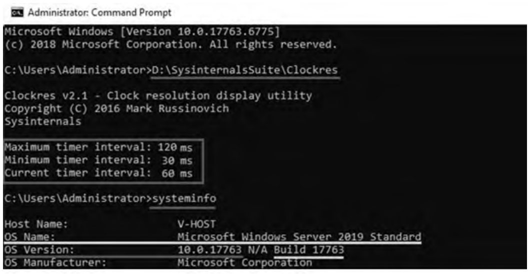

Fig. 2 Processor time quantum value for Windows Server 2019 OS

The processor time quantum was changed in the range of 100÷30 ms (the value of 30 ms corresponded to the upper value of the client version of Windows OS). In all cases, testing was

[4] Parameters of a single computer: CPU-i9, RAM 16Gb.

performed with the security software disabled and the OS updated to the current state [16]. The batching of processes was changed separately based on the developed script.

Training was carried out in three stages:

- training with the standard value of the processor time quantum with the batching change script disabled,
- training with the changed value of the processor time quantum, with the batching change script disabled,
- training with the changed value of the processor time quantum with the batching change script enabled.

The learning rate was compared with the learning rate at the standard, upper value of the processor time quantum (120 ms) for the given OS.

The reliability of the output values of the trained neural network was checked by comparing it with the a priori known output values of the neural network trained in the research [17] (reference network).

The comparison was performed by WinMerge software [18].

Research Results

The research results change in learning rate at different values of the processor time quantum are presented in Tab. 2. The dependence of the learning rate on the value of the processor time quantum is shown in Fig. 3.

Table 2

Results of the research on changes in learning speed

OS	Value of quantum of processor time (ms)	Convolutional neural network learning rate increment*(%) / confidence (%)			Convolutional neural network learning rate increment*(%) / confidence (%)		
		Number of layers			Number of layers		
		3	5	7	3	5	7
Windows Server 2019	100	0.6/97	0.5/98	0.2/95	0.9/96	0.7/92	0.4/97
	90	0.8/95	0.4/90	0.4/88	0.8/98	1.0/92	0.8/93
	80	1.3/96	0.9/91	0.6/81	1.7/95	1.6/88	0.8/90
	70	1.8/85	1.3/90	0.8/88	2.5/92	1.9/90	1.2/87
	60	2.4/97	1.6/85	0.8/83	3.7/89	2.6/91	1.8/89
	50	3.7/96	2.3/88	0.9/85	4.3/91	2.9/94	1.9/92
	40	3.2/94	2.1/90	1.1/82	4.0/88	2.3/89	1.5/89
	30	2.6/92	1.9/89	1.0/82	3.7/91	2.2/92	1.3/90

* learning speed with batching disable,
** learning speed with batching enable.

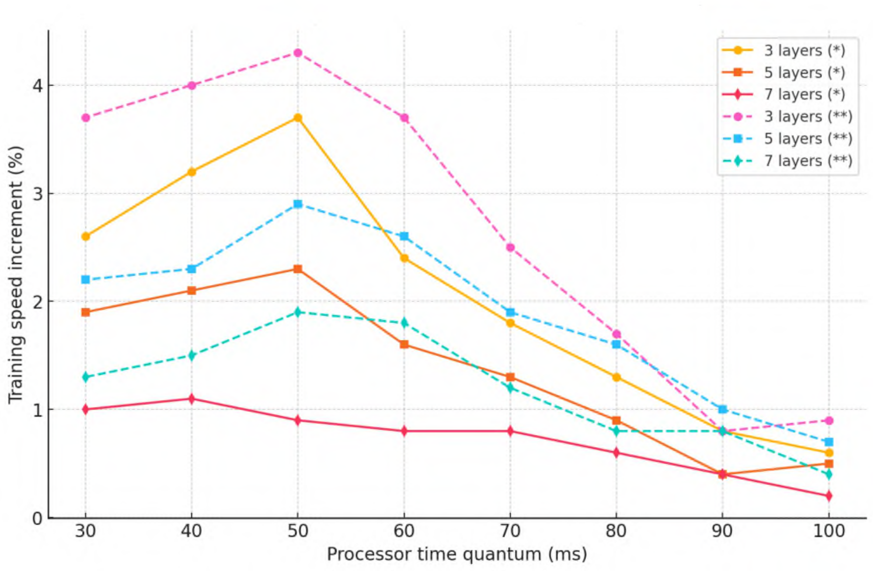

Fig. 3 Dependence of the learning rate on the quantum of processor time

Based on the experiment, the following conclusions can be drawn:

