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BUSINESS & "INDUSTRY 4.0"
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Using Digital Twins in the Engineering Industry: A Comprehensive Overview

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Abstract— Digital twin technology has rapidly evolved into a foundational pillar of modern engineering practice. By creating high-fidelity, data-driven virtual replicas of physical systems, digital twins enable continuous monitoring, predictive analytics, and advanced optimization throughout the lifecycle of assets. This extended article expands on the conceptual, technical, and practical dimensions of digital twins, providing deeper insights into architectures, data frameworks, integration strategies, real-world case studies, economic implications, and emerging research directions.

KEYWORDS— DIGITAL TWIN, SMART ENGINEERING, INDUSTRY 4.0, PREDICTIVE ANALYTICS, IOT, SIMULATION, DIGITAL TRANSFORMATION, CYBER-PHYSICAL SYSTEM

S

I. Introduction

A Digital Twin (DT) is a virtual replica of a physical asset, process, or system. It serves as a dynamic, continually updated digital counterpart that mirrors the characteristics, behavior, and state of its physical twin in real-time. This dynamic connection is established through sensors, the Internet of Things (IoT), and data analytics, enabling seamless, bidirectional data flow between the physical and virtual worlds. The concept, which originated in the aerospace industry, has evolved significantly with the advent of Industry 4.0, becoming a cornerstone for smart manufacturing, predictive maintenance, and optimized operations across various sectors [1].

Key Components of a Digital Twin:

- **Physical Twin:** The actual physical asset, system, or process.
- **Virtual Twin:** The digital model of the physical twin, including its geometric, behavioral, and analytical representations.
- **Digital Threads:** The communication channels and data flows that link the physical and virtual entities, enabling real-time data exchange and synchronization [mdpi.com].
- **Data:** Information collected from sensors, historical logs, and other sources, which feeds the virtual twin and drives its intelligence.
- **Analytics & AI Models:** Algorithms and machine learning models that process data within the virtual twin to generate insights, predictions, and recommendations.

Advantages of Digital Twins:

- **Real-time Monitoring and Diagnostics:** Provides continuous oversight of physical assets, allowing for immediate identification of issues.
- **Predictive Maintenance:** Anticipates equipment failures before they occur, reducing unplanned downtime and maintenance costs. Studies show potential reductions of 30-50% in downtime and 20-35% in maintenance costs [2].
- **Process Optimization:** Allows for the simulation of various scenarios to identify the most efficient operating parameters, leading to improved productivity and energy efficiency.
- **Design and Prototyping:** Enables virtual testing and refinement of products or systems before physical production, accelerating development cycles and reducing costs.
- **Risk Mitigation:** Simulating potential failures or operational changes in a virtual environment helps identify and address risks without impacting physical operations.
- **Enhanced Decision-Making:** Provides data-driven insights that support more informed and strategic decisions.

II. Digital twins in manufacturing

Manufacturing is one of the most prominent sectors benefiting from Digital Twin technology. DTs enable manufacturers to create virtual models of production lines, machinery, and products, leading to significant improvements in efficiency, quality control, and responsiveness [3].

Applications:

- **Real-time Structural Health Monitoring (SHM):** DTs, integrated with Industry 4.0 principles and edge computing, can monitor the structural integrity of manufacturing facilities and equipment in real time. This allows for predictive anomaly detection and significant reductions in maintenance costs, downtime, and energy consumption. One study reported a 42.1% reduction in maintenance costs, 31.1% in downtime, and 23.2% in energy intensity [4].
- **Predictive Maintenance:** DTs analyze sensor data from industrial machinery to predict potential failures, allowing for scheduled maintenance and preventing costly breakdowns. This shifts maintenance from a reactive to a proactive approach.
- **Process Optimization:** By simulating various production scenarios, DTs help fine-tune machine settings, material flow, and overall production processes to maximize throughput and minimize waste. Siemens' Amberg Electronics Plant, for example, uses a virtual replica of its factory to simulate operations, identifying bottlenecks before they impact actual production.
- **Quality Control:** DTs can predict product quality based on real-time manufacturing parameters, ensuring consistency and reducing rejection rates. In a metalworking facility, implementing a digital twin led to a 30% reduction in material waste and a 40% decrease in the rejection rate of milled parts [5].

- **Supply Chain Optimization:** Digital twins can model complex supply chains, allowing companies to simulate disruptions and optimize logistics.

Challenges in Implementation:

- **Integration Complexity:** Integrating diverse systems like SCADA, CMMS, ERP, and IoT platforms is a significant hurdle.
- **Data Quality Issues:** Ensuring high-quality, synchronized, and contextualized data from multiple sources is crucial for the accuracy of the virtual twin.
- **Model Drift:** Digital twins can become less accurate over time as equipment ages or conditions change, necessitating continuous validation and retraining of models.

Table 1: Comparison of Digital Twin Architecture Types in Manufacturing [6]

Approach	Best For	Accuracy	Performance & Notes
Physics-Based	New equipment, safety-critical assets	90–98%	Build time: 16–24 weeks. Requires domain experts and specialized simulation software. High cost but extremely accurate.
Data-Driven (ML)	Equipment with rich sensor history	75–88%	Build time: 8–12 weeks. Fast to deploy, but retraining required when conditions change. Struggles with unseen scenarios.
Hybrid	Production environments, complex systems	85–95%	Build time: 12–18 weeks. Balances physics + ML accuracy. Complex to maintain; needs both engineering and data-science teams.
Rule-Based	Simple assets, clear failure thresholds	60–75%	Build time: 4–6 weeks. Quick to implement but limited predictive capability and adaptability.

Digital twins allow the creation of a virtual model of a production system that simulates its real-world operation. These models allow the analysis of the impact of various changes on energy efficiency and the optimization of processes without the need for physical intervention. Digital twins provide a detailed view of the system behavior in real time and help identify areas with high energy consumption, see Fig. 1 [7]. In addition, they allow the testing of different strategies to reduce consumption and improve system performance.



Fig.1 Digital Twin as a Service (DTaaS) in Industry 4.0 [7]

Top use cases of digital twins in manufacturing

Factory design and layout – Optimize machine layouts, assembly flows, employee interactions, and more by spatially mapping factories.

Robotics simulation – Build fundamentally safer systems by training robots in simulated environments.

Operator training – Increase the efficiency of knowledge transfer with immersive, interactive training applications that maximize safety and reduce costs.

Monitoring, guided maintenance and repair – Transform routine, time-consuming procedures into seamless processes with remote-enabled AR technologies [8].

III. Medical Digital Twins (Digital Twins in Healthcare)

The concept of digital twins is extending into healthcare, creating "patient digital twins" or "human digital twins." These are virtual models of individual patients, organs, or even biological systems, built from various data sources.



Fig.2 Digital twin of human body [13]

Applications:

- **Personalized Medicine:** Creating a digital twin of a patient based on their medical history, genetic data, lifestyle, and real-time physiological data allows for highly personalized diagnoses and treatment plans.

- **Drug Discovery and Development:** Simulating drug interactions and efficacy on virtual organs or patient models can accelerate the drug development process and reduce the need for extensive animal testing.

- **Surgical Planning and Simulation:** Surgeons can practice complex procedures on a patient's digital twin, refining techniques and minimizing risks before actual surgery.

- **Chronic Disease Management:** Digital twins can continuously monitor patients with chronic conditions, predict exacerbations, and adjust treatment protocols proactively.

- **Organ-on-a-Chip and Body-on-a-Chip Systems:** These micro-physiological systems offer a physical representation that can be twinned digitally to study disease progression and drug responses more effectively.

IV. Digital Twins in Automotive

The automotive industry leverages digital twins throughout the entire vehicle lifecycle, from design and manufacturing to operation and maintenance [9].

Applications:

- **Vehicle Design and Development:** Creating digital twins of car components, subsystems, or even entire vehicles for virtual prototyping, crash testing, and aerodynamic simulations, significantly reducing physical prototyping costs and time.

- **Manufacturing Process Optimization:** Similar to general manufacturing, DTs are used to optimize assembly lines, robot movements, and quality control in automotive production. An example includes optimizing paint shop processes [maintenanceonline.org].

- **Predictive Maintenance for Vehicles:** Digital twins of individual vehicles can monitor their performance in real-time, predicting wear and tear on components like engines, brakes, or tires, and recommending maintenance before failures occur.

- **Autonomous Driving Simulation:** DTs create realistic virtual environments for testing autonomous vehicle software under various conditions, enhancing safety and accelerating development.

- **Fleet Management:** Managing fleets of vehicles through their digital twins allows for optimized routing, fuel efficiency, and maintenance scheduling.

V. Digital Twins in Energy

The energy sector uses digital twins to enhance the efficiency, reliability, and sustainability of power generation, distribution, and consumption. Energy companies generate a wealth of data, especially as operations are increasingly outfitted with Internet of Things (IoT) sensors, high-definition cameras with artificial intelligence (AI) capabilities, and more. Digital technologies like real-time 3D can visualize this data to provide right-time insights, better-informing decisions around production, maintenance, safety and security, and optimization [10].

Applications:

- **Power Plant Optimization:** Digital twins of power plants (e.g., thermal, nuclear, renewable) optimize operational parameters, predict equipment failures, and improve energy output.

- **Grid Management:** Creating digital twins of entire power grids helps analyze load distribution, predict outages, and manage renewable energy integration more effectively.

- **Renewable Energy Management:** DTs can optimize the performance of wind turbines or solar farms by predicting maintenance needs, adjusting operational settings based on weather conditions, and forecasting energy output.

- **Oil and Gas Exploration and Production:** Digital twins of oil rigs, pipelines, and drilling equipment monitor their integrity, optimize extraction processes, and predict maintenance requirements in harsh environments.

- **Energy Efficiency in Buildings:** Used in conjunction with smart cities, digital twins of buildings can monitor energy consumption, optimize HVAC systems, and reduce overall energy waste.

Top use cases of digital twins in energy:

Design visualization and collaboration – Walk through sites before they are built by creating immersive experiences from BIM data.

Learning, training and safety – Transform job-critical learning and training into interactive, immersive environments across key scenarios.

Field service – Enhance quality, reliability, and speed of service while reducing error with AR-assisted maintenance and empower your employees by putting all the information they need right before their eyes.

Site operations and maintenance – Get insight into the design, management and performance of assets, while tracking your sites' status remotely in real-time with a digital twin of any facility, pipeline, or physical asset [11].

VI. Digital Twins in Smart Cities

Smart cities harness digital twin technology to create comprehensive virtual models of urban environments, enabling better planning, management, and resource allocation [12].

Applications:

- **Urban Planning and Development:** Simulating the impact of new infrastructure projects, traffic flows, and zoning changes before physical construction.

- **Traffic Management:** Real-time digital twins of traffic systems help optimize signal timings, manage congestion, and respond to incidents more efficiently.

- **Environmental Monitoring:** Monitoring air quality, noise levels, and waste management systems, allowing city planners to implement targeted interventions.

- **Public Safety and Emergency Response:** Simulating disaster scenarios and optimizing emergency response strategies.

- **Infrastructure Management:** Monitoring the health of bridges, roads, and utilities, enabling predictive maintenance and extending asset lifespan.

- **Building Energy Optimization:** As mentioned in the energy section, digital twins of buildings contribute to overall city-wide energy efficiency [13].

Researchers collected academic publications that contain digital twin as a keyword for 5 years period. Among these academic articles, top digital twin use cases were found for urban spaces and smart cities.

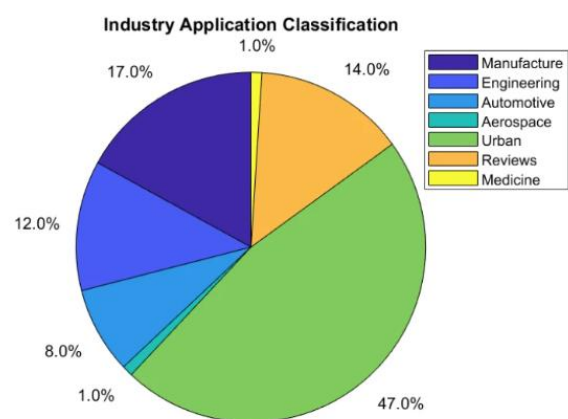


Fig.3 The publications on digital twin by use case/ application [13]

VII. Human Digital Twins

While often overlapping with "Medical Digital Twins," Human Digital Twins specifically refer to highly detailed, holistic virtual replicas of individual human beings. This goes beyond just organs to encompass a complete biological, physiological, and even behavioral model [14].

Applications:

- **Personalized Health and Wellness:** Offering highly customized health advice, dietary plans, and exercise regimes based on a person's unique digital twin.

- **Aging Simulation:** Modeling the effects of aging on an individual's body to provide proactive health interventions.

- **Virtual Clinical Trials:** Conducting clinical trials on populations of human digital twins, potentially speeding up drug development and reducing ethical concerns.

- **Performance Optimization (e.g., Athletes):** Creating digital twins of athletes to optimize training regimens, prevent injuries, and improve performance.

- **Prosthetics and Implants Design:** Designing and testing personalized prosthetics or medical implants in a virtual environment to ensure perfect fit and functionality.

VIII. Siemens Digital Twins: Specific Applications

Siemens is a pioneer and a leading provider of Digital Twin solutions, offering a comprehensive portfolio that spans across various industries. Their approach often integrates mechanical, electrical, and software aspects into a single, cohesive virtual model [15].

Specific Applications & Platforms:

- **Xcelerator Portfolio:** This integrated portfolio includes software for product design, manufacturing engineering, and production operations, all centered around the concept of digital twins. It covers CAD (Computer-Aided Design), CAE (Computer-Aided Engineering), PLM (Product Lifecycle Management), and MES (Manufacturing Execution Systems).
- **Product Digital Twin:** Siemens enables companies to create a comprehensive digital twin of a product, from its initial design concept through engineering, simulation, and eventual realization. This twin allows for virtual testing, performance prediction, and iterative design improvements.
- **Production Digital Twin:** This involves creating a digital twin of the entire manufacturing process, including factory layouts, production lines, machines, and automation systems. This allows for simulation of production flow, optimization of machine utilization, and predictive maintenance of manufacturing assets. This is exemplified by their Amberg Electronics Plant, which operates at extremely high quality and automation levels due to its advanced digital twin implementation [maintenanceonline.org].
- **Performance Digital Twin:** Focuses on monitoring and analyzing the real-world performance of products and production systems once they are in operation. Data from real-time sensors feeds back into the digital twin, allowing for continuous optimization, predictive maintenance, and informing future product design cycles.
- **MindSphere:** Siemens' industrial IoT-as-a-service solution that connects physical assets to their digital twins. It enables data collection, analysis, and generation of actionable insights for various industrial applications.
- **Predictive Maintenance Solutions:** Siemens uses digital twins to provide advanced predictive maintenance for a wide range of industrial equipment, from gas turbines to industrial robots, significantly extending asset lifespan and reducing unplanned downtime.
- **Logistics Simulation:** Utilizing digital twins to simulate and optimize complex logistics and supply chain networks, particularly in large-scale manufacturing and distribution.

IX. conclusion

Digital twins are reshaping the engineering landscape by enabling a deeper integration of physical and digital systems. Their ability to provide real-time insights, predictive capabilities, and optimization strategies makes them indispensable in modern engineering.

As technologies such as AI, IoT, and 5G continue to evolve, digital twins will become more intelligent, scalable, and widely adopted. Organizations that invest in this technology today will be better positioned to navigate the complexities of tomorrow's engineering challenges.

Overall, simulation-based Digital Twins, combined with Artificial Intelligence, have strong potential to transform operational decision support in manufacturing. Realizing this vision, however, will require addressing technical challenges alongside building trust through explainability, systematic validation, and domain-specific adaptation. Bridging these barriers represents an active and promising research frontier at the intersection of simulation, data-driven intelligence, and automation. If these challenges are met, simulation-

based Digital Twins can evolve from case-specific prototypes into widely adopted tools that enable faster, more transparent, and more reliable decision-making across industries [16].

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Hybrid AI architecture for autonomous structural inspection using multimodal llms

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Abstract: This paper proposes a hybrid artificial intelligence architecture for autonomous structural inspection using unmanned aerial vehicles, multimodal large language models and image embeddings. A UAV is an unmanned aerial vehicle; in this paper it denotes a drone carrying imaging sensors for close visual inspection of infrastructure assets. Images are uploaded to Azure cloud storage, transformed into multimodal evidence and evaluated by a Microsoft Foundry agent under deterministic risk rules. A preliminary simulated benchmark shows improved recall, fewer false alerts and shorter engineer review time while preserving auditable human-supervised decisions.

Keywords: UAV INSPECTION, STRUCTURAL HEALTH MONITORING, MULTIMODAL LLM, IMAGE EMBEDDINGS, MICROSOFT AZURE, MICROSOFT FOUNDRY, PREDICTIVE MAINTENANCE, INDUSTRY 4.0

1. Introduction

Autonomous inspection of bridges, retaining walls, industrial halls and utility structures is becoming a practical requirement for Industry 4.0 infrastructure. Traditional visual inspection remains valuable, but it is slow, subjective and difficult to repeat at high temporal frequency. UAV imagery and computer vision increase coverage, yet pure classification can lose context: a crack on a cosmetic layer is not equivalent to a crack crossing a load-bearing zone. Recent work on UAV inspection, crack detection and

multimodal reasoning shows that effective systems need both visual perception and evidence-based interpretation [1-5].

The proposed solution treats inspection as a multimodal reasoning problem. A drone captures geo-referenced images; image embeddings retrieve visually similar cases; and a multimodal LLM evaluates the current image together with structural metadata, historical trend and inspection rules. The final decision is not made by free text alone. Risk scores, work orders and alarms are accepted only after deterministic validation and, for high-risk cases, engineer approval.

Azure + Microsoft Foundry solution architecture

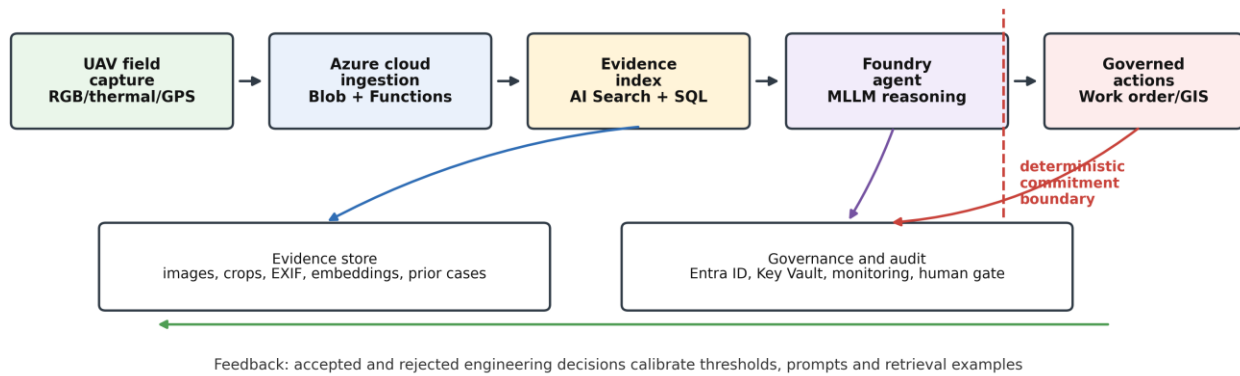


Fig. 1. Azure and Microsoft Foundry solution architecture for autonomous structural inspection.

2. Preconditions and means for resolving the problem

2.1. Inspection task and data model

The inspected asset is represented as structural zones: deck, column, beam, connection, facade panel, corrosion-prone steel detail and non-structural surface. Every captured frame stores EXIF time, GPS/RTK position, camera angle, flight segment, asset identifier and expected member type. Detected anomaly classes are crack, corrosion, spalling, moisture staining, deformation trace, exposed reinforcement and normal surface. The system stores an evidence package containing the original image, crop, embedding, retrieved neighbours, LLM explanation, risk score and final reviewer decision.

2.2. Preliminary Microsoft stack

The experimental setup is implemented as a Microsoft cloud stack. Azure Blob Storage receives the UAV images, and an event-based Azure Function is triggered when new files arrive [9]. The function normalizes metadata, creates thumbnails and sends images for embedding. Azure AI Vision multimodal embeddings place images and text queries in a compatible vector space [6]. Azure AI Search performs vector and hybrid retrieval over prior defects and normal

examples [7,8]. Microsoft Foundry coordinates the agent, tracing, evaluation and governed reasoning workflow [10-12].

Table 1. Preliminary experimental setup.

Item	Configuration	Purpose
Image set	2400 source images; 70/15/15 split	Validation and test
UAV	20 MP RGB; 1.5-3.0 m distance	Close inspection
Cloud	Blob, Event Grid, Functions	Automated ingestion
AI	Vision embeddings + LLM agent	Detection and explanation
Review	Engineer gate for $R > 0.70$	Safety and audit

3. Solution of the examined problem

3.1. Cloud ingestion and multimodal reasoning

The workflow has five stages. First, the UAV mission planner produces overlapping image strips for repeatable coverage. Second, Event Grid and Azure Functions create a low-latency path between field acquisition and cloud analysis. Third, the embedding service maps every crop and text label into a vector space. Fourth, Azure AI Search retrieves similar historical defects and nearby normal examples. Fifth, a Microsoft Foundry agent receives the current image, metadata and retrieved evidence, then returns a structured JSON proposal: anomaly class, severity, confidence, explanation, cited evidence and recommended action.

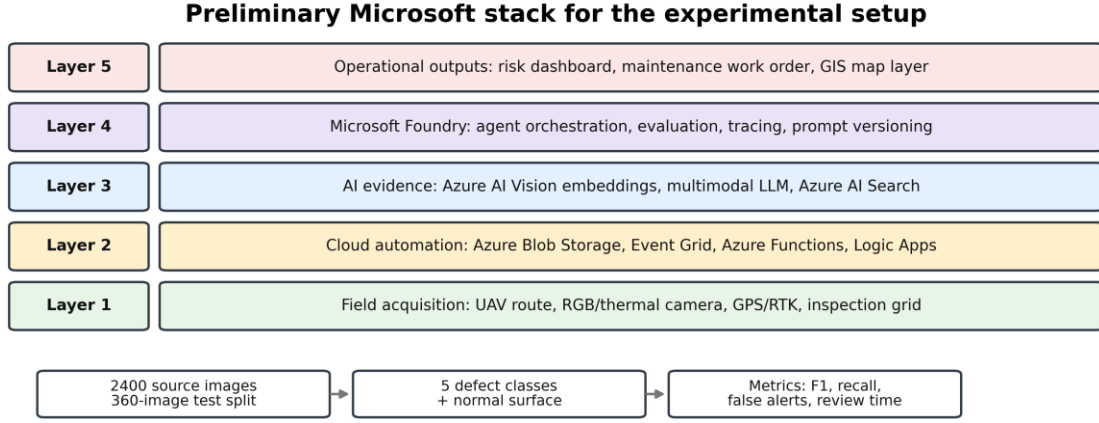


Fig. 2. Preliminary Microsoft stack used for the simulated experiment.

3.2. Evidence and risk governance

The LLM does not directly approve maintenance actions. The hybrid risk score is calculated by transparent control logic: $R = 0.35p_a + 0.25s + 0.20c + 0.20h$, where p_a is visual anomaly probability, s is structural severity, c is contextual exposure and h is historical trend. Low-risk cases are archived for monitoring; medium-risk cases are queued for engineer review; high-risk cases create an urgent inspection task only after validation of required evidence.

Evidence-bound risk decision loop

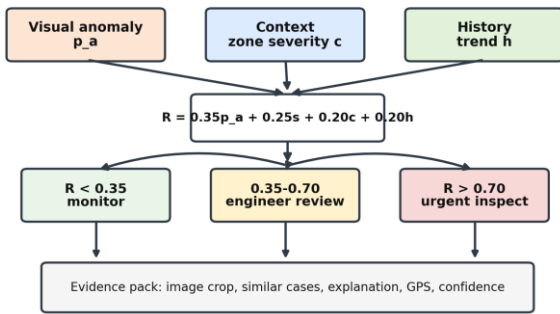


Fig. 3. Evidence-bound risk decision loop.

Table 2. Risk classes and preventive action rules.

Risk R	System action	Engineer action
< 0.35	Store trend evidence	No immediate action
0.35-0.50	Monitor next mission	Check if trend increases
0.50-0.70	Queue review pack	Confirm defect severity
> 0.70	Create urgent task	On-site inspection

4. Results and discussion

A realistic simulation was carried out before field deployment. The test set contains class imbalance similar to real inspections: 65% normal surfaces, 15% cracks, 8% corrosion, 6% spalling, 4% moisture traces and 2% exposed reinforcement. Service latencies were modelled with parallel Azure Function execution and cached vector retrieval. The values are design-validation estimates, not undisclosed production measurements.

Table 3. Simulated benchmark results on 360 test images.

Method	Prec.	Recall	F1	FA/100	p95
CNN only	0.812	0.760	0.785	12.8	1.4s
Embedding	0.862	0.840	0.850	8.4	2.1s
Hybrid	0.892	0.910	0.900	5.7	4.6s

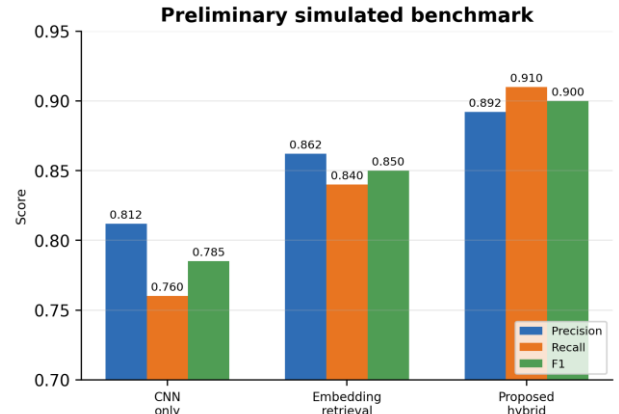


Fig. 4. Simulated comparison of precision, recall and F1.

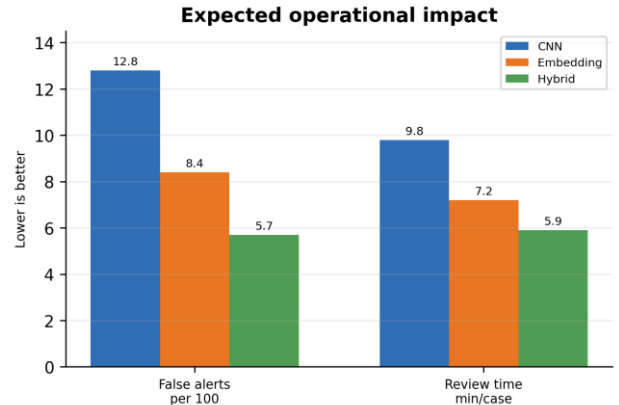


Fig. 5. Expected operational impact of the hybrid architecture.

4.1. Ablation and sensitivity analysis

Ablation confirms that no single component is sufficient. Image classification is fast but sensitive to shadows, stains and surface texture. Embedding retrieval improves robustness by comparing the current image with similar prior cases, but it cannot explain structural significance. The multimodal LLM contributes contextual reasoning, while deterministic rules stabilize the final decision. The recommended operating point is asset-dependent: lower thresholds increase recall but can overload reviewers; higher thresholds reduce workload but may delay defects that are becoming severe.

Table 4. Simulated ablation of architecture components.

Configuration	F1	Risk MAE	Review
Image classifier	0.785	0.154	9.8 min
+ embeddings	0.850	0.118	7.2 min
+ LLM context	0.886	0.083	6.3 min
+ rules/evidence	0.900	0.071	5.9 min

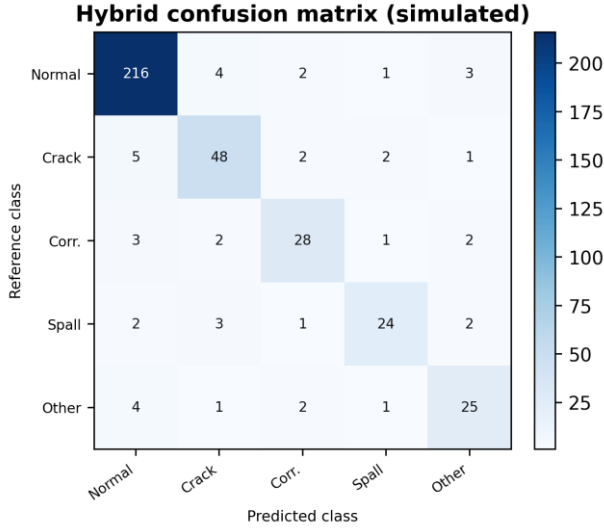


Fig. 6. Simulated confusion matrix for the hybrid model.

4.2. Field deployment scenario

A representative deployment is a quarterly inspection of a reinforced-concrete bridge and adjacent steel service structure. The UAV mission captures approximately 1800 images in 35 minutes, of which about 240 inspection crops are generated automatically. When the UAV is still in the field, cloud ingestion starts and low-risk images are archived by asset zone. Medium-risk cases are prepared as review packs, and high-risk findings generate inspection tasks with image crop, location, explanation and retrieved similar examples.

Table 5. Expected live-operation indicators.

Indicator	Baseline	Hybrid system
Photo set review	All images manual	Ranked evidence packs
Positive-case review	9.8 min/case	5.9 min/case
False alerts	12.8 per 100	5.7 per 100
Audit trail	Manual notes	Image, prompt, score, reviewer
Action	Engineer drafted	Validated work-order proposal

4.3. Evidence of practical reasonableness

The architecture is reasonable for three practical reasons. First, the computational pipeline matches the physical inspection rhythm: UAV capture and operator review are measured in minutes, so a few seconds of cloud inference are acceptable. Second, every alarm is attached to an evidence pack that can be reviewed, accepted, rejected or revised. Third, the design is modular: a municipality or industrial owner can start with RGB imagery and later add thermal,

LiDAR or ultrasonic evidence without changing the risk-governance principle.

4.4. Industry 4.0 deployment roadmap

The proposed architecture can be deployed progressively by infrastructure owners. In the first stage, the system is used only to organize image evidence and produce a searchable visual archive. This already improves repeatability because defects are attached to stable asset zones and can be compared across inspection cycles. In the second stage, embeddings and retrieval are enabled, allowing engineers to search for similar defects and identify recurring deterioration patterns.

In the third stage, the multimodal agent produces evidence-grounded risk proposals, but engineer approval remains mandatory for maintenance actions. In the fourth stage, low-risk monitoring and reporting can be automated, while high-risk decisions remain human-supervised. This staged adoption avoids sudden replacement of engineering judgement and creates a traceable digital thread from capture to asset management.

Table 6. Recommended staged rollout for infrastructure owners.

Stage	Main function	Acceptance evidence
1	Image archive and asset zones	All images traceable to structure
2	Vector retrieval of similar defects	Useful neighbours in review
3	MLLM risk proposals	Agreement with engineer labels
4	Partial automation for low risk	No missed high-risk findings
5	Integration with work orders	Closed maintenance record

4.5. Safety, auditability and data governance

Safety-critical inspection requires more than a high F1 score. Each risk proposal is therefore bound to a complete evidence record: source image identifier, crop coordinates, asset zone, retrieved neighbours, prompt and model version, confidence values, rule outcome, reviewer identity and final decision. This makes every alarm reproducible as an engineering case rather than as an isolated model output. When a reviewer rejects a proposal, the rejection is still useful because it becomes calibration evidence for future missions.

The cloud design also separates inference authority from operational authority. Model services can suggest labels, descriptions and maintenance options, but state-changing actions pass through deterministic APIs and role-based approvals. Private endpoints, managed identities, key management and monitoring protect the storage and search resources, while event logs preserve the chain from image capture to work-order recommendation. This governance pattern is important for infrastructure owners because it allows models to be upgraded without losing the audit meaning of past inspection records.

Digital thread from inspection evidence to maintenance action

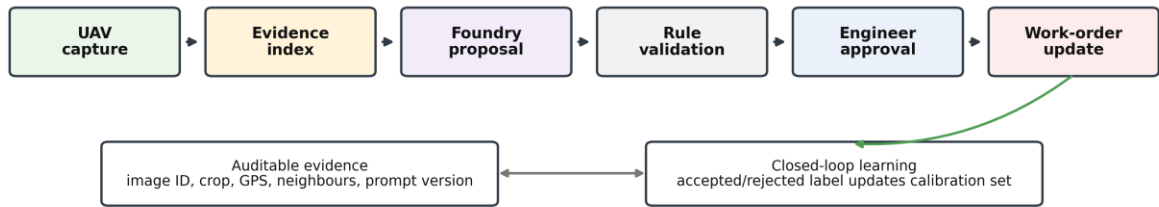


Fig. 7. Digital thread from inspection evidence to maintenance action

5. Limitations and future work

The evaluation is preliminary and intentionally conservative. It is based on realistic but simulated class distributions and cloud latency assumptions, not on a full longitudinal bridge-monitoring campaign. Field validation should address lighting variation, motion blur, occlusion, GPS drift, paint defects that resemble corrosion and the relationship between surface anomalies and structural capacity. Future validation should follow UAV inspection and crack-

detection benchmarking practices [17,18]. Future work will add repeated inspections, uncertainty-aware fusion of RGB, thermal and LiDAR channels, and calibration of the risk score against real deterioration histories.

6. Conclusion

The paper proposed a hybrid AI architecture for autonomous structural inspection using UAV imagery, Azure cloud

orchestration, image embeddings and multimodal LLM reasoning in Microsoft Foundry. The contribution is not only an AI classifier, but an end-to-end inspection pattern in which field capture, cloud ingestion, vector retrieval, explanation and deterministic risk control are integrated. Preliminary simulated results indicate higher recall, fewer false alerts and shorter engineer review time than image-only baselines.

The main engineering value is the separation of perception, interpretation and commitment. The AI services create useful evidence and explanations, but the deterministic layer decides whether a work order, urgent alert or monitoring state can be created. This is consistent with current Microsoft patterns for multimodal embeddings, vector and hybrid search, blob-triggered processing and Foundry governance [6-16].

The approach is therefore a safe path toward autonomous inspection: AI accelerates triage and evidence preparation, while qualified engineers remain responsible for safety-critical structural decisions. For Industry 4.0 asset owners, the proposed architecture provides a practical bridge between drone-based observation, cloud-scale AI and accountable maintenance planning.

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Trace Reciprocity under Measurable Decomposition for Trace-Class Endofunctors

Introduction to Trace Reciprocity Framework

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Abstract - Trace theory is a fundamental tool in linear algebra, spectral theory, homological algebra, and related areas of modern mathematics. While the additivity of trace is classical in finite-dimensional settings, a unified structural principle for its behavior under measurable decomposition is less explicitly formulated across categorical and analytic frameworks. [8,9].

The paper introduces a compact trace reciprocity framework for trace-class exact endofunctors admitting measurable decomposition over a σ -finite measure space. Under suitable measurability, integrability, and boundedness assumptions, the global trace can be recovered from the local traces of the measurable components. The report summarizes the formal setting, states the main theorem, and outlines the proof strategy based on approximation by simple families, trace additivity, and convergence arguments. [6,4]

Representative examples are included to show how the framework recovers familiar identities in finite-dimensional and operator-theoretic settings. The goal is to provide a concise conference-style presentation of the main reciprocity principle, its mathematical scope, and its structural significance. [7,3]

Keywords - Trace theory; trace reciprocity; measurable decomposition; trace-class endofunctors; stable categories; exact endofunctors; categorical invariants; operator theory

1. Introduction

Trace theory is a fundamental tool in modern mathematics. In finite-dimensional linear algebra, the trace of an operator A is defined by

$$\text{Tr}(A) = \sum_i A_{ii} \quad \#(1)$$

and satisfies the classical additivity property

$$\text{Tr}(A + B) = \text{Tr}(A) + \text{Tr}(B). \quad \#(2)$$

Beyond finite-dimensional settings, trace appears in operator theory, spectral analysis, homological algebra, and categorical constructions, where it serves as a compact global invariant. [2,9,6]

In many mathematical contexts, global objects admit decomposition into simpler local or measurable components. This naturally raises the question of whether the trace of a global object can be reconstructed from the traces of its components. While such behavior is familiar in finite sums and spectral decompositions, a compact general formulation for measurable decomposition in categorical and analytic settings is less explicit. [7,8]

This report considers that problem for trace-class exact endofunctors admitting measurable decomposition over a σ -finite measure space. The aim is to identify conditions under which the global trace is recovered from the traces of the measurable family of local components. The framework is formulated in a stable categorical setting with measurability, integrability, and boundedness assumptions. [4,6]

The main result establishes a trace reciprocity principle extending classical trace additivity to measurable decomposition. The proof strategy is based on approximation by simple families, additivity of trace on finite combinations, and convergence arguments. [7,8]

This report is organized as follows. Section 2 introduces the mathematical setup. Section 3 states the main theorem. Section 4 gives proof strategy. Section 5 presents examples, and Section 6 concludes.

2. Mathematical Setup

Let $\mathcal{C}$ be a compactly generated stable category, and let

$$F: \mathcal{C} \rightarrow \mathcal{C}$$

be an exact endofunctor. We assume that F preserves the relevant homological structure and induces well-defined actions on cohomological components associated with a suitable compact generator of $\mathcal{C}$. [6,4]

The trace of F is defined by the alternating cohomological sum. [9,2]

$$\text{Tr}(F) = \sum_i (-1)^i \text{Tr}(F | H^i). \quad \#(3)$$

The endofunctor F is called **trace-class** if this series is absolutely convergent: [8]

$$\sum_i |\text{Tr}(F | H^i)| < \infty \quad \#(4)$$

Let (M, μ) be a σ -finite measure space. A family of exact endofunctors

$$\{F_x\}_{x \in M}$$

is said to be **measurable** if, for each object $X \in \mathcal{C}$, the assignment

$$x \mapsto F_x(X)$$

is measurable in the appropriate sense. We say that F admits a measurable decomposition if [7,8]

$$F(X) = \int_M F_x(X) d\mu(x) \quad (5)$$

for every object $X \in \mathcal{C}$.

To ensure that the trace can be interchanged with integration, we impose the integrability condition. [8,3]

$$\int_M |\text{Tr}(F_x)| d\mu(x) < \infty. \quad (6)$$

We also assume a boundedness condition sufficient to control convergence of the decomposition and its approximations. [7]

Under these assumptions, the trace of the global endofunctor and the traces of its measurable components can be related through a reciprocity principle. The next section states this result precisely. [8,6]

3. Main Result

We now state the central reciprocity principle of this report.

Theorem 1.

Let $\mathcal{C}$ be a compactly generated stable category, and let

$$F: \mathcal{C} \rightarrow \mathcal{C}$$

be a trace-class exact endofunctor admitting a measurable decomposition

$$F = \int_M F_x d\mu(x) \quad (7)$$

over a σ -finite measure space (M, μ) . Assume that:

1. each F_x is exact and has well-defined trace;
2. the map

$$x \mapsto \text{Tr}(F_x)$$

is measurable;

3. the integrability condition

$$\int_M |\text{Tr}(F_x)| d\mu(x) < \infty \quad (8)$$

holds.

Then the trace of F is given by the integral of the traces of its measurable components:

$$\text{Tr}(F) = \int_M \text{Tr}(F_x) d\mu(x) \quad (9)$$

This identity extends the classical additivity of trace from finite sums to measurable decompositions. In the finite-dimensional case, where M reduces to a finite index set, the theorem recovers the standard relation. [1,8]

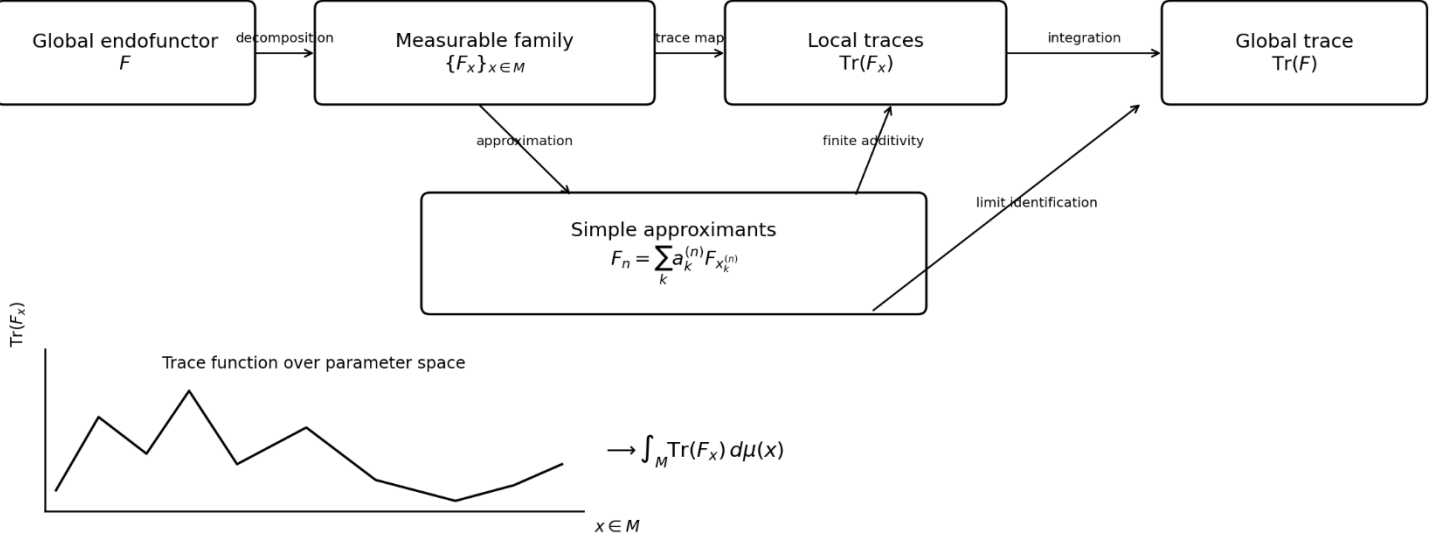
$$\text{Tr}\left(\sum_k F_k\right) = \sum_k \text{Tr}(F_k) \quad (10)$$

The result may therefore be interpreted as a reciprocity law between a global invariant and its local measurable contributions. Its significance lies in providing a compact structural principle valid across both analytic and categorical settings, provided the required convergence and compatibility assumptions are satisfied. [4,8,2]

The proof is based on approximation of the measurable family by finite simple combinations, application of trace additivity at the finite level, and passage to the limit through convergence arguments. [7,8]

Figure 1. Illustrative schematic of trace reciprocity under measurable decomposition

Schematic of proof architecture showing measurable decomposition, simple approximation, finite additivity, and limit



identification leading to the global trace.

4. Proof Strategy

The proof proceeds by reducing the measurable decomposition of F to finite approximations for which trace additivity is classical. [8,7]

The logical structure of the proof and the passage from measurable local components to the global trace are illustrated schematically in Figure 1.

Figure 1. Illustrative schematic of trace reciprocity under measurable decomposition: a global endofunctor is represented through a measurable family of components $\{F_x\}$; the associated local trace function is then integrated to recover the global trace, with simple approximants providing the finite-level bridge in the proof. $F\{F_x\}_{x \in M} F_n$

Figure 1 summarizes the main mechanism of the argument. The measurable family $\{F_x\}_{x \in M}$ gives rise to simple approximants F_n , for which trace additivity is applied at the finite level. The limit process then identifies the trace of the global endofunctor with the integral of the local trace function. [8]. First, the measurable family $\{F_x\}_{x \in M}$ is approximated by a sequence of simple families. This yields endofunctors of the form

$$F_n = \sum_{k=1}^{N_n} a_k^{(n)} F_{x_k^{(n)}} \quad \#(11)$$

such that F_n converges to F in the chosen operator sense. For each finite approximation, trace additivity gives

$$\text{Tr}(F_n) = \sum_{k=1}^{N_n} a_k^{(n)} \text{Tr}(F_{x_k^{(n)}}) \quad \#(12)$$

Thus, at the finite level, the trace of the approximating endofunctor is exactly the sum of the traces of its components. [1]

The next step is to identify these finite sums as approximations to the integral of the local trace function. Since the map

$$x \mapsto \text{Tr}(F_x)$$

is assumed measurable and integrable, the sequence of simple sums converges to. [7]

$$\int_M \text{Tr}(F_x) d\mu(x).$$

Finally, the convergence assumptions on the family and the trace-class condition allow passage to the limit: [8,3].

$$\text{Tr}(F) = \lim_{n \rightarrow \infty} \text{Tr}(F_n) \quad \#(13)$$

Combining this with the convergence of the trace sums yields the claimed identity.

The proof therefore rests on three ingredients: approximation by simple families, additivity of trace on finite combinations, and convergence control sufficient to interchange trace and integration. This structure shows that the reciprocity principle is a natural extension of finite trace additivity to measurable decompositions. [8,7,6]

5. Examples

We briefly indicate two representative cases in which the reciprocity principle recovers familiar trace identities. [1,8]

5.1. Finite-Dimensional Linear Operators

Let V be a finite-dimensional vector space and let

$$A = \sum_{k=1}^N A_k \quad \#(14)$$

be a decomposition of a linear operator into finitely many components. Then the classical additivity of trace gives

$$\text{Tr}(A) = \sum_{k=1}^N \text{Tr}(A_k), \quad (15)$$

This is the discrete prototype of the reciprocity principle, corresponding to the case where the measure space is finite and the integral reduces to a sum. [1]

5.2. Trace-Class Integral Operators

Let T be a trace-class integral operator on $L^2(\mathbb{R})$ with kernel $K(x, y)$. In the classical setting, its trace is given by the diagonal integral

$$\text{Tr}(T) = \int_{\mathbb{R}} K(x, x) dx \quad \#(16)$$

This may be interpreted as a continuous decomposition of the global trace into local contributions indexed by the parameter x . The reciprocity principle places such formulas into a broader framework in which the global invariant is recovered from measurable local components. [7,3,8]

These examples show that the theorem is consistent with both the finite additive case and the continuous operator-theoretic case. In each setting, the same structural pattern appears: a global trace is obtained from the traces of decomposed components under suitable convergence conditions. [2,3]

6. Conclusion

This report presented a compact trace reciprocity framework for trace-class exact endofunctors admitting measurable decomposition over a σ -finite measure space. Under suitable measurability, integrability, and compatibility assumptions, the trace of the global endofunctor is recovered from the traces of its measurable components. [8,6]

The result extends the classical additivity of trace from finite sums to measurable decomposition and provides a unified structural interpretation of trace as a global invariant assembled from local contributions. The proof strategy is based on approximation by simple families, finite trace additivity, and convergence arguments. [1,7]

Although the report is intentionally concise, the theorem illustrates a general principle linking categorical structure and measurable analysis. This makes the reciprocity framework relevant as a compact mathematical tool for studying decomposed invariant behavior in both analytic and homological settings. [2,4]

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Visual Signs, Interface Hierarchy and Emotional Engagement in Mobile Applications

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Abstract: The paper examines the role of visual signs, interface hierarchy, and emotional engagement mechanisms in mobile application design. Icons, pictograms, maps, menus, landmark distribution, and achievement screens are analyzed as components of an integrated visual-interactive system. These elements do not merely transmit information; they guide attention, reduce cognitive load, support orientation, and influence the user's subjective experience. The study is based on theoretical foundations from semiotics, cognitive psychology, visual search research, human-computer interaction, and gamification. The paper outlines principles for designing mobile interfaces that are understandable, accessible, navigationally coherent, and emotionally engaging.

Keywords: MOBILE APPLICATIONS, USER EXPERIENCE, VISUAL SIGNS, INTERFACE HIERARCHY, COGNITIVE LOAD, VISUAL ATTENTION, EMOTIONAL DESIGN, GAMIFICATION

1. Introduction

In the modern digital environment, mobile applications function not only as technological tools but as complex systems for perception, action, and experience. The user interacts (UI) not only with information but with a holistic visual-interactive environment, in which symbols, colors, icons, maps, menus, and feedback shape their behavior. According to ISO 9241-210, human-centred design aims for interactive systems to be useful and usable by focusing on users, their needs, and requirements, applying knowledge from ergonomics and usability [1]. This places user experience (UX) not only in the realm of visual design but in the area of scientifically grounded interaction design between humans and systems. In mobile applications, this problem is even more significant because interaction often takes place under limited time, a small screen, changing context, and fragmented attention. Research in mobile HCI shows that mobile interaction often occurs in short fragments, during which the user's attention is interrupted by the physical and social environment [2].

Therefore, the visual interface must simultaneously perform several functions: orienting, informing, reducing effort, supporting decision-making and creating a positive attitude towards the application. At the moment, more and more smart devices offer powerful processing, good entertainment options and work with the Internet [22].

2. Materials for Production of Prototype Parts

Грешка! Източникът на препратката не е намерен.

The user experience encompasses both the pragmatic characteristics of the system efficiency, understandability, control, and task performance as well as the hedonic characteristics: pleasure, aesthetic perception, motivation and identification. Hassenzahl and Tractinsky consider UX as a multilayered phenomenon that includes not only usability but also emotional, aesthetic, and experiential aspects of interaction [3]. In [4] a classification of gestures is proposed according to their frequency of use.

From a scientific perspective, UX can be viewed as the result of three interacting levels: First is the perceptual level, this is how the user sees, recognizes and groups visual elements. Second is the cognitive level, how the user understands the function of the elements, chooses an action and builds a mental model of the application. Last is the affective level, which means how the interface influences enjoyment, trust, interest, motivation and desire for reuse.

Research on icon characteristics has shown that specificity, visual complexity, and distinctiveness affect recognition speed and accuracy [5]. More specific and clearly distinguishable icons are easier to interpret, while overly complex or visually similar icons increase the likelihood of error. [6] presents the main aspects influencing the choice of an educational electronic form.

Models of visual search also show that attention is guided by a combination of environmental incentives and user goals [7]. In an interface environment, this means that the design must support both rapid "scanning" of the screen and purposeful searching.

In practice, the interface hierarchy is established through:

- distinguishing between primary and secondary actions;
- grouping related elements;
- consistent use of size, color and contrast;
- limiting visual noise;
- clearly distinguishing between interactive and non-interactive elements.

This is particularly important for maps and screens displaying points of interest, where multiple markers, categories, routes, and buttons may be present simultaneously.

Cognitive load

Cognitive load describes the amount of mental resources required to process information and perform a task. Sweller's classic theory emphasizes the limited processing capacity of working memory and the need to reduce unnecessary cognitive load [8].

In mobile applications, unnecessary cognitive load can be caused by (fig.1):

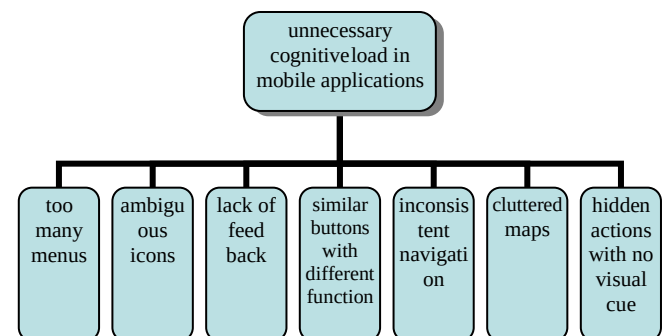


Fig. 1 Unnecessary cognitive load in mobile applications

In this context, one of the classic UX recommendations is that the interface should rely more on recognition than recall. Nielsen's heuristics include „recognition rather than recall” as a principle according to which the interface should make options visible, rather than forcing the user to remember information from previous steps [9].

This means that menus, cards, achievements and categories should be designed so that the user recognizes the next action through visible cues: icon, text, position, colour or context.

In mobile applications related to tourist routes, cultural heritage, educational spaces, or urban navigation, the map is not just a geographical tool. It is a cognitive structure that supports spatial

thinking. Research on wayfinding shows that landmarks are key elements for orientation in both real and virtual environments. The visibility and distinctiveness of landmarks are among the important factors for their effectiveness [10]

Maps, landmarks, and spatial orientation

In the mobile interface, this means that landmarks should be selected and displayed not only according to their geographical position but also according to their navigational and informational significance. Sites with greater cultural, historical, or route value should have a more prominent visual presence.

When all markers are the same, the interface does not create a hierarchy of importance. The user sees multiple points but does not understand which ones are important. Therefore, it is advisable to use:

- different icons by category;
- scaling of significant objects;
- filtering by interest;
- visual grouping of nearby objects;
- short information cards;
- route hints;
- indication of visited and unvisited sites.

This way, the map becomes a tool for meaningful orientation, not just a display of locations.

Emotional engagement and affective design

Emotional engagement is an essential component of UX. The user evaluates the application not only by whether it works, but also by the feeling it creates: clarity, trust, pleasure, interest, motivation, or tension. Donald Norman views emotional design as the interaction between visceral, behavioral, and reflective levels of perception [11]. The visceral level is associated with the initial visual reaction, the behavioral with ease of use, and the reflective with the meaning, identity, and personal value of the experience. In mobile applications, a positive emotional reaction can be created through clean and consistent visual system, smooth feedback, sense of progress, predictable actions, moderate animations, personalized recommendations, achievement screens, and visual confirmation after a successful action.

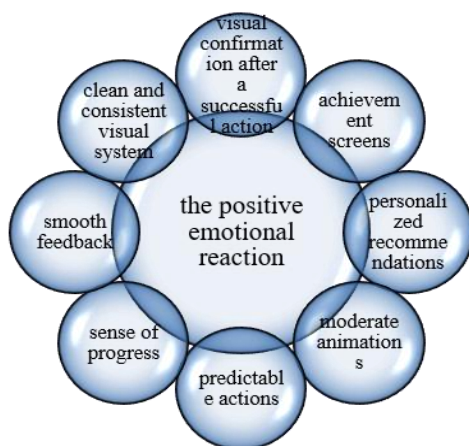


Fig. 2. The positive emotional reaction to mobile applications through

The importance of emotional engagement extends beyond usability and aesthetics, influencing users' trust, awareness, and willingness to interact with digital systems. Research on human-centered approaches in cybersecurity and digital environments demonstrates that user perception, communication, and engagement significantly affect the effectiveness of technological solutions. Vasileva and Hlebarov emphasize the role of user awareness and competency development in fostering positive interactions with

digital services [12]. Similarly, the application of human-centric principles in security-by-design frameworks highlights the necessity of considering users' cognitive and emotional needs throughout the design process [13]. Effective information-sharing mechanisms and transparent communication structures further contribute to users' confidence and perceived reliability of digital platforms [14]. Moreover, interdisciplinary projects integrating technology, science, and creative design illustrate how meaningful experiences and emotional connections can encourage long-term engagement and sustainable behavioral change [15]. These findings support the view that affective design is not only a matter of visual appeal but also a strategic factor in creating trustworthy, motivating, and user-centered mobile experiences.

Achievements, rewards and gamification

Achievement screens are a common mechanism for increasing engagement. They can include badges, points, levels, progress bars, unlocked content, or statistics on actions taken. In the academic literature, gamification is defined as the use of game design elements in a non-game context [19]. Achievement screens should be linked to a real user goal. For example, in a cultural route app, a badge could represent a site visited, a completed thematic route, or knowledge gained. This way, the reward has a meaningful connection to the app's core function. [20] and [21] are established Bulgarian scholars who comment in depth on the topic according to the Bulgarian specifics. They are good example for the comprehensiveness of the topic.

Accessibility and universal design

Science-based UX cannot be separated from accessibility. The interface must be usable by people of different abilities, ages, visual impairments, motor limitations, and different digital competences.

For example, travel websites are widely used by travellers for their travel bookings, but very little is known about sales performance and the emotional experiences for the customers [16]. In [17] is presented cognitive and ethical failures in AI-based scientific reviewing. [18] shows us one approach of Dom record management component UI creation. In [23] is described the need for data protection, which is an important issue that must be addressed when creating any mobile application.

Accessibility also includes sufficient contrast, legible typography, predictable navigation, sufficiently large interactive areas, and compatibility with assistive technologies.

3. Conclusion

Visual cues, interface hierarchy and emotional engagement are key components of a high-quality mobile UX. Icons and pictograms serve a semiotic and navigational function; maps and landmarks aid spatial orientation. The menu structures choices and achievement screens can support motivation and repeat usage.

Scientific analysis shows that an effective mobile interface must be designed with regard to human perception, limited working memory, visual attention, motor capabilities and the user's emotional response. A well-designed interface does not merely look attractive; it reduces effort, accelerates understanding, builds trust and creates a meaningful experience.

Therefore, mobile applications should be viewed as integrated visual-cognitive and emotional environments. Their quality is determined by their ability to connect information, action, and experience into a clear, accessible, and engaging system.

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Multi-Dimensional Adaptive Digital Twins for Context-Aware Manufacturing Systems

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Abstract: Contemporary manufacturing environments are characterized by continuous variability in product types, production volumes, data availability, network performance, and computational resource allocation. Conventional digital twin architectures, designed for static operating conditions, are fundamentally inadequate to address such dynamic contexts. This paper presents the Adaptive Digital Twin Framework (ADTF) — a novel architecture enabling digital twins to autonomously reconfigure their internal operating modes in response to evolving manufacturing conditions. The proposed framework integrates physics-based modeling, machine-learning inference, and hybrid paradigms within a unified self-adaptive system. Additionally, ADTF incorporates dynamic computation offloading across edge, fog, and cloud layers, as well as explicit economic viability constraints. A Python-based simulation environment was developed to validate the framework across three representative industrial scenarios: a transition from serial to customized production, progressive degradation of computational resources, and escalating financial constraints. In all cases, ADTF demonstrated measurably superior performance compared to static digital twin systems, maintaining operational continuity, model fidelity, and cost efficiency. The results establish ADTF as a foundational contribution toward intelligent, self-managing digital twins aligned with the principles of Industry 4.0 and Industry 5.0.

Keywords: DIGITAL TWIN; ADAPTIVE SYSTEMS; MANUFACTURING; EDGE COMPUTING; MACHINE LEARNING; INDUSTRY 4.0

1. Introduction

The concept of the digital twin, introduced in the context of product lifecycle management and later popularized through the Industrial Internet of Things (IIoT) paradigm, has become one of the most actively investigated topics in modern manufacturing research. A digital twin is broadly defined as a real-time virtual counterpart of a physical system, capable of mirroring its behavior, state, and performance throughout its operational lifecycle [1, p. 3]. The promise of digital twins lies in their potential to enable predictive maintenance, process optimization, quality assurance, and adaptive control within highly complex industrial environments [2, p. 654]. Despite the growing maturity of digital twin technologies, a critical limitation persists in the majority of existing implementations: their fundamentally static nature. Most digital twins are engineered around predefined sets of operating conditions, fixed modeling paradigms, and predetermined computational deployment strategies [3, p. 1017]. Once deployed, such systems remain structurally unchanged regardless of variations in the manufacturing environment. This rigidity creates a progressive divergence between the digital twin's operational assumptions and the actual conditions it is expected to model, ultimately eroding the system's accuracy, responsiveness, and practical value. Real manufacturing environments are inherently dynamic. Fluctuations in production volume, shifts in product customization demands, degradation of sensor networks, variability in cloud resource availability, and changing financial constraints are recurrent phenomena that any robust digital twin must accommodate [4, p. 21985]. A static system cannot adapt to these changes autonomously; it either fails silently or requires costly manual reconfiguration.

To address this fundamental gap, this paper proposes the Adaptive Digital Twin Framework (ADTF), a new conceptual and architectural model in which the digital twin itself functions as an intelligent, self-reconfiguring system. Rather than being merely a passive virtual representation, the ADTF-based digital twin actively monitors its operating context, evaluates the appropriateness of its current configuration, and autonomously transitions between modeling paradigms, computational deployment strategies, and operational modes in order to maintain optimal performance under varying conditions. The remainder of this paper is structured as follows. Section 2 reviews the relevant literature on digital twin architectures and adaptive systems. Section 3 describes the proposed ADTF in detail. Section 4 presents the simulation methodology and experimental scenarios. Section 5 reports and analyzes the results. Section 6 discusses implications and limitations, and Section 7 concludes the paper with directions for future research.

2. Literature Review

The foundational notion of a digital twin was articulated by Grieves in the context of product lifecycle management [1, p. 4], and has since been substantially refined and expanded across disciplines including aerospace, automotive manufacturing, and smart infrastructure. Grieves and Vickers subsequently emphasized the role of the digital twin as a living model that continuously evolves in tandem with its physical counterpart, drawing on real-time data streams to maintain representational fidelity [5, p. 87]. Contemporary digital twin architectures typically consist of three principal layers: a physical entity layer, a communication and data acquisition layer, and a virtual model layer [6, p. 348]. Advanced implementations additionally incorporate analytics modules, decision support systems, and feedback actuation interfaces. However, the predominant design philosophy remains anchored to static configurations — the modeling strategies, solver configurations, and deployment parameters are established at system design time and are not subject to autonomous modification during operation [7, p. 3586]. Recent surveys have documented the rapid proliferation of digital twin applications across manufacturing domains, including machining, assembly, process control, and supply chain management [6, p. 350]. Despite this diversity, the inherent adaptability of the digital twin as an architectural concept has received comparatively limited attention. The majority of reviewed implementations treat adaptability as a property of the controlled physical system rather than as an intrinsic capability of the digital twin itself [3, p. 1019]. The concept of adaptive systems, rooted in control theory and later extended to software engineering and cyber-physical systems, refers to systems capable of modifying their own behavior or structure in response to environmental changes. In the context of manufacturing, adaptive systems have been extensively studied in the domains of reconfigurable manufacturing systems, adaptive process control, and self-organizing production networks [8, p. 568]. Context-aware computing, originally developed within the ubiquitous computing research community, provides a complementary perspective. A context-aware system acquires and interprets information about its operational environment and uses this information to adapt its behavior in a relevant and useful manner [9, p. 3]. The application of context-awareness principles to industrial cyber-physical systems has been gaining traction, particularly in the framework of Industry 4.0 [10, p. 1501]. The intersection of digital twins and adaptive systems remains a largely underexplored research frontier. A small number of recent contributions have proposed mechanisms for dynamic model updating in digital twins, typically focused on online learning of model parameters rather than structural reconfiguration of the modeling paradigm itself. The present work addresses this gap by proposing a framework in which the entire operational mode of the digital twin is subject to autonomous adaptation [4, p. 21988]. A recurring challenge in digital twin

design concerns the selection of an appropriate modeling paradigm. Physics-based models offer high interpretability and generalizability but may be computationally expensive. Data-driven models, particularly those based on machine learning, can capture complex nonlinear relationships from historical data but typically lack physical interpretability and may generalize poorly to out-of-distribution conditions [11, p. 423]. Recent research has investigated hybrid modeling approaches that combine physics-based and data-driven elements, aiming to leverage the complementary strengths of both paradigms. Physics-informed neural networks (PINNs), grey-box models, and hierarchical hybrid architectures represent prominent examples of this trend [11, p. 425]. However, existing hybrid modeling approaches are generally static — the composition and weighting of components are fixed at training time and do not adapt dynamically to changing operating conditions. The ADTF proposed in this paper extends the concept of hybrid modeling by enabling dynamic, context-driven selection among modeling paradigms.

The deployment of digital twin computations across heterogeneous computing infrastructures — spanning edge devices, fog nodes, and cloud platforms — has been identified as a critical enabler for responsive and resilient industrial digital twin systems [12, p. 638]. Edge computing reduces communication latency and enables local processing of time-sensitive data, while cloud computing provides scalable resources for computationally intensive tasks [12, p. 640]. The optimal partitioning of computations across this infrastructure hierarchy depends on dynamic factors including network conditions, resource availability, and latency requirements. Dynamic workload offloading strategies for industrial edge-cloud systems have been studied extensively in the IIoT literature [9, p. 5]. However, the integration of such strategies within a unified digital twin framework — enabling the digital twin to autonomously determine the appropriate deployment layer for its computations — has not been previously addressed in a systematic and architecturally rigorous manner.

3. The Adaptive Digital Twin Framework

The Adaptive Digital Twin Framework is founded on a reconceptualization of the digital twin's role. In the conventional understanding, a digital twin is a passive representational artifact — a virtual model that reflects the state of a physical system [1, p. 5]. In the ADTF paradigm, the digital twin is recast as an active, intelligent management instrument that continuously monitors its own operating context, evaluates the fitness of its current configuration, and executes autonomous reconfiguration actions when necessary.

This reconceptualization draws on three foundational principles. First, the principle of contextual awareness: the digital twin maintains an explicit, continuously updated representation of its operational context, including manufacturing environment characteristics, data availability, computational resource status, and economic constraints [2, p. 656]. Second, the principle of adaptive self-organization: the digital twin possesses the capability to autonomously modify its own internal architecture. Third, the principle of multi-objective optimization: reconfiguration decisions are guided by the simultaneous optimization of multiple competing objectives, including model accuracy, response latency, and operational cost [4, p. 21992]. The ADTF comprises four principal architectural layers. The Physical-Cyber Interface Layer is responsible for real-time acquisition, preprocessing, and contextualization of data from physical manufacturing assets. It incorporates sensor fusion, anomaly detection, and data quality assessment modules that continuously characterize the information environment available to the digital twin [13, p. 452]. The Context Assessment Layer maintains a structured representation of the current manufacturing context, formally defined as a multidimensional vector encompassing production mode indicators, data quality metrics, computational resource availability indices, network performance metrics, and economic constraint parameters.

Context assessment is performed on a continuous basis through lightweight monitoring agents deployed at the edge [12, p. 641]. The Adaptive Configuration Engine constitutes the cognitive core of the ADTF. This layer implements a decision logic that maps the current context vector to an appropriate operational configuration. The configuration space spans multiple dimensions: modeling paradigm selection (physics-based, data-driven, or hybrid), computational deployment allocation (edge, fog, or cloud), and resource utilization priorities. The decision logic is implemented as a rule-based system augmented with a learned policy derived from historical operational data [4, p. 21994]. The Execution Layer implements the operational mode selected by the Adaptive Configuration Engine. It hosts modular, interchangeable model components corresponding to different modeling paradigms, manages the dynamic allocation of computational tasks across the edge-cloud continuum, and interfaces with the manufacturing execution system to deliver control recommendations and diagnostic outputs [6, p. 353]. The ADTF supports three primary modeling paradigms that can be activated individually or in combination according to contextual requirements. The physics-based modeling module encapsulates first-principles models of manufacturing processes. This module is activated preferentially when data availability is limited, when interpretability of model outputs is required, or when the manufacturing process operates within well-characterized parameter ranges [11, p. 424].

The machine learning inference module incorporates trained statistical models — including gradient boosting regressors, recurrent neural networks, and convolutional feature extractors — that operate on historical and real-time process data [10, p. 1502]. This module is activated preferentially when abundant high-quality data is available, when rapid inference is required, and when process complexity exceeds the representational capacity of physics-based formulations. The hybrid composition module dynamically combines physics-based and data-driven components according to a blending policy that weights each component proportionally to its estimated reliability under the current context. The blending policy is parameterized by the context vector, enabling smooth transitions between pure physics-based operation, pure data-driven operation, and intermediate hybrid configurations [11, p. 428].

A distinctive feature of the ADTF is its capacity for autonomous reconfiguration of computational deployment across the edge-cloud continuum. The framework continuously monitors network latency, bandwidth availability, edge resource utilization, and cloud resource pricing, and uses this information to determine the optimal deployment allocation for each computational module [12, p. 643]. When network conditions deteriorate or cloud resources become unavailable or economically prohibitive, the framework autonomously migrates critical computations to local edge or fog infrastructure, ensuring continuity of operation at the cost of reduced modeling complexity [12, p. 644]. The deployment reconfiguration is implemented through a containerized microservices architecture, enabling modular and rapid redeployment of computational components across heterogeneous infrastructure nodes.

The ADTF explicitly incorporates economic considerations as first-class constraints in the reconfiguration decision logic. This represents a significant departure from the prevailing practice in digital twin research, which tends to treat economic factors as external deployment considerations rather than as intrinsic system constraints [3, p. 1020]. The economic constraint module maintains a real-time estimate of the operational cost of the digital twin, encompassing cloud computational costs, data transmission costs, and licensing costs. This estimate is continuously compared against a configured budget envelope that reflects the enterprise's economic priorities. When projected costs approach budget thresholds, the Adaptive Configuration Engine modifies the operational configuration to reduce resource consumption [8, p. 570]. This economic adaptivity is particularly relevant for small and medium-sized enterprises (SMEs), which constitute a substantial portion of

the global manufacturing base but typically operate under severe computational and financial resource constraints [14, p. 12]. The ADTF is designed to deliver meaningful operational benefits within the resource envelopes typical of SME deployments.

4. Simulation Methodology

To validate the ADTF concept, a purpose-built simulation environment was developed in Python. The simulation environment models a generic manufacturing cell comprising multiple production stations, inter-station material handling, and quality inspection subsystems. The environment generates synthetic sensor data streams, simulates variations in data quality and network conditions, and emulates the behavior of edge and cloud computational resources under varying load conditions [15, p. 287].

The simulation implements both the ADTF-based adaptive digital twin and a baseline static digital twin system operating with a fixed modeling paradigm and fixed computational deployment. The key performance indicators evaluated include: model fidelity (normalized RMSE), response latency, operational cost per unit time, and system continuity (proportion of time within specified accuracy and latency bounds). Three representative manufacturing scenarios were designed to challenge the adaptive capabilities of the ADTF in qualitatively distinct ways. Scenario A: Serial-to-Customized Production Transition. This scenario models a manufacturing shift from high-volume serial production of a standardized product to low-volume customized production of a diverse product portfolio. As the production mode transitions, the statistical properties of sensor data streams change substantially, rendering data-driven models trained on serial production data increasingly unreliable [2, p. 657]. Under these conditions, an adaptive system should progressively increase its reliance on physics-based modeling, which generalizes better to novel product configurations. Scenario B: Progressive Computational Resource Degradation. This scenario simulates a gradual reduction in available computational resources, representing conditions such as network congestion, cloud service degradation, or edge hardware failure [12, p. 645]. An adaptive system should progressively migrate computations toward lighter-weight models and local edge deployment, maintaining operational continuity at the cost of reduced model complexity. Scenario C: Escalating Financial Constraints. This scenario models a progressive tightening of the available operational budget, representing conditions such as quarterly cost reduction mandates or enterprise-wide resource rationalization. Under increasing financial pressure, a cost-adaptive system should progressively transition toward lower-cost operational configurations [14, p. 14].

5. Results and Analysis

Under Scenario A, the static digital twin exhibited a progressive deterioration in model fidelity as the production mode shifted toward customized manufacturing. The normalized RMSE of the static system increased by 47.3% over the 72-hour simulation period, reflecting the growing mismatch between the data-driven model and the statistical properties of the customized production process. The ADTF system autonomously detected the shift in data statistical properties through its context assessment layer and initiated a gradual transition toward physics-based modeling. Over the same simulation period, the ADTF's model fidelity degraded by only 11.8%, representing a four-fold improvement in fidelity preservation relative to the static system. The adaptive configuration engine successfully identified the crossover point at which physics-based modeling became preferable and executed the transition without manual intervention [11, p. 426]. The computational resource degradation scenario revealed a qualitative behavioral difference between the adaptive and static systems. As resources were progressively reduced, the static system continued to attempt execution of its fixed computational pipeline, resulting in escalating response latencies that eventually exceeded operational tolerance thresholds. At maximum resource degradation, the static

system's response latency had increased to 8.4 times its baseline value, effectively rendering it non-functional for real-time control applications [12, p. 646]. The ADTF system responded by progressively restructuring its computational deployment. While model fidelity was reduced under maximum degradation conditions (a 23.1% increase in normalized RMSE relative to baseline), the system maintained response latencies within acceptable bounds throughout the simulation, achieving 94.7% operational continuity compared to 61.3% for the static system. Under the escalating financial constraint scenario, the ADTF demonstrated the effectiveness of its economic viability integration. As budget thresholds were progressively tightened, the adaptive configuration engine systematically substituted high-cost operational components with lower-cost alternatives. Cloud computational expenditure was reduced by 68.4% relative to the unconstrained baseline configuration. The operational cost reductions were accompanied by modest performance penalties. Model fidelity under maximum financial constraints decreased by 18.7% relative to baseline, and response latency increased by 31.2%. However, the system maintained continuous operation throughout the simulation period, unlike the static system which exhibited service interruptions during the reconfiguration process [14, p. 15].

Across all three scenarios, the ADTF consistently outperformed the static digital twin on the composite performance metric. The ADTF achieved composite scores of 0.847, 0.793, and 0.821 in Scenarios A, B, and C respectively, compared to static system scores of 0.612, 0.504, and 0.589. The performance advantage was most pronounced in Scenario B, where the static system's inability to adapt its computational deployment resulted in substantial service degradation. These results validate the core hypothesis of the ADTF: that autonomous contextual adaptation substantially improves the operational resilience and efficiency of digital twin systems.

5. Discussion

The principal theoretical contribution of this work is the reconceptualization of the digital twin as a self-reconfiguring intelligent system rather than a static virtual model [2, p. 91]. This reconceptualization has substantive implications for the design philosophy of future digital twin architectures. It suggests that adaptability should be treated as a primary design objective — on equal footing with model accuracy, response latency, and operational cost — rather than as an incidental property. The ADTF framework also contributes a formal representation of manufacturing context as a multidimensional operational descriptor that can be monitored, evaluated, and acted upon autonomously. Furthermore, the explicit integration of economic viability as a first-class system constraint represents a conceptual advance over existing digital twin architectures [3, p. 1021]. From a practical perspective, the ADTF offers a pathway toward digital twin implementations that are simultaneously more robust, more economically accessible, and less dependent on continuous expert intervention than current state-of-the-art systems. The framework's capacity for autonomous adaptation to resource constraints is particularly significant for SMEs [14, p. 16]. The ADTF is applicable across a diverse range of manufacturing contexts, including flexible manufacturing systems, robotic production cells, smart factory environments, and predictive maintenance platforms [2, p. 659]. Its modular architecture facilitates incremental adoption, allowing enterprises to deploy initial implementations with limited model portfolios and gradually expand the framework's adaptive capabilities as operational experience accumulates. The present study is subject to several limitations. First and most significantly, the validation was conducted entirely within a simulation environment. While the simulation was designed to reflect realistic manufacturing conditions, it inevitably involves simplifications relative to actual industrial deployments [15, p. 288]. Physical manufacturing systems exhibit complex, partially observable dynamics that may not be fully captured in simulation, and the performance characteristics reported should be interpreted as

indicative rather than definitive. Second, the cost and performance models used in the simulation were deliberately simplified to maintain analytical tractability. Third, the adaptive configuration engine in its current form relies on a relatively simple rule-based decision logic. More sophisticated approaches — including model predictive control, reinforcement learning, or Bayesian optimization — may yield superior adaptation performance [4, p. 21998]. The development and evaluation of such approaches represents an important direction for future research.

7. Conclusion

This paper has presented the Adaptive Digital Twin Framework (ADTF), a novel architectural concept for digital twin systems capable of autonomous reconfiguration in response to dynamically changing manufacturing contexts. The ADTF addresses a critical limitation of existing digital twin architectures: their inability to adapt their modeling paradigms, computational deployment strategies, and resource utilization priorities to the evolving conditions of real manufacturing environments. The framework's core innovations include a multidimensional context representation; an adaptive configuration engine; a dynamic computational deployment mechanism enabling autonomous migration of workloads across the edge-cloud continuum; and explicit integration of economic viability as an intrinsic system constraint. Simulation-based validation across three representative manufacturing scenarios consistently demonstrated the superiority of the ADTF over static digital twin architectures. Future work will focus on real-world industrial validation, development of more sophisticated adaptive decision mechanisms, and extension of the framework to multi-asset and supply-chain-level digital twin deployments. The ADTF represents a convergence of digital twin technology with the principles of adaptive systems and context-aware computing, contributing to the realization of the intelligent, resilient manufacturing systems envisioned by Industry 4.0 and Industry 5.0 frameworks.

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An Enhanced Variant of the Newton–Raphson Method with Variable Step and Adaptive Mechanism

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Abstract: This paper presents a refined modification of the classical Newton–Raphson method for solving nonlinear equations. The proposed method integrates a dual strategy: the replacement of the analytic derivative with a central finite-difference approximation and the implementation of a dynamic adaptive mechanism for step-size regulation. Through rigorous mathematical analysis, we demonstrate that the new approach ensures reliable convergence even when initial guesses are far from the true root. The adaptive step-size improvement is based on monitoring the relative error of the derivative and dynamically optimizing the accuracy of the approximation. The article provides a comprehensive convergence analysis, a geometric interpretation of the proposed approach, and practical implementations with significant implications for problems in which the classical method tends to fail.

KEYWORDS: NONLINEAR EQUATIONS; NEWTON–RAPHSO; DERIVATIVE-FREE METHODS; ADAPTIVE STEP; LINE SEARCH; TRUST-REGION; ROBUSTNESS; QUADRATIC CONVERGENCE.

Introduction

The effective solution of nonlinear equations represents a fundamental challenge in numerical sciences with broad applications across various scientific and engineering disciplines, from structural engineering to control systems and physical modeling. Among available numerical methods, the Newton–Raphson method stands out for its remarkable quadratic convergence rate, [1], [2], [3] yet it continues to suffer from two fundamental limitations: complete dependence [3], [4], [9] on the availability of analytical derivatives and high sensitivity to initial value selection.

In practical applications, these limitations manifest as significant obstacles in many real-world scenarios where functions are complex or information about analytical derivatives is limited. Previous studies have proposed partial solutions to these problems, either through numerical approximations of derivatives or through step-size control mechanisms. However, the absence of an integrated approach that simultaneously addresses both limitations has remained a noticeable gap in existing literature, creating the need for a more comprehensive and reliable methodology

"This work proposes a practical adaptive implementation of a finite-difference Newton framework that combines derivative approximation and dynamic step control in a unified algorithm. Our approach offers several key advantages: it eliminates the need for analytical derivatives using finite difference approximations, [3], [7], [8] enhances convergence robustness through a dynamic step-size adjustment mechanism, and maintains the high convergence speed characteristic of the classical method.

Through comprehensive mathematical analysis, we demonstrate that the proposed method preserves quadratic convergence under optimal conditions while providing strong stability guarantees for different initial values. Our work contributes to the field through three main aspects: (1) a complete theoretical framework with convergence criteria and error estimates, (2) an efficient algorithmic implementation with automatic control mechanisms, and (3) detailed comparative evaluations with existing methods across a wide range of test functions.

The paper is organized logically to present and evaluate the new method: Section 2 presents the mathematical foundations of the method, Section 3 analyzes convergence and stability, Section 4 describes practical implementation and algorithmic considerations, Section 5 presents numerical results and comparisons with existing methods, and Section 6 summarizes conclusions and future research directions. This clear structure provides readers with a logical

journey through the development and evaluation of the proposed method, ensuring comprehensive understanding of both theoretical foundations and practical applications.

1. Introduction to the Newton–Raphson Method

The Newton–Raphson method (often called simply Newton's method) is one of the cornerstones of numerical analysis and nonlinear computation. Originally developed by Isaac Newton (1669) and later refined by Joseph Raphson (1690), it provides one of the most elegant and powerful approaches for approximating the roots of nonlinear equations of the form

$$f(x) = 0, \quad (1)$$

where $f: \mathbb{R} \rightarrow \mathbb{R}$ is a continuous and differentiable function over a given interval.

1.1. Fundamental Principle

The basic idea of the Newton–Raphson method [2], [3] arises from the linear approximation of a nonlinear function near an initial estimate x_0 . By employing the first-order Taylor expansion, we can write:

$$f(x) \approx f(x_0) + f'(x_0)(x - x_0).$$

By imposing $f(x_1) = 0$, we obtain:

$$0 = f(x_0) + f'(x_0)(x_1 - x_0),$$

which leads directly to the iterative formula:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (2)$$

Through repeated application of this update rule, one can generate a sequence $\{x_n\}$ that, under suitable conditions, converges to the actual root r with **second-order (quadratic) convergence**.

1.2. Convergence Conditions

For the sequence $\{x_n\}$ to converge to the true root r , several assumptions must hold:

1. f is continuously differentiable on an interval $I \subset \mathbb{R}$,

2. There exists a simple root $x^* \in I$ such that $f(x^*) = 0$ and $f'(x^*) \neq 0$;
3. The initial guess x_0 lies sufficiently close to r .

Under these assumptions, the convergence is quadratic [3], [4], [5], that is,

$$|x_{n+1} - x^*| \leq C|x_n - x^*|^2$$

for some constant $C > 0$ that depends on the higher derivatives of f .

1.3. Geometric Interpretation

Geometrically, the Newton-Raphson method represents the process of finding the intersection of the tangent line to $f(x)$ at x_n with the x-axis.

At each iteration, a tangent line is drawn at the current point $(x_n, f(x_n))$, and its intersection with the x-axis defines the next approximation x_{n+1} .

This makes the method a differentially informed root-finding process, accelerating convergence by incorporating local slope information.

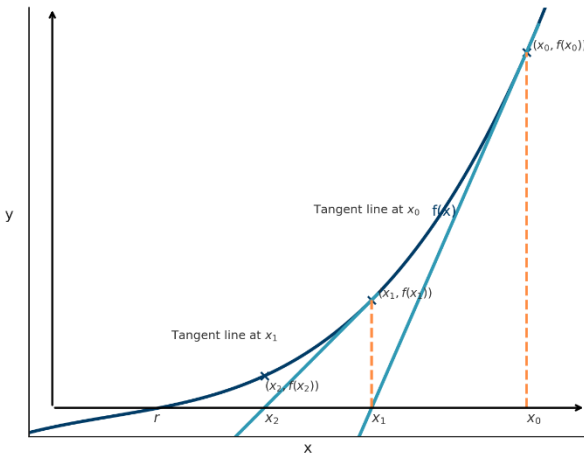


Figure 1. Geometric interpretation of the Newton-Raphson method.