- the optimal value of the processor time quantum for Windows Server 2019 OS when training a convolutional neural network is in the range of (40÷60) ms,
- the increase in the learning rate at the optimal value is (3.7÷4.3)%,
- reliability, with an increase in the learning rate, decreases on average by (3÷13)%.

Conclusion

The paper considers a model for accelerating the training of a convolutional neural network based on a hardware cluster with a variable value of the quantum of processor time and software optimization. The change in the quantum of processor time was controlled by the *Clockres* utility from the *Sysinternals* software package.

It was determined that in all cases, when the quantum of processor time is reduced, the training speed increases, with a parallel decrease in the reliability of output values. Using a large quantum of time allows ensuring the stability of long-term computing processes.

For deep networks (7+ layers), it is recommended to use server OS. For small and medium networks with less intensive calculations, client OS or server OS with a minimum quantum of processor time may be optimal.

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ՆԵՅՐՈՆԱՅԻՆ ՑԱՆՑԻ ՈՒՍՈՒՑՄԱՆ ԱՐԱԳՈՒԹՅԱՆ ԲԱՐՁՐԱՑՄԱՆ ՄՈԴԵԼԻ ՀԵՏԱԶՈՏՈՒԹՅՈՒՆ WINDOWS ՕՊԵՐԱՑԻՈՆ ՀԱՄԱԿԱՐԳՈՒՄ

Թ.Վ. Ջամղարյան
Հայաստանի ազգային պոլիտեխնիկական համալսարան

Հոդվածում ներկայացված է պրոցեսորի ժամանակի քվանտի չափի փոփոխման ազդեցությունը նեյրոնային ցանցի ուսուցման արագության վրա: Փորձերն անցկացվել են Windows Server 2019 Standard օպերացիոն համակարգի միջավայրում: Հետազոտության արդյունքները ցույց են տալիս, որ բատչինգի մեթոդի կիրառումը և պրոցեսորի ժամանակի քվանտի չափը նվազեցնելն արագացնում է փաթույթային նեյրոնային ցանցի ուսուցումը հաշվողական ռեսուրսների ավելի ռացիոնալ բաշխման շնորհիվ: Ստացված արդյունքները թույլ են տալիս լավարկել նեյրոնային ցանցերի ուսուցման գործընթացները բազմաֆունկցիոնալ միջավայրերում:

T.V. Jamgharyan

RESEARCH OF MODEL FOR INCREASE LEARNING SPEED OF A NEURAL NETWORK IN THE WINDOWS OPERATING SYSTEM

Բանալի բառեր. *հիպերպարամետր, օպերացիոն միջավայր, փաթույթային նեյրոնային ցանց, պրոցեսորի ժամանակի քվանտ, batching, clockres,* failover cluster*:*

ИССЛЕДОВАНИЕ МОДЕЛИ ПОВЫШЕНИЯ СКОРОСТИ ОБУЧЕНИЯ НЕЙРОННОЙ СЕТИ В ОПЕРАЦИОННОЙ СИСТЕМЕ WINDOWS

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В статье рассматривается влияние размера кванта времени процессора на скорость обучения нейронных сетей. В качестве операционной среды выбрана операционная система Windows Server 2019, где анализировалась скорость обучения нейронной сети при различных настройках системы. Для ускорения обучения нейронной сети использовался метод на основе применения автоматического совмещения команд и уменьшение размера кванта времени процессора. Проведен анализ взаимосвязи между параметрами планирования вычислительных ресурсов и скоростью обучения, а также предложены рекомендации по оптимизации систем с учётом специфики работы нейронных сетей.

Ключевые слова: гиперпараметр, операционная среда, квант времени процессора, сверточная нейронная сеть, batching, clockres, failover cluster.

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