1.4. Advantages and Limitations

The Newton-Raphson method is renowned for its remarkable speed of convergence, especially when the initial guess x_0 is near the true root. However, it is not free from limitations [6]:

- If $f'(x_n)$ is small or changes sign, the iteration may diverge;
- For multiple roots, convergence becomes linear rather than quadratic;
- It requires the computation of the derivative $f'(x)$, which can be analytically or computationally expensive.

2. The Proposed Method

2.1 Finite Difference Approximation

The analytical derivative $f'(x_n)$ in (2) is replaced by a central difference approximation [7], [8]:

$$f'(x_n) \approx D_h f(x_n) = \frac{f(x_n + h_n) - f(x_n - h_n)}{2h_n}$$

where $h_n > 0$ is an adaptive step size that evolves during the iteration process.

The choice of the central difference approximation is motivated by its superior accuracy properties. For sufficiently smooth functions, the truncation error satisfies:

$$|f'(x_n) - D_h f(x_n)| = \mathcal{O}(h_n^2)$$

providing second-order accuracy while maintaining computational efficiency.

2.2 Modified Iteration Scheme

Substituting (3) into (2) yields the modified iteration:

$$x_{n+1} = x_n - \frac{2h_n f(x_n)}{f(x_n + h_n) - f(x_n - h_n)}$$

This formulation eliminates the need for analytical derivatives while preserving the essential structure of the Newton-Raphson method.

2.3 Adaptive Step-Size Control

The effectiveness of the finite-difference approximation (3) critically depends on the appropriate selection of the step size h_n . A step size that is too large introduces significant truncation errors, while one that is too small amplifies rounding errors in finite-precision arithmetic.

2.4 .Relative Error Monitoring

We introduce a monitoring mechanism based on the relative change in the derivative approximation:

$$\delta_n = \left| \frac{D_h f(x_n) - D_h f(x_{n-1})}{D_h f(x_{n-1})} \right|, n \geq 1$$

This quantity serves as a proxy for the stability and accuracy of the derivative approximation.

1.2.2 Step-Size Adjustment Strategy

The step size is dynamically adjusted according to the following rules:

$$h_{n+1} = \begin{cases} \min(1.2h_n, h_{\max}), & \text{if } \delta_n < \tau, \\ \max(0.8h_n, h_{\min}), & \text{if } \delta_n \geq \tau, \end{cases}$$

where:

- $\tau = 10^{-5}$ is a tolerance parameter controlling the adaptation sensitivity;
- $h_{\min} > 0$ prevents excessively small step sizes;
- $h_{\max} < \infty$ bounds the step size to maintain approximation quality.

The expansion factor of 1.2 and the contraction factor of 0.8 were determined empirically to provide a balance between responsiveness and stability in the adaptation process.

3.1 Convergence Analysis

[Local Convergence] Let $f \in C^3(I)$ and let $x^* \in I$ be a simple root of f , i.e. $f(x^*) = 0$ and $f'(x^*) \neq 0$. Then there exists $\epsilon > 0$ and a sequence of step sizes $h_n = \mathcal{O}(|x_n - x^*|)$, such that, for every initial approximation $x_0 \in (x^* - \epsilon, x^* + \epsilon)$, the improved Newton-type iteration

$$x_{n+1} = x_n - \frac{2h_n f(x_n)}{f(x_n + h_n) - f(x_n - h_n)}$$

converges quadratically to x^* , i.e.

$$|x_{n+1} - x^*| \leq K|x_n - x^*|^2,$$

where $K > 0$ is a constant depending on f and x^* .

Proof: Let $e_n = x_n - x^*$ denote the error at iteration n . Since $f \in C^3$, the Taylor expansions around x^* and x_n yield:

$$f(x_n) = f'(x^*)e_n + \frac{f''(x^*)}{2}e_n^2 + \frac{f'''(x^*)}{6}e_n^3 + \mathcal{O}(e_n^4),$$

$$f(x_n \pm h_n) = f(x_n) \pm h_n f'(x_n) + \frac{h_n^2}{2} f''(x_n) \pm \frac{h_n^3}{6} f'''(x_n) + \mathcal{O}(h_n^4).$$

Subtracting the latter two expressions gives the central finite difference:

$$f(x_n + h_n) - f(x_n - h_n) = 2h_n f'(x_n) + \frac{h_n^3}{3} f'''(x_n) + \mathcal{O}(h_n^4),$$

so that the symmetric difference quotient satisfies:

$$\begin{aligned} D_{h_n} f(x_n) &= \frac{f(x_n + h_n) - f(x_n - h_n)}{2h_n} \\ &= f'(x_n) + \frac{h_n^2}{6} f'''(x_n) + \mathcal{O}(h_n^4). \end{aligned}$$

The iterative formula can thus be written as:

$$x_{n+1} = x_n - \frac{f(x_n)}{D_{h_n} f(x_n)} = x_n - \frac{f(x_n)}{f'(x_n) + \frac{h_n^2}{6} f'''(x_n) + \mathcal{O}(h_n^4)}.$$

Hence,

$$e_{n+1} = e_n - \frac{f(x_n)}{f'(x_n) + \frac{h_n^2}{6} f'''(x_n) + \mathcal{O}(h_n^4)}$$

Expanding $f(x_n)$ and $f'(x_n)$ around x^* gives:

$$\begin{aligned} f(x_n) &= f'(x^*)e_n + C_2 e_n^2 + \mathcal{O}(e_n^3), \quad C_2 = \frac{f''(x^*)}{2} \\ f'(x_n) &= f'(x^*) + C_3 e_n + \mathcal{O}(e_n^2), \quad C_3 = f''(x^*) \end{aligned}$$

Using the expansion

$$\frac{1}{f'(x^*) + \delta} = \frac{1}{f'(x^*)} \left(1 - \frac{\delta}{f'(x^*)} + \mathcal{O}(\delta^2) \right)$$

where $\delta = C_3 e_n + \frac{h_n^2}{6} f'''(x_n) + \mathcal{O}(e_n^2 + h_n^4)$, and substituting into the iteration, we obtain after simplification

$$\begin{aligned} e_{n+1} &= e_n - \left[e_n + \frac{C_2}{f'(x^*)} e_n^2 - \frac{C_3}{f'(x^*)} e_n^2 - \frac{f'''(x_n)}{6f'(x^*)} h_n^2 e_n + \mathcal{O}(e_n^3) \right] \\ &= \left(\frac{C_3}{f'(x^*)} - \frac{C_2}{f'(x^*)} \right) e_n^2 + \frac{f'''(x_n)}{6f'(x^*)} h_n^2 e_n + \mathcal{O}(e_n^3) \end{aligned}$$

Since $C_3 = f''(x^*)$ and $C_2 = f''(x^*)/2$, we have

$$\frac{C_3}{f'(x^*)} - \frac{C_2}{f'(x^*)} = \frac{f''(x^*)}{2f'(x^*)}$$

Thus,

$$e_{n+1} = \frac{f''(x^*)}{2f'(x^*)} e_n^2 + \frac{f'''(x_n)}{6f'(x^*)} h_n^2 e_n + \mathcal{O}(e_n^3)$$

If we choose $h_n = \mathcal{O}(|e_n|)$, then $h_n^2 e_n = \mathcal{O}(|e_n|^3)$, leading to,

$$e_{n+1} = \frac{f''(x^*)}{2f'(x^*)} e_n^2 + \mathcal{O}(e_n^3)$$

Consequently,

$$|e_{n+1}| \leq K|e_n|^2 + M|e_n|^3,$$

for constants $K, M > 0$. For sufficiently small $|e_n|$ (i.e. that is, for x_0 close enough to x^*), the cubic term is negligible compared to the quadratic one, establishing quadratic convergence $\mathcal{O}(e_n^3)$. When h_n is too large, oscillations may appear and convergence may deteriorate; however, by adaptively monitoring the relative derivative error, h_n can be progressively reduced as $n \rightarrow \infty$, restoring stability and ensuring second-order accuracy. Hence, the method achieves an asymptotically quadratic convergence:

$$|e_{n+1}| \leq K|e_n|^2$$

It is generally recommended that the initial step size h_0 of the proposed method be chosen within the interval $h_0 \in [0.1, 10]$. This range provides a practical balance between derivative accuracy and numerical stability during the early iterations. In this regime, the algorithm effectively reveals potential sensitivity to the initial approximation-allowing the detection of ill-scaled or poorly conditioned problems while preventing excessive oscillations due to large finite-difference spacing. Once the initial behavior is stabilized within this interval, the adaptive mechanism naturally drives h_n toward smaller values as $n \rightarrow \infty$, ensuring that the iteration rapidly transitions into the regime of quadratic convergence. Therefore, the choice $h_0 \in [0.1, 10]$ is not only empirically justified but also theoretically consistent with the convergence analysis, providing both robustness in initialization and optimal asymptotic accuracy.

4. Practical Implementation and Algorithmic Considerations

The theoretical form of the proposed iteration becomes useful in applications only when it is accompanied by stable stopping rules, safeguards against nearly zero finite-difference denominators, and a clear strategy for updating the adaptive step. In this section we present the complete computational version of the method. The implementation is designed for scalar nonlinear equations $f(x)=0$, but the same logic can be extended to systems by replacing the scalar finite difference with a numerical Jacobian.

4.1. Complete Adaptive Newton-Type Algorithm

Let x_0 be the initial approximation, $h_0 > 0$ the initial finite-difference step, τ the derivative stability tolerance, and $h_{\min}, h_{\max}$ the lower and upper bounds for the adaptive step. At iteration n , the central finite-difference derivative is evaluated by

$$D_{h_n} f(x_n) = \frac{f(x_n + h_n) - f(x_n - h_n)}{2h_n}. \quad \#(1)$$

The preliminary Newton displacement is defined as

$$s_n = -\frac{f(x_n)}{D_{h_n}f(x_n)} \#(2)$$

To avoid instability when the full displacement increases the residual, a damping parameter $\lambda_n \in (0,1]$ may be introduced and reduced until a residual-decrease condition is satisfied [9], [10], [11]. The corrected update is therefore

$$x_{n+1} = x_n + \lambda_n s_n, s_n = -\frac{f(x_n)}{D_{h_n}f(x_n)} \#(3)$$

In the undamped case $\lambda_n = 1$, formula (3) coincides with the modified iteration introduced previously. The damping mechanism does not change the local quadratic behavior near a simple root, because λ_n becomes equal to one once the iteration enters the convergence neighborhood. Its role is mainly global: it prevents large jumps when the initial value is far from the root or when the finite-difference derivative is temporarily inaccurate.

Algorithm 1. Adaptive Finite-Difference Newton Method
Input: nonlinear function f , initial approximation x_0 , initial step h_0 , tolerance ε , maximum number of iterations $N_{\max}$, derivative-stability tolerance τ , and bounds $h_{\min}, h_{\max}$.

For $n = 0, 1, \dots, N_{\max}$, perform the following steps:

1. Compute $F_n = f(x_n)$.

If $|F_n| < \varepsilon$, stop and return x_n as the approximate root.

2. Compute the central finite-difference derivative

$$D_n = \frac{f(x_n + h_n) - f(x_n - h_n)}{2h_n}.$$

If $|D_n|$ is too small, reduce h_n and recompute D_n .

3. Set

$$s_n = -\frac{F_n}{D_n}$$

If damping is required, choose $\lambda_n \in (0,1]$ so that the residual decreases, and set

$$x_{n+1} = x_n + \lambda_n s_n$$

Otherwise, take $\lambda_n = 1$.

4. For $n \geq 1$, compute the relative derivative-variation indicator

$$\delta_n = \left| \frac{D_n - D_{n-1}}{D_{n-1}} \right|$$

5. Update the finite-difference step according to

$$h_{n+1} = \begin{cases} \min(1.2h_n, h_{\max}), & \text{if } \delta_n < \tau \\ \max(0.8h_n, h_{\min}), & \text{if } \delta_n \geq \tau \end{cases}$$

Output: approximate root x_n , number of iterations, final residual $|f(x_n)|$, and final adaptive step size h_n .

4.2. Stopping Criteria and Numerical Safeguards

A practical implementation should not rely on only one stopping criterion. In the numerical experiments below, convergence is accepted when either

$$|f(x_n)| < \varepsilon \#$$

or

$$|x_{n+1} - x_n| < \varepsilon(1 + |x_n|). \#$$

The first condition checks the nonlinear equation itself, while the second condition detects stagnation of the iterates. In this way, the algorithm is able to terminate not only when the residual becomes sufficiently small, but also when successive approximations no longer produce a meaningful improvement. If the finite-difference denominator

$$f(x_n + h_n) - f(x_n - h_n) \#$$

becomes too small, the derivative approximation may become unstable. In this case, the algorithm reduces the adaptive step size h_n and recomputes the finite-difference derivative. If this correction fails repeatedly, the iteration is stopped and the initial value is considered unsuitable for the selected tolerance. This safeguard prevents division by very small quantities and avoids the generation of excessively large Newton displacements [8].

The recommended initial interval

$$h_0 \in [0.1, 10] \#(4)$$

is suitable for many scaled one-dimensional problems. Nevertheless, for functions involving very large or very small physical units, the initial step should be scaled according to the expected magnitude of the initial approximation. A dimensionless and more robust choice is

$$h_0 = \eta(1 + |x_0|), \#(5)$$

where η is typically chosen in the range

$$10^{-3} \leq \eta \leq 10^{-1}. \#(6)$$

This scaling makes the finite-difference step consistent with the size of the problem and improves the reliability of the adaptive Newton-type iteration in problems with different physical units or numerical scales.

5 Numerical Experiments and Comparative Analysis

To illustrate the behavior of the proposed method, several nonlinear equations were tested and compared with the classical Newton method and the secant method. The experiments use the stopping tolerance

$$\varepsilon = 10^{-10},$$

with $h_0 = 0.1$ for the proposed method, $\tau = 10^{-5}$, $h_{\min} = 10^{-8}$, $h_{\max} = 10$, and maximum number of iterations $N_{\max} = 100$. Table 1 reports the number of iterations required to reach the tolerance and the final residual.

Table 1: Comparison between the classical Newton method, the secant method, and the proposed adaptive finite-difference Newton method.

Test equation	Initial data	Newton	Secant	Proposed method
$x^2 - 2 = 0$	$x_0 = 5;$ $x_1 = 4.5$ secant	6 iter.; 4.44×10^{-16}	8 iter.; 9.77×10^{-15}	6 iter.; 4.44×10^{-16}
$x^2 - 2x + 2 = 0$	$x_0 = 0;$ $x_1 = -1$ secant	failed: cycle/max iter.	49 iter.; 2.80×10^{-14}	28 iter.; 0.00×10^0
$\cos(x) - x = 0$	$x_0 = 1.5;$ $x_1 = 1$ secant	4 iter.; 5.55×10^{-16}	5 iter.; 3.55×10^{-15}	4 iter.; 6.18×10^{-11}
$x^{10} - 1 = 0$	$x_0 = 2;$ $x_1 = 1.5$ secant	11 iter.; 8.88×10^{-15}	12 iter.; 3.12×10^{-12}	12 iter.; 0.00×10^0
$\exp(x) - x = 0$	$x_0 = 2;$ $x_1 = 1.5$ secant	4 iter.; 4.72×10^{-11}	6 iter.; 1.11×10^{-16}	5 iter.; 1.03×10^{-12}

The results show that the proposed adaptive finite-difference Newton method preserves the fast convergence of Newton-type iterations in well-conditioned cases, while improving robustness in cases where the classical Newton method may fail due to poor initialization or unstable local behavior. In particular, for the nonlinear equation $x^3 - 2x + 2 = 0$, the classical Newton method fails from the selected initial value because the iterates enter a cycle or reach the maximum number of iterations. In contrast, the proposed method converges successfully by combining finite-difference derivative approximation with adaptive step-size regulation and damping.

5.1 Interpretation of the Results

The results confirm that the modified method preserves the fast local behavior of Newton-type iterations while reducing the dependence on analytical derivatives. For regular problems, such as

$$x^2 - 2 = 0$$

and

$$\cos(x) - x = 0,$$

the number of iterations required by the proposed method is essentially the same as that of the classical Newton method.

The most informative case is

$$x^3 - 2x + 2 = 0, x_0 = 0.$$

For this initial approximation, the classical Newton method oscillates between two points and fails to converge within the prescribed iteration limit. In contrast, the proposed method escapes this cycle through adaptive derivative control and damping. This demonstrates the practical value of combining a symmetric finite-difference derivative with step-size regulation.

The experiments also show that the proposed method is not intended to replace the classical Newton method when an exact derivative is inexpensive, well conditioned, and the initial approximation is already close to the root. Its main advantage appears in derivative-free or derivative-expensive problems, black-box models, and nonlinear equations where the initial approximation may not be sufficiently close to the desired root.

5.2 Computational Cost

Each iteration of the proposed method requires three function evaluations in its basic form:

$$f(x_n), f(x_n + h_n), f(x_n - h_n).$$

This is more expensive than one classical Newton step when $f'(x)$ is explicitly available. However, in black-box situations, derivative evaluation may be unavailable or substantially more expensive than function evaluation. In such cases, the symmetric finite-difference derivative provides a favorable compromise between accuracy and computational cost.

The second-order truncation error of the central finite-difference approximation is particularly important because it allows the method to recover the standard quadratic Newton behavior when the adaptive step h_n decreases proportionally to the current error. More precisely, if

$$h_n = \mathcal{O}(|x_n - x^*|),$$

then the perturbation introduced by the numerical derivative becomes asymptotically negligible compared with the dominant Newton error term.

6 Conclusions and Future Work

This paper introduced an enhanced Newton-type method that replaces the analytical derivative by a central finite-difference approximation and regulates the finite-difference step through an adaptive mechanism. The local convergence analysis shows that, under the standard assumption of a simple root and a sufficiently smooth function, the method preserves quadratic convergence when

$$h_n = \mathcal{O}(|x_n - x^*|).$$

The numerical experiments support the theoretical result and indicate improved robustness in cases where the classical Newton method may cycle or become unstable.

The main contribution of the method is the integration of three complementary ideas: derivative-free Newton correction, dynamic finite-difference step control, and optional damping for residual decrease. This combination makes the algorithm attractive for practical nonlinear equations where the derivative is not available in closed form, is contaminated by numerical noise, or is expensive to compute.

Future work will focus on four directions. First, the adaptive rule for h_n can be refined by comparing $D_h f(x_n)$ with $D_{h/2} f(x_n)$, which provides a direct local estimator of the finite-difference error. Second, the method can be generalized to systems of nonlinear equations by constructing adaptive numerical Jacobians. Third, the damping rule can be replaced by a trust-region strategy in order to obtain stronger global convergence guarantees. Finally, the algorithm should be tested on nonlinear models [12] from engineering, mechanics, and scientific computing in order to evaluate its performance on large-scale and ill-conditioned problems.

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Adaptive Mesh-Free Numerical Integration on Algebraic Surfaces Using Local Polynomial Reconstruction

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Abstract: This paper presents AMNI-AS, a compact method and Python package for surface integration on non-parametrized geometries known only through point-cloud samples. The method extends a corrected minterpy_levelsets [9] workflow: first, a global polynomial level-set function ϕ_h reconstructs the surface as $\Gamma_h = \{x \in \mathbb{R}^3: \phi_h(x) = 0\}$; [6] second, nodal values of the integrand are extended by regression; third, a closest-point projection and a regularized coarea formula [4], [5], produce a mesh-free quadrature rule. The theoretical core is the identity $\int_{\Gamma_h} f dS = \int_{\Omega} f(x) \delta(\phi_h(x)) \|\nabla \phi_h(x)\| dx$, implemented with a compact smooth delta and data-driven evaluation $\tilde{f}_h(\Pi_h(x))$. The prototype package AMNI-AS, contains adapters to minterpy_levelsets, an SVD fallback level-set fit, RBF/nearest integrand regression [3], [15], [16], [17], projection, and quadrature routines. Numerical checks on the unit sphere show relative errors near 10^{-5} for area and polynomial integrands on a moderate grid. The method is intended as a short, reproducible bridge from global polynomial level-set reconstruction to integration tasks on data-defined surfaces.

KEYWORDS: GLOBAL POLYNOMIAL LEVEL SET; POINT CLOUD; SURFACE QUADRATURE; COAREA FORMULA; REGRESSION; MESH-FREE GEOMETRY; TUBULAR NEIGHBORHOOD.

Introduction

Surface integration on data-defined geometries appears in numerical differential geometry, geometric partial differential equations, and mechanics on manifolds [2]. A common difficulty is that the surface is not available as a parametrization $X(u, v)$ or as a high-quality triangulation [14]. Instead, the input is a point cloud

$$P_N = \{p_i\}_{i=1}^N \subset \mathcal{S} \subset \mathbb{R}^3 \# (1)$$

and, in data-only cases, the integrand is known only by nodal values $f_i = f(p_i)$. The objective is

$$I(f, \mathcal{S}) = \int_{\mathcal{S}} f dS \# (2)$$

The proposed method, AMNI-AS, connects two ideas. The first is global polynomial level-set (GPLS) reconstruction [6], [9], where a polynomial ϕ_h is built so that $\mathcal{S} \approx \Gamma_h = \{\phi_h = 0\}$. The second is a regularized coarea formula [4], [5], [12], which converts a surface integral into a narrow-band volume integral. The contribution is a practical integration layer over the corrected minterpy_levelsets package, together with a minimal standalone fallback. The new package gpls rq is orga nized around four operations: reconstruct, regress, project, and integrate

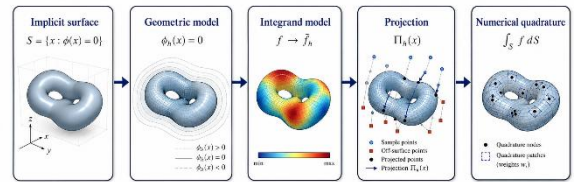
2 Global Polynomial Level-Set Reconstruction

Let $\{\psi_j\}_{j=1}^M$ be a multivariate polynomial basis [6], [7], [8] . GPLS seeks

$$\phi_h(x) = \sum_{j=1}^M c_j \psi_j(x) \# (3)$$

such that

$$\phi_h(p_i) \approx 0, i = 1, \dots, N. \# (4)$$



Numerical Integration on Implicit Surfaces

Figure 1: AMNI-AS pipeline. Point-cloud geometry is converted into a global polynomial level set and then into a surface quadrature rule through regression, projection, and coarea integration.

With the evaluation matrix $A_{ij} = \psi_j(p_i)$, the fitting condition is

$$Ac \approx 0. \# (5)$$

This is the algebraic core of the BK strategy [6], [9]: find a nontrivial vector in the approximate nullspace of A . The corrected minterpy_levelsets implementation stores the result as a Newton polynomial [7], [8], [9], which is convenient for evaluation and differentiation. The geometry is then represented by

$$\Gamma_h = \{x \in \mathbb{R}^3: \phi_h(x) = 0\}. \# (6)$$

The surface normal follows directly from the level-set function [1], [6], [10]:

$$n_h(x) = \frac{\nabla \phi_h(x)}{\|\nabla \phi_h(x)\|}. \# (7)$$

A useful geometric residual is [6]:

$$e_i = \frac{|\phi_h(p_i)|}{\|\nabla \phi_h(p_i)\|}. \# (8)$$

For small residuals, e_i approximates the normal distance from p_i to the reconstructed zero level set. This residual is used to assess whether the polynomial surface is sufficiently close to the data cloud.

3 AMNI-AS Method

AMNI-AS uses the reconstructed ϕ_h as the geometric support for quadrature. It consists of three additional steps.

3.1 Integrand regression

If f is given only as values f_i , the method constructs an extension $\tilde{f}_h$ satisfying $\tilde{f}_h(p_i) \approx f_i$. The package currently supports nearest-neighbor extension and radial basis function (RBF) regression [3], [15], [16], [17]:

$$\tilde{f}_h(x) = \sum_{i=1}^N w_i \rho(\|x - p_i\|), \#(9)$$

where the weights solve

$$(K + \lambda I)w = f, K_{ij} = \rho(\|p_i - p_j\|), \#(10)$$

Nearest-neighbor regression is robust but low-order; RBF regression is smoother and more appropriate when the nodal values come from a smooth surface field.

3.2 Closest-point projection

Since volume-grid points do not lie exactly on Γ_h , evaluation is performed after projection [1], [10]. Starting from a point x^0 near Γ_h , the normal Newton correction is

$$x^{k+1} = x^k - \frac{\phi_h(x^k)}{\|\nabla \phi_h(x^k)\|^2} \nabla \phi_h(x^k). \#(11)$$

Regularized coarea quadrature

For a smooth level set, the coarea relation gives [4], [5]

$$\int_{\Gamma_h} f dS = \int_{\Omega} f(x) \delta(\phi_h(x)) \|\nabla \phi_h(x)\| dx \#(12)$$

In computation, AMNI-AS uses the compact cosine delta [11], [12]

$$\delta_\varepsilon(t) = \begin{cases} \frac{1}{2\varepsilon} \left(1 + \cos \frac{\pi t}{\varepsilon}\right), & |t| \leq \varepsilon, \\ 0, & |t| > \varepsilon. \end{cases} \#(13)$$

The final rule is

$$I_h = \sum_{x_q \in \Omega_h} \tilde{f}_h(\Pi_h(x_q)) \delta_\varepsilon(\phi_h(x_q)) \|\nabla \phi_h(x_q)\| \Delta V, \#(14)$$

where Ω_h is a Cartesian grid in a bounding box around the point cloud [12], [13]. Only the narrow band $|\phi_h| \leq \varepsilon$ contributes.

3.4 Algorithmic summary

The full computational pipeline is deliberately short. It can be written as the following reproducible sequence.

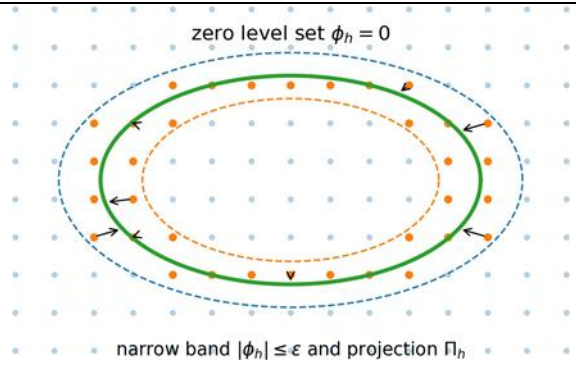


Figure 2: Narrow-band interpretation of AMNI-AS. Grid points in $|\phi_h| \leq \varepsilon$ are projected to $\phi_h = 0$ before the data-regressed integrand is evaluated.

Algorithm 1: AMNI-AS.

1. Input point cloud P_N and optional values f_i .
2. Build ϕ_h by LevelsetPoly or by the SVD nullspace fallback.
3. Build $\tilde{f}_h$ from f_i by RBF or nearest-neighbor regression.
4. Create a Cartesian grid in a bounding box around P_N .
5. Keep only grid nodes with $|\phi_h(x_q)| \leq \varepsilon$.
6. Project each retained node with Eq. (11).
7. Accumulate Eq. (14) and return the integral and diagnostics.

The output object reports the integral, the area estimate obtained by setting $f = 1$, the number of narrow-band nodes, the chosen band width, and diagnostic information about the bounding box and gradient values. This is useful for detecting under-resolved bands or poor polynomial reconstructions.

Compact Theoretical Justification

The following statement explains why the method is consistent at the formal level.

Proposition. Assume that $\mathcal{S}$ is a smooth closed surface, $\phi_h \rightarrow \phi$ in C^1 in a tubular neighborhood of $\mathcal{S}$, where $\mathcal{S} = \{\phi = 0\}$ and $\|\nabla \phi\| \neq 0$ on $\mathcal{S}$. Assume also that $\tilde{f}_h \rightarrow f$ uniformly on the surface and that the projection Π_h is welldefined in the narrow band. If $\varepsilon \rightarrow 0$ and the volume-grid spacing $h \rightarrow 0$ with a resolved band, then the AMNI-AS approximation satisfies

$$I_h \rightarrow \int_{\mathcal{S}} f dS \#(15)$$

Proof sketch. Since $\phi_h \rightarrow \phi$ in C^1 , [4], [5], [6] the reconstructed zero level Γ_h converges to $\mathcal{S}$ in a tubular-neighborhood sense, and the normal field $\nabla \phi_h / \|\nabla \phi_h\|$ converges to the true normal. The projection Π_h therefore approaches the closest-point map onto $\mathcal{S}$. Uniform convergence of $\tilde{f}_h$ gives $\tilde{f}_h(\Pi_h(x)) \rightarrow f(\Pi(x))$ in the band. The regularized delta δ_ε is an approximate identity [4], [11], [12] in the normal coordinate, so

Table 1: Main implementation components.

Module	Role
adapters.py	connection to LevelsetPoly
levelset.py	SVD fallback and projection
integrand.py	RBF and nearest regression
quadrature.py	coarea rule and diagnostics
sampling.py	benchmark point clouds

the volume integral converges to the surface integral by the coarea formula. Finally, the Cartesian quadrature converges to the regularized volume integral as $h \rightarrow 0$. Combining these three limits gives the claim.

This result is not a complete high-order error theorem; rather, it states the consistency mechanism.

A practical interpretation of the proposition is the following error splitting:

$$|I - I_h| \lesssim E_{\text{geom}} + E_{\text{reg}} + E_{\text{band}} + E_{\text{grid}}. \quad (16)$$

Here E_{geom} is controlled by the GPLS residual in Eq. (8) and by the C^1 error of ϕ_h ; E_{reg} is the error of approximating f by $\tilde{f}_h$; E_{band} is the bias introduced by the regularized delta width ε ; and E_{grid} is the Cartesian quadrature error inside the narrow band. This splitting is important because it separates the package into testable components. For example, if $\max_i e_i$ is large, increasing the grid resolution cannot repair the geometry; if E_{reg} is dominant, a smoother RBF or better nodal sampling is required.

In the present prototype, ε is chosen in units of ϕ_h so that the geometric band corresponds to a few grid cells in the normal direction. This avoids an empty band and keeps the cost proportional to the number of grid points close to the surface rather than to all grid points.

Package Implementation

The prototype package is designed as a small research extension rather than a replacement for `minterpy_levelsets`. Its structure is:

- [levelset.py](#): SVD fallback implicit polynomial and projection;
- [adapters.py](#): bridge to `minterpy_levelsets.LevelsetPoly`;
- [integrand.py](#): nearest and RBF data regression;
- [quadrature.py](#): coarea integration and diagnostics;
- [sampling.py](#): sphere, torus, and ellipsoid point clouds. A typical call is:

```
from AMNI_AS import fibonacci_sphere,
    integrate_from_pointcloud
points = fibonacci_sphere(700, radius=1.0)
values = points[:,2]**2
res = integrate_from_pointcloud(points,
    values=values,
    degree=2, levelset_backend="auto",
    regressor="rbf", grid_size=56)
print(res.integral)
```

With `levelset_backend="auto"`, the package first tries the corrected `minterpy_levelsets` backend and otherwise falls back to the standalone SVD fit.

Table 2: Unit-sphere verification for AMNI-AS.

Integrand	Approx.	Exact	Rel. error
1	12.566039	12.566371	2.64×10^{-5}
z^2	4.188681	4.188790	2.61×10^{-5}
$x^2 + y^2$	8.377359	8.377580	2.65×10^{-5}
$x^2 y^2$	0.837789	0.837758	3.64×10^{-5}

Practical parameter choice.

For a smooth closed surface, the polynomial degree controls the geometry model [6], [8], [9]. A low degree is sufficient for algebraic benchmarks such as the sphere, while toroidal and more deformed surfaces typically require degree four or higher. The grid size controls the quadrature resolution, and the delta width ε must be large enough [11], [12] to include several grid layers but not so large that it blurs the surface. In data-only settings, the RBF ridge parameter prevents instability [3], [15], [16] when sample nodes are close or mildly nonuniform. These choices are exposed in the package interface because the method is intended for research experiments rather than as a black-box numerical routine.

6 Numerical Verification

The first validation uses the unit sphere S^2 . For the fallback degree-two fit, the reconstructed polynomial represents the sphere up to numerical precision, with $\max_i |\phi_h(p_i)| \approx 5 \times 10^{-16}$ on 500 Fibonacci nodes. The quadrature is then tested on four integrals with known exact values. A 42^3 Cartesian grid is used in the bounding box. Results are reported in Table 2.

These results show that the prototype captures both the geometry term $\|\nabla \phi_h\|$ and the data-driven integrand evaluation. The method is not yet a machine-precision spectral quadrature rule. Its present role is to provide a reliable bridge from point-cloud GPLS reconstruction to executable surface integration. The next extension is to replace the Cartesian coarea sum with patch-wise high-order quadrilateral or square-squeezed spectral rules [12], [13] on local surface charts.

7 Conclusion

AMNI-AS provides a compact and implementable route from point-cloud geometry to surface integration. It uses a global polynomial level-set surface, regresses integrand values known only at nodes, projects narrow-band samples to the reconstructed surface, and integrates with a regularized coarea formula. The method directly extends the corrected `minterpy_levelsets` package and adds the integration layer needed for non-parametrized surfaces. The short theoretical argument explains consistency under C^1 level-set convergence, integrand-regression convergence, and resolved narrow-band quadrature. Numerical tests on the sphere give relative errors of order 10^{-5} on a moderate grid, supporting the method as a practical base for future high-order spectral surface integration.

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ВАРИАНТ УСОВЕРШЕНСТВОВАНИЯ СУЩЕСТВУЮЩЕЙ ТЕХНОЛОГИЧЕСКОЙ СХЕМЫ ДЕФОРМИРОВАНИЯ «РАДИАЛЬНО- СДВИГОВАЯ ПРОКАТКА С ПРОТИВОДАВЛЕНИЕМ»

OPTIMIZATION OF THE EXISTING TECHNOLOGICAL PROCESS OF DEFORMATION "RADIAL-SHEAR ROLLING WITH BACKPRESSURE

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Abstract. This work is devoted to the improvement of the previously developed technological deformation scheme of cylindrical workpieces "radial-shear rolling with backpressure". In the course of the research conducted on the basis of computer modeling in the DEFORM program and a physical experiment, a comparative analysis of the influence of RSR and various combined processes created on the basis of RSR on the microstructure evolution was carried out, and the force of pushing the workpiece through equal-channel stepped and conical calibration matrices (when implementing combined processes created on the basis of RSR) was determined. A comparative analysis of various combined processes created on the basis of RSR showed that with almost the same level of grain refinement, the force of pushing the workpiece through a conical die when ultrasonic vibrations are applied to it is on average 42% less than when using this die without ultrasonic vibrations and almost 205% lower, than when pushing the workpiece through an equal-channel step matrix.

Keywords: COMBINED PROCESS, RADIAL-SHEAR ROLLING, EQUAL-CHANNEL STEP MATRIX, ULTRASONIC VIBRATIONS, CALIBRATING CONICAL MATRIX, MICROSTRUCTURE

1. Введение

В век ускоренного развития научно-технического прогресса вопрос получения новых конструкционных материалов, в том числе металлических, с улучшенным комплексом механических, физических и эксплуатационных свойств является очень актуальным. В настоящее время существует множество различных вариантов получения металлических материалов с повышенным уровнем физико-механических и эксплуатационных свойств. При этом не обязательно создавать новые материалы. Так, например, одним из вариантов получения конструкционных материалов с повышенным уровнем свойств является измельчение его микроструктуры до ультрамелкозернистого состояния. При этом одним из наиболее эффективных способов получения ультрамелкозернистых материалов является интенсивная пластическая деформация [1], которую можно реализовать в металлах различными способами, в том числе, с помощью радиально-сдвиговой прокатки (РСП) [2], или с помощью различных совмещенных процессов, в основе которых лежит все также РСП. И одним из таких совмещенных процессов является РСП с противодавлением и дополнительным наложением ультразвуковых колебаний (рис. 1), который был разработан в рамках грантового проекта АР26100119.

Суть данного технологического процесса деформирования, включающего процесс радиально-сдвиговой прокатки с противодавлением и ультразвуковую обработку, заключается в следующем: предварительно нагретая до температуры начала деформирования заготовка 2 подается к прокатным коническим валкам 1, которые за счет сил контактного трения захватывают её и за счет смещения осей валков, обеспечивают осевую составляющую сил прокатки, и, следовательно, поступательное движение прокатываемой заготовки, и ее проталкивание на выходе из валков через калибрующую матрицу 3. В ходе деформирования на калибрующую матрицу 3, которая установлена в волноводе 4 через концентратор ультразвуковых колебаний 5 от ультразвукового преобразователя 6, накладываются ультразвуковые колебания. После того, как заготовка полностью выйдет из валков, к ним подается следующая заготовка, которая, пройдя через валки и попав в матрицу, выталкивает ранее деформированную заготовку из матрицы.

Целью данной работы являлось проведение сравнительного анализа (на основе компьютерного моделирования в программе DEFORM и физического эксперимента) РСП и различных совмещенных процессов, созданных на базе РСП.

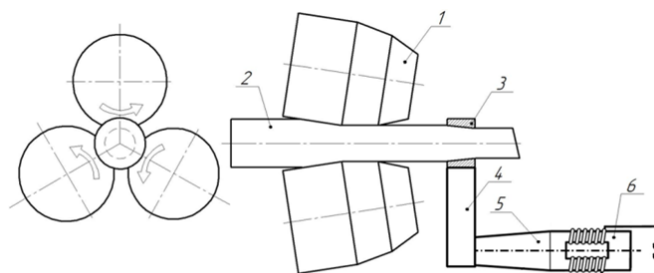


Рис. 1. Схема нового совмещенного процесса: РСП с противодавлением и дополнительным наложением ультразвуковых колебаний: 1 – конические валки, 2 – заготовка, 3 – калибрующая коническая матрица, 4 – волновод, 5 – концентратор ультразвуковых колебаний, 6 – ультразвуковой преобразователь

2. Методика

Для достижения поставленной цели было проведено компьютерное моделирование в программе DEFORM эксперимента по оценке измельчения зерна металла, исходный размер которого был равен 30 мкм. Моделировались следующие процессы: РСП [2] и совмещенные процессы: РСП–РКУП [3]; РСП с противодавлением [4]; РСП с противодавлением и дополнительным наложением ультразвуковых колебаний.

В основу компьютерного моделирования процесса радиально-сдвиговой прокатки с противодавлением и дополнительным наложением ультразвуковых колебаний была положена методика, рассмотренная в работе [5].

Во всех четырех случаях на стадии прокатки заготовка с исходным диаметром 30 мм прокатывалась до диаметра 27 мм. РКУ-матрица имела канал диаметром 28 мм для свободного попадания заготовки в канал. Калибрующая матрица имела диаметр выходного отверстия 26 мм.

Условия и допущения, принятые при моделировании:

- заготовка представляла собой полностью изотропное тело, в котором отсутствовали какие-либо напряжения, дефекты, несплошности и т.п.;

- заготовка имела следующие начальные размеры: диаметр 30 мм и длину 250 мм. На заготовку была нанесена сетка из 170 000 конечных элементов, средний размер элемента составил 1 мм;

- материал заготовки – сталь AISI 1015, соответствующая стали 15;

- температура нагрева заготовки 1000 °С;

- коэффициенты трения на контакте заготовки и инструмента были приняты следующие: на контакте с валками – 0,5; на контакте с матрицей – 0,1 (в 4-м случае, т.е. с дополнительным наложением ультразвуковых колебаний коэффициенты трения на контакте заготовки с матрицей был принят $5,4 \cdot 10^{-4}$);

- окружная скорость валков была равна 50 об/мин.

3. Результаты и обсуждение

Результаты компьютерного моделирования представлены на рисунке 2. Анализ результатов моделирования показал, что после РСП исходный размер зерна уменьшился с 30 мкм до 20 мкм в поверхностной зоне и до 28 мкм в центральной. При совмещенном процессе РСП-РКУП за счет реализации дополнительной деформации сдвига в равноканальной ступенчатой матрице исходный размер зерна уменьшился с 30 мкм до: 17 мкм (поверхность), 22 мкм (центр). При РСП с противодавлением за счет дополнительного обжатия в калибрующей конической матрице исходный размер зерна уменьшился с 30 мкм до: 18 мкм (поверхность), 23 мкм (центр). При РСП с противодавлением и дополнительным наложением ультразвуковых колебаний размер зерна уменьшился с 30 мкм до: 19 мкм (поверхность), 23 мкм (центр). Полученные закономерности изменения микроструктуры металла были подтверждены и в ходе физического эксперимента.

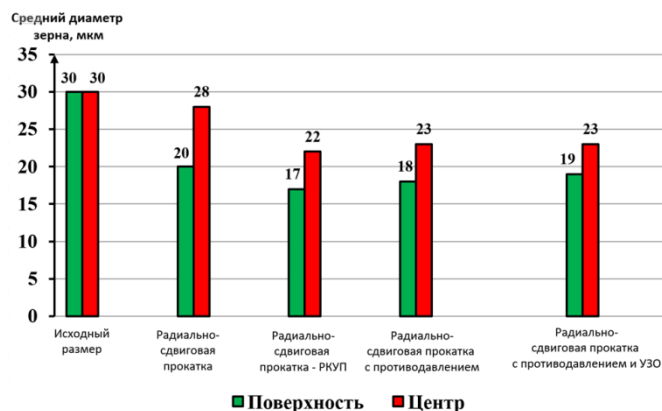


Рис. 2. Результаты компьютерного моделирования

Также было проанализировано усилие, необходимое для проталкивания заготовки через равноканальную ступенчатую и коническую калибрующую матрицы (рис. 3). Анализ результатов измерения усилия показал, что значение усилия, необходимого для проталкивания заготовки через равноканальную ступенчатую матрицу, находится на уровне 29 кН. Значение усилия, необходимого для проталкивания заготовки через коническую калибрующую матрицу, находится на уровне 14,5 кН, а при наложении на калибрующую матрицу ультразвуковых колебаний на уровне 9,5 кН.

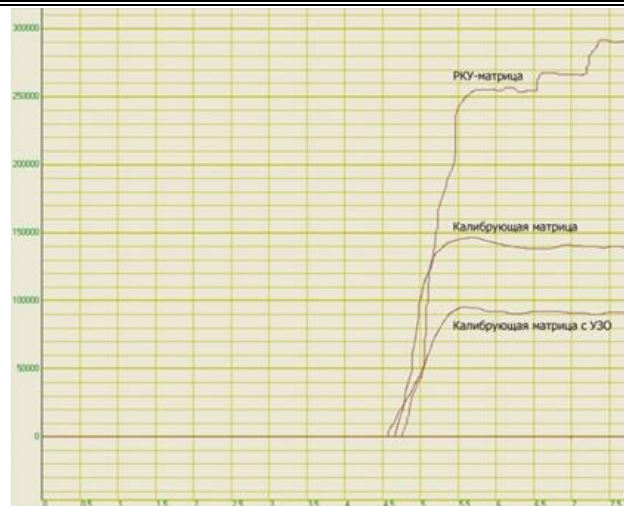


Рис. 3. График усилия, возникающего при проталкивании заготовки через равноканальную ступенчатую и коническую калибрующую матрицы

Вывод: Проведенный сравнительный анализ различных совмещенных процессов, созданных на базе РСП, показал, что при почти одинаковом уровне измельчения зерна, значение усилия проталкивания заготовки через коническую матрицу при наложении на нее ультразвуковых колебаний в среднем на 42% меньше, чем при использовании данной матрицы без наложения на нее ультразвуковых колебаний и почти на 205% ниже, чем при проталкивании заготовки через равноканальную ступенчатую матрицу. Т.е. можно утверждать, что усовершенствованная технологическая схема радиально-сдвиговой прокатки с противодавлением является наиболее перспективным способом получения высококачественных цилиндрических заготовок с ультрамелкозернистой структурой с точки зрения энергосбережения по сравнению с ранее существующими совмещенными способами деформирования, созданными на базе РСП.

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ПЕРСПЕКТИВЫ ИСПОЛЬЗОВАНИЯ ТЕХНОЛОГИИ ЦЕНТРОБЕЖНОГО ЛИТЬЯ ДЛЯ ПОЛУЧЕНИЯ ГЕТЕРОФАЗНОЙ ДИСПЕРСНО-АРМИРОВАННОЙ СТАЛИ

PROSPECTS OF USING CENTRIFUGAL CASTING TECHNOLOGY TO PRODUCE HETEROPHASE DISPERSED REINFORCED STEEL

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Abstract. This work is devoted to studying the state of the issue of obtaining heterophase dispersed reinforced steel with an unexpressed interface between the layers. The existing technologies for injecting ultrafine particles into a crystallizing melt were considered in order to obtain gradient mechanical characteristics in cast blanks. Based on a review of the scientific literature and an analysis of the currently existing methods of dispersed hardening, the advantage of introducing ultrafine particles into a crystallizing melt using centrifugal casting was substantiated. At the same time, the quantity, dispersion, different density, the ability to vary the rotation speed of the horizontal mill, as well as a huge variety of hard refractory fine particles create the prerequisites for obtaining new gradient materials using centrifugal casting.
Keywords: GRADIENT MATERIALS, DISPERSED HARDENING, DISPERSED REINFORCED STEEL, ULTRAFINE PARTICLES, CENTRIFUGAL CASTING, CRYSTALLIZING MELT

Развитие таких стратегических отраслей, как добыча минерально-сырьевых ресурсов, военно-космическая отрасль, металлургия, тяжелого машиностроения, сельского хозяйства, является приоритетом для нашей страны. Обеспечение этих отраслей современными материалами с самыми различными функциональными свойствами в настоящее время в большинстве случаев осуществляется из-за рубежа, поскольку отечественные предприятия, работающие в данной отрасли, до сих пор еще руководствуются советской концепцией конструирования материалов. Эта концепция была целесообразна в то время и подразумевала обеспечение необходимых свойств материалов за счет применения дефицитных, дорогостоящих материалов без оглядки на их количество и рыночную стоимость. Современный мир диктует необходимость менять парадигму мышления и разрабатывать рациональные технологии конструирования материалов, обеспечивающие необходимые свойства только в тех объемах изделия, которые непосредственно подвергаются нагрузкам.

Традиционно, повышение механических свойств черных металлов и сплавов достигается за счет введения в состав металла (основа железо) или сплава значительного количества легирующих элементов. В настоящее время существуют марочных композиций более чем достаточно, чтобы решать большинство текущих задач промышленности. В тоже время, анализ рынка стоимости на легирующие элементы показал, что с каждым годом цены на ферросплавы (легирующие композиции) увеличиваются. Альтернативой использованию дорогостоящих легирующих элементов могут служить гетерофазных дисперсно-армированные стали с невыраженной границей раздела слоев, полученные технологией инжестирования ультрадисперсных частиц в кристаллизующийся расплав с целью получения градиентных механических характеристик. Такие стали являются представителями современных материалов, поскольку в технологии их создания реализуется механизм рационального конструирования и обеспечения необходимыми свойствами только тех объемов, которые подвергаются воздействию именно теми свойствами, которые требуются от данного объема.

По этой причине весьма актуальной задачей является разработка технологии получения металлов, отвечающих специфическим запросам существующей промышленности и при этом имеющих сравнительно низкую себестоимость.

Существующие технологии получения градиентных материалов можно условно разделить на две большие группы:

1. Материалы основаны на соединении разнородных материалов (пакетирование, прокатка, наплавка, напайка, аддитивные технологии и т.д.) [1-2]. У таких способов есть существенные недостатки: требуется сложное оборудование, а также наличие переходной зоны между материалами, участки не сваривания, концентрационные неоднородности являющейся концентратором напряжений, являющейся наиболее частой причиной выхода изделия из строя.

2. Материалы, полученные технологией спекания порошков, последовательно набранных в одну пресс-форму изделие и отличающиеся по стехиометрическому составу [3-4]. Такая технология обеспечивает получения градиента свойств, однако он незначителен, а сама технология очень трудоемка, затратна и главным недостатком технологии является невозможность получения деталей объемом более 15-20 кубических сантиметров - большой размер практически невозможно качественно пропрессовать.

Наиболее перспективным направлением создания материалов с высоким уровнем свойств, по нашему мнению, является дисперсное упрочнение, т.е. микроструктурирование материалов методом инжестирования требуемых по морфологии ультрадисперсных частиц в кристаллизующийся расплав, что дает возможность получать гетерогенные градиентные дисперсно-армированные стали с невыраженной границей раздела слоев. В отличие от наночастиц, ультрадисперсные частицы более доступны и не имеют такого недостатка как агломерация, поэтому более предпочтительны для создания градиента свойств. Для реализации механизма дисперсного упрочнения, существует несколько способов, которые рассмотрены ниже.

1. Введение дисперсных микропорошков в слиток на стадии разливки сверху. Исследования, проведенные авторами работы [5], показали у модифицированного металла возросли на 18% прочностные и на 37-50% пластические свойства, в 1,5-2 раза повысились трещиностойкость и ударная вязкость. Данный способ дисперсионного упрочнения достаточно интересен и прост в реализации, однако следует отметить, что при реализации данного метода отсутствует возможность прогнозировать и управлять распределением частиц. Весьма сомнительно, что введенные частицы в полученных слитках расположились равномерно по всему сечению: кристаллизация заготовки идет от стенки изложницы к центру, при этом фронт кристаллизации перенесет непрогнозируемое количество частиц в центр слитка, часть частиц, подчиняясь конвективным потокам, всплывет, часть опустится на дно слитка. При этом неравномерность распределения приведет к непрогнозируемой

неравномерности свойств. К тому же данный способ может быть реализован только в случае использования изложниц сравнительно маленького диаметра – чтобы увеличить скорость кристаллизации заготовки и распределить вводимые частицы достаточно равномерно по сечению слитка.

2. Введение дисперсных частиц в металл при непрерывной разливке. Авторами работы [6] было отмечено, что подача нанопорошковых модификаторов в кристаллизатор МНЛЗ не позволяет получить концентрации инокуляторов в слитке выше 0,005-0,007% из-за технологических особенностей введения. При исследовании металла, полученного с введением частиц в ковш, отмечается существенное увеличение ряда показателей: повысилась удельная плотность модифицированного металла до 48-82 кг/м³ (в зависимости от вида частиц); снизилась бальность развития внутренних дефектов на 40-56%; увеличилась толщина корочки на 25,8-26,9%; сократились области равноосных кристаллов (на 46,7-53,5%), сократилась дендритная зона (20,5-25,4%) и длина первичных осей дендритов (23,9-25,5%). Механические испытания образцов модифицированной стали показали увеличение предела текучести в среднем на 7,2%; временного сопротивления разрыву – 1,0%; предела прочности – 1,7%; относительного удлинения – 8,4%; относительного сужения – 14,8 %.

Преимущество данного метода получения дисперсно-упрочненного материала в том, что он высокотехнологичен: для получения материала практически не требуется никаких дополнительных механизмов (за исключением трайб-аппарата), при этом получаемый опытный металл значительно превосходит по свойствам не модифицированные образцы сравнения. Однако при таком методе введения невозможно добиться управляемого распределения вводимых модификаторов по сечению получаемой заготовки, как вследствие кристаллизационных явлений, так и вследствие седиментации по удельному весу, а значит, и градиента свойств. Таким образом, в жидком металле все вводимые частицы будут всплывать на поверхность расплава за исключением тех, которые будут захватываться потоками металла (при введении в ковш) или растущими дендритами (при введении в кристаллизатор). В связи с этим весьма сомнительно, что возможно прогнозировать количество частиц, вводимых в формируемую заготовку. К тому же управление распределением в этом методе сводится только лишь к возможности варьировать скорость подачи порошковой проволоки в кристаллизатор или промежуточный ковш.

3. Введение дисперсных частиц при центробежном электрошлаковом литье. Сущность данной технологии, которая была рассмотрена в патенте на изобретение [7], заключается в электрошлаковом переплаве электрода в плавильной емкости, обеспечивающей накопление жидкого металла и шлака в нужных количествах, и последующей его заливке во вращающуюся форму. В качестве модификатора выступают синтетические ультрадисперсные частицы карбонитрида титана в количестве 0,3...0,5 % от массы расплава. Модификатор получали смешиванием порошковых компонентов с последующим холодным прессованием в таблетки и добавляли их в промежуточный ковш. Исследователи утверждают, что введение в металл 0,4 % модификатора приводит к существенному изменению структуры и свойств литого металла. Устраняются зоны транскристаллизации в кольцевых отливках, резко уменьшаются размеры дендритов, которые к тому же приобретают благоприятную форму по всему объему закристаллизовавшегося металла.

Структура отливок характеризуется наличием ферритно-мартенситной матрицы с компактными карбидами, расположенными большей частью в микрозернах, а разрушение ударных образцов носит в основном транскристаллитный характер. В этом случае уровень механических свойств отливок практически не отличается от свойств кововой заготовки.

Данная технология достаточно интересна и перспективна, в силу применения в качестве способа распределения частиц по объему получаемой заготовки центробежных сил. Однако описанный способ имеет существенный недостаток: модификаторы вводят в прессованных таблетках в плавильную емкость. Сомнительно, что возможно прогнозировать, насколько равномерно дисперсные частицы распределяться по объему металла. К тому же частицы, находящиеся «на поверхности» «таблеток», будут иметь существенно большее время взаимодействия с расплавом, чем частицы, находящиеся внутри таблеток. Соответственно, даже при условии отсутствия химического взаимодействия частиц с расплавом, частицы будут подвергаться температурному воздействию, что приведет к их частичной диссоциации. Это может вызывать изменение гранулометрического состава, что также затруднит прогнозирование распределения частиц по объему металла. Таким образом, существующие на сегодняшний день способы упрочнения металлов за счет введения частиц имеют существенные недостатки, заключающиеся в ограниченной возможности прогнозирования вводимых частиц по объему получаемого металла и управления распределением вводимыми частицами.

4. Введение дисперсных частиц при вытяжке в направлении обратном гравитационному полю. Одним из перспективных методов внедрения дисперсных частиц в расплав является "Метод повышения износостойкости композиционного материала" [8]. Этот подход осуществляется на оборудовании для непрерывного литья с вытяжкой формирующейся заготовки против направления действия гравитации (рис. 1).

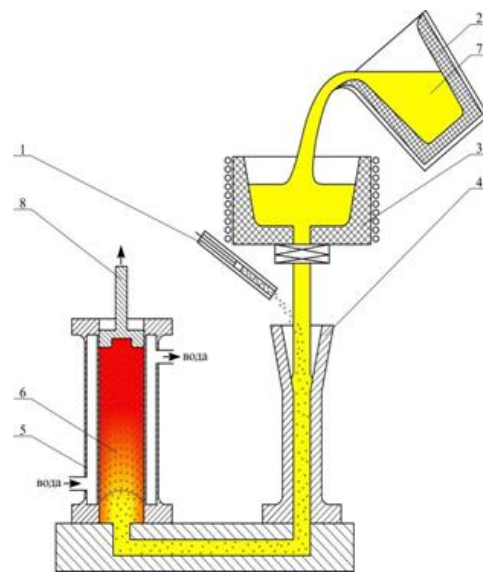


Рис. 1. Способ получения композиционного материала с повышенной износостойкостью с вводом упрочняющей фазы: 1 – дозатор; 2 – ковш; 3 – промежуточный ковш с подогревом; 4 – центровая; 5 – водоохлаждаемый кристаллизатор; 6 – мелкодисперсные твердые тугоплавкие частицы; 7 – упрочняемый расплав; 8 – механизм обратной вытяжки

В процессе заливки, перед подачей металла в кристаллизатор, на поток присаживаются дисперсные тугоплавкие частицы. Металл, содержащий инжестированные частицы, проходит через кристаллизатор, где происходит его затвердевание и вытяжка заготовки в противоположном направлении гравитации. Благодаря разнице в плотности между вводимыми частицами и основным материалом, под действием архимедовой силы они перемещаются вверх. При определенных условиях можно достичь совпадения перемещения фронта кристаллизации с движением частиц, что позволяет создать композиционные материалы с улучшенными прочностными характеристиками. Данный метод интересен тем, что он учитывает различия в плотностях дисперсной фазы и основного материала, однако для его реализации необходимо

специальное оборудование. Хотя этот метод позволяет упрочнять весь объем заготовки дисперсными частицами, получение градиентного композиционного материала с различными слоями, обладающими различными свойствами, остается проблематичным.

Все выше перечисленные способы дисперсного упрочнения имеют, как свои преимущества, так и свои недостатки, которые не позволили повсеместно использовать эти способы на практике.

Проанализировав все выше рассмотренные способы дисперсного упрочнения мы пришли к выводу, что введение ультрадисперсных частиц в кристаллизующийся расплав в ходе центробежного литья может устранить многие недостатки выше рассмотренных способов получения дисперсно-армированной стали и стать одним из перспективным и экономически выгодным способом.

Особенность стальной, полученных таким способом, состоит в том, что вводимые ультрадисперсные микрочастицы встраиваются в кристаллическую решетку формируемого материала, увеличивая количество центров кристаллизации, что ведет к значительному увеличению механических свойств, увеличивают его удельную плотность (за счет измельчения структуры), обеспечивают более мелкое зерно, что ведет к увеличению коррозионностойких свойств, приносят свойства, характерные для вводимых частиц тем объемам материала, где они располагаются. Расположением инжектируемых в расплав в ультрадисперсных частиц можно управлять, что позволяет прогнозировать и задавать различные свойства различным объемам получаемой стали.

Сущность же самого метода инжектирования ультрадисперсных частиц в кристаллизующийся расплав при центробежном литье заключается в следующем: при заливке металлического материала на машину центробежного литья на поток металла непрерывно, в течение всей процедуры разлива, подаются твердые тугоплавкие мелкодисперсные частицы различной плотности. Когда плотность тугоплавкой дисперсной частицы, погруженной в расплав, отличается от плотности самого расплава, сила, воздействующая на эту частицу, не компенсируется ни ее собственной центробежной силой, ни силой тяжести. Вследствие этого создаются условия для перемещения частиц либо внутрь, либо наружу формирующегося изделия, то есть к внутренней или внешней поверхности заготовки. Как только частица достигает фронта кристаллизации, она прижимается расплавленным металлом к этому фронту и перестает всплывать, будучи захваченной растущими дендритами. В итоге происходит упрочнение поверхности.

Чтобы укрепить наружную поверхность трубной заготовки, используются тугоплавкие дисперсные частицы, чья плотность превышает плотность расплава. В таком случае центробежная сила превосходит силу Архимеда, и частица в расплавленном материале движется от оси вращения к фронту кристаллизации. Она прижимается расплавом к фронту кристаллизации, не всплывает и захватывается растущими дендритами, что приводит к укреплению наружной поверхности трубной заготовки. Для укрепления внутренней поверхности трубной заготовки применяются тугоплавкие дисперсные частицы, плотность которых меньше плотности расплава. Здесь сила Архимеда доминирует над центробежной силой, и частица в расплаве направляется к оси вращения, всплывая на свободную поверхность расплава и захватываясь растущими дендритами. Это приводит к усилению внутренней поверхности трубной заготовки.

Для одновременного усиления как внешней, так и внутренней поверхностей трубной заготовки используются частицы разной плотности (как большей, так и меньшей, чем плотность расплава), подаваемые в смесь одновременно. После попадания в изложницу, под влиянием центробежных сил и силы Архимеда всплытия, частицы разделяются, обеспечивая одновременное дисперсное упрочнение как внутренней, так и внешней поверхности трубной заготовки (рис. 2).

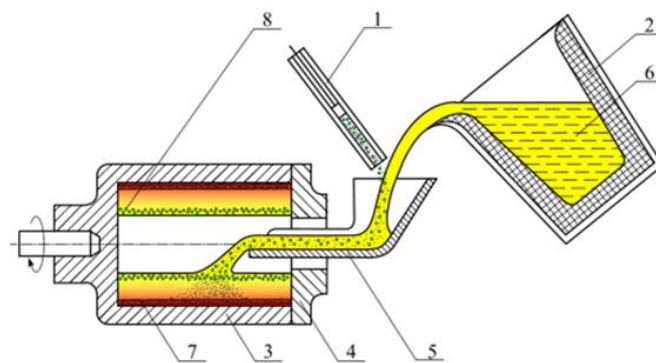


Рис. 2. Способ получения градиентного материала: 1 – дозатор; 2 – ковш; 3 – горизонтальная изложница; 4 – крышка изложницы; 5 – стелеразливочный носок; 6 – упрочняемый расплав; 7 – карбиды с удельной плотностью равной или выше плотности металла; 8 – карбиды с удельной плотностью меньшей плотности металла

Вывод: На основе выше представленной информации можно сделать вывод, что количество, дисперсность, различная плотность, возможность варьировать скоростью вращения горизонтальной изложницы, а также огромное многообразие твердых тугоплавких мелкодисперсных частиц, и, как следствие, многообразие физико-химических и механических свойств создают предпосылки для получения новых градиентных материалов именно с помощью центробежного литья.

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РАЗРАБОТКА И АНАЛИЗ НОВОЙ МАТЕМАТИЧЕСКОЙ МОДЕЛИ ПЛОСКОЙ ЗАДАЧИ ТЕОРИИ ПРОКАТКИ ПРИ АСИММЕТРИЧНОМ ВЗАИМОДЕЙСТВИИ РАЗНОНАПРАВЛЕННЫХ ЗОН В ЕДИНОМ ОЧАГЕ ДЕФОРМАЦИИ

DEVELOPMENT AND ANALYSIS OF A NEW MATHEMATICAL MODEL OF A PLANE PROBLEM OF ROLLING THEORY WITH ASYMMETRIC INTERACTION OF DIFFERENT-DIRECTION ZONES IN A SINGLE DEFORMATION ZONE

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Abstract: The paper presents the results of the development of a mathematical model of a plane problem of rolling theory under conditions of asymmetric interaction of lag and advance zones in a single deformation zone. Mathematical analysis shows that, taking into account the boundary conditions, two attenuating reciprocal penetrating functions appear along the edges of the deformation zone, forming overlapping zones. Different boundary conditions along the edges of the deformation zone analytically characterize the interaction of multidirectional metal flow flows in a single deformation zone. Taking into account the obtained mathematical model, it becomes possible to study and analyze the loss of stability of the process, to determine the effects that occur in the zones of availability of the limiting deformation zone, to use them in the development of new technologies and equipment.

Keywords: MATHEMATICAL MODEL, FLAT ROLLING THEORY, ASYMMETRIC ZONE, LAG AND ADVANCE ZONES.

Причиной сложности многих теоретических задач является незнание особенностей, эффектов и процессов, определяющих взаимодействие зон отставания и опережения в едином очаге деформации. Взаимодействие зон проявляется в том, что изменение кинематических, силовых параметров в локальной зоне, приводят к изменению параметров процесса всего очага деформации. Возникает эффект асимметричного взаимодействия разнонаправленных зон в едином очаге деформации. Суммарный эффект взаимодействующих зон может быть разным и регулируемым [1].

Рассматривается замкнутая задача теории пластичности и на ее базе прикладная задача теории пластичности, со сложным физическим процессом, реализуемым в условиях с противоположенными течением металла при сложном асимметричном нагружении. В работах [2, 3] представлены общие подходы решения задач механики сплошной среды с использованием метода аргумент функций комплексной переменной. Учитывая, что анализируется асимметричное нагружение, постановку и решение задачи представляется в напряжениях, т.е.:

$$\begin{aligned} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} &= 0; \\ \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \sigma_y}{\partial y} &= 0; \\ (\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2 &= 4k^2, \end{aligned} \quad (1)$$

границные условия:

$$\tau_n = -\left[\frac{\sigma_x - \sigma_y}{2} \sin(2\varphi) - \tau_{xy} \cos(2\varphi) \right]. \quad (2)$$

Уравнения (1) приводятся к виду:

$$\frac{\partial^2 \tau_{xy}}{\partial x^2} - \frac{\partial^2 \tau_{xy}}{\partial y^2} = \pm 2 \frac{\partial^2}{\partial x \partial y} T_i \sqrt{1 - \left(\frac{\tau_{xy}}{T_i} \right)^2}. \quad (3)$$

В этом случае присутствует нелинейность, как в граничных условиях (2), так и в дифференциальном уравнении (3), которое является основным для определения касательных напряжений. Зависимости (2), (3) можно линеаризовать, т.е. упростить, с

помощью тригонометрической подстановки, а граничные условия приводятся к виду:

$$\tau_n = -T_i \sin(\Lambda\Phi - 2\varphi), \quad (4)$$

С учетом тригонометрической подстановки (4), уравнение (3) можно переписать:

$$\frac{\partial^2 (T_i \sin \Lambda\Phi)}{\partial x^2} - \frac{\partial^2 (T_i \sin \Lambda\Phi)}{\partial y^2} = \pm 2 \frac{\partial^2}{\partial x \partial y} T_i \cos \Lambda\Phi. \quad (5)$$

Используя фундаментальную подстановку, используя функцию комплексной переменной для касательного напряжения можно записать:

$$\tau_{xy} = H_\sigma \frac{\exp(\theta + i\Lambda\Phi) - \exp(\theta - i\Lambda\Phi)}{2i}. \quad (6)$$

Используя выражения (6) в уравнении (5), имеем:

$$\begin{aligned} &\frac{1}{2i} \exp(\theta + i\Lambda\Phi) \cdot \left\{ (H_\sigma)_{xx} - (H_\sigma)_{yy} + 2i(H_\sigma)_{xy} \right\} + 2(H_\sigma)_x \left[(\theta_x + \Lambda\Phi_x) - \right. \\ &\quad \left. - i(\theta_y - \Lambda\Phi_y) \right] - 2(H_\sigma)_y \left[i(\theta_x + \Lambda\Phi_x) - (\theta_y - \Lambda\Phi_y) \right] + H_\sigma \left[(\theta_{xx} - \theta_{yy} + 2\Lambda\Phi_{xy}) + \right. \\ &\quad \left. + i(\Lambda\Phi_{xx} - \Lambda\Phi_{yy} - 2\theta_{xy}) \right] + H_\sigma \left[(\theta_x + \Lambda\Phi_x) - i(\theta_y - \Lambda\Phi_y) \right]^2 \Big\} - \\ &\quad - \frac{1}{2i} \exp(\theta - i\Lambda\Phi) \cdot \left\{ (H_\sigma)_{xx} - (H_\sigma)_{yy} + 2i(H_\sigma)_{xy} \right\} + 2(H_\sigma)_x \left[(\theta_x + i\Lambda\Phi_x) + \right. \\ &\quad \left. + i(\theta_y - \Lambda\Phi_y) \right] - 2(H_\sigma)_y \left[(\theta_y - \Lambda\Phi_x) - i(\theta_x + \Lambda\Phi_x) \right] + H_\sigma \left[(\theta_{xx} - \theta_{yy} + 2\Lambda\Phi_{xy}) - \right. \\ &\quad \left. - i(\Lambda\Phi_{xx} - \Lambda\Phi_{yy} - 2\theta_{xy}) \right] + H_\sigma \left[(\theta_x + \Lambda\Phi_x) + i(\theta_y - \Lambda\Phi_y) \right]^2 \Big\} = 0. \end{aligned} \quad (7)$$

После приведения и упрощений имеем аналитическое выражение для касательных напряжений в виде:

$$\tau_{xy} = H_\sigma \exp \theta \sin \Lambda\Phi, \quad (8)$$

при условии:

$$\theta_x = -\Lambda\Phi_x, \theta_y = \Lambda\Phi_y, \theta_{xx} + \theta_{yy} = 0, \Lambda\Phi_{xx} + \Lambda\Phi_{yy} = 0. \quad (9)$$

Условие (9) определяет дифференциальные соотношения Коши-Римана и уравнения Лапласа, т.е. условия существования решения уравнения (5). Функция асимметрии H_σ удовлетворяет дифференциальное уравнение (7), имеет вид:

$$H_{\sigma} = \frac{C_0 \left(\frac{l}{2} - x \right) + C_1 \left(\frac{l}{2} + x \right)}{l}, \quad (10)$$

После подстановке выражения (8), с учетом (10), в уравнения равновесия, после интегрирования имеем:

$$\sigma_x = - \frac{\frac{k_0}{\cos A \Phi_0} \left(\frac{l}{2} - x \right) \exp(\theta - \theta_0) + \frac{k_1}{\cos A \Phi_1} \left(\frac{l}{2} + x \right) \exp(\theta - \theta_1)}{l} \cos A \Phi + k_0,$$

$$\sigma_y = -3 \frac{\frac{k_0}{\cos A \Phi_0} \left(\frac{l}{2} - x \right) \exp(\theta - \theta_0) + \frac{k_1}{\cos A \Phi_1} \left(\frac{l}{2} + x \right) \exp(\theta - \theta_1)}{l} \cos A \Phi + k_0, \quad (11)$$

$$\tau_{xy} = \frac{\frac{k_0}{\cos A \Phi_0} \left(\frac{l}{2} - x \right) \exp(\theta - \theta_0) + \frac{k_1}{\cos A \Phi_1} \left(\frac{l}{2} + x \right) \exp(\theta - \theta_1)}{l} \sin A \Phi.$$

Анализ полученной математической модели (11) показывает, что с учетом граничных условий по краям очага деформации появляются две затухающие взаимообратные проникающие друг в друга функции, образующие зоны перекрытия. Эти зоны перекрытия могут влиять на распределение обобщенных функций по длине очага деформации. С точки зрения физической модели указанные математические зоны перекрытия, разные граничные условия по краям очага деформации аналитически характеризуют взаимодействие разнонаправленных потоков течения металла в едином очаге деформации. Используя полученную математическую модель (11) были подсчитаны значения относительных контактных напряжений.

На рисунке 1 показано распределение нормальных и касательных напряжений по длине очага деформации в зависимости от коэффициента трения.

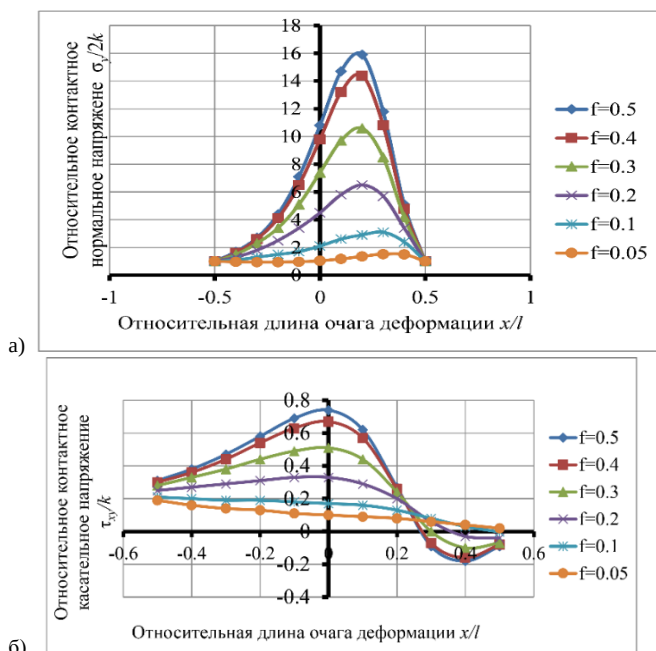


Рис. 1. Распределение относительных контактных напряжений по длине очага деформации в зависимости от контактного трения, при $l/h=15.49$; $\alpha=0.077$; $f=0.05 \dots 0.5$: а – распределение нормальных напряжений; б – распределение касательных напряжений

Касательные напряжения представляют двухзонный и однозонный очаг при минимальном коэффициенте трения, равным 0.05. В зоне отставания эпюры нормальных напряжений в основном имеют вогнутую форму, что характеризуется ослаблением нагрузки на участке; в зоне опережения – выпуклую, что характеризуется усилением нагрузки. Это приводит к усилению асимметричности

контактных напряжений между зонами отставания и опережения в пределах единой области деформации. Касательные напряжения в зоне отставания обозначены максимальными значениями и разной по протяженности зонами опережения.

В основе такой асимметрии распределения напряжений лежит определенная физическая модель процесса, характеризуемая взаимодействием зон разнонаправленного течения металла. В зоне отставания, действуют выталкивающие контактные силы нормального давления p_x , и втягивающие силы трения τ_x , которые направлены в противоположные стороны, вызывая появление продольных растягивающих напряжений в пластической среде. В зоне опережения эти силы сонаправлены и расположены против хода прокатки.

В первом случае имеет место уменьшение контактных напряжений, во втором – усиление влияния подпирющих контактных сил в зоне опережения. С увеличением обжатия (снижение захватывающей способности валков) действие выталкивающей силы возрастает, что увеличивает растягивающую составляющую. Усиливается взаимодействие зон, ослабляется влияния подпирющих сил контактного трения в этой части очага деформации. При этом увеличивается прогиб эпюр нормальных напряжений (снижение контактных напряжений).

На рисунке 2 показано распределение контактных напряжений в зависимости от коэффициента трения f , с пробуксовкой валков, при значении фактора формы равном 11.07, при угле захвата равном 0.129.

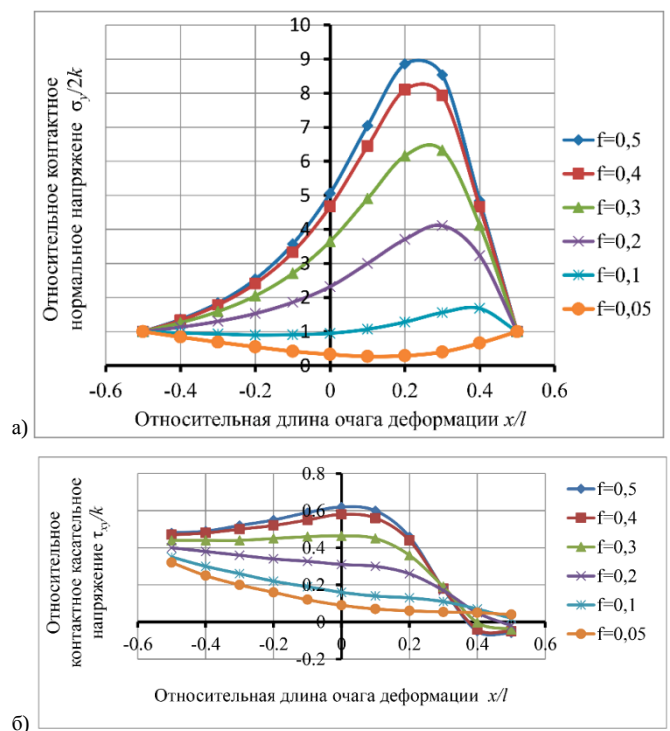


Рис. 2. Распределение контактных напряжений по длине очага деформации в зависимости от контактного трения, при $l/h=11.04$, $\alpha=0.129$, $f=0.05 \dots 0.5$: а – распределение нормальных напряжений; б – распределение касательных напряжений

Из рисунка 2 видно, что математическая модель (11) реагирует на потерю устойчивости процесса прокатки, при сопоставимости коэффициентов трения и углов захвата. В этом случае обжатие было увеличено с $\alpha=0.077$ до $\alpha=0.129$. Особенностью данной эпюры является возможность наглядного анализа процесса, связанного с его потерей устойчивости при прокатке. Имеет место однозонный очаг деформации, эпюра касательных напряжений, и вогнутая эпюра нормальных напряжений, которые характеризует

процесс потери устойчивости при прокатке, буксование полосы [4].

Следует добавить, что рассмотрен единый очаг деформации, учитывающий взаимодействие разно нагруженных зон очага деформации в условиях асимметричного нагружения.

С учетом разработанной математической модели (11) появляется возможность изучить и проанализировать потерю устойчивости процесса, определить эффекты, возникающие в зонах доступности предельного очага деформации, использовать их при разработке новых технологий и оборудования.

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ОПТИМИЗАЦИЯ ТЕХНОЛОГИЧЕСКОЙ СХЕМЫ ВЫЕМОЧНО-ПОГРУЗОЧНЫХ РАБОТ В КАРЬЕРАХ ПРИ ИСПОЛЬЗОВАНИИ ФРОНТАЛЬНЫХ ПОГРУЗЧИКОВ

OPTIMIZATION OF THE TECHNOLOGICAL SCHEME OF EXCAVATION AND LOADING OPERATIONS IN OPEN-PIT MINES USING FRONT-END LOADERS

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Abstract. The article addresses the optimization of the technological scheme of excavation and loading operations in open-pit mines using front-end single-bucket loaders. The structural and operational characteristics of loaders are analyzed in comparison with conventional shovel-truck systems. Technological parameters of loader operation under deep open-pit conditions are substantiated, including bench geometry, maneuvering schemes, and organization of loading and haulage processes. A technical and economic assessment of loaders with different bucket capacities is carried out, considering transportation distance and lifting height. The relationships between productivity, capital investments, and annual haulage volumes are identified. The study demonstrates the feasibility of integrating front-end loaders into combined transport systems under specific geological and production conditions.

Keywords: OPEN-PIT MINING, EXCAVATION AND LOADING OPERATIONS, FRONT-END LOADERS, TECHNOLOGICAL SCHEME OPTIMIZATION, TRANSPORTATION DISTANCE, LIFTING HEIGHT, CAPITAL EXPENDITURES, COMBINED TRANSPORT SYSTEMS

1. Введение

В современных условиях особое внимание уделяется совершенствованию технологий открытой добычи полезных ископаемых с целью повышения производственной мощности карьеров. В структуре горных работ ведущая роль принадлежит выемочно-погрузочным операциям, для выполнения которых применяются механические и гидравлические экскаваторы (с прямой и обратной лопатой), фронтальные погрузчики и вспомогательная техника. Особое внимание уделяется применению погрузчиков при разработанной контейнерной технологии транспортирования горной массы, при этом их применение возможно в забоях карьера и на перегрузочном складе отвала [1].

В условиях внедрения современных технологий фронтальные погрузчики демонстрируют высокую универсальность и конкурентоспособность, в ряде случаев превосходя традиционные экскаваторы по показателям мобильности и производительности. Они представляют собой автономные машины с дизельным двигателем, отличающиеся высоким уровнем маневренности и способными перемещаться между различными уровнями карьера со скоростью до 30-40 км/ч. Данная скоростная характеристика позволяет им одновременно обслуживать несколько забоев, а также эффективно транспортировать сырьё на дистанции до 500-700 метров до точек выгрузки [2].

В крупных карьерах фронтальные погрузчики дополняют работу мощных экскаваторов, особенно при селективной выемке в сложных забоях, ограниченных пространствах, на перегрузочных пунктах и складах. В составе комбинированных транспортных схем они обеспечивают подачу горной массы к дробильно-перегрузочным узлам, рудоспускам и загрузочным устройствам.

Погрузчики также выполняют вспомогательные операции, включая очистку уступов и технологических дорог от крупнокусковых обломков, препятствующих работе основного оборудования. Расширение функциональных возможностей достигается за счет применения сменных рабочих органов, в том числе бульдозерных отвалов. Универсальность, меньшая масса и сравнительно простая конструкция обуславливают их экономическую привлекательность и широкое применение на карьерах различной производственной мощности.

К ограничениям относится невозможность эффективной работы в забоях высотой более 10–12 м, а также сравнительно невысокое усилие внедрения в массив, что затрудняет выемку крупнокусковых пород после взрывных работ [3].

Критерием сравнительной эффективности погрузочного оборудования служит отношение массы полезной нагрузки ковша к общей массе машины. У канатных экскаваторов этот показатель составляет 5–7%, у гидравлических экскаваторов с прямой лопатой — 8–11%, тогда как у колесных погрузчиков достигает 18–21%, что обуславливает их высокую удельную производительность и технологическую мобильность.

Современные фронтальные пневмоколесные погрузчики, предназначенные для работы с взорванной горной массой, оснащаются износостойкими ковшами, системами оперативного взвешивания и бортовой диагностикой. По сравнению с гусеничными экскаваторами они значительно легче и дешевле, обеспечивают снижение эксплуатационных расходов на 30–70% и уменьшение себестоимости погрузки на 15–50% [2].

2. Методика

Для ведения работ на карьере предлагается применение погрузочно-транспортного комплекса, включающего фронтальный колесный погрузчик L-1350 (объем ковша 21 м³) и карьерный автосамосвал Hitachi EH-4000 грузоподъемностью 221 т.

Принятая схема, изображенная на рисунке 1, обеспечивает рациональную организацию погрузочно-транспортных процессов, повышение производительности и соблюдение требований промышленной безопасности.

В данной технологической схеме работы погрузчиков минимально допустимая ширина рабочей площади принимается 25 м. При этом данное оборудование может проводить заполнение контейнеров, которые им самим будут доставляться на отвал.

Процесс выемки мягких и предварительно взорванных пород фронтальным погрузчиком включает внедрение ковша в нижнюю часть забоя, его заполнение за счет подъема стрелы гидросистемой с одновременным горизонтальным маневрированием, последующий выход из забоя и разгрузку в транспортное средство. При высоте забоя до 10 м и достаточной ширине рабочего пространства обеспечивается свободный доступ к массиву и возможность полной зачистки без привлечения бульдозера.

3. Результаты и обсуждение

Анализ технико-экономических показателей 29 моделей фронтальных погрузчиков (объем ковша 2,2÷40,5 м³) ведущих производителей выявил зависимость производительности от грузоподъемности, высоты подъема и расстояния транспортирования, а также их влияние на капитальные и

эксплуатационные издержки. В условиях углубления карьеров до значительных отметок целесообразно применение многоступенчатых транспортных схем с использованием скиповых или крутонаклонных конвейерных подъемников.

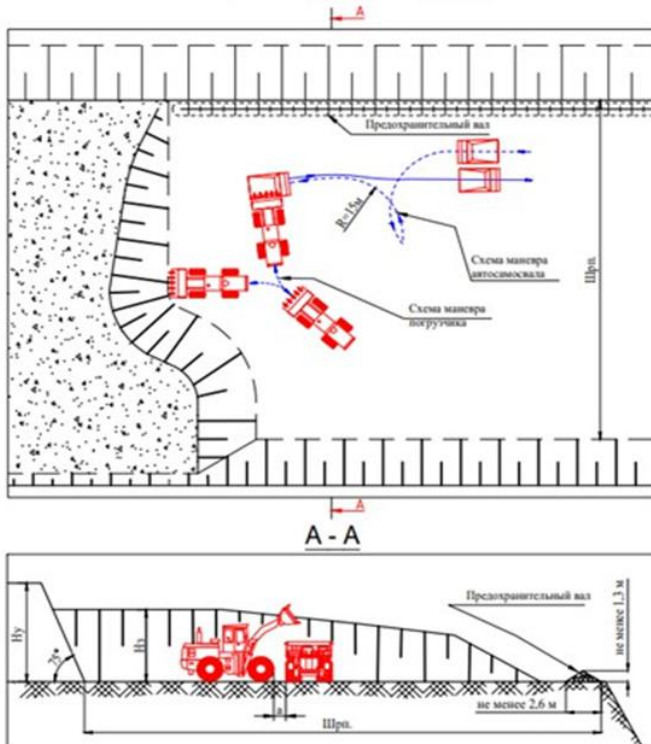


Рис. 1. Паспорт работы погрузчика L-1350 с погрузкой в автосамосвал Hitachi EH-4000

Объединение функций выемки и первичного транспортирования с использованием фронтальных одноковшовых погрузчиков рассматривается как альтернатива традиционным экскаваторно-автомобильным комплексам. Эффективность таких решений зависит от качества взрывной подготовки пород и оптимизации технологических параметров. Перспективным направлением является внедрение дистанционного и роботизированного управления для повышения безопасности и устойчивости производственного процесса.

Для транспортных трасс принимается продольный уклон 8% с учетом требуемой высоты подъема и общей протяженности маршрута. На участках с меньшей суммарной высотой подъема уклон сохраняется до достижения проектной отметки, после чего трасса переводится в горизонтальное положение.

Экономическая оценка эксплуатации фронтальных погрузчиков базируется на показателях производительности, пробега и расхода топлива и включает текущие затраты и капитальные вложения. В структуру эксплуатационных расходов входят: оплата труда операторов; затраты на дизельное топливо; расход масел и технических жидкостей; техническое обслуживание и ремонт; износ и замена шин; амортизация по линейному методу; накладные расходы в размере 5% от суммарных затрат. Капитальные вложения предусматривают приобретение техники, строительство транспортных коммуникаций и обустройство стояночной инфраструктуры.

Ключевым технологическим параметром является производительность погрузчиков. Анализ зависимости производственной мощности от расстояния транспортирования показывает ее существенное увеличение при сокращении длины перемещения, что соответствует аналогичной закономерности для карьерного автотранспорта.

В рамках данного исследования основным технологическим показателем погрузчиков выступает их производительность. Из данных, представленных на графике 2,

который иллюстрирует зависимость производственной мощности погрузчиков от расстояния транспортировки, видно, что при сокращении транспортного расстояния производительность погрузчиков значительно возрастает. Эта закономерность находится в соответствии с динамикой изменения производительности карьерных автосамосвалов.

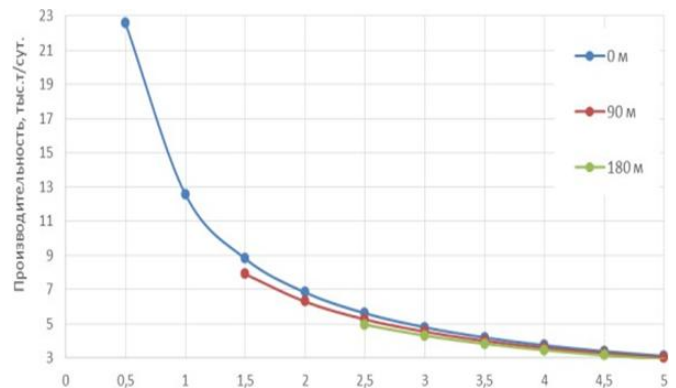


Рис. 2. Влияние дистанции транспортировки на расчетную эффективность погрузчика Le Tourneau L-2350 при различных высотах подъема (указанных в метрах)

На рисунке 3 представлены диаграммы, иллюстрирующие зависимость производительности от грузоподъемности фронтальных погрузчиков. Теоретически, эти зависимости должны представлять собой линейные графики. Однако, уникальные характеристики отдельных моделей вносят вариации, в результате чего данные демонстрируют дисперсию от предполагаемых линейных трендов. Существенно отметить, что погрузчики с большей емкостью ковша демонстрируют повышенную чувствительность к колебаниям производительности, вызванным изменениями в высоте подъема. Тем не менее, влияние этого фактора уменьшается с ростом расстояний транспортировки.

Для проведения исследований были отобраны три модели высокопроизводительных погрузчиков с объемами ковшевой варьирующимися от 10 до 40 кубических метров. Включены модели с ковшом 11,5 м³, LeTourneau L-1350 с ковшом 21 м³ и L-2350 с емкостью 40,5 м³. Этот выбор был обусловлен требованиями поддержания высокой производственной мощности на дальних транспортировках для обеспечения экономической эффективности.

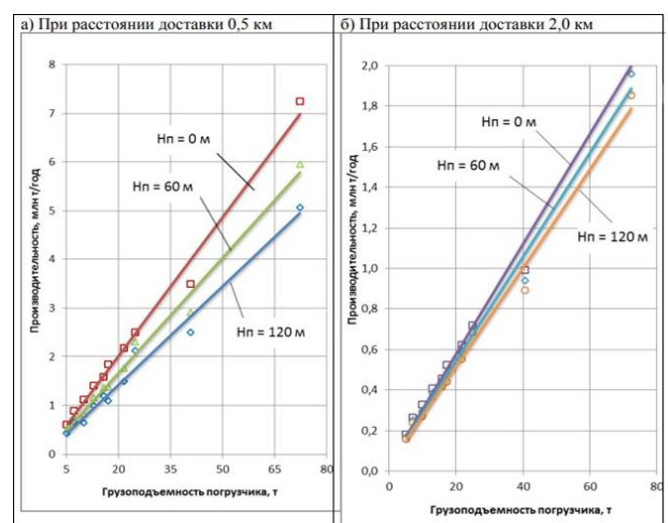


Рис. 3. Воздействие грузоподъемности на эффективность работы погрузчиков при транспортировке горной породы (H_n – высота подъема)

Вывод: Применение фронтальных погрузчиков в составе выемочно-транспортных комплексов при контейнерной

технологии является технологически обоснованным. Их преимущества заключаются в высокой мобильности, эффективном взаимодействии с крупнотоннажными автосамосвалами и меньших капитальных затратах по сравнению с экскаваторами. Быстрое перемещение между забоем и местом разгрузки способствует сокращению продолжительности цикла и росту производительности.

Эффективность погрузчиков зависит от состояния рабочей площадки и качества взрывной подготовки пород; на неровных и переувлажненных поверхностях преимущество сохраняют гусеничные экскаваторы. Производительность определяется объемом ковша, высотой черпания и усилием отрыва; машины с ковшом 20–40 м³ обеспечивают сопоставимые с экскаваторами показатели при коротких расстояниях транспортирования и умеренных высотах подъема.

Экономическая оценка включает капитальные и эксплуатационные затраты, формируемые на основе производительности, пробега и расхода топлива. Погрузчики с электромеханической трансмиссией характеризуются пониженными эксплуатационными расходами. Их применение целесообразно при расстояниях транспортирования до 2–5 км и годовом объеме перевозок до 10 млн тонн, особенно в условиях ограниченного пространства, селективной выемки и необходимости гибкой организации работ.

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НОВЫЙ ВАРИАНТ АСИММЕТРИЧНОЙ ПРОКАТКИ ТОЛСТОГО ЛИСТА В РЕЛЬЕФНЫХ ВАЛКАХ

NEW VARIANT OF ASYMMETRIC ROLLING OF THICK SHEET IN RELIEF ROLLS

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Abstract: The paper presents the concept of an improved method of asymmetric rolling in relief rolls, followed by the alignment of the wavy workpiece in several passes in smooth rolls. The key feature of the new rolling method is that only one of the relief rolls is driven, while the other roll is idled and is driven by friction forces when in contact with the moving workpiece. The presence of a single driven roll with the ability to adjust its rotational speed allows for a higher asymmetry coefficient.

Keywords: ASYMMETRIC ROLLING, RELIEF ROLLS, ASYMMETRY FACTOR, THICK SHEET METAL.

1. Введение

В работе [1] была исследована технология прокатки толстолистного металла, которая решила проблему получения высококачественного толстолистного металла без существенного изменения начальных размеров заготовки. Для этой цели были разработаны два варианта валков с рельефным профилем в виде кольцевых проточек. Было выявлено, что наиболее оптимальной конструкцией являются рельефные валки с неодинаковым отношением выступа к углублению. В работе [2] были представлены результаты исследований по совершенствованию технологии деформации толстолистных заготовок в рельефных валках. Учитывая, что асимметричная прокатка позволяет увеличить уровень деформации сдвига во время прокатки, в эту технологию был введен коэффициент асимметрии. Также в лабораторных условиях был реализован способ геометрической асимметрии с применением рельефных валков разного диаметра (Рис. 1).

Данный способ оказался весьма эффективным в плане проработки металла по сечению, а также улучшению механических свойств алюминиевых и медных толстолистных заготовок [3]. При этом необходимо отметить, что оба наиболее распространенных способа реализации асимметричной прокатки (геометрический и кинематический) имеют свои технологические недостатки. Реализация геометрической асимметрии при прокатке широкого сортамента толстолистного проката требует изготовления целого парка валков различного диаметра. Также хочется отметить, что при геометрической асимметрии чаще всего невозможно добиться высокого значения коэффициента асимметрии по причине ограничения диапазона диаметров валков конструктивными габаритами станы. Реализация кинематической асимметрии не имеет явных ограничений коэффициента асимметрии и зависит от возможности регулирования скоростей электродвигателей. Однако для данного варианта асимметрии необходима кардинальная реконструкция прокатного стана путем обеспечения индивидуального привода валков с возможностью регулировки окружных скоростей каждого рабочего валка по отдельности.

2. Новая концепция деформирования

Альтернативным решением данных недостатков может стать вариант прокатки с одним приводным валком [4], который позволит еще больше повысить технологичность процесса получения высококачественных металлоизделий в виде горячекатаного листа и толстых плит. В этом случае устраняются все перечисленные выше недостатки - наличие валков с разными диаметрами не является обязательным требованием для создания асимметрии, а их наличие будет

благоприятным условием для усиления эффекта асимметрии. Наличие одного приводного валка с возможностью регулирования скорости вращения приводного валка позволит развивать более высокий коэффициент асимметрии, поскольку второй валок является не приводным (холостым), который будет вращаться лишь от контакта с заготовкой за счет активных сил трения. В этом случае достаточно физически отсоединить один валок от системы привода, что не потребует существенной модернизации прокатного стана.



Рис. 1. Прокатка в рельефных валках с геометрической асимметрией

Ранее авторы данной работы уже проводили исследования, связанные с разработкой нового способа асимметричной прокатки. Суть предложенного решения заключалось в использовании при асимметричной прокатке рельефных валков, профиль которых выполнен в виде трапециевидных выступов и впадин [2, 3]. Использование таких валков позволяет реализовывать при прокатке дополнительную

сдвиговую деформацию не только в продольном направлении (как при асимметричной прокатке в гладких валках), но и в поперечном направлении. Также в ходе проведенных исследований было установлено, что в ходе прокатки в гладких валках с различными коэффициентами асимметрии заготовка изгибается в вертикальной плоскости, причем угол изгиба увеличивается с повышением коэффициента асимметрии даже при небольшом относительном обжатии 10%, что создает проблемы для реализации асимметричной прокатки в непрерывной линии прокатного стана из-за необходимости захвата заготовки последующими клетями. В случае использования рельефных валков с трапецевидным профилем, даже при достаточно высоком уровне асимметрии, заготовка после выхода из очага деформации рельефных валков практически не изгибалась, сохраняя свою горизонтальную траекторию движения. Такой эффект достигался за счет получаемого рельефного профиля заготовки, в котором выступы и впадины выполняли роль ребер жесткости.

Поэтому предлагается следующая концепция нового способа асимметричной прокатки (Рис. 1). Первый проход осуществляется в рельефных валках с фактором асимметрии (геометрическим или кинематическим). При этом лишь один из валков является приводным, второй валок является холостым и приводится во вращение за счет сил трения при контакте с движущейся заготовкой. После прокатки в рельефных валках заготовка подвергается операции выравнивания в гладких валках.

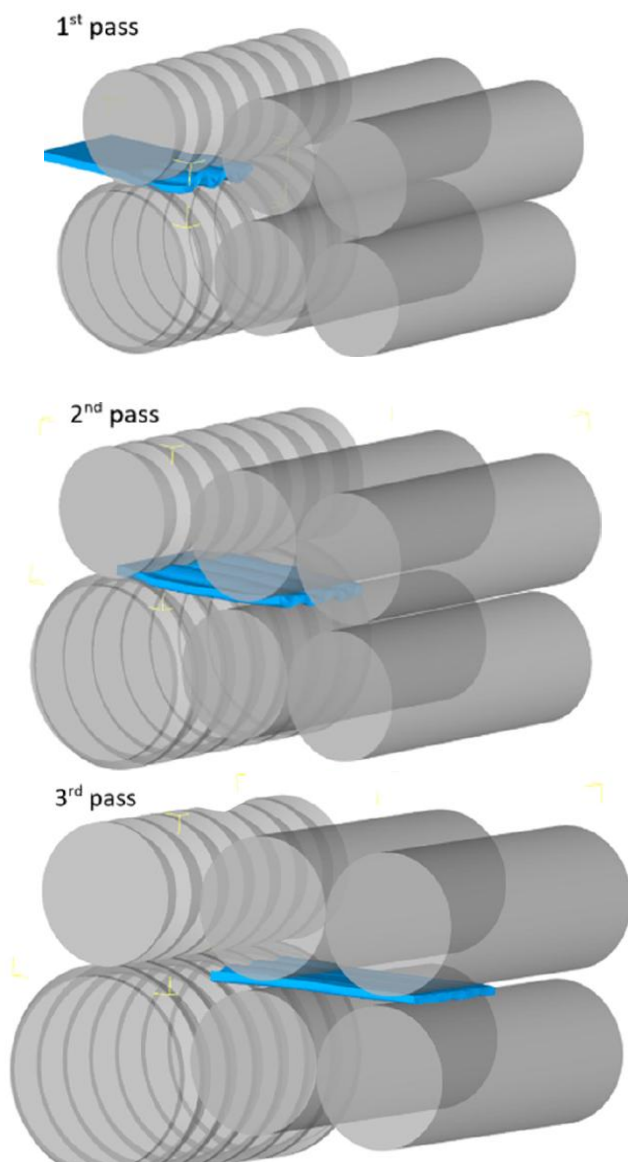


Рис. 2. Концепция нового способа асимметричной прокатки

В качестве исходных материалов для исследования будут использованы толстолистовой стальной прокат и биметаллические стальные плиты, полученные одновременной прокаткой двух заготовок различных металлов (или сплавов).

Такой выбор исходного материала для исследований обоснован тем, что толстолистовой стальной прокат с высокими механическими свойствами широко используется для изготовления цистерн и других ёмкостей высокой прочности и объёма. Высокие прочностные характеристики делают металлические плиты, изготовленные из толстолистового проката, отличным исходным материалом для сварных металлоконструкций. Отдельного упоминания заслуживают металлические плиты с повышенной износостойкостью, которые предназначены для защиты поверхностей от различных видов износа, в сочетании с умеренными ударными нагрузками. Для изготовления подобной металлопродукции используется весьма широкий ряд марок сталей, начиная от простых марок типа Ст3 и заканчивая дорогостоящими высоколегированными различного профиля: криогенные (12X18H10T), кислотоупорные (08X17H5M3), высокопрочные (20X17H2), для работы в условиях ударных нагрузок (25X13H2) и другие.

Если останавливаться на биметаллах, то их применяют для повышения прочности и жаростойкости конструкций, снижения их массы с целью экономии дорогостоящих и дефицитных металлов или как материал со специальными свойствами. Основными потребителями биметаллов являются ведущие отрасли машиностроения: нефтехимическая (корпуса реакторов, колонн, сосудов и т.п.), атомная и энергетическая (трубные решетки, сосуды и т.п.) судостроительная (корпуса, переходные элементы, сосуды, и т.п.). Уникальные свойства биметаллов объясняются тем, что основной слой (углеродистая или низколегированная сталь) обеспечивает конструктивную прочность и другие механические свойства изделий, а плакирующий слой (нержавеющая сталь, никель, титан, медь, алюминий или другие металлы) позволяет, например, обеспечивать требуемую износостойкость или же коррозионную стойкость. В данном случае дополнительная обработка биметаллических стальных плит по предлагаемой технологии, т.е. дополнительное деформирование их с помощью асимметричной одноприводной прокатки в рельефных валках, позволит обеспечить повышения механических и эксплуатационных свойств основного и плакирующего слоев.

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THERMODYNAMIC ANALYSIS OF HELIUM CLOSED-CYCLE GAS TURBINE PLANT WITH NUCLEAR REACTOR AS THE MAIN HEATER

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Abstract: In this paper is performed exergy and isentropic analysis of a helium closed-cycle gas turbine plant and all its main components. In the real operating conditions, turbine produces mechanical power equal to 546.27 MW, turbocompressor consumes mechanical power of 268.74 MW and the useful mechanical power delivered for the electric generator drive is equal to 277.53 MW. The highest possible mechanical power which can theoretically be delivered for the electrical generator drive (ideal useful mechanical power) is equal to 351.89 MW. Helium gas turbine is the component in the observed plant which has the lowest exergy destruction (9.40 MW) and the highest exergy efficiency (98.31%) of all components. Precooler has the lowest exergy efficiency of all plant components, equal to 47.66% only. Due to the usage of cooling water, precooler exergy parameters are highly sensitive to the ambient temperature change. Whole analyzed plant has exergy destruction of 261.79 MW and exergy efficiency of 48.69%, what is in the same range as for the comparable closed-cycle gas turbine plants.

KEYWORDS: CLOSED-CYCLE GAS TURBINE, HELIUM, NUCLEAR REACTOR, THERMODYNAMIC ANALYSIS

1. Introduction

Standard gas turbines can operate as stand-alone components or as a part of various complex energy systems [1, 2]. In the most of the cases they are used for the electrical generators drive, however, they also can have various other interesting applications [3, 4]. Standard gas turbines have inevitable connection with the atmosphere – air is taken from the atmosphere to the turbocompressor, while combustion gas after expansion in the turbine is released to the atmosphere [5].

One specific field of the gas turbines is reserved for the closed-cycle gas turbines which did not have any connection with the atmosphere [6]. Closed-cycle gas turbines have many benefits in comparison to the standard gas turbines: their load can be easily regulated by changing operating gas mass flow rate, components durability is increased, system is independent of the atmospheric influences, for operating gas heating and cooling can be used various heat sources and cooling mediums, etc. [7]. However, closed-cycle gas turbines has also various disadvantages due to the system complexity, operating gas is expensive and is not always available on the market, operating gas proper sealing must be ensured through entire process, etc. [8]. Regardless of the disadvantages, closed-cycle gas turbines can be interesting alternatives to standard gas turbines.

In this paper is performed thermodynamic (exergy and isentropic) analysis of one helium closed-cycle gas turbine plant and all its components. It is calculated current and maximum mechanical power which can be delivered from the plant. Exergy efficiencies and exergy destructions are calculated, presented and compared for all components and whole plant. Finally, it is investigated which component is the most sensitive to the ambient temperature change.

2. Description and operating characteristics of the helium closed-cycle gas turbine plant

General scheme of the helium closed-cycle gas turbine plant analyzed in this paper is presented in Fig. 1. Plant is composed of five components and the useful produced mechanical power from the plant is applied for the electric generator drive.

Main helium heater in this power plant is nuclear gas reactor which operating parameters and specifications can be found in the literature [9]. At the nuclear reactor outlet, helium has the highest temperature in the plant and is delivered to the gas turbine through which expands. After expansion in the turbine, helium passes through recuperator, which is a helium/helium heat exchanger (in recuperator warmer helium after turbine is used for heating colder helium after turbocompressor). The main aim of the recuperator is increasing helium temperature before its delivery to nuclear reactor. After recuperator, helium is delivered to precooler which is used for the helium cooling on the lowest temperature in the plant (turbocompressor inlet). In precooler, helium is cooled using a cooling water flow rate. Turbocompressor increases helium pressure (and consequently helium temperature) and delivers it to the nuclear reactor through recuperator.

It should be highlighted that this paper considers main plant components only. Additional and auxiliary components (such as helium tanks, transfer compressors, regulating valves, etc.) which are standard components of closed-cycle gas turbine plants [6, 8] are not observed in this analysis.

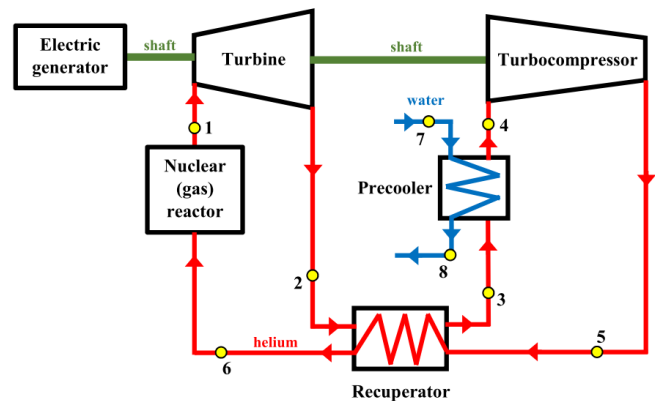


Fig. 1. General scheme of the helium closed-cycle gas turbine plant with operating points required for the thermodynamic analysis

3. Equations for the exergy and isentropic analysis

Thermodynamic analysis performed in this paper contains exergy analysis of all components and whole plant as well as isentropic analysis of turbine and turbocompressor.

Exergy analysis has a baseline in the second law of thermodynamics and it is influenced by the ambient conditions [10]. Exergy analysis is a baseline of many further more complex analyses (economic, environmental, etc.) [11].

Isentropic analysis of turbine and turbocompressor is performed with the main aim to obtain maximum useful mechanical power which can be delivered from this plant [12]. Any improvements related to the turbine and turbocompressor will be visible through increase in produced mechanical power (by the turbine) or through decrease in consumed mechanical power (by the turbocompressor), so it is important to know maximum limits of such improvements.

Energy analysis is also performed for all heat exchangers in the observed plant (reactor, recuperator, precooler). However, the energy analysis results are not shown due to the fact that heat exchangers are almost perfect components from the energy viewpoint, what is also highlighted in the literature [13].

3.1. Base exergy analysis equations

Base exergy balance equation at steady state, valid for any plant or component is [14]:

$$\dot{X}_{\text{HEAT}} - P - \sum(\dot{m} \cdot \varepsilon)_{\text{OUT}} + \sum(\dot{m} \cdot \varepsilon)_{\text{IN}} - \dot{E}x_D = 0, \quad (1)$$

where P is mechanical power and indexes OUT, IN and D are related to outlet (output), inlet (input) and destruction, respectively. Fluid specific exergy (ε) is defined as [15]:

$$\varepsilon = (h - h_{AMB}) - T_{AMB} \cdot (s - s_{AMB}), \quad (2)$$

where h is fluid specific enthalpy, s is fluid specific entropy, T is a temperature and index AMB is related to the base ambient state. Mass flow rate ($\dot{m}$) balance for any plant or component is:

$$\sum \dot{m}_{IN} = \sum \dot{m}_{OUT}. \quad (3)$$

Exergy transfer by heat at the temperature T ($\dot{X}_{HEAT}$) is [16]:

$$\dot{X}_{HEAT} = \sum (1 - \frac{T_{AMB}}{T}) \cdot \dot{Q}_{HEAT}, \quad (4)$$

where $\dot{Q}_{HEAT}$ is an energy transfer by heat.

3.2. Equations for the exergy and isentropic analysis of helium closed-cycle gas turbine plant and its components

Exergy and isentropic analysis equations are defined according to the guidelines and recommendations from the literature [17, 18]. Indexes and markings in all equations are related to the operating points presented in Fig. 1, Table 1 and Table 2. During the investigation of the plant component's sensitivity to the ambient temperature change, all exergy equations remain the same as presented in this paper part (the change occur in the specific exergies only).

Isentropic analysis

Turbine

Ideal mechanical power produced by the turbine is obtained if all losses during the expansion process are neglected (isentropic expansion process). In the ideal expansion process, fluid mass flow rate as well as fluid pressures at the turbine inlet and outlet remain the same as in the real (polytropic) expansion process, but ideal process is characterized with always the same fluid specific entropy (in ideal process did not occur an increase in fluid specific entropy as in the real expansion process). Ideal fluid expansion process through the turbine is obtained mathematically.

Turbine is a mechanical power producer, therefore in ideal (isentropic) expansion process turbine will develop the highest possible mechanical power, higher than in the real expansion process (according to the fluid mass flow rate and pressures at the turbine inlet and outlet).

Real (RE) and ideal (ID) produced mechanical power are:

$$P_{TURB,RE} = \dot{m}_1 \cdot (h_1 - h_2), \quad (5)$$

$$P_{TURB,ID} = \dot{m}_1 \cdot (h_1 - h_{2ID}). \quad (6)$$

Turbocompressor

Turbocompressor consumed ideal mechanical power if all the losses during the compression process are neglected (isentropic compression process). In the ideal compression process, fluid mass flow rate as well as fluid pressures at the turbocompressor inlet and outlet remain the same as in the real (polytropic) compression process, but ideal process is characterized with always the same fluid specific entropy (in ideal process did not occur an increase in fluid specific entropy as in the real compression process). Ideal fluid compression process through the turbocompressor is obtained mathematically.

Turbocompressor is mechanical power consumer, so in ideal (isentropic) compression process turbocompressor will consume the lowest possible mechanical power, lower than in real compression process (according to the fluid mass flow rate and pressures at the turbocompressor inlet and outlet).

Real (RE) and ideal (ID) consumed mechanical power are:

$$P_{TCOMPR,RE} = \dot{m}_4 \cdot (h_5 - h_4), \quad (7)$$

$$P_{TCOMPR,ID} = \dot{m}_4 \cdot (h_{5ID} - h_4). \quad (8)$$

Useful mechanical power

Useful mechanical power is delivered from the plant and can be used for the drive of any mechanical power consumer (in this case, mechanical power consumer is an electric generator). Ideal useful mechanical power is the highest possible mechanical power (according to the presented operating parameters) which can be delivered from the analyzed plant.

Real (RE) and ideal (ID) useful mechanical power are:

$$P_{USEFUL,RE} = P_{TURB,RE} - P_{TCOMPR,RE}, \quad (9)$$

$$P_{USEFUL,ID} = P_{TURB,ID} - P_{TCOMPR,ID}. \quad (10)$$

Exergy analysis

Turbine

Turbine exergy destruction and exergy efficiency are:

$$\dot{X}_{D,TURB} = \dot{m}_1 \cdot \varepsilon_1 - \dot{m}_2 \cdot \varepsilon_2 - P_{TURB,RE}, \quad (11)$$

$$\eta_{EX,TURB} = \frac{P_{TURB,RE}}{\dot{m}_1 \cdot \varepsilon_1 - \dot{m}_2 \cdot \varepsilon_2}. \quad (12)$$

Turbocompressor

Turbocompressor exergy destruction and exergy efficiency are:

$$\dot{X}_{D,TCOMPR} = \dot{m}_4 \cdot \varepsilon_4 + P_{TCOMPR,RE} - \dot{m}_5 \cdot \varepsilon_5, \quad (13)$$

$$\eta_{EX,TCOMPR} = \frac{\dot{m}_5 \cdot \varepsilon_5 - \dot{m}_4 \cdot \varepsilon_4}{P_{TCOMPR,RE}}. \quad (14)$$

Precooler

Precooler exergy destruction and exergy efficiency are:

$$\dot{X}_{D,PRCOOL} = \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_7 \cdot \varepsilon_7 - \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_8 \cdot \varepsilon_8, \quad (15)$$

$$\eta_{EX,PRCOOL} = \frac{\dot{m}_8 \cdot \varepsilon_8 - \dot{m}_7 \cdot \varepsilon_7}{\dot{m}_3 \cdot \varepsilon_3 - \dot{m}_4 \cdot \varepsilon_4}. \quad (16)$$

Recuperator

Recuperator exergy destruction and exergy efficiency are:

$$\dot{X}_{D,RECUP} = \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_3 \cdot \varepsilon_3 - \dot{m}_6 \cdot \varepsilon_6, \quad (17)$$

$$\eta_{EX,RECUP} = \frac{\dot{m}_6 \cdot \varepsilon_6 - \dot{m}_5 \cdot \varepsilon_5}{\dot{m}_2 \cdot \varepsilon_2 - \dot{m}_3 \cdot \varepsilon_3}. \quad (18)$$

Nuclear reactor

For the exergy analysis of nuclear reactor is required reactor cumulative thermal energy released by the nuclear fuel ($\dot{Q}_{REA}$). According to the producer specifications [9], gas nuclear reactor used in the analyzed plant has cumulative thermal energy of 600 MWt, therefore, in this case $\dot{Q}_{REA} = 600$ MW. In the reactor is used nuclear fuel which exergy coefficient (EXC) according to [19] is equal to 0.95. Nuclear reactor exergy destruction and exergy efficiency are:

$$\dot{X}_{D,REA} = \dot{Q}_{REA} \cdot EXC + \dot{m}_6 \cdot \varepsilon_6 - \dot{m}_1 \cdot \varepsilon_1, \quad (19)$$

$$\eta_{EX,REA} = \frac{\dot{m}_1 \cdot \varepsilon_1 - \dot{m}_6 \cdot \varepsilon_6}{\dot{Q}_{REA} \cdot EXC}. \quad (20)$$

Whole plant

Whole plant exergy destruction and exergy efficiency are:

$$\dot{X}_{D,PLANT} = \sum \dot{X}_{D,all\ components}, \quad (21)$$

$$\eta_{EX,PLANT} = \frac{P_{USEFUL,RE}}{\dot{Q}_{REA} \cdot EXC}. \quad (22)$$

It should be highlighted that all components from the analyzed plant (Eq. 21) are turbine, turbocompressor, precooler, recuperator and nuclear reactor.

4. Helium/Water operating parameters required for the analysis

Helium and water operating parameters in each operating point from Fig. 1 are required for each component and whole observed plant exergy analysis. These operating parameters are found in [9] and presented in Table 1. It should be highlighted that, in comparison to [9], in this paper are neglected helium mass flow rates used for the

cooling (turbine and reactor vessel cooling), because these mass flow rates are very low in comparison to the cumulative helium mass flow rate. In addition, in [9] are found helium and water mass flow rates, temperatures and pressures in each operating point from Fig. 1. Other required operating parameters in each operating point from Fig. 1 (specific enthalpies, specific entropies and specific exergies) are calculated using NIST-Refprop 9.0 software [20].

Turbine and turbocompressor isentropic analysis requires real helium operating parameters (presented in Table 1) as well as ideal helium operating parameters obtained mathematically during isentropic helium expansion through the turbine and isentropic helium compression through the turbocompressor. Helium operating parameters related to the ideal (isentropic) expansion and compression processes are presented in Table 2.

The base ambient state definition is required in exergy analysis of any plant or a component [21]. In this analysis, the base ambient state is defined by the ambient temperature of 20 °C and the ambient pressure of 1 bar.

Exergy analysis of all components from the observed plant also contains research related to each component sensitivity on the ambient temperature change. The sensitivity of each component on the ambient pressure change is not analyzed, because in real operating conditions ambient pressure change is small and it has negligible influence on any component exergy destruction and exergy efficiency.

Table 1. Helium and water operating parameters required for the plant and its components exergy analysis (real process)

O. P. *	Temp. (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Specific exergy (kJ/kg) **
1	850.0	68.4	437.4	5857.3	26.147	4856.7
2	611.2	36.3		4608.4	26.221	3586.3
3	164.7	35.4		2290.1	22.623	2322.6
4	28.0	35.0		1580.1	20.703	2175.4
5	144.2	70.0		2194.5	20.961	2714.3
6	587.4	69.6		4494.6	24.729	3909.9
7	22.0	3.0	1014.6	92.56	0.3249	0.2288
8	90.0	2.9		377.21	1.1927	30.47

* O. P. = Operating Point (in accordance to Fig. 1.)

** At the base ambient state (20 °C; 1 bar)

Table 2. Helium operating parameters required for the turbine and turbocompressor isentropic analysis (ideal process)

O. P. *	Pressure (bar)	Mass flow rate (kg/s)	Specific entropy (kJ/kg·K)	Ideal (isentropic) specific enthalpy (kJ/kg)
1	68.4	437.4	26.147	5857.3
2ID	36.3		26.147	4543.5
4	35.0	437.4	20.703	1580.1
5ID	70.0		20.703	2089.4

* O. P. = Operating Point (in accordance to Fig. 1.)

5. Results and discussion

In the real operating conditions, turbine produces mechanical power equal to 546.27 MW, turbocompressor consumes mechanical power of 268.74 MW, so the useful mechanical power delivered for the electric generator drive is equal to 277.53 MW, Fig. 2. Therefore, in real operating conditions turbocompressor consumes 49.19% of cumulative mechanical power produced in the turbine.

In ideal operating conditions, turbine will produce higher mechanical power in comparison to real process – in ideal process turbine will produce mechanical power of 574.66 MW. Turbocompressor in ideal process will consume the lowest possible mechanical power for the compression equal to 222.77 MW.

Therefore, the highest possible mechanical power which can theoretically be delivered for the electrical generator drive (ideal useful mechanical power) is equal to 351.89 MW, Fig. 2. In the ideal operating conditions, turbocompressor will consume only 38.77% of cumulative mechanical power produced in the turbine.

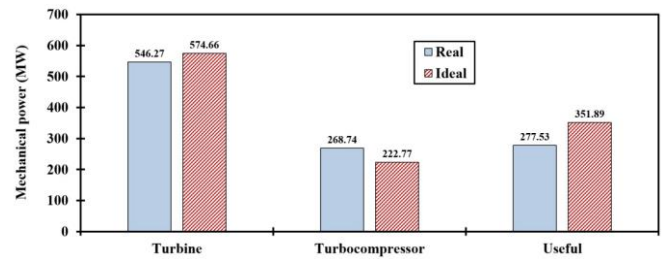


Fig. 2. Produced (turbine), consumed (turbocompressor) and useful mechanical power (in both ideal and real operating conditions)

Exergy destructions and exergy efficiencies of all components and whole analyzed plant are presented in Fig. 3.

Helium gas turbine is the component in the observed plant which has the lowest exergy destruction (equal to 9.40 MW) and the highest exergy efficiency (98.31%) of all components. As expected, nuclear reactor has the highest exergy destruction of all components (155.87 MW) and acceptable exergy efficiency (72.65%). Recuperator has the highest exergy efficiency (94.61%) of all heat exchangers inside the analyzed plant.

Precooler has the lowest exergy efficiency of all plant components, equal to 47.66% only. Such low precooler exergy efficiency is expected, because cooling fluid in precooler is water which operating parameters are close to the ambient state. This fact results with low water specific exergies (operating points 7 and 8, Table 1), what finally leads to very low precooler exergy efficiency. The same occurrence can be found in the literature for the precoolers in similar gas turbine closed-cycle plants [22].

Whole analyzed plant has exergy destruction of 261.79 MW and exergy efficiency of 48.69%, Fig. 3. Exergy efficiency of this power plant is in the same range as for the comparable closed-cycle gas turbine plants presented in the literature [6, 22].

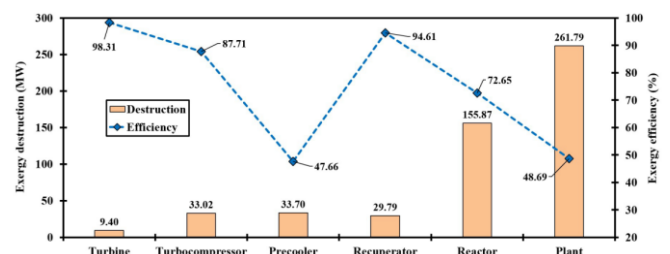


Fig. 3. Exergy destruction and exergy efficiency of all components and whole analyzed plant

Sensitivity of all components from the observed plant to the ambient temperature change is observed in a manner that ambient temperature is varied from 10 °C up to 40 °C in steps of 10 °C. The difference in each component exergy efficiency between ambient temperatures 10 °C and 40 °C is presented in Fig. 4. Increase in the ambient temperature decrease all components exergy efficiency and vice versa.

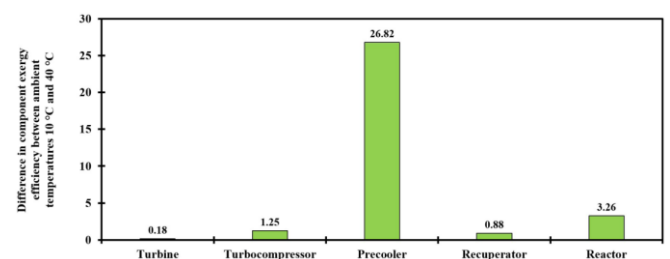


Fig. 4. Helium closed-cycle gas turbine plant components sensitivity to the ambient temperature change

Due to the usage of cooling water, precooler exergy parameters are highly sensitive to the ambient temperature change. Between mentioned ambient temperatures, precooler exergy efficiency will change for 26.82%, notably higher in comparison to all other components. The second component from the observed plant notable influenced by the ambient temperature change is a nuclear reactor – between observed ambient temperatures nuclear reactor exergy efficiency will change for 3.26%. Therefore, precooler and nuclear reactor are the components from the analyzed plant for which the change in ambient temperature must be highly considered.

Further investigation related to the helium closed-cycle gas turbine plant and its components will be based on the usage of various conventional as well as machine learning methods and processes [23-25] with the main goal to obtain optimal operating conditions of each component and to perform whole plant optimization.

6. Conclusions

This paper presents thermodynamic (exergy and isentropic analysis) results of a helium closed-cycle gas turbine plant. Along with the whole plant, analysis considers all plant main components. The most important obtained conclusions are:

- In the real operating conditions, turbine produces mechanical power equal to 546.27 MW, turbocompressor consumes mechanical power of 268.74 MW and the useful mechanical power delivered for the electric generator drive is equal to 277.53 MW.
- The highest possible mechanical power which can theoretically be delivered for the electrical generator drive (ideal useful mechanical power) is equal to 351.89 MW.
- In real operating conditions turbocompressor consumes 49.19% of cumulative mechanical power produced in the turbine, while in the ideal operating conditions, turbocompressor will consume only 38.77% of cumulative mechanical power produced in the turbine.
- Helium gas turbine is the component in the observed plant which has the lowest exergy destruction (9.40 MW) and the highest exergy efficiency (98.31%) of all components. Precooler has the lowest exergy efficiency of all plant components, equal to 47.66% only.
- Whole analyzed plant has exergy destruction of 261.79 MW and exergy efficiency of 48.69%.
- Due to the usage of cooling water, precooler exergy parameters are highly sensitive to the ambient temperature change. Between ambient temperatures 10 °C and 40 °C, precooler exergy efficiency will change for 26.82%, notably higher in comparison to all other plant components.

7. Acknowledgment

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THE INFLUENCE OF REGENERATIVE HEATERS ON STEAM POWER PLANT FUEL CONSUMPTION AND EFFICIENCY

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Abstract: This paper shows analysis of each regenerative heater's influence on global steam power plant operating parameters. Analysis is performed for nine steam power plant versions (configurations) - from the Base power plant without regenerative heating system up to the Final plant which consists of eight regenerative heaters (one mixing and seven non-mixing regenerative heaters). According to the defined fluid operating parameters throughout the plant, it is obtained that each new regenerative heater added to the plant continuously reduces the mechanical power produced by the turbine, for 4.33 MW on average. Simultaneously, each added regenerative heater increases feedwater temperature at the steam generator inlet, which results in power plant cumulative fuel consumption continuous decrease (for 0.414 kg/s on average) to obtain the same steam outlet parameters. Considering plant overall efficiency, it must be highlighted that each regenerative heater added to the plant continuously increases plant overall efficiency from the Base plant until the Final plant, for 0.43% on average.

KEYWORDS: REGENERATIVE HEATERS, STEAM POWER PLANT, FUEL CONSUMPTION, PLANT EFFICIENCY

1. Introduction

Steam power plants are nowadays notable mechanical power producers worldwide [1]. In conventional steam power plants, all produced mechanical power is used for electricity generation [2, 3]. However, steam power plants can also be used for various other purposes, instead of electricity production only [4, 5].

Regardless of the steam power plant's final purpose, the regenerative heating system is one of the essential parts inside such plants [6]. Regenerative heaters are placed between the main steam condenser and the steam generator, while each regenerative heater uses extracted steam from the turbine with the aim of condensate/feedwater heating [7, 8]. In any steam power plant, regenerative heaters reduce cumulative fuel consumption and increase overall plant efficiency [9, 10]. However, it is important to analyze how each regenerative heater mounted in the plant influences at least global plant operating parameters.

This paper presents analysis related to regenerative condensate/feedwater heaters addition in the steam power plant. The main intention is to observe how exactly each regenerative heater influences cumulative produced plant mechanical power, cumulative plant fuel consumption, and finally overall plant efficiency. For all regenerative heaters, the average influence of each regenerative heater on the plant main operating parameters is calculated and presented. This analysis should be used as a guideline for proper and efficient condensate/feedwater heating system arrangement and for all possible further optimizations and improvements.

2. Base power plant description and the process of regenerative heaters addition

Schematic presentation of Base steam power plant without regenerative heating system is shown in Fig. 1.

Base steam power plant consists of three turbine cylinders (High Pressure Cylinder – HPC, Intermediate Pressure Cylinder – IPC, and Low Pressure Cylinder – LPC). HPC and IPC are single-flow, while LPC is a dual-flow turbine cylinder. All turbine cylinders are connected to the same shaft, which drives an Electric Generator (EG). The plant uses natural gas with a lower heating value of 47 MJ/kg in both Steam Generator (SG) and ReHeater (RH). ReHeater is mounted between HPC and IPC, as shown in Fig. 1.

After expansion in LPC, steam is delivered to Condenser (C), in which it condenses by transferring heat to cooling water. Obtained condensate in the Condenser is further delivered to the Steam Generator using two pumps: the Condensate Pump (CP) and the Main Feedwater Pump (MFP), Fig. 1.

Base steam power plant in Fig. 1 did not contain any regenerative condensate/feedwater heater, so this plant will have the highest produced mechanical power in any observed condition with simultaneously the highest fuel consumption in the Steam Generator and ReHeater. Moreover, in the Base plant, the steam Condenser will be notably loaded due to high steam mass flow rate which condenses.

Analyzed power plant produces electric power only (there is no heat delivery to heat consumers), so the plant is a conventional steam power plant.

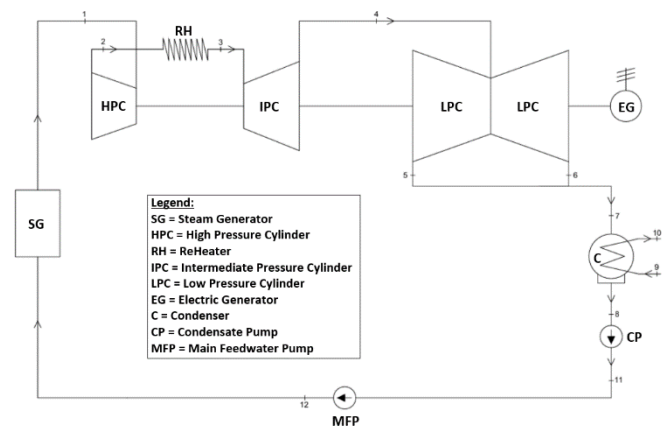


Fig. 1. Base steam power plant without regenerative heating system

The first upgraded version of the steam power plant from Fig. 1 contains the addition of the Deaerator (DEA) between CP and MFP, Fig. 2. Deaerator is used for deaerating purposes (removing dissolved gasses from the condensate) and simultaneously for condensate heating by direct heat transfer between extracted steam and condensate (mixing heat exchanger). Moreover, deaerator divides the whole condensate/feedwater heating system into two parts: low pressure condensate part (between Condenser and Deaerator) and high pressure feedwater part (between Deaerator and Steam Generator). In traditional condensate/feedwater heating systems, the Deaerator is the only mixing heat exchanger.

It must be noted that any regenerative heater (mixing or non-mixing type) must get heating steam from the steam turbine extraction (in the case of Deaerator, that heating steam is marked with operating point A, Fig. 2). Deaerator gets heating steam from IPC because the pressures of condensate from steam Condenser and heating steam should be the same (or very similar) for obtaining the best mixing efficiency.

Addition of each new regenerative heater (regardless of its type) requires re-calculation of the entire plant because each steam extraction reduces cumulative produced mechanical power in the turbine, reduces steam mass flow rate which enters the Condenser, and increases the temperature of feedwater delivered to the Steam Generator.

Operating parameters of all fluid streams during the addition of each new regenerative heater are obtained by assuming components energy and isentropic efficiencies as well as by using data from the literature for similar steam power plants [6, 7, 11]. The exact assumed energy and isentropic efficiencies of each component are explained in the next Section.

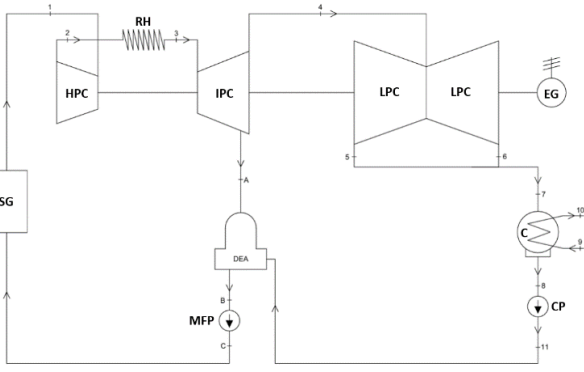


Fig. 2. The first version of upgraded steam power plant

The second version of the upgraded steam power plant is presented in Fig. 3. In comparison to Fig. 2, in the second steam power plant upgrade is added one new non-mixing regenerative heater after Condensate Pump (Low Pressure Heater 1 – LPH1). For condensate heating purposes in LPH1, steam is extracted from LPC, while condensate obtained from heating steam in LPH1 is returned to the steam Condenser through a pressure reducing valve (V1). LPH1, in comparison to the previous plant upgrade (Fig. 2), additionally increases condensate temperature, and re-calculation of the entire plant should be performed again.

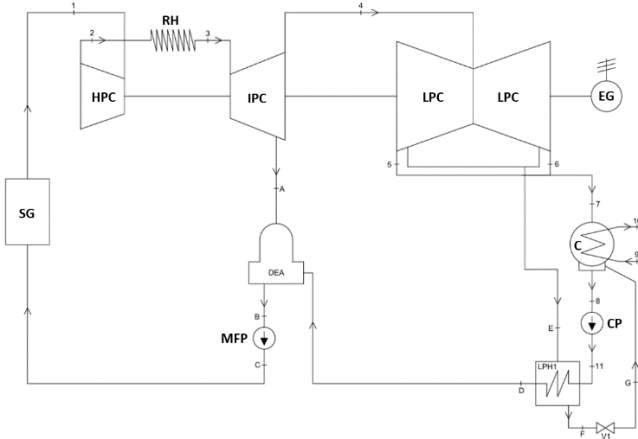


Fig. 3. The second version of upgraded steam power plant

Due to the limited space, in this paper will not be presented all upgraded steam power plant versions, but it should be stated that for each further upgrade in the plant is added a new non-mixing regenerative heater. After the addition of each new regenerative heater, the whole plant is re-calculated again. The Final version of the observed plant (after all implemented upgrades – the eight upgraded plant version) is presented in Fig. 4.

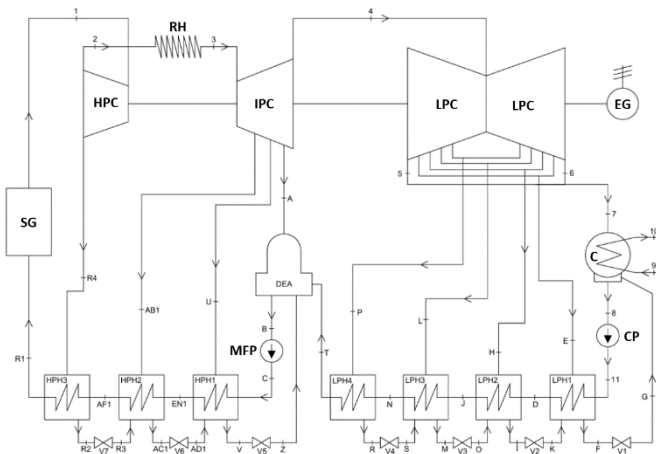


Fig. 4. The eighth version of upgraded steam power plant (Final plant version)

The Final plant version consists of four low pressure non-mixing condensate heaters (from LPH1 to LPH4), deaerator, and three high pressure non-mixing feedwater heaters (from HPH1 to HPH3), Fig. 4. The final configuration of the condensate/feedwater heating system is very similar to configurations presented in the literature [7, 8]. For all non-mixing regenerative heaters, return of the condensate (obtained from the heating steam) is performed to the lower pressure plant part through pressure reducing valves [12].

The performed analysis did not consider more than eight regenerative heaters cumulatively, which is in accordance with recommendations and examples from the literature [13, 14].

3. Calculation procedure of global power plant operating parameters observed in this analysis

To obtain required thermodynamic parameters of all fluid streams in each operating point from Fig. 1 up to Fig. 4 (pressures, temperatures and mass flow rates), along with the literature data, energy and isentropic efficiencies of all components are assumed and kept constant for each plant version. According to the literature recommendations [9, 15], energy efficiencies of Steam Generator and ReHeater are equal to 90%, isentropic efficiencies of turbine cylinders are 90% for HPC, 95% for IPC, and 85% for LPC. Isentropic efficiencies of pumps are 75% for CP and 85% for MFP. Energy efficiency of the Condenser is assumed to be 85%. In the literature [8, 16], it is found that energy efficiencies of all regenerative heaters are near perfect, so for the Deaerator, it is assumed energy efficiency of 98%, while for all other non-mixing regenerative heaters, energy efficiency is assumed to be 99%. All pressure reducing valves are ideal from the energy point of view.

Plant overall efficiency is defined as:

$$\eta_{\text{plant}} = \frac{P_{\text{cum.}}}{\dot{m}_{\text{fuel,cum.}} \cdot \text{LHV}} \quad (1)$$

In Eq. 1, LHV is fuel Lower Heating Value and $P_{\text{cum.}}$ is cumulative mechanical power delivered to the Electric Generator, which is defined as the difference of mechanical power produced by the turbine and consumed by all pumps:

$$P_{\text{cum.}} = P_{\text{turb.}} - P_{\text{pumps}} \quad (2)$$

where:

$$P_{\text{turb.}} = P_{\text{HPC}} + P_{\text{IPC}} + P_{\text{LPC}} \quad (3)$$

$$P_{\text{pumps}} = P_{\text{CP}} + P_{\text{MFP}} \quad (4)$$

Cumulative fuel consumption in the plant ($\dot{m}_{\text{fuel,cum.}}$) is the sum of fuel consumption in the Steam Generator and in the ReHeater:

$$\dot{m}_{\text{fuel,cum.}} = \dot{m}_{\text{fuel,SG}} + \dot{m}_{\text{fuel,RH}} \quad (5)$$

Fuel consumption in the Steam Generator is defined as:

$$\dot{m}_{\text{fuel,SG}} = \frac{(h_{\text{out,SG}} - h_{\text{in,SG}}) \cdot \dot{m}_1}{\eta_{\text{SG}} \cdot \text{LHV}} \quad (6)$$

where $h_{\text{out,SG}}$ is specific enthalpy of steam at the SG outlet, $h_{\text{in,SG}}$ is specific enthalpy of feedwater at the SG inlet, and η_{SG} is SG energy efficiency. Similar to Eq. 6, ReHeater fuel consumption is:

$$\dot{m}_{\text{fuel,RH}} = \frac{(h_{\text{out,RH}} - h_{\text{in,RH}}) \cdot \dot{m}_3}{\eta_{\text{RH}} \cdot \text{LHV}} \quad (7)$$

where $h_{\text{out,RH}}$ is specific enthalpy of steam at the RH outlet, $h_{\text{in,RH}}$ is specific enthalpy of steam at the RH inlet, and η_{RH} is RH energy efficiency.

4. Operating parameters of all fluid streams from Base and Final steam power plant

Operating parameters of all fluid streams from Base steam power plant are presented in Table 1, while operating parameters of all fluid streams from Final steam power plant are presented in Table 2. Steam specific enthalpies, entropies, and quality are calculated for each operating point according to fluid temperature and pressure by using NIST-REFPROP 9.0 software [17].

Table 1. Operating parameters of all fluid streams from Base steam power plant

O. P. *	Temp. (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality (-) **
1	550.00	140.00	200	3460.90	6.5648	Superh.
2	360.43	40.00	200	3119.17	6.6254	Superh.
3	550.00	39.00	200	3561.30	7.2480	Superh.
4	298.76	7.00	200	3056.85	7.2949	Superh.
5	32.87	0.05	100	2349.27	7.7029	0.913
6	32.87	0.05	100	2349.27	7.7029	0.913
7	32.87	0.05	200	2349.27	7.7029	0.913
8	32.87	0.05	200	137.75	0.4762	0
9	15.00	3.00	8989	63.27	0.2244	Subc.
10	25.00	2.80	8989	105.09	0.3672	Subc.
11	32.98	10.00	200	139.08	0.4773	Subc.
12	33.89	145.00	200	154.99	0.4851	Subc.

* O. P. = Operating point (in accordance with Fig. 1)

** Superh. = Superheated steam; Subc. = Subcooled (condensate); 0 = Water; 1 = Dry saturated steam

Table 2. Operating parameters of all fluid streams from Final steam power plant

O. P. *	Temp. (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality (-) **
1	550.00	140.00	200	3460.90	6.5648	Superh.
2	360.43	40.00	193	3119.17	6.6254	Superh.
3	550.00	39.00	193	3561.30	7.2480	Superh.
4	298.76	7.00	173	3056.85	7.2949	Superh.
7	32.87	0.05	143	2349.27	7.7029	0.912
8	32.87	0.05	173	137.75	0.4762	0
11	32.98	10.00	173	139.08	0.4773	Subc.
A	352.97	10.59	5	3163.33	7.2850	Superh.
B	152.88	10.00	200	644.92	1.8705	Subc.
C	154.99	145.00	200	662.25	1.8766	Subc.
D	55.45	10.00	173	232.98	0.7733	Subc.
E	63.19	0.23	6	2527.70	7.6000	0.963
F	63.00	0.23	30	263.74	0.8688	0
G	36.16	0.06	30	263.74	0.8838	0.047
H	102.34	0.76	9	2683.80	7.5100	Superh.
I	91.04	0.73	24	381.42	1.2049	0
J	85.49	10.00	173	358.84	1.1398	Subc.
K	63.01	0.23	24	381.42	1.2189	0.050
L	157.48	1.52	8	2787.90	7.4500	Superh.
M	111.15	1.49	15	466.28	1.4315	0
N	111.41	10.00	173	468.01	1.4336	Subc.
O	91.04	0.73	15	466.28	1.4379	0.037
P	203.26	2.58	7	2874.58	7.4000	Superh.
R	128.07	2.55	7	538.13	1.6142	0
S	111.15	1.49	7	538.13	1.6185	0.032
T	133.45	10.00	173	561.60	1.6703	Subc.
U	407.08	15.58	7	3270.89	7.2750	Superh.
V	198.92	15.20	22	847.39	2.3203	0
Z	179.88	10.00	22	847.39	2.3254	0.042
EN1	176.65	145.00	200	755.52	2.0891	Subc.
9	15.00	3.00	6504	63.27	0.2244	Subc.
10	25.00	2.80	6504	105.09	0.3672	Subc.
AB1	487.04	26.46	8	3432.23	7.2600	Superh.
AC1	226.25	26.10	15	972.64	2.5755	0
AD1	198.92	15.20	15	972.64	2.5856	0.064
AF1	199.79	145.00	200	856.83	2.3087	Subc.
R1	215.58	145.00	200	927.30	2.4553	Subc.
R2	249.91	39.70	7	1085.30	2.7927	0
R3	226.25	26.10	7	1085.30	2.8011	0.062
R4	360.43	40.00	7	3119.17	6.6254	Superh.

* O. P. = Operating point (in accordance with Fig. 4)

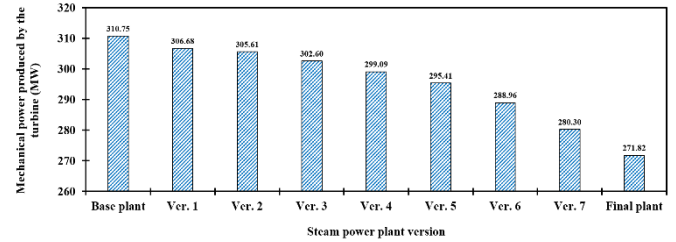
** Superh. = Superheated steam; Subc. = Subcooled (condensate); 0 = Water; 1 = Dry saturated steam

5. Results and discussion

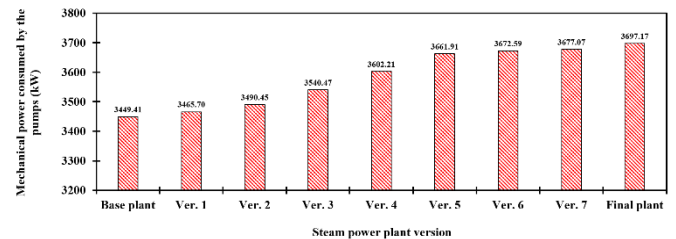
Results of global steam power plant operating parameters will be presented for all observed plant versions – from Base plant until the Final plant.

Fig. 5 presents mechanical power produced by the turbine in all turbine cylinders. In the Base plant, the turbine develops mechanical power of 310.75 MW. Each new regenerative heater added to the plant reduces mechanical power produced by the turbine due to increasing steam extractions [18]. Therefore, starting from the Base plant, the addition of each new regenerative heater continuously decreases the mechanical power produced by the turbine, Fig. 5. In the Final plant version, mechanical power produced by the turbine is the lowest and equals 271.82 MW.

According to selected plant operating parameters, it can be stated that each new regenerative heater added to the plant reduces mechanical power produced by the turbine for 4.33 MW on average.

**Fig. 5.** Mechanical power produced by the turbine in all observed steam power plant versions

Mechanical power consumed by the pumps inside the observed plant continuously increases from the Base plant (3449.41 kW) until the Final plant (3697.17 kW), Fig. 6. Main Feedwater Pump (MFP) consumes much higher mechanical power in comparison to Condensate Pump (CP) [19]. Each new regenerative heater added to the plant increases feedwater temperature; therefore, for each new regenerative heater, the MFP must operate between higher and higher specific enthalpy differences, which increases her consumed mechanical power. Each new regenerative heater increases mechanical power consumed by the pumps for 27.5 kW on average.

**Fig. 6.** Mechanical power consumed by the pumps in all observed steam power plant versions

In the observed plant, used fuel (natural gas) is consumed in the Steam Generator (SG) as well as in the ReHeater (RH). Cumulative fuel consumption in the plant is presented in Fig. 7. Each new regenerative heater increases feedwater temperature at the steam generator inlet; therefore, less fuel should be used for obtaining the same parameters of the steam at the SG outlet [20, 21]. Cumulative fuel consumed in the plant continuously decreases from the Base plant (17.721 kg/s) until the Final plant (13.996 kg/s). Therefore, for the selected plant operating parameters, the addition of each new regenerative heater in the plant reduces cumulative plant fuel consumption by 0.414 kg/s on average.

Each new regenerative heater added to the plant increases plant overall efficiency, Fig. 8. Base plant has overall efficiency of 36.90%, while the Final plant after all added regenerative heaters has overall efficiency of 40.76%, which is a notable increase in overall plant efficiency (for 3.86%). For the plant operating parameters defined in this analysis, each regenerative heater added to the plant increases plant overall efficiency by 0.43% on average.

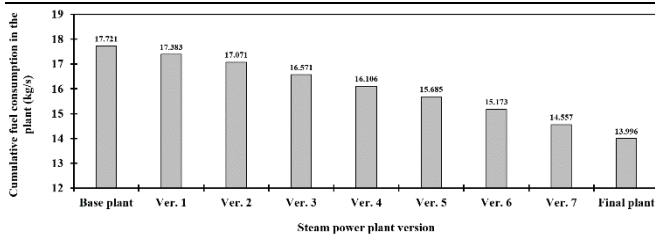


Fig. 7. Cumulative plant fuel consumption in all observed steam power plant versions

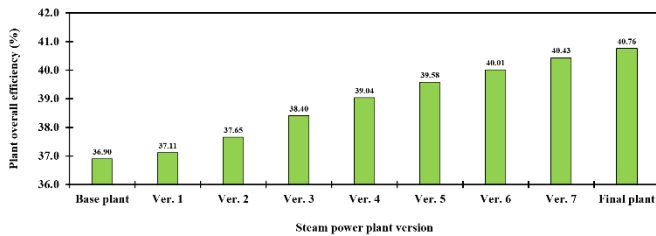


Fig. 8. Plant overall efficiency in all observed steam power plant versions

6. Conclusions

In this paper, results of each regenerative heater's influence on global steam power plant operating parameters are presented. Nine steam power plant versions were considered – from the Base power plant without regenerative heating system up to the Final plant which consist of four non-mixing Low Pressure Heaters (LPH's), one Deaerator (mixing regenerative heater) and three non-mixing High Pressure Heaters (HPH's). The most important obtained results are:

- Due to the continuously increasing steam mass flow rate extracted from the steam turbine cylinders, each new regenerative heater added to the plant continuously reduces the mechanical power produced by the turbine, for 4.33 MW on average.
- Each new regenerative heater continuously increases mechanical power consumed by the pumps, for 27.5 kW on average (dominantly due to increased feedwater specific enthalpy difference between Main Feedwater Pump inlet and outlet).
- Each added regenerative heater increases feedwater temperature at the Steam Generator inlet, which results in a continuous decrease in the plant cumulative fuel consumption from the Base plant until the Final plant. Each added regenerative heater continuously decreases cumulative plant fuel consumption, for 0.414 kg/s on average.
- Finally, it should be highlighted that each regenerative heater added to the plant continuously increases plant overall efficiency from the Base plant until the Final plant, for 0.43% on average.

7. Acknowledgment

This research has been supported by the University of Rijeka scientific grants: Funded by the European Union – NextGenerationEU – ENERGOPT - uniri-iz-25-6 and GENE-CLASS - uniri-iz-25-220.

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Optimal Control Of Electrohydraulic Positioning System

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Abstract: This work presents a study of applicability of optimal control theory to the design of a electrohydraulic power transmission. The system involve hydraulic cylinder, loaded with time-variable force and two-stage electrohydraulic servovalve, including elasticity of steal cylinder and tubing and compressibility of oil. An optimal control low has been formulated with performance index requiring maximum quickness and output power and minimum control energy. The obtained optimal low can be used for industrial optimal automatic controller. There are shown optimal dynamic processes for different initial conditions and loading force.

Keywords: ELECTROHYDRAULIC POSITIONING SYSTEM, OPTIMAL CONTROL, ELECTROHYDRAULIC SERVOVALVE

1. Introduction

Electrohydraulic power transmission and servo system have found widespread use in industrial automation, aircraft and missile controls, automotive steering, earthmoving equipment control, and simulation and training systems [2, 4, 8]. For automated systems involving high levels of power, and requiring precision and high speeds of response, electrohydraulic systems are potential choice. There is also wide interest in academic as well as industrial research in the application modern control techniques to electrohydraulic systems to improve their performance. The servo-actuators usually employ electrohydraulic servo-valves for precise control of position or force in different points on the load. Electrohydraulic cylinder drive servomechanisms combine the versatility and the precision available from electrical measurement and signal processing techniques with the rapid response and loading capacity of hydraulic cylinder drives [2, 6, 8]. Much work has been conducted in an effort to improve the dynamic control systems of hydraulic actuators. The stepless control of the kinetic characteristic by hydraulic resistance variation of the system is possible with the servovalve input voltage.

Problems of optimal control have received a great deal of attention during the past decade awing to increasing demand for systems of high performance and to the ready availability of the digital controller. The concept of control system optimization comprises a selection of a performance index and a design which yields the optimal control system within limits imposed by physical constraints. Such an optimal control system differs from an ideal one in that the former is the best attainable in the presents of physical constrains whereas the latter may well be an unattainable goal.

This paper summarizes a study on the applicability of nonlinear optimal control to an hydraulic cylinder that is controlled by means of a two-stage, electrohydraulic servovalve. The optimal control law is obtained by the method – “the maximums principle” of Pontragin [1, 3, 6].

2. Dynamic Model Of The System

The physical model of the electrohydraulic power [3, 4] transmission is illustrated in Fig. 1

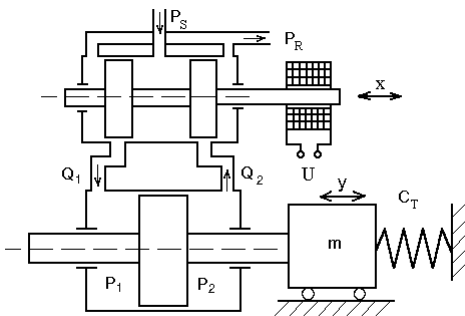


Fig. 1 Physical model of electrohydraulic system.

The following linearized equations of the system are used:

Actuator force assuming inertia load, viscose damping and spring force:

$$m \frac{d^2 y}{dt^2} + f \frac{dy}{dt} + C_T y = A_p p_h \quad (1)$$

Linearized flow in the valve:

$$Q = K_x \cdot x - K_p \cdot p_h \quad (2)$$

Flow entering in actuator, taking into account the compressibility of fluid:

$$Q = A \frac{dy}{dt} + \frac{V_0}{2E} \frac{dp_h}{dt} \quad (3)$$

Force in the valve spool, assuming inertia load, damping and force in proportional magnet:

$$T_v^2 \frac{d^2 x}{dt^2} + 2\zeta T_v \frac{dx}{dt} + x = K_U U \quad (4)$$

3. State Space Representation Of The System.

Let us choose the state variables as:

$$\begin{aligned} x_1 &= y; & x_3 &= p_h \\ x_4 &= x; & x_5 &= \frac{dx}{dt} \end{aligned}$$

The input is:

$$u = U \quad (5)$$

The State-space representation of system is:

$$\text{State equation: } \dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$$

$$\text{Output equation: } \mathbf{y} = \mathbf{Cx} + \mathbf{Du}$$

$$\mathbf{D} = 0 \quad \mathbf{y} = y$$

$$\mathbf{y} = \mathbf{Cx} \quad \mathbf{C} = [1 \ 0 \ 0 \ 0 \ 0]$$

The output equation is:

$$y = x \quad (6)$$

The state equation is:

$$\begin{aligned} \frac{dx_1}{dt} &= a_{12} x_2 \\ \frac{dx_2}{dt} &= a_{21} x_1 + a_{22} x_2 + a_{23} x_3 \\ \frac{dx_3}{dt} &= a_{32} x_2 + a_{33} x_3 + a_{34} x_4 \\ \frac{dx_4}{dt} &= a_{45} x_5 \\ \frac{dx_5}{dt} &= a_{54} x_4 + a_{55} x_5 + b_5 u \end{aligned} \quad (7)$$

where:

$$\begin{aligned} a_{21} &= -\frac{C_T}{m} & a_{22} &= -\frac{f}{m} \\ a_{23} &= \frac{A}{m} & a_{32} &= -\frac{2AE}{V_0} \\ a_{33} &= -\frac{2K_p E}{V_0} & a_{34} &= \frac{2K_x E}{V_0} \\ a_{54} &= -\frac{1}{T_v^2} & a_{55} &= -\frac{2\xi}{T_v} \\ b_5 &= \frac{K_U}{T_v^2} \end{aligned}$$

The matrix are:

$$\mathbf{A} = \begin{bmatrix} 0 & a_{12} & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} & 0 \\ 0 & 0 & 0 & 0 & a_{45} \\ 0 & 0 & 0 & a_{54} & a_{55} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ b_5 \end{bmatrix}$$

Controllability of the system

For the controllability of the system is defined a matrix $\mathbf{Q}$ [4, 7]:

$$\mathbf{Q} = [\mathbf{B}, \mathbf{AB}, \mathbf{A}^2\mathbf{B}, \mathbf{A}^3\mathbf{B}, \mathbf{A}^4\mathbf{B}]$$

For the values of coefficients in **Table 1** the rank of the matrix $\mathbf{Q}$ is :

$$\text{rank } \mathbf{Q} = 5$$

The system is therefore completely state controllable.

Optimal Control Formulation

The optimum control law is to obtain an maximum outlet power of the system and minimum input control power.

The performance index is:

$$I = \int_{t_0}^{t_1} (-P(t) + \lambda u^2(t)) dt \quad (8)$$

where:

$$\begin{aligned} P(t) &= p_H \cdot Q = x_3(K_x \cdot x_4 - K_p \cdot x_3) = \\ &-K_p \cdot x_3^2 + K_x \cdot x_3 \cdot x_4 \end{aligned} \quad (9)$$

The performance index, having in mind the state variables can be expressed as:

$$I = \int_{t_0}^{t_1} (K_p \cdot x_3^2 - K_x \cdot x_3 \cdot x_4 + \lambda u^2) dt = \int_{t_0}^{t_1} f_0 dt \quad (10)$$

where:

$$\frac{dx_0}{dt} = f_0(x_3, x_4, u) \quad (11)$$

The physical limits are:

$$|u| \leq u_{max} \quad |x_1| \leq x_{1max} \quad |x_3| \leq x_{3max} \quad |x_4| \leq x_{4max}$$

The Hamilton function is [1, 4]:

$$\begin{aligned} H &= \psi_0 (K_p \cdot x_3^2 - K_x \cdot x_3 \cdot x_4 + \lambda u^2) \\ &+ \psi_1 (a_{12} \cdot x_2) + \\ &+ \psi_2 (a_{21} \cdot x_1 + a_{22} \cdot x_2 + a_{23} \cdot x_3) + \\ &\psi_3 (a_{32} \cdot x_2 + a_{33} \cdot x_3 + a_{34} \cdot x_4) \\ &+ \psi_4 (a_{45} \cdot x_5) + \\ &\psi_5 (a_{54} \cdot x_4 + a_{55} \cdot x_5 + b_5 \cdot u) \end{aligned} \quad (12)$$

The subsidiary functions are:

$$\begin{aligned} \frac{d\psi_0}{dt} &= -\frac{\partial H}{\partial x_0} = 0 \\ \frac{d\psi_1}{dt} &= -\frac{\partial H}{\partial x_1} = -(a_{21} \cdot \psi_2) \\ \frac{d\psi_2}{dt} &= -\frac{\partial H}{\partial x_2} = -(a_{12} \cdot \psi_1 + a_{22} \cdot \psi_2 + a_{32} \cdot \psi_3) \\ \frac{d\psi_3}{dt} &= -\frac{\partial H}{\partial x_3} = -\left(2 \cdot \psi_0 \cdot K_p \cdot x_3 - \right. \\ &\quad \left. \psi_0 \cdot K_x \cdot x_4 + a_{23} \cdot \psi_2 + a_{33} \cdot \psi_3 \right) \\ \frac{d\psi_4}{dt} &= -\frac{\partial H}{\partial x_4} = -\left(\psi_3 \cdot a_{34} - \right. \\ &\quad \left. \psi_0 \cdot K_x \cdot x_3 + \psi_5 \cdot a_{54} \right) \\ \frac{d\psi_5}{dt} &= -\frac{\partial H}{\partial x_5} = -(\psi_4 \cdot a_{45} + \psi_5 \cdot a_{55}) \end{aligned} \quad (13)$$

For the maximum of Hamilton function – H is necessary:

$$\frac{\partial H}{\partial u} = 0 \quad \frac{\partial^2 H}{\partial u^2} < 0$$

In that case

$$\begin{aligned} \frac{\partial H}{\partial u} &= b_5 \cdot \psi_5 + 2\lambda \cdot u \cdot \psi_0 = 0 \Rightarrow u = -\frac{\psi_5 \cdot b}{2\psi_0 \lambda} \\ \frac{\partial^2 H}{\partial u^2} &= 2\psi_0 \lambda \end{aligned}$$

We assume: [1, 4, 7] $\psi_0 = -1$ and the equation is:

$$\frac{\partial^2 H}{\partial u^2} = -2\lambda < 0; \quad u = \frac{\psi_5 \cdot b_5}{2\lambda} \quad (14)$$

The equation (13) is the optimum control law.

4. Results

The optimal control input variable can be expressed by combining of equations (13) and (14).

$$u = \frac{b_5}{2\lambda} \frac{A(s)}{B(s)} \left\{ \begin{aligned} &[B(s)K_x + 2K_p a_{34}]x_3 \\ &-a_{34}K_x x_4 \end{aligned} \right\}, \quad (15)$$

where:

$$A(s) = \frac{a_{45}}{(s^2 - a_{55}s - a_{45}a_{54})};$$

$$B(s) = \frac{\begin{bmatrix} s^3 + s^2(a_{22} + a_{33}) \\ + s(a_{22}a_{33} - a_{12}a_{55} - a_{23}a_{32}) \\ - a_{12}a_{55}a_{33} \end{bmatrix}}{(s^2 + a_{22}s + a_{12}a_{22})}.$$

The equations (7), (13) and (150) have been modeled and the simulation was done with MatLab Simulink. The model is shown in fig. 2. The result time-response curves for u are shown in Fig. 2, and for x_1 x_2 x_3 x_4 are shown in Figs. 3 - 6.

The values of coefficients is shown in Table 1.

Table 1. The values of coefficients

For Fig. 2-6 - **line 1**

$$a_{12}=1, a_{21}=-20000, a_{22}=-25,$$

$$a_{23}=7780, a_{32}=-247, a_{33}=-492.35, a_{34}=1646, a_{45}=1,$$

$$a_{54}=2000, a_{55}=-30, b_5=2000$$

For Fig. 2-6 - **line 2**

$$a_{12}=1, a_{21}=-5000, a_{22}=-25, a_{23}=7780, a_{32}=-247, a_{33}=-492.35, a_{34}=1646, a_{45}=1, a_{54}=-2000, a_{55}=-30, b_5=2000$$

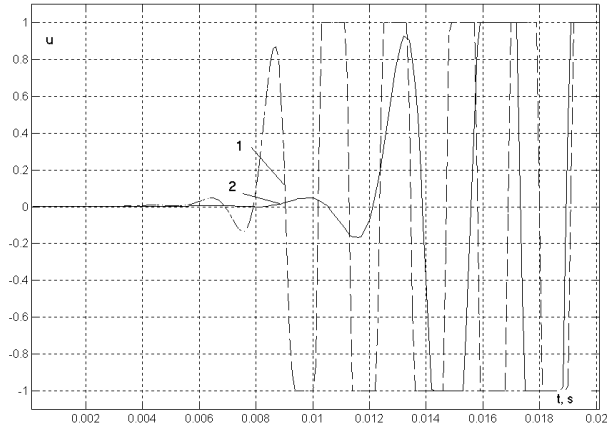


Fig. 2. Input control variable time-response curve.

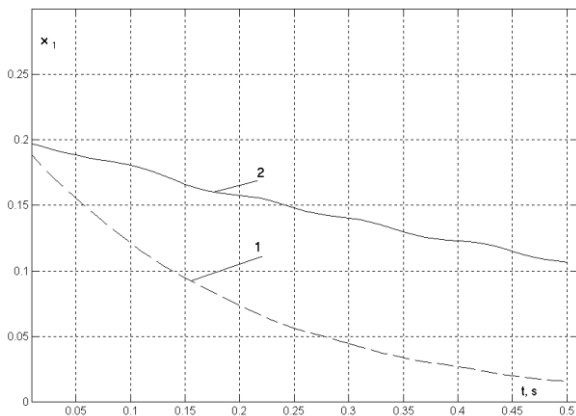


Fig. 3. State variable x_1 responses curves

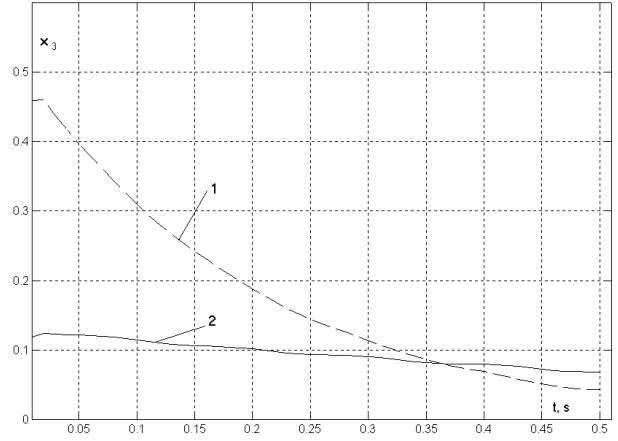


Fig. 4. State variable x_2 responses curves

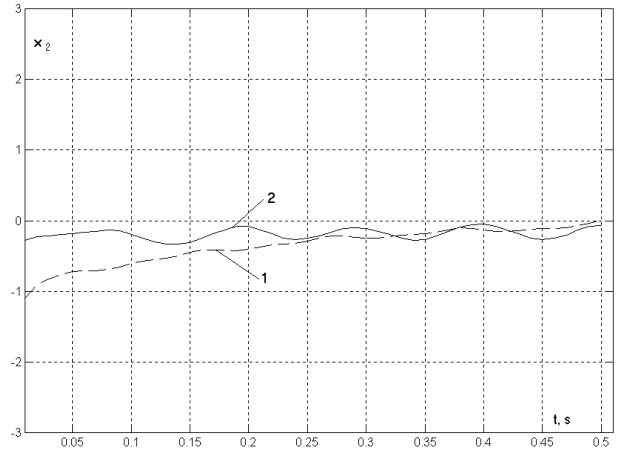


Fig. 5. State variable x_3 responses curves

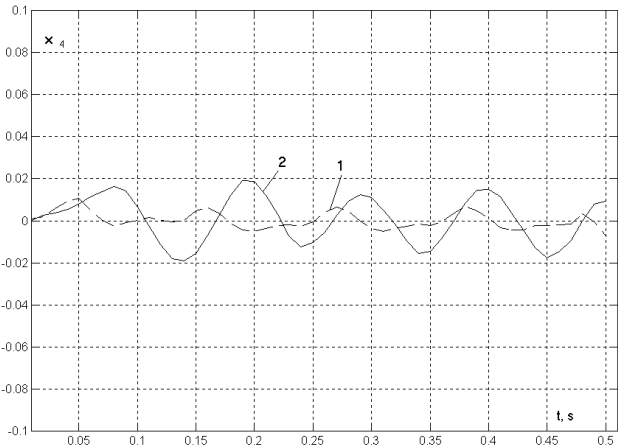


Fig. 6. State variable x_4 responses curves

5. Conclusions

A commercially available hydro cylinder that uses a two-stage servovalve has been modeled and the optimum control law as a function of state variables - x_3 and x_4 (17) have been define. The variables which is forming optimal law can be observe and measure in a real time working and an automatic controller can be made using this law.

The mathematical procedure used here assured that the response was optimal for the specifications of a performance index and for real physical limits in the system

The optimal control law shows that in that system is possible to use (with approximations) an electric directional control valves instead servovalve. The valve natural frequency must be higher than the frequency of input control signal.

Acknowledgment

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Nomenclature

A - effective areas piston, m^2 ;

m - mass load, kg;

C_T - spring constant, N/m;

E - bulk modulus of hydraulic fluid, Pa;

f - viscous friction coefficient for actuators Ns/m;

I - error performance index;

K_P - flow pressure gain, $m^3/s.Pa$;

K_U - gain of servovalve, m/V ;

K_X - low gain, m^2/s ;

$p_H = p - p_2$ - pressure difference in hydraulic cylinder, head and rod sides, Pa;

p_S - supply pressure, Pa;

p_R - drain (return line) pressure, Pa;

$Q = \frac{Q_1 + Q_2}{2}$ - flow, m^3/s ;

T_V - time constant of servovalve, s;

U - input voltage of servovalve, V;

V_0 - volume of hydraulic oil, m^3 ;

x - servovalve spool displacement, m;

y - hydraulic piston displacement, m;

ζ - servovalve time constant damping ratio;

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Experimental Investigation of the Influence of the Hydraulic Fluid Temperature to The Dynamic Characteristics of the Hydraulic Power Transmission Systems

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Abstract: In working process a certain part of energy transmitted by the fluid in every hydraulic system is transferred to the consumer, while the other part (because of hydraulic pressure loss) is transformed into heat. The temperature of the fluid is rising during the working cycle with power loss. Is the temperature of the hydraulic fluid is higher the physical characteristic of hydraulic fluids is changed. Some of this is viscosity, density, specific gravity, compressibility and modulus of elasticity and gas absorption. The experimental investigation of dynamic characteristics changes of a closed electrohydraulic power transmission system with the variation of hydraulic fluid temperature is presented in this paper. The experimental test stand was used for dynamic processes investigation in an electrohydraulic positioning system for different operating temperatures. The obtained step time responses are shown in few graphics.

Keywords: ELECTROHYDRAULIC POSITIONING SYSTEM, OPTIMAL CONTROL, ELECTROHYDRAULIC SERVOVALVE

1. Introduction

In working process a certain part of energy transmitted by the fluid in every hydraulic system is transferred to the consumer, while the other part (because of hydraulic pressure loss) is transformed into heat. The temperature of the fluid is rising during the working cycle with power loss [1]. The heat transfer capability of correctly designed hydraulic apparatus must be such that thermal balance is reached at 50 -70°C. Is the temperature of the hydraulic fluid is higher the physical characteristic of hydraulic fluids is changed. Some of this is viscosity, density, specific gravity, compressibility and modulus of elasticity and gas absorption. In some cases the change of physical characteristic of hydraulic fluids can change influence in dynamic characteristic of hydraulic power transmission [1, 5, 8, 9]. The influence of rising temperature is a great in starting time, when the fluid is cold and after some operating cycles the

temperature is rising and become constant, when the heat generated in the system become equal to absorbed by the hydraulic fluid and heat transferred to the surrounds. For the precise control of electrohydraulic traction systems, the influence of temperature is essential [10, 11, 12, 13, 14, 15]

The experimental investigation of dynamic characteristics changes of a closed electrohydraulic power transmission system with the variation of hydraulic fluid temperature is presented in this paper.

The experimental test stand was used for dynamic processes investigation in an electrohydraulic positioning system for different operating temperatures. The obtained step time responses are shown in few graphics. This gives opportunity for correct evaluation the accuracy of the hydraulic actuator motion in static and in dynamic conditions.

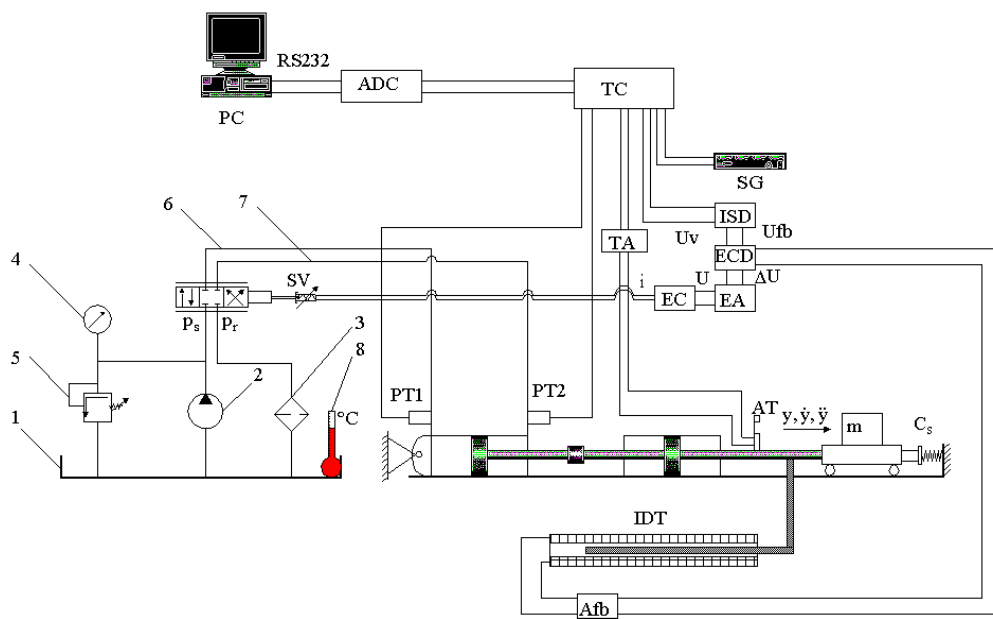


Fig. 1. Experimental test stand

Some recommendations are done for automatic controller adjustment for the bad influence compensation of hydraulic oil temperature variations.

The differential equation of the temperature change is the following [1]:

$$T \frac{d\vartheta}{dt} + \vartheta = A_w \Phi_{in} + \vartheta_0 \quad (1)$$

where:

$$T = \frac{m \cdot c_f}{k \cdot A}, \text{ s} \quad \text{time constant of heating process;}$$

$$A_w = \frac{1}{k \cdot A}, \text{ s}^\circ\text{C/J heat transfer coefficient;}$$

$$\Phi_{in} = (1 - \eta_{tot}) P_{in}, \text{ J/s input heat flux}$$

The formula (1) in a control technique sense is the differential equation of a first order proportional element, whose solution in the case of step function input signal is

$$\vartheta = \vartheta_0 + A_w \left(1 - e^{-\frac{t}{T}} \right). \quad (2)$$

In the practice some of the heat generated is transferred to the surroundings by every system, in natural way.

The natural heat dissipation is realized by radiation, conduction, convection and heat exchange. Most of the heat is transferred to the surroundings by the supply unit of the hydraulic apparatus.

In this paper has been investigated the influence of fluid temperature variation to the operating process in electrohydraulic positioning system. The investigation has been made experimentally in a corresponding test stand.

2. Experimental Test Stand

An automated test stand [3] for dynamic processes investigation with oil temperature variation in the electrohydraulic power systems has been developed (see Fig. 1). This is a universal stand for modelling different types of mechanical loads in electrohydraulic power transmission. The dynamic responses for different kinds of loads, conditions and input signals (step, ramp, sinusoidal, stochastic, etc.) can be measured at this stand.

Experimental process control, data collection and preservation are performed with the help of personal computer – PC in “real time”. Special data acquisition software “EXADIP” have been created for the aim of practical measure of the time responses and for communication between interface card (analogue-digital module) and the transducers and control elements.

The system employed for the experimental portion of this work is shown in Fig. 1. The main elements are: 1-tank; 2- hydraulic gear pump; 3-filter; 4-gauge; 5- pressure relief valve; 5 – supply pressure line; 7- drain line; ADC – analog digital converter; 8- thermometer; TC – terminal card, TA – tenzomeric amplifier; SG – signal generator; ISU - input signal unit, SV – electrohydraulic servovalve, Afb - feedback amplifier; IDT – inductive displacement transducer; AT – acceleration transducer; EA - error amplifier; PT1, PT2 - pressures; ECD - error converter device; EC – electronic controller.

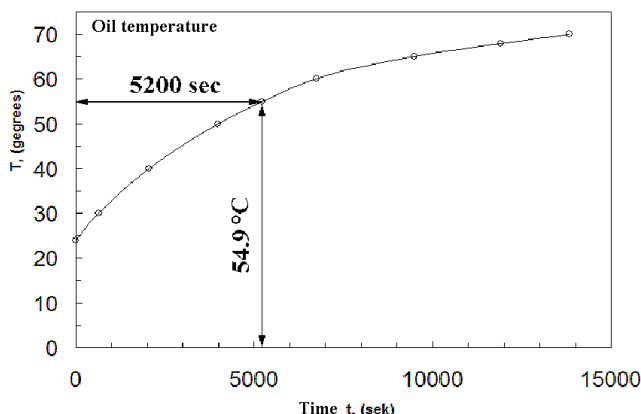


Fig.2. Oil Temperature vs. operating time

The module ExADIO (ADC) is made of the base of MC68HC11A1 microprocessor, Analog to Digital (A/D) and Digital to Analog (D/A) converters and RS232/RS485 interface. ADC is a device for data collection, transformation and communication with PC. The experimental data are saved in DAT files. The terminal card TC is used for collection and filtration the

signals from transducers and the other electronic devices. For the experiment PID controller was optimal tuned [2], [3].

The corresponding step responses are shown in Fig.3, Fig.4 and Fig.5.

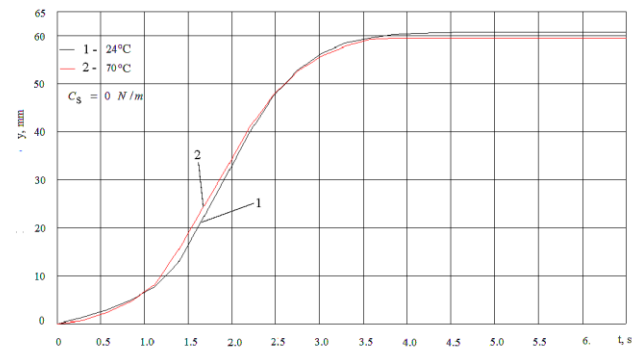


Fig.3 Step responses for 24 and 70 °C without position force

The experiment started with measurement the hydraulic oil temperature on thermometer 8. After that from the ISU the electric step signal was send to the electrohydraulic system. The output responses were measured and stored in data files in the personal computer. The time for temperature rising with 10°C is measured and the graphic presentation oil temperature vs. operating time was done (see Fig. 2).

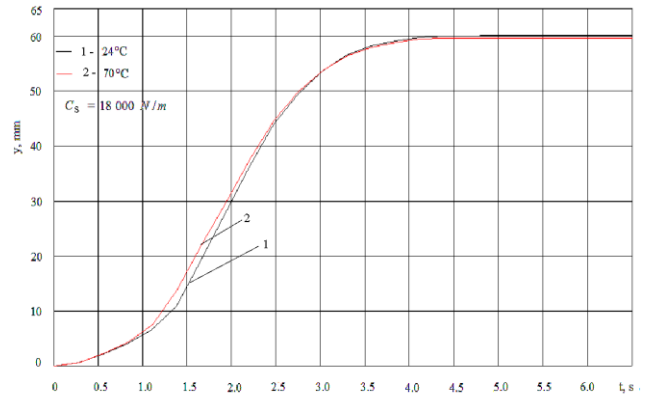


Fig.4 Step responses for 24 and 70 °C with position force with spring constants $C_s = 18000 \text{ N/m}$

From Fig. 2 the time constant for oil heating process (according the eq.1) is $T = 5200 \text{ s}$.

3. Experimental Results

For temperature interval from 24°C to 70°C the step responses were obtained from the experimental test stand for loads with spring constants $C_s = 0 \text{ N/m}$, $C_s = 18000 \text{ N/m}$ and $C_s = 51000 \text{ N/m}$.

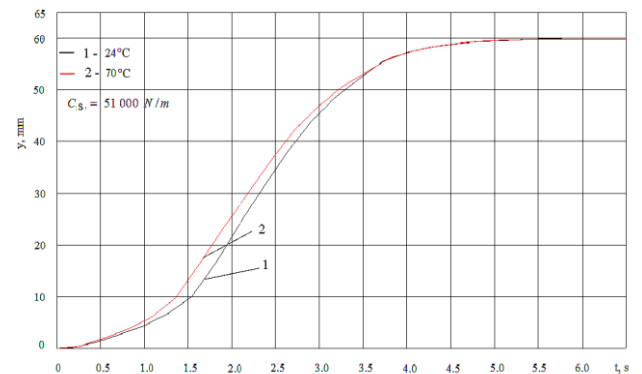


Fig.5. Step responses for 24 and 70 °C with position force with spring constants $C_s = 51000 \text{ N/m}$.

For temperature interval from 60°C to 70°C the step responses were obtained from the experimental test stand for loads with spring constants $C_S = 0$ N/m, $C_S = 18000$ N/m and $C_S = 51000$ N/m.

The corresponding step responses are shown in Fig. 6, Fig. 7 and Fig. 8.

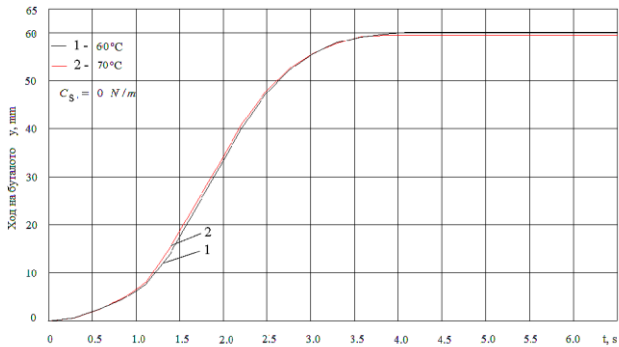


Fig.6 Step responses for 60 and 70 °C without position force

The system without position force

For the fluid temperature 24°C, the piston displacement is $y_{24} = 61.0$ mm and for the temperature 70°C, displacement is $y_{70} = 59.1$ mm. The absolute steady-state error is:

$$\Delta y = y_{24} - y_{70} = 61.0 - 59.4 = 1.6 \text{ mm},$$

and the relative steady-state error is:

$$\varepsilon = \frac{\Delta y}{y_{70}} 100\% \Rightarrow \varepsilon = \frac{1.6}{61.0} 100 = 2.6\%.$$

For the hydraulic oil temperature 60°C, the corresponding data are:

$$y_{60} = 60.3 \text{ mm},$$

$$\Delta y = 60.2 - 59.4 = 0.8 \text{ mm},$$

$$\varepsilon = \frac{0.8}{60.2} \cdot 100 = 1.3\%.$$

At the moment $t = 1.5$ s piston displacement for temperature 24°C is $y_{24} = 19.2$ mm and for temperature 70°C - $y_{70} = 16.5$ mm, the absolute dynamic error is

$$\Delta y(1.5) = y_{24} - y_{70} = 19.2 - 16.5 = 2.7 \text{ mm},$$

and the relative dynamic error is

$$\varepsilon(1.5) = \frac{2.7}{19.2} \cdot 100 = 14\%.$$

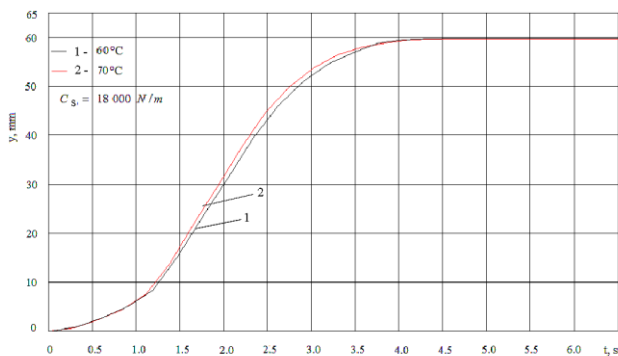


Fig.7 Step responses for 60 and 70 °C with position force with spring constants $C_S = 18000$ N/m.

For the oil temperature 60°C, the corresponding data are:

$$y_{60} = 17.4 \text{ mm}, \Delta y(1.5) = y_{24} - y_{60} = 19.2 - 17.4 = 1.8,$$

$$\varepsilon(1.5) = \frac{1.8}{19.2} \cdot 100 = 9.3\%$$

The system with position force with spring constant $C_S = 18000$ N/m

For the fluid temperature 24°C, the piston displacement is $y_{24} = 60.2$ mm and for the temperature 70°C, displacement is $y_{70} = 59.5$ mm. The absolute steady-state error is:

$$\Delta y = y_{24} - y_{70} = 60.2 - 59.5 = 0.7 \text{ mm},$$

and the relative steady-state error is:

$$\varepsilon = \frac{\Delta y}{y_{70}} 100\% \Rightarrow \varepsilon = \frac{0.7}{60.2} 100 = 1.16\%.$$

For the hydraulic oil temperature 60°C, the corresponding data are:

$$y_{60} = 59.9 \text{ mm},$$

$$\Delta y = 59.9 - 59.5 = 0.4 \text{ mm}, \varepsilon = \frac{0.4}{59.9} \cdot 100 = 0.67\%.$$

At the moment $t = 1.5$ s piston displacement for temperature 24°C is $y_{24} = 14.5$ mm and for temperature 70°C - $y_{70} = 17.4$ mm, the absolute dynamic error is

$$\Delta y(1.5) = y_{70} - y_{24} = 17.4 - 14.5 = 2.9 \text{ mm},$$

and the relative dynamic error is

$$\varepsilon(1.5) = \frac{2.9}{17.4} \cdot 100 = 16.6\%.$$

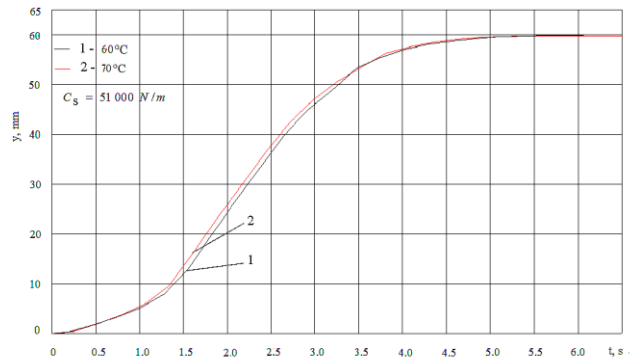


Fig. 8 Step responses for 24 and 70 °C with position force with spring constants $C_S = 51000$ N/m.

For the oil temperature 60°C, the corresponding data are:

$$y_{60} = 16.5 \text{ mm}, \Delta y(1.5) = y_{70} - y_{60} = 17.4 - 16.5 = 0.9,$$

$$\varepsilon(1.5) = \frac{0.8}{17.4} \cdot 100 = 4.6\%$$

The system with position force with spring constant $C_S = 51000$ N/m

For the fluid temperature 24°C, the piston displacement is $y_{24} = 60.0$ mm and for the temperature 70°C, displacement is $y_{70} = 59.8$ mm. The absolute steady-state error is:

$$\Delta y = y_{24} - y_{70} = 60.0 - 59.8 = 0.2 \text{ mm},$$

and the relative steady-state error is:

$$\varepsilon = \frac{\Delta y}{y_{70}} 100\% \Rightarrow \varepsilon = \frac{0.2}{60.0} 100 = 0.33\%$$

For the hydraulic oil temperature 60°C, the corresponding data are:

$$y_{60} = 60 \text{ mm},$$

$$\Delta y = 59.9 - 59.8 = 0.1 \text{ mm}, \quad \varepsilon = \frac{0.1}{59.9} \cdot 100 = 0.16\%$$

At the moment $t = 1.5$ s piston displacement for temperature 24°C is $y_{24} = 14.5$ mm and for temperature 70°C - $y_{70} = 13$ mm, the absolute dynamic error is

$$\Delta y(1.5) = y_{70} - y_{24} = 13 - 9.5 = 3.5 \text{ mm},$$

and the relative dynamic error is

$$\varepsilon(1.5) = \frac{3.5}{13} \cdot 100 = 26.9\%$$

For the oil temperature 60°C, the corresponding data are:

$$y_{60} = 11.8 \text{ mm}, \quad \Delta y(1.5) = y_{70} - y_{60} = 13 - 11.8 = 1.2,$$

$$\varepsilon(1.5) = \frac{1.2}{13} \cdot 100 = 9.2\%$$

The experiment data and graphics shows that the oil temperature increasing cause to decreasing of steady state value of the piston displacement and to increasing the step respond speed. With the increasing of the spring (position) force the response speed become slower and the steady state error (between two oil temperatures) decreasing.

The system step response is quicker for higher oil temperature.

5. Conclusions

For the oil temperature raising from 24°C to 79°C the steady-state error depending on positioning force is -2.6-3.3%.

The step response rate increasing with the fluid temperature rising and for the process without a position force reaches 14% (the increasing of position force cause to decreasing of steady-state error).

For the great position forces ($C_s = 51000 \text{ Nm}$) the oil temperature rising from 24°C to 79°C lead to dynamic error at about 26.9% ($t = 1.5$ s).

The obtained results show that for the hydraulic transmissions that must have a great operating accuracy in dynamic and static conditions is necessary to account the oil temperature variation. For the automatic system this problem can be avoided with an appropriate tuning and retuning the parameters of the automatic controller. For the hydraulic systems without a controller is necessary to create a suitable cooling unit, which must maintain the constant oil temperature.

For a preliminarily studying the influence of the fluid temperature to the hydraulic systems operating processes is necessary to develop an appropriate mathematical model for dynamics characteristics calculating.

Acknowledgment

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Nomenclature

A	heat transfer surface of the apparatus	m
A_w	heat transfer coefficient	s°C/J
c_f	specific heat of the fluid	J/kg.K
k	heat transfer coefficient	J/m ² sK
m	fluid mass	kg
P_{in}	power	J/s
t	time	s
T	time constant of the heating process	s
ϑ	instantaneous temperature of the hydraulic fluid	K
ϑ_0	ambient temperature	K
η_{tot}	total efficiency	-
Φ_{in}	input heat flux	J/s

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Experiment preparation with Phase Changing Materials for industrial application

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Abstract: This article summarizes the preliminary preparations for conducting experiments with phase change materials to determine their behavior during continuing heating and cooling processes. The goal is to summarize conclusions about the possibilities of using these materials in boilers and other water-heating tanks for industrial and domestic applications. The techniques, materials, and equipment that will be used are described, as well as the theoretical behavior of the materials that will be compared.

Keywords: ENERGY EFFICIENCY, PHASE-CHANGING MATERIALS, HOT WATER STORAGE, INTELIGENT SOLUTIONS

1. Introduction

Achieving a highly efficient building that ensures optimal thermal comfort and quality of life brings enormous benefits in terms of return on investment, energy savings, longer service life, significantly improved productivity and comfort for residents, while also causing minimal impact on the surrounding environment. Regardless of whether it concerns single-family houses, public buildings, or industrial premises, all new buildings are built according to the new European requirements for energy efficiency. They require less pollution, cleaner air and, at the same time, a reduction of cost, especially from the use of energy for heating. For existing buildings, measures must be taken to increase their energy efficiency in all aspects of consumption - heating, ventilation, air conditioning, water supply, lighting, etc.

Studies show that a large proportion of European consumers still use water heaters for water heating, [1]. This is why new, efficient solutions for heating water that consume less energy are being developed. The problem with water heaters is that they heat a large amount of water that may not be used at a certain time. In this way, energy consumption is unjustified. Another disadvantage associated with the use of traditional boilers is the accumulation of limescale, which leads to a decrease in efficiency and the need for repairs. One of the options chosen by European households is tankless water heaters. They are compact and space saving. They supply hot water, with no preheating and waiting-time required. This also avoids running out of hot water during peak consumption in the morning or evening hours, when the consumption is higher. In countries with milder and warmer climates, they are also used for outdoor use. These water heating systems have a longer life, do not require complex maintenance and in long term prove to be effective. The possibilities for their integration into installations powered by renewable energy sources are also developing, which will further improve their energy efficiency, [2]. Unfortunately, tankless water heaters are only suitable for family houses with up to several households. They cannot be used in larger buildings such as industrial, agricultural and public, since the consumption of hot water is significantly higher and the purchase of a large number of these devices becomes unjustified.

The phase change materials (PCM) store and release heat at the temperature at which it melts or solidifies. It can hold a large amount of thermal energy per unit volume because it relies on latent heat, which is greater than sensible heat. Latent heat can be used by solid-gas, solid-liquid, and liquid-gas transition states, with the solid-liquid transition being the most preferred because the volume doesn't change much.

The use of PCM for latent heat storage allows energy storage even with a small temperature difference if integrated into a hot water tank. This combination increases energy capacity and improves performance under specific load patterns, [3].

This article is related to a project for developing a water tank with an integrated phase change material into the construction to increase energy efficiency. The publication outlines the preliminary studies and prerequisites for conducting experiments with PCM to determine their real qualities and the possibilities for their use in

boilers. Chapter 2 examines the essence of PCM and their application possibilities. Chapter 3 describes the preparation for conducting experiments with PCM. The last chapter draws conclusions about the conduct of the experiment and the expected results.

2. Application of Phase Change Materials

Phase Change Materials (PCMs) are an extremely suitable solution for the regulation of thermodynamic processes. This is because they store and release thermal energy when they change their state (from one phase to another). When this happens, they release a large amount of energy in the form of latent heat of fusion. In the opposite case, when heated, the material absorbs a large amount of energy and retains it. The types of PCM are mainly Solid-Solid and Solid-Liquid, and their subdivisions are described in Figure 1.

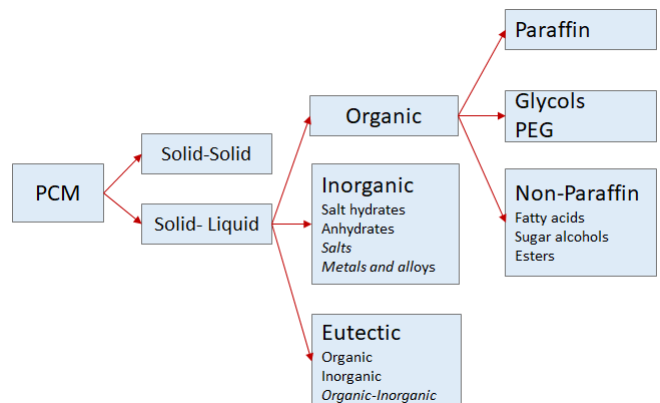


Fig. 1 Types of PCMs

PCMs can be widely used in various industries due to their beneficial characteristics. Their most common applications are:

Construction – used as a component of materials for various surfaces – walls, floors, ceilings to maintain temperature, by absorbing heat during the day and returning it at night.

Energy storage from solar panels – on the same principle of absorbing and releasing heat, PCMs, such as Sodium sulfate decahydrate, help solar systems to be more efficient.

Refrigeration – refrigerators, refrigerating trucks and cold storages use these materials (e.g. mix of ammonium chloride and water) to ensure cold temperatures in emergency situations, such as power outages, technical malfunctions, etc.

Textiles – Paraffin wax is most often used for clothing that protects against extreme hot or cold temperatures.

Heat pumps – materials (paraffin-based PCMs or salt hydrates) store excess heat generated during the operation of the heat pump. When demand increases, the stored energy is released. The frequency of switching on and off is reduced, which helps save energy and extend the life of the compressor.

Table 1 summarizes the main advantages and disadvantages of working with phase change materials:

Table 1 – PCMs Advantages and Disadvantages

Advantages	Disadvantage
Energy efficiency	High price of some materials
Temperature control	The organic materials have low durability
Environment-friendly	Requires extensive research in the field

Given the potential of these materials, their research is essential for achieving high energy efficiency in the above-described industries, [4]. In water heaters, research and improvement of the use methodology are yet to be conducted, but the current results are promising, [5].

In one of the studies on the subject, the boiler system is used as the main heating unit through hot water, and the PCM-based waste heat recovery system is used as the air heating unit. In experiments conducted at 24-minute intervals, interesting conclusions have been made, proving the possibilities of achieving high energy efficiency (between 24% and 51%, depending on the state of the PCM) in building heating systems. The maximum efficiency of the PCM heat exchanger is about 13%, achieved around the time of the phase change, in which latent heat is obtained. This efficiency is an addition to the heating of the building with a boiler system. This is because the heat exchanger system supported by the PCM is used as a supplement to the building heating unit. The combination of PCM with the building heating unit shows that hybridization positively affects the system and, therefore, lower energy consumption may be possible thanks to the energy stored in the PCM, [6].

To achieve even higher energy efficiency, the combination with a renewable energy source is suitable. In another study, a PCM layer was integrated within a solar collector connected to a hot water tank system. In this way, hot water with a constant temperature close to the melting temperature of the PCM can be produced for a long period of operation. The results of the annual performance study of the system show that the production of hot water with a constant temperature throughout the year can be achieved with an appropriate choice of effective parameters. At high water flow rates through the system, multiple collectors can be used in a sequential configuration. By using two consecutive collectors, the system performance is increased by more than two times compared to that of a single solar collector, [7].

Several main economic advantages of using FPM in hot water heaters can be outlined. The first of these is that fewer boilers can cover the hot water demand, which in turn saves usable space. In addition, the integration of such a system allows energy to be consumed in evening peak tariff windows, when there is no high demand, and the stored heat to be released when needed, [8].

3. Experiment preparation

The experiment aims to investigate the behavior of three types of phase change materials (PCMs): paraffin, sodium thiosulfate pentahydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$), and sodium acetate trihydrate ($\text{NaCH}_3\text{COO} \cdot 3\text{H}_2\text{O}$), in order to select the most suitable material for use in a hot water heater (Figure 2). Their properties and characteristics will be subjected to real experiments and will be examined closely. The conclusions from the experiments performed will be useful in determining the material that will be used for a real water heating system, which will be the subject of further studies (Figure 3).



Fig. 2 (Left to Right) Paraffin, Sodium thiosulfate pentahydrate and Sodium acetate trihydrate

The properties of the selected materials are described in Table 2. They may vary depending on the quality and purity of the material. The selection of these materials is related to their good thermodynamic performance and their temperature compatibility with water heating vessels.

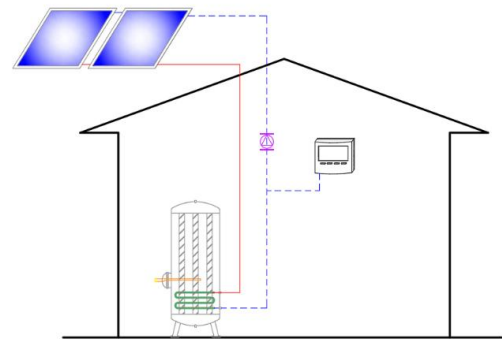


Fig. 3 PCMs water tank with solar panel integration

Table 2 – PCMs Characteristics

Material	Melting temperature T_m (°C)	Latent heat λ (kJ/kg)	Advantages	Disadvantages
Paraffin - Organic $\text{C}_n\text{H}_{2n+2}$	~55–58	150 – 210	Stable Safe No overcooling Non-corrosive	Low thermal conductivity Slower heat transfer
Sodium thiosulfate pentahydrate - Salt-hydrate $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$	~48	200 – 250	High density and thermal conductivity Good heat transfer Low cost	Super cooling Possible phase separation
Sodium acetate trihydrate - Salt-hydrate $\text{NaCH}_3\text{COO} \cdot 3\text{H}_2\text{O}$	~58	260 – 290	Very high thermal conductivity Suitable melting temperature Affordable	Need for thickeners/nucleators for stability

Paraffin is chemically inert, does not react with most building materials and has excellent resistance to repeated heating and cooling cycles, during which it does not overcool and its structure

does not separate. Salt hydrates are non-toxic and safe, their practical use is mainly in medicine. Although some salt hydrates show a tendency to phase separation or overcool, the selected materials are among the most stable in their group and this behavior can be controlled by appropriate engineering solutions, additives or optimization of the hot water tank. With the right choice of container for storing the material, the risk of corrosion is minimal, which allows for reliable long-term operation.

The experiment will observe the behavior of materials during heating and cooling, primarily in terms of changing their structure and the process of phase change with temperature, and their thermodynamic properties.

One of the reasons for choosing these materials is that they are widely available on the European market. They exist in various degrees of purity. Their price is relatively low compared to other PCMs with similar characteristics. Their application in the chemical, pharmaceutical, and food industries makes them widely available and maintains stable and competitive market prices, [9].

Regarding engineering compatibility and integration possibilities, the different phase transition mechanisms of organic and inorganic PCMs allow different combinations through which the properties of the materials complement each other – stability, high latent heat, and different temperature behavior. The selected materials can be encapsulated or integrated into modular systems that do not require complex technological modulations, thus reducing integration costs.

The experiment to test paraffin, $\text{NaCH}_3\text{COO} \cdot 3\text{H}_2\text{O}$ and $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ is planned to be conducted in a laboratory environment, where their temperature behavior will be monitored under identical conditions (Figure 4).



Fig 4: Experimental setup

The following equipment will be used:

- Glass flasks with the same geometry and volume;
- Electric heating plate with the ability to change the heating intensity;
- Thermographic camera for non-contact measurement and recording of the temperature in different areas of the set in real time. FLIR X6800sc MWIR (Figure 5) with a resolution of 640×512 and a temperature range: -45°C to $+600^\circ\text{C}$, from 250°C to 2000°C will be used;
- Thermometers for detecting temperature inside the material and ambient temperature;
- Scale for precise measurement of equal amounts of material. Equal portions of 250 ml of each material will be used to avoid errors caused by the amount of material;



Fig 5: Thermographic imaging with FLIR X6800sc MWIR

- Precision microscope for monitoring corrosion processes. A modern Olympus BX53M microscope (Figure 6) is used, which has high-intensity White LED illumination with constant color temperature, versatile observation methods (brightfield, darkfield, DIC, polarization, MIX), and seamless integration with PRECIV software for digital imaging and reporting.



Fig 6: Olympus BX53M microscope setup

The flasks are centrally located on the heating plate to ensure the most even heat transfer conditions. Maintaining a constant situation and heating conditions is extremely important for a reliable comparison of materials, since the charging/discharging behavior of PCM is highly sensitive to boundary conditions and heat transfer area. For this reason, the temperature must be constantly monitored.

Basic safety guidelines should be followed for each experiment to reduce the risks associated with chemicals and ensure the safety of the researchers. Safety glasses, a lab coat, closed-toe shoes, and gloves appropriate for the specific chemicals being handled should be worn. The work area should be kept clean and flasks should be kept away from the body when mixing or diluting chemicals. Chemical materials should be disposed of in designated waste containers according to specific disposal instructions. Through the experimental setup thus established, the following processes will be observed:

1. Heating the materials from room temperature $22\text{--}24^\circ\text{C}$ until their phase state changes (to about $75\text{--}80^\circ\text{C}$). Their physical state will be monitored and their temperatures recorded at regular intervals, recorded using a stopwatch.
2. Non-invasive (without intervention) cooling of the materials to convert them to their original physical state. Again, their physical state will be monitored and their

temperatures recorded at regular intervals of time, detected by a stopwatch.

3. In addition to the heating and cooling processes (50-100 cycles expected), the development of corrosion in a metal element will be observed under a microscope to determine the interaction of materials with the surrounding systems in the heating container. Corrosion in such vessels is extremely dangerous because it can lead to the malfunction of the entire system. For this reason, techniques for preventing corrosion should be selected during the production of the product. This improves its life cycle and safety, [10].

4. Conclusion

In the search of intelligent solutions for water heating, one of the modern solutions stands out - the use of phase changing materials. In order to develop a water heating system with an integrated phase-change material to increase energy efficiency, the properties and behavior of the material must be studied in an environment resembling the real one. Through solid theoretical preparation and a number of experiments, conclusions will be drawn about the possibilities of using paraffin, $\text{NaCH}_3\text{COO} \cdot 3\text{H}_2\text{O}$ and $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$. According to the results obtained, these experiments will show which of these materials will be most suitable for incorporation into a water heating system. Such a system, especially connected to a renewable energy source, would be extremely energy-efficient, since the PCM helps retain heat and thus the consumption of heating energy would decrease. The future of water heaters undoubtedly includes the use PCM, which requires their experimental study to obtain reliable results.

Acknowledgment

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Study on patterns in electron beam lithography for sub-micrometer line gratings

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Abstract: This work presents a combined experimental and simulation study of resist profile evolution in electron beam lithography (EBL) using poly(methyl methacrylate) (PMMA) resist. The influence of key process parameters, including exposure dose, electron beam energy, and resist thickness on the resist profile formation, sidewall shape, and feature fidelity is systematically investigated. Particular attention is given to proximity effects caused by forward and backscattered electrons, which lead to dose redistribution and profile distortions. Experimental results show a strong dependence of PMMA resist profiles on lithographic conditions, affecting sidewall angle and linewidth variation. Bilayer PMMA systems are also examined to evaluate improvements in profile control and undercut formation for lift-off processes. Simulation of resist development is employed to model resist profile evolution and predict structural changes under varying conditions. The comparison between experimental and simulated results demonstrates good agreement, confirming the validity of the modeling approach. The study provides deeper insight into PMMA resist behavior and supports optimization of EBL process parameters for improved nanoscale patterning accuracy.

Keywords: ELECTRON BEAM LITHOGRAPHY, RESIST PROFILE, PMMA RESIST

1. Introduction

Electron beam lithography (EBL) is a key nanofabrication technique enabling high-resolution patterning for micro- and nanoscale device fabrication. The final pattern quality is strongly governed by resist profile evolution during exposure and development, which determines critical dimensions, sidewall geometry, and overall fidelity.

Resist profile formation depends on multiple process parameters, including exposure dose, accelerating voltage, resist thickness, and development conditions. In commonly used resists such as poly(methyl methacrylate) (PMMA), systematic studies have shown a strong dependence of resist profile and proximity effects on lithographic parameters [1]. Further investigations confirm that both exposure dose and resist thickness significantly influence sidewall shape evolution [2].

A major limitation in EBL is the proximity effect caused by forward and backscattered electrons, which leads to undesired exposure in adjacent regions. This effect is strongly influenced by substrate and resist material properties, as demonstrated in studies of HSQ resist on TiO₂ thin films [3]. Similar sensitivity to process conditions has been reported for negative-tone resists such as AR-N 7520, where optimization of lithographic parameters is essential for improving pattern fidelity [4, 5]. Comparative analyses of different negative resists further highlight variations in resist behavior depending on material composition and processing conditions [6].

Multilayer resist systems, including bilayer and trilayer configurations, have been introduced to improve process flexibility and profile control. PMMA-based multilayers on SiO₂/Si substrates enable improved undercut formation and are widely used in lift-off processes. Their effectiveness has been demonstrated in trilayer system studies [7] and detailed bilayer investigations under varying exposure conditions [8].

Despite extensive experimental progress, accurate prediction of resist profile evolution remains challenging due to the coupled effects of scattering, material response, and process parameters. Therefore, integrating experimental analysis with simulation is essential for deeper understanding and process optimization.

This work presents a combined experimental and simulation study of resist profile evolution in EBL, focusing on the influence of key lithographic parameters and their correlation with profile formation mechanisms.

The goal of this work was to optimize EBL process parameters for the fabrication of diffraction line gratings with periods of 600–800 nm for applications in optoelectronics, particularly in devices where light interacts with electronic or photonic systems, including optical sensors, spectrometers, laser systems, photonic integrated circuits, fiber-optic communication, and others.

2. Experimental Part

Electron beam lithography (EBL) was performed using a ZBA21 (Vistec Electron Beam, Jena) system at an acceleration voltage of 20 keV. The electron beam was defined as a rectangular, variably shaped beam cross-section with a homogeneous electron energy distribution (tolerance 10%). For line grating exposure, a nominal shot size of 100 × 3000 nm² was used to provide geometric proximity effect correction, with the aim of achieving a final line grating with a 500/500 nm line/space ratio.

The beam current density was set to 800 μA/cm², ensuring a balance between exposure speed and resolution. A bilayer resist system based on poly(methyl methacrylate) (PMMA) was employed to facilitate high-resolution pattern transfer and appropriate lift-off behavior. The total resist thickness was 550 nm, consisting of a 100 nm layer of 950 PMMA A2 (top layer) and a 450 nm layer of 495 PMMA A6 (bottom layer).

The PMMA bilayer was spin-coated onto a substrate composed of 100 nm thermally grown SiO₂ on a 350 μm Si wafer, providing a mechanically stable and electrically insulating platform suitable for microelectronic device fabrication. The PMMA bilayer consists of 495 PMMA A6 (Kayaku) thin film with the thickness of 450 nm (bottom layer) and 950 PMMA A2 (Kayaku) with the thickness of 100 nm (top layer). Both thin films were separately prebaked at 170°C on a hot plate for 5 minutes. The resist thickness was measured using the profilometer Alphastep.

Following exposure, the resist was developed in a solution of MIBK:IPA (1:3) for 60 seconds, followed by rinsing in isopropyl

alcohol (IPA) to terminate the development process and reduce residual swelling effects.

Test structures consisted of line gratings with line-to-space (L/S) ratios of 100/500 nm and 100/700 nm, designed to evaluate resolution limits, dose uniformity, and pattern fidelity under the selected lithographic conditions. The resulting patterns were subsequently observed and measured using scanning electron microscopy (SEM) FEG 250 (FEI, USA).

3. Results and Discussion

Optimization of exposure dose for line gratings with 600–800 nm period fabricated by EBL is one of the most critical process steps because the optical performance depends strongly on the final linewidth, duty cycle, and edge quality.

Key problems include proximity effect (PE), line edge roughness (LER), stitching errors, resist collapse, dose control sensitivity (dense gratings require very precise electron dose calibration), limited throughput (EBL is a serial writing technique so large-area gratings require long exposure times), charging effects on insulating substrates), development nonuniformity (resist development can vary across dense periodic structures), thermal and mechanical drift due to a long write times, and finally pattern fidelity transfer during etching (after EBL, the patterns are subsequently transferred into the substrate using reactive ion etching).

PE is caused by electron scattering within the resist and the substrate. Primary electrons generate backscattered electrons (from the substrate) and secondary electrons (from the resist), which lead to unintended exposure of nearby regions.

Partially, PE depends on beam energy (higher energy leads to larger backscattering range in substrate), resist thickness (thicker resist causes more forward scattering), substrate material (higher atomic number of substrates increase backscattering), and pattern density (dense periodic structures enhance cumulative exposure overlap). For dense gratings with 600–800 nm pitch, this can result in linewidth broadening and distortion of the resist profile, so proximity effect correction (PEC) is required.

Although using a variable-shaped beam (VSB) in electron beam lithography (EBL) increases the throughput of large-area line grating fabrication, it also introduces additional limitations when fabricating gratings with a 600–800 nm period. In our case, the ZBA21 equipment is characterized by a minimum beam size of approximately 100 nm and an electron energy of 20 keV. In this case, the dose optimization becomes especially sensitive due to forward scattering and proximity effects as the proximity effect typically extends over a lateral range on the order of a few micrometres ($\approx 1\text{--}5\ \mu\text{m}$) in many resist/substrate combinations, depending on material properties and substrate atomic number.

To optimize the EBL process parameters for the fabrication of line gratings with periods in the range of 600–800 nm, both geometrical and exposure dose corrections were employed. Initially, geometrical correction was established. For gratings with a period of 600 nm, L/S of 100/500 nm was defined, whereas for gratings with a period of 800 nm, a line-to-space ratio of 100/700 nm was used.

Subsequently, exposure dose correction was carried out using a standard dose test, in which the exposure dose was systematically varied within the range of 360–1560 $\mu\text{C}/\text{cm}^2$.

An important part of this work is the characterization of the PMMA resist sidewall shape. Resist linewidths were measured on PMMA resist bilayer cross-sections along the resist thickness at five different levels - at the resist thickness (L4), at 50 nm below the PMMA resist thickness (L3), at the middle of the resist thickness (L2), at 50 nm above the substrate (L1), and

at the substrate (L0), in order to obtain data for resist sidewall profile simulations.

In Figure 1 are compared sidewall shapes in case of 550 nm thin bilayer of PMMA for line dense grating: (a) L/S 100/500 nm and (b) L/S 100/700 at the same exposure dose 520 $\mu\text{C}/\text{cm}^2$.

The same comparison is shown for exposure dose 600 $\mu\text{C}/\text{cm}^2$, in Figure 2, and for exposure dose 760 $\mu\text{C}/\text{cm}^2$ in Figure 3.

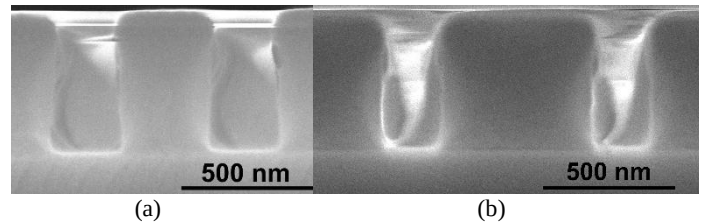


Fig. 1 Comparison of sidewall shapes in case of 550 nm thin bilayer of PMMA at the same exposure dose 520 $\mu\text{C}/\text{cm}^2$ for line grating: (a) L/S 100/500 nm and (b) L/S 100/700.

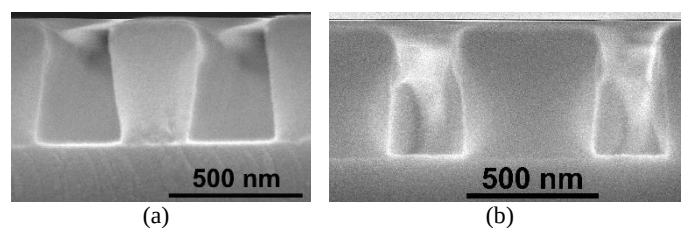


Fig. 2 Comparison of sidewall shapes in case of 550 nm thin bilayer of PMMA at the same exposure dose 600 $\mu\text{C}/\text{cm}^2$ for line grating: (a) L/S 100/500 nm and (b) L/S 100/700.

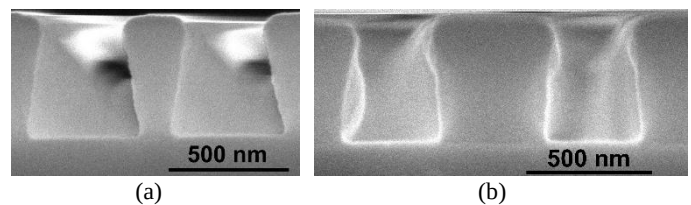


Fig. 3 Comparison of sidewall shapes in case of 550 nm thin bilayer of PMMA at the same exposure dose 760 $\mu\text{C}/\text{cm}^2$ for line grating: (a) L/S 100/500 nm and (b) L/S 100/700.

The comparison of sidewall profiles in 550 nm thin PMMA bilayers reveals a strong dependence of pattern fidelity on both exposure dose and line-to-space ratio.

The results demonstrate that exposure dose plays a critical role in defining the balance between resolution and profile quality in PMMA based EBL. The optimal process window for the investigated systems is observed around 500 - 600 $\mu\text{C}/\text{cm}^2$, where sufficient resist contrast is achieved while minimizing both underexposure and overexposure effects. Furthermore, pattern density strongly influences sensitivity to proximity effects, with denser gratings consistently exhibiting greater sidewall distortion across all exposure conditions. These findings indicate the importance of dose optimization in conjunction with proximity correction, which depends on the geometric arrangement of the lines, to achieve a highly accurate line grating.

4. Simulation results

The profile linewidth (LW) values of the images after resist development were measured at five levels along the bilayer PMMA resist depth - at the resist thickness (L4), at 50 nm below the PMMA resist thickness (L3), at the middle of the resist thickness (L2), at 50 nm above the substrate (L1), and at the substrate (L0), respectively (Figure 4).

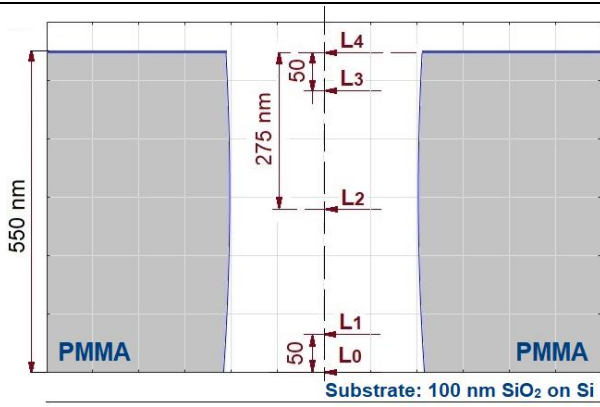


Fig 4. Details of profile measurement in the case of developed line grating (L/S 100/700) in bilayer PMMA resists.

Based on profile measured data for the developed line grating test structures L/S 100/500 and L/S 100/700 in bilayer PMMA resists with thickness of 550 nm for exposure doses in the range of $440 \mu\text{C}/\text{cm}^2$ to $1240 \mu\text{C}/\text{cm}^2$, a simulation study on the line grating resist profiles and optimization procedure are performed and results are discussed. The applied modeling approach (statistical approach) [9] and its application enable a more precise determination of the EBL parameters (such as an exposure dose D , resist thickness, acceleration voltage, pattern dimensions, etc.) on the quality of the obtained developed images in the studied structures as well as to access the relations between lithography process parameters and the shape (geometry) of the studied resist images. The proposed optimization procedure makes it possible to formulate recommendations regarding the controlled EBL process parameters for obtaining vertical profile side walls.

The applied statistical approach [9] is programmed and corresponding equations (1) and (2) for both grating test structures and data of practical importance for the geometry characteristics of the developed profiles in the studied resists structures are obtained and they determine the shapes of the resist images which are important for the quality of the obtained structures. According to the values of the determination coefficients R^2 (around 92%), a good correspondence between experimental data and calculated by the model equations (1) and (2): Y_{hlw1} - half profile linewidth for L/S 100/500 nm, Y_{hlw2} - half profile linewidth for L/S 100/700 nm is seen:

$$(1) Y_{\text{hlw1}} = 147.3 + 54.8x_1 - 11.53x_2 - 20.24x_1x_2 + 12.23x_1x_1x_2$$

$$(2) Y_{\text{hlw2}} = 194.18 + 70.12x_3 - 14.78x_4 - 15.77x_3x_3 - 23.04x_3x_4$$

where x_1 is the dose of exposure and x_2 – the resist thickness coded parameters for L/S 100/500 [9], and x_3 and x_4 are the same parameters for the case of L/S 100/700, correspondingly.

To obtain profiles with vertical side walls in the investigated bilayer resists system, the following optimization criterion is proposed: $d = \text{LW}(L_3) - \text{LW}(L_0)$, where $\text{LW}(L_3)$ and $\text{LW}(L_0)$ are the profile line width at the resist levels L_3 and L_0 (Figure 4), respectively. Evaluated equations (based on the experimental data) for the proposed criterion as functions of the exposure dose for line gratings in PMMA bilayer resists were obtained. The values of the coefficients of determination are around 99% for both studied structures, which indicate that the models exhibit minimal errors. Figure 5 shows the dependences of the values of d on the dose of exposure for the studied gratings L/S 100/500 nm and L/S 100/700 nm. The optimal EBL process modes according to the optimization criterion d are reached for the exposure doses (D) for which $d=0$ and the values are: $D_{\text{opt},1} = 504 \mu\text{C}/\text{cm}^2$ for L/S 100/500 nm and $D_{\text{opt},2} = 613 \mu\text{C}/\text{cm}^2$ for L/S 100/700 nm, respectively.

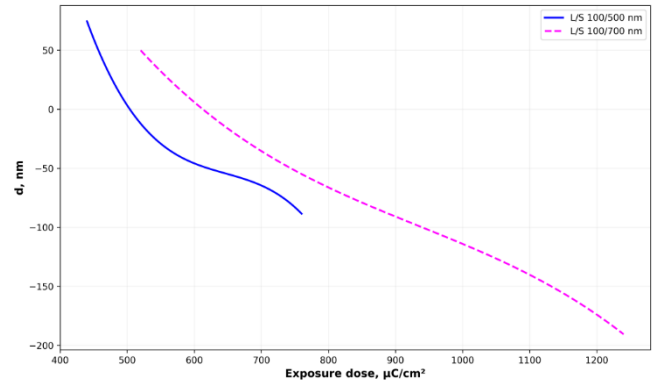


Fig. 5. Dependence of the value of the criterion d on the exposure dose for the grating test structures L/S 100/500 nm and L/S 100/700 nm in bilayer PMMA resists.

Figure 6 presents the simulated optimal developed profiles (with near to vertical sidewalls) in the studied PMMA bilayer resists systems for the corresponding exposure doses according to the optimization criterion d .

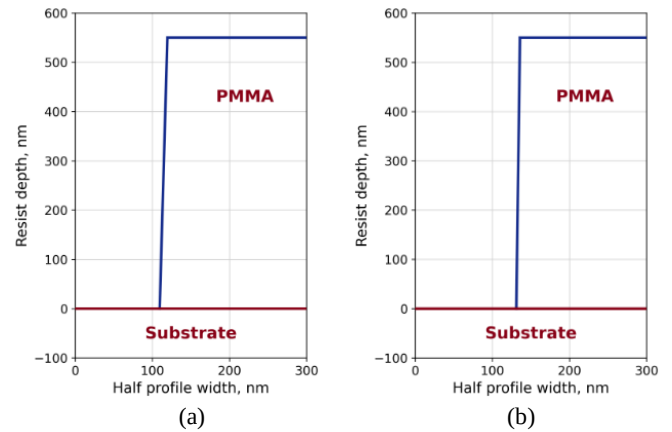


Fig. 6. Optimal developed half line profile in the bilayer PMMA for: (a) $D = 504 \mu\text{C}/\text{cm}^2$ for L/S 100/500 nm, (b) $D = 613 \mu\text{C}/\text{cm}^2$ for L/S 100/700 nm.

Figure 7 presents a comparison between experimental profiles and simulated ones in the studied line gratings L/S 100/500 nm and L/S 100/700 nm in the bilayer PMMA for $600 \mu\text{C}/\text{cm}^2$ dose of exposure. The results show a very good agreement between the experimental and model developed profiles for both cases. The results also demonstrate that reduced line spacing significantly enhances proximity effects, leading to increased distortion of the resist profile.

5. Conclusions

Accurate modeling of resist profile shape is essential for optimizing e-beam lithography processes, especially for submicron grating structures, where proximity effects and the development process strongly influence the fidelity of the resulting pattern. This work presents experimental and simulation results for resist profile formation for periodic line gratings with line/space dimensions of 100/700 nm and 100/500 nm. The applied developed simulation approach is based on experimentally measured linewidths along the resist profile under varying exposure doses. The optimal process window for the investigated patterns is around $500\text{--}600 \mu\text{C}/\text{cm}^2$. The results demonstrate that reduced line spacing significantly enhances proximity effects, leading to increased distortion of the resist profile. Incorporating experimental linewidth measurements enables more accurate process modeling and improved optimization

of nanoscale EBL patterning for advanced nanofabrication applications.

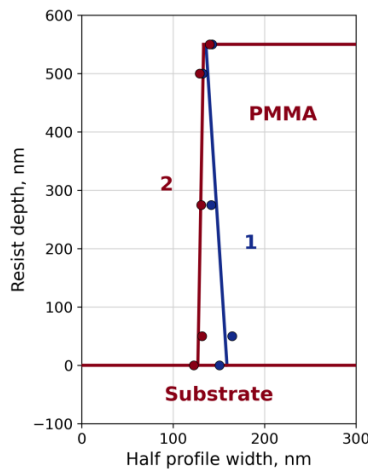


Fig. 7. Comparison between half profiles developed for line grating L/S 100/500 nm (line 1) and line grating L/S 100/700 nm (line 2) in the bilayer PMMA resists with 550 nm thicknesses for the exposure dose of $600 \mu\text{C}/\text{cm}^2$; experimental data (●) and simulated (solid lines).

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Synthesis of polyphase materials containing pseudowollastonite

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Abstract: Based on waste biogenic calcium carbonate CaCO_3 and silicon dioxide SiO_2 , polyphase materials with a predominant content of calcium silicate phases and a limited presence of silicon dioxide were synthesized in laboratory conditions. When preparing the experimental samples, solid-phase synthesis and thermal treatment modes with a maximum temperature of up to 1300°C were used. During the X-ray phase analysis of the obtained experimental samples, the presence of $\text{Ca}_3(\text{SiO}_3)_2$ pseudowollastonite (dominant phase) was registered, $\beta\text{-Ca}_2\text{SiO}_4$ and SiO_2 cristobalite. The main possibilities for further expedient modification of the used technological regimes are analyzed. The prospects for potential application of the synthesized phases for the preparation of various functional materials are considered. The study is consistent with modern trends in the use of technological approaches that allow the utilization of waste materials.

Keywords: CALCIUM SILICATE MATERIALS, PSEUDOWOLLASTONITE, DICALCIUM ORTHOSILICATE

1. Introduction

A main direction in the development of modern materials science is the study of phase formation in various oxide systems in a wide concentration and temperature range [1]. Based on the established processes of phase formation, appropriate technological approaches have been developed for obtaining materials with different structural and operational characteristics [2-4].

Modern silicate technologies allow the production of a current assortment of traditional, standard and innovative products with successful market realization [5-9]. Industrial enterprises equipped with specialized facilities (tailored to the specifics of the technological methods used) have been built, ensuring the implementation of cost-effective production processes and obtaining materials with a certain phase composition and appropriate functionality [10,11].

In this aspect, calcium silicates are considered a particularly promising group of materials, for the production of which various technological methods have been developed [12,13]: high-temperature solid-phase synthesis, hydrothermal synthesis, sol-gel synthesis, precipitation and others. Materials obtained through high-temperature synthesis are characterized by a more distinct crystal structure and lower porosity when compared to products prepared through other technological methods (e.g. hydrothermal synthesis).

Calcium silicate materials combine a number of favorable characteristics [12-18]: good mechanical resistance, thermal insulation properties, moisture resistance, fire resistance, non-flammability, workability, relatively low weight, biocompatibility, recyclability, environmental friendliness, durability and a long service life.

Tricalcium silicate Ca_3SiO_5 (alite, $3\text{CaO} \cdot \text{SiO}_2$ or C_3S according to CCN) and dicalcium orthosilicate $\beta\text{-Ca}_2\text{SiO}_4$ (belite, $2\text{CaO} \cdot \text{SiO}_2$ or C_2S according to CCN) represent a significant part of the phase composition of Portland cement clinker and significantly determine its characteristics [19]. As functional fillers, calcium silicate phases are present in various product categories (plastics, rubber, paints, paper, etc.) [12]. Various modifications of calcium silicate biomaterials have been developed for use in implantology and dentistry [20]. Dicalcium orthosilicate (Ca_2SiO_4) is applicable in the food industry as an anti-caking agent [12].

Calcium silicate materials in the form of thermal insulation and refractory elements (plates, slabs, blocks and others) are found active use in modern residential, public and industrial construction [14-18]. The performance characteristics of the various products allow the implementation of modern energy-efficient and environmentally friendly design solutions with a high level of safety. A standard approach is the construction of long-lasting thermal insulation, interior partitions, suspended ceilings and other structural and decorative interior elements, as well as cladding of fireplaces, wet rooms and building facades [15-17]. Wollastonite (CaSiO_3) is a full-fledged, environmentally friendly and safe alternative substitute for asbestos materials [14,15].

Calcium silicate materials are used for the construction of various fire protection structures in the energy, metallurgical, chemical, silicate and oil refining industries and other manufacturing sectors. In this aspect, an effective solution is the construction of fire protection barriers and the lining of high-temperature industrial facilities, chimneys, pipelines, various industrial equipment, installations, doors, walls, ceilings, beams, columns, shafts and metal structures [12,15].

During their normal operation, the materials do not emit toxic products and limit the development of fungal cultures on the products.

The favorable performance characteristics of silicate products and their importance for various economic sectors are a prerequisite for the development of functional materials with the presence of silicate phases [15]. The synthesis of materials with a phase composition formed by the joint presence of various calcium silicate and other phases (combining their specific characteristics) allows the production of materials with diverse properties, adapted to specific application possibilities [21]. At the same time, a current environmental interest is the use of technological approaches that allow for the effective and cost-effective utilization of various waste raw materials, sustainable in the natural environment [22-25].

The main objective of the present work is to study the phase composition of experimental samples obtained by solid-phase synthesis based on waste biogenic carbonate raw material and silicon dioxide SiO_2 .

2. Experimental procedures

When preparing the experimental samples, standard laboratory equipment was used: a precision balance model RSV 200-2 KERN, a Sartorius MSU225P analytical balance, a scale up to 10 kg, a porcelain ball mill with a working volume of 50 L (rotation speed up to 260 rev/min) and a set of grinding bodies, an "Astel" laboratory dryer, a set of standard laboratory sieves, an agate mortar, corundum crucibles, laboratory glass baths and others.

The thermal treatment of the experimental compositions was carried out in a laboratory programmable muffle furnace (with Kanthal Super heating elements), equipped with an electronic programmer, allowing controlled change and maintenance of the temperature regime parameters: rate of temperature increase and decrease, isothermal holds, and others.

In the preparation of the batch compositions, waste biogenic calcium carbonate CaCO_3 and SiO_2 (Fused silica, Dupre Minerals Limited) were used. As a promising raw material for introducing CaO into the reaction system, waste shells (from marine organisms) formed from calcium carbonate CaCO_3 were used. The provided amount of waste shells was subjected to mechanical processing by primary crushing and wet grinding for 24 h and drying treatment (at 90°C for 3 h).

The required quantities of the obtained fraction CaCO_3 (after grinding) and SiO_2 were weighed, mixed and subjected to joint wet grinding in a laboratory mill (for 3 h). After completion of the

milling process, the compositions were dried (at 90°C for 3 h), finally homogenized in an agate mortar and sieved (through a 0.315 mm sieve) to a suitable fractional composition. The prepared batch compositions were placed in corundum crucibles (in an amount of 15 g) and introduced into the working space of the furnace before the start of the thermal treatment.

The thermal treatment of the compositions was carried out in an air environment by applying two temperature regimes with three isothermal holds and different maximum temperatures:

- first temperature regime 900°C (30 min), 950°C (30 min) and maximum temperature 1250°C (1 h);
- second temperature mode 900°C (30 min), 950°C (30 min) and maximum temperature 1300°C (1 h).

After completion of the heat treatment, the samples were subjected to free cooling (in the furnace space) to room temperature.

The experimental samples were studied with a PANalytical Aeris X-ray diffractometer with Cu-K α radiation ($\lambda=1.5406\text{\AA}$) and θ - θ Bragg-Brentano geometry. The initial X-ray diffraction patterns were obtained at room temperature, constant scanning speed and reflection angle 2θ in the range 7-90° with a step of 0.02°. The obtained diffractograms were interpreted using the PDF 2-2022 database, ICDD.

An Epsilon 1 spectrometer (Panalytical) with an Ag X-ray tube at a voltage of 50 kV and a maximum power of 10 W was used to determine the elemental composition.

3. Results and Discussion

Based on waste biogenic calcium carbonate CaCO₃ and SiO₂, polyphase materials with a predominant content of calcium silicate phases and a limited presence of silicon dioxide were obtained in laboratory conditions. In preparing the experimental samples, solid-phase synthesis was used, carried out through two heat treatment regimes, characterized by the application of two intermediate isothermal holds (at 900°C for 30 min and 950°C for 30 min), but with different maximum final temperatures at 1250°C and 1300°C for 1 h (Figure 1).

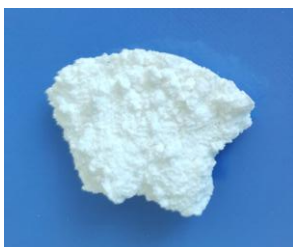


Fig 1. Fragment of an experimental sample, obtained at a maximum temperature of 1300°C.

The X-ray phase analysis (Figure 2) revealed the presence of Ca₃(SiO₃)₃ pseudowollastonite (PDF 01-089-6485), β -Ca₂SiO₄ (PDF 01-077-0388) and SiO₂ cristobalite (PDF 01-076-0939).

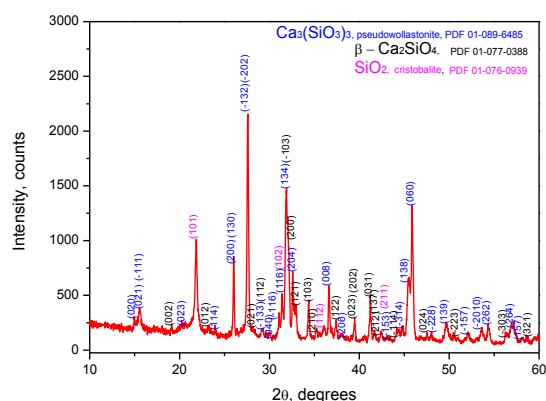


Fig 2. X-ray phase analysis of an experimental sample, obtained at a maximum temperature of 1300°C.

The oxide content of the experimental samples was determined (Table 1). The obtained samples showed the presence of oxide impurities in different concentrations (Al₂O₃-1.988%, TiO₂-0.098%, V₂O₅-0.053%, Fe₂O₃-0.071%, SrO-0.248%), which is interpreted as a consequence of the use of waste biogenic raw material and the specificity of the material of the laboratory crucibles used.

Table 1. Oxide content determined.

Oxides	Concentration, %
Al ₂ O ₃	1.988
SiO ₂	44.950
CaO	52.591
TiO ₂	0.098
V ₂ O ₅	0.053
Fe ₂ O ₃	0.071
SrO	0.248

The applied technological approach allows the use of the main capabilities of classical solid-phase synthesis and successful recycling of naturally sustainable waste materials of biogenic origin.

The existing possibilities for potential application of the synthesized polyphase material are determined by the specific characteristics of the established phase composition.

A suitable prospective direction is the use of the material as a full-fledged filler in combination with various polymer compositions or binders.

Compositions prepared on the basis of the synthesized polyphase material and additionally introduced plastic clays allow the molding of blanks with a variety of geometries. The preparation of durable samples is carried out after drying and final high-temperature thermal treatment (according to a developed regime) of the materials.

The considered technological scheme is applicable for obtaining cladding elements, profiles and other products with specific functional characteristics potentially applicable in construction and other technical fields.

The obtained experimental results are a prerequisite for optimizing the used technological regimes and further development of an additional series of compositions. The main technological direction is the implementation of synthesis at lower temperature values and the production of materials with modified polyphase or monophase composition (for a specific target need).

Appropriate technological modifications include the application of mechanochemical activation of the compositions, limited introduction of additional components, modifiers and appropriate technological additives.

At the same time, the introduction of SiO₂ (into the compositions) via a suitable waste raw material (with significant economic importance) is considered a feasible option. This allows the use of a cost-effective and environmentally friendly technological approach based on two waste raw materials, applicable for the introduction of the two oxide components into the compositions.

4. Conclusions

In a summarized form, some of the prevailing trends and prospects regarding the main areas of application of calcium silicate materials are discussed.

Based on waste biogenic CaCO₃ and SiO₂, polyphase materials with a dominant presence of calcium silicate phases and a negligible content of silicon dioxide were obtained.

The experimental samples were prepared in laboratory conditions by classical solid-phase synthesis under thermal treatment regimes up to 1300°C and isothermal retention of 1 h. The approach used allows for effective and cost-effective utilization of waste raw material, stable in the natural environment.

The X-ray phase analysis of the obtained samples demonstrated the presence of $\text{Ca}_3(\text{SiO}_3)_3$ pseudowollastonite (dominant phase), $\beta\text{-Ca}_2\text{SiO}_4$ and SiO_2 (cristobalite).

The presence of impurities (in concentrations from 0.053 to 1.988%) was found in the samples studied, which is due to the use of biogenic waste raw material and the material of the crucibles used.

The recorded phase composition is a fundamental prerequisite for specifying the prospects for potential application of the obtained material. The technological possibilities for the preparation of various products with specific functional characteristics have been analyzed.

Some of the existing opportunities for optimizing the conditions of the technological regimes have been examined, in accordance with certain further priorities.

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Monitoring the production process in production organization

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Abstract: The article deals with the assessment of the suitability of the manufacturing process and the analysis of the gear runout. The measurements were carried out using the 3D measuring device Wenzel WGT 280. The Palstat CAQ software was used to evaluate the process, while control charts for individual values and the sliding range were applied. The average value of the process reached 0.1460 and the sliding range was 0.00409. The suitability of the process was assessed using the Cp and Cpk indices with a required value ≥ 1.33 , while the calculated values were 1.47 and 1.34. The results confirm that the monitored process is suitable. Subsequently, a comparison of the runout before and after heat treatment - nitriding was performed. The specified tolerance limits (0 μm to 0.0320 μm) were not exceeded, which confirmed the satisfactory state of the process even after the treatment.

Keywords: QUALITY, PRODUCTION PROCESS, CONTROL DIAGRAMS

1. Introduction

The approach to managing an organization is no longer just a competitive advantage, but also one of the conditions for certification. The competitive environment leads organizations to deal with their processes and look for opportunities to improve them. [12] The power of the customer has increased the importance of marketing specialists who study the market and look for new forms of competition. Price is no longer the only decisive factor. It is precisely due to the influence of the competitive environment that the problem of insufficient adaptability of companies with a traditional organizational structure has become apparent. Process organizations with effectively functioning quality management are able to respond quickly to changes and maintain or improve their position in the market. [1] However, not only the ability to respond quickly to changes, but also the willingness to accept change as an everyday part of the organization's life is a key factor in success. [4] Just as product development time is constantly shortening and it is necessary to constantly seek new improvements and innovations, an organization must, if it wants to be successful, take this attitude not only to its products, but also to its processes. Appropriately selected monitoring and measurement of processes will reveal weaknesses in the organization, which are also opportunities for process improvement. [11] The quality system is primarily about continuous improvement of everything that happens in the organization and therefore affects practically all company processes. Improvement is a de facto necessity for organizations operating on the market. [7] Whoever stops improving will be overcome by the competition. Quality management and improvement are therefore a key and natural part of the normal management of successful organizations. [6]

We focused on the gear manufacturing process and the measurement of gear runout on the Wenzel WGT 280 3D measuring stand. [3] We will evaluate the suitability of the manufacturing process using the Palstat CAQ software. Control is used in cases where it is not possible to create logical subgroups. [2] Finally, we will compare the gear runout before and after heat treatment - nitriding at an external supplier, how large the deformations were there and whether the prescribed tolerance value was observed.

There are various suitable methods for this type of quality improvement in organizations, and it is up to them which method to use in improving quality in their conditions. [10]

Nowadays, product quality is constantly improving, so it is more than necessary for organizations to place high emphasis on quality management and monitoring. It is imperative to ensure that the products are of the highest quality. This is what the competitiveness of the organization and its survival in the constantly changing market are built on. [5] The introduction of statistical methods is an important tool for organizations to control the state of processes, which helps to correct and improve the final

products. Therefore, in my diploma thesis, I decided to focus on the use of statistical methods in production processes. [8]

In the article, we focused on evaluating the capability of a selected production process using the Palstat CAQ software. Using the control diagram for individual values and sliding range and using capability indices, we determined whether the production process is capable. Finally, we compared the measured values of runout before and after heat treatment. [14]

2. Materials and Methods

Different types of gearing can be seen in mechanical engineering, automotive, aviation and other industries. The wide application of gears in mechanical engineering and in everyday use has led to the emergence of a large number of methods for producing gears. The production method and the technology used are chosen based on the requirements for gear accuracy.

In a manufacturing organization that produces gears, we selected 50 consecutively manufactured wheels per shift and focused on gear runout. The measurement was carried out on a Wenzel WGT 280 machine. From the measured values, we will determine the process capability and the sliding range in the Palstat CAQ software.

Subsequently, we will focus on comparing the gear runout Fr. We compare the measured values after production with the values measured after heat treatment (nitriding). The measurement will be carried out on the same Wenzel WGT 280 measuring machine at the input inspection. We will compare the differences between the measured values and make the average change in the runout Fr of the gears. The component is made of ETG 88 – 44SMn28(1.0762) material with a diameter of 100 mm. This steel grade generally shows relatively good machinability on machine tools. Gear milling (Fig. 2) on a Liebherr LC 180 milling machine (Fig. 1) using the rolling method.



Fig. 1 Liebherr LC 180 milling cutter

Hobbing is the most common method of gear production. This method uses hobbing cutters, which are cylindrical shaped cutters that represent a worm that meshes with machined gear. The spiral of the worm is interrupted around the circumference by milled grooves that create the front surfaces of the tooth edges.



Fig. 2 Part after milling

Performing an input inspection of gear deformation on a Wenzel WGT 280 machine.

The Wenzel WGT280 (Fig. 3) is a 3D measuring device designed for gear measurement. It offers a higher measurement speed and therefore more efficient inspection from small to large wheels. The software developed for this device provides optimal 4-axis inspection and high measurement performance. The measuring device is equipped with modular software packages.



Fig. 3 3D measuring machine Wenzel WGT 280

The monitored gear runout parameter (Tab. 1) Fr has a tolerance value from 0 μm to 0.0320 μm .

Palstat CAQ Software Palstat CAQ and the modules it consists of are computer software used to support quality management. Palstat CAQ information software fully covers the requirements of ISO 9001, ISO/TS 16949 and also the requirements of VDA (Čablová 2013). The software was created based on the optimization and increase of the performance of the quality management system. Its main task is the regulation of variable quality characteristics with normal distribution. Production process control and statistical analysis follow each other and stabilize the production process in three steps:

- determine the instability of the production process,
- bring the production process from an unstable to a stable state,
- try to maintain the process in a stable state

Quality monitoring:

- Supplier evaluation – monitoring their performance,
- Monitoring, measurement of production processes – SPC – statistical process control,
- Monitoring, measurement of parts / products, dimensional control and functional tests,
- Incoming inspection – parts and products,
- SQC – production control,
- Inter-operational inspections of parts / products,
- Output inspection – parts and products.

Tab.

Mating gear: BM1-6 / Center distance a = 35,00 mm		
Description	Symbol	Finish hobbing
Tip diameter [mm]	d_s	63,03-0,02
Root diameter [mm]	d_r	59,77
Module [mm]	m_s	0,65
No. of teeth	z	84
Theoretical profile shift factor (zero backlash)	x	+0,05832
Pressure angle [°]	α	20°
Helix angle [°]	β	27° R
Tooth length [mm]	b	9,00
Chordal dimension over two teeth		
Chordal dimension over two teeth min [mm]	$W_{s \min}$	24,9935
Chordal dimension over two teeth max [mm]	$W_{s \max}$	25,0171
No. of teeth for span measurement	Z_{me8}	13
Diametral dimension over balls		
Diametral dimension over balls min [mm]	$Mdk \min$	62,6276
Diametral dimension over balls max [mm]	$Mdk \max$	62,6945
Ball diameter [mm]	$\varnothing D_m$	1,10
Tip chamfer [mm]	h_k	0 ... 0,10
Tip relief [μm]	c_s	5 $\pm$ 2
Mesh distance [mm]	g_s	2,5829
Crowning [μm]	c_g	8 $\pm$ 2
DIN Quality		8
Gas nitrocarburisation depth [mm]	N_{ht}	0,25 ... 0,40
Compound layer thickness [μm]	VS	9 ... 12
Oxidisation layer thickness [μm]	OS	1 ... 1,50
Surface hardness [HV]		650 $\pm$ 50
Radial size of addendum reduction	h_a	0,455
Machining allowance [mm]	q	-

1

3. Results

Gears are among the most important machine components. As more and more high-speed and high-performance machines are used, which must have high efficiency and quiet operation, ever greater demands are placed on gears for accuracy. The demands placed on gears depend on the conditions and purpose of their use. Gears have different shapes and therefore it is necessary to use different types of measurements of individual quantities.

In terms of correct engagement and torque transmission, the gears that mesh together must meet the following conditions:

- Accuracy and correctness of the tooth thickness,
- Accuracy and correctness of the tooth shape and tooth surface quality
- Minimum runout.

A sample of 50 gears selected by us is measured on a Wenzel WGT280 3D measuring machine (Fig. 4). The basis for accurate measurement is the cleanliness of the machine and degreased, deburred gears (Fig. 5). The measured gears were stored at the measuring center for 24 hours at a temperature of 21°C to prevent the occurrence of factors affecting the measurement results.

Calibration of the measuring device consists of two parts:

- calibration of the diameter of the measuring contact,
- calibration of the axis of the device.

Starting the measurement program – the measuring probe finds a reference point and centers itself. The evaluation is determined on 4 teeth at 90° apart and evaluates the side and profile of the tooth from the measured values. It then measures the spacing of each tooth and evaluates the tooth runout based on the measured values.



Fig. 4 Calibrating the measuring probe

Mounting the measured gear into the fixture.

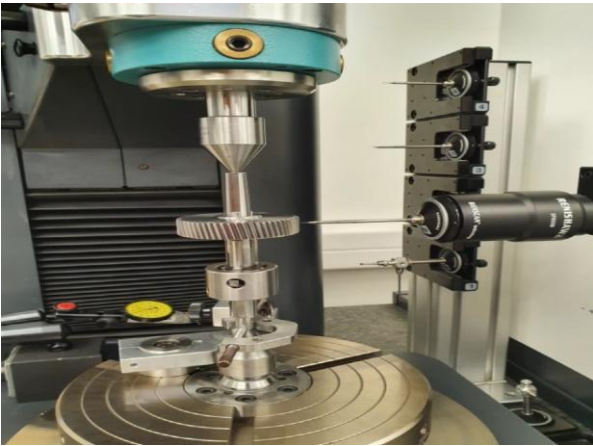
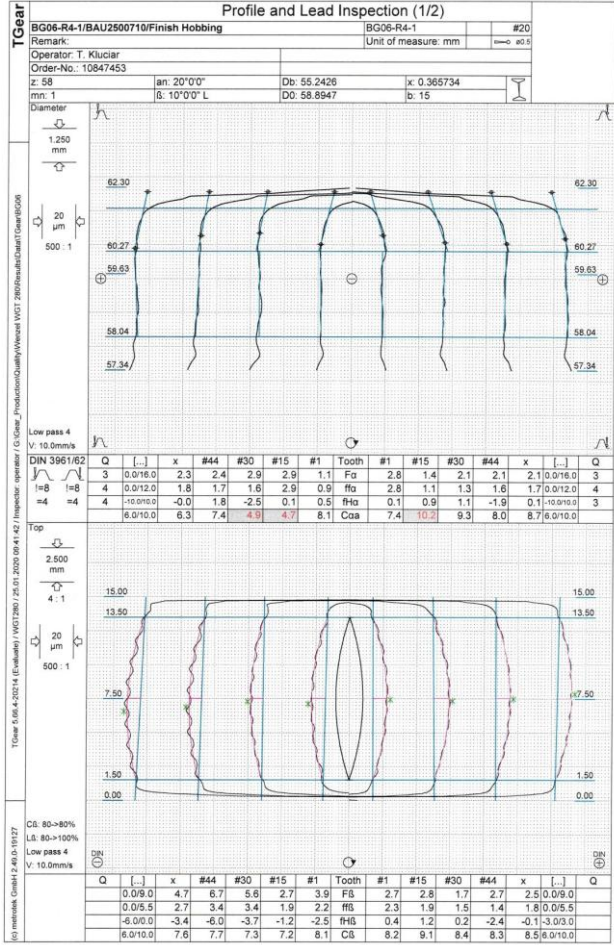
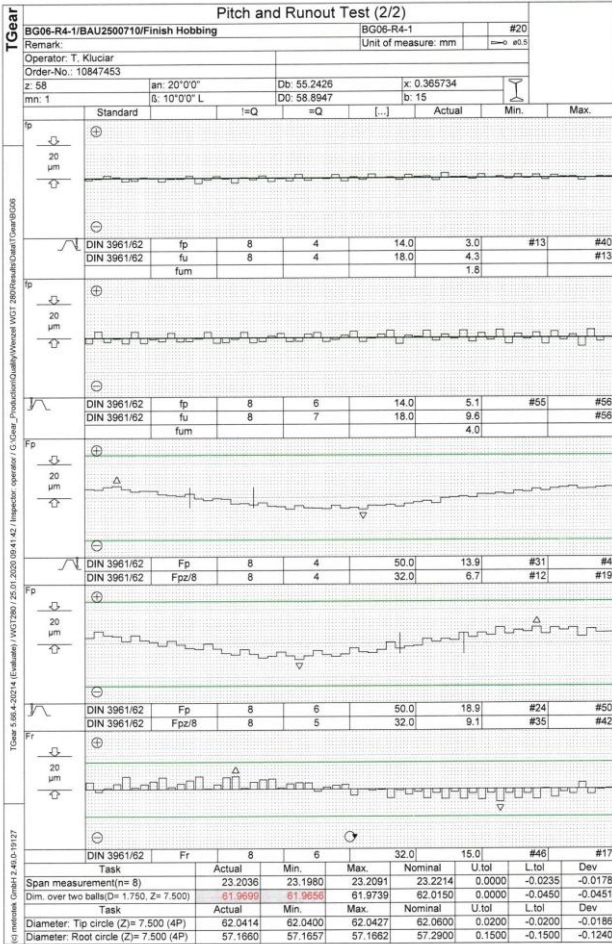


Fig. 5 Gear measurement

Tab. 2 Measurement report



The actual curves of the profiles are translated by theoretical curves and are projected into straight lines (Tab. 2). These curves should ideally be symmetrical. If they are not symmetrical, this is due to the angular deviation of the profile. In reality, care must be taken to ensure that their dispersion is as small and one-sided as possible.



Results from Palstat CAQ software

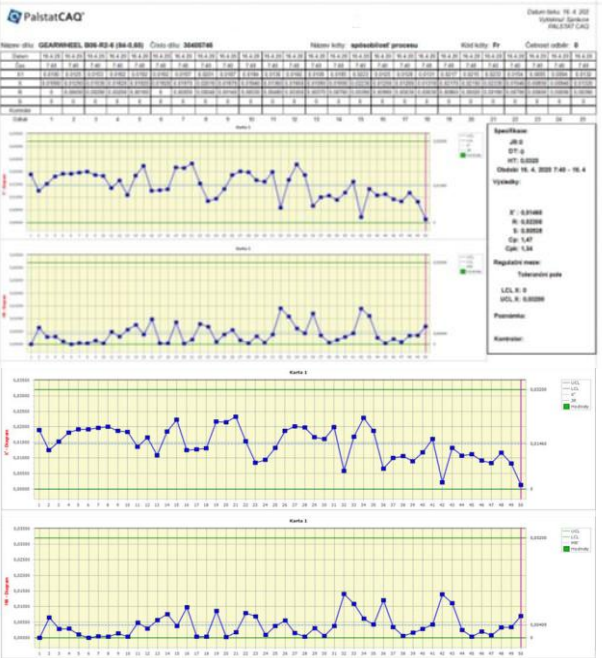


Fig. 6

Product quality depends on a properly set and statistically managed process. Certified organizations strive to create the most suitable conditions for managing their process, which includes all quality tools and methods.

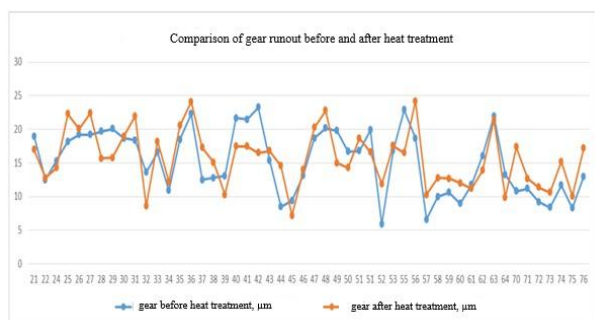


Fig. 7 Comparison of gear runout before and after heat treatment

The table we created shows the differences in the measured values of gear runout before and after heat treatment (Fig. 6). All values are in the given tolerance field from 0 μm to 0.0320 μm . When comparing, we can notice that not all values increased (Fig. 7), but in some cases we got below the basic value, which results in surface deformation during heat treatment in our case of nitriding.

In the presented article, we investigated the capability of the production process. We evaluated the control charts for individual values, sliding range and process capability indices. They showed us that the process is in a capable state. By introducing control charts to other production processes, the organization can reduce the number of non-conforming products to a minimum. By applying them and with the help of the developed methodology, they can identify definable causes, eliminate them from the process and minimize time and economic losses. Process capability verifications can be applied to almost any process, improving an organization's competitiveness.

4. Conclusion

A perfectly designed quality monitoring in the production process must be understood and controlled by employees, whose task is to know the goals and quality policy. Meeting these goals should be their priority in order to meet the demanding requirements of all customers. An organization that wants to progress should pay great attention to improving quality and proactively seek opportunities for its improvement. And that is why it is a never-ending process that includes not only employees, but also all activities and departments.

Measuring instruments have a leading position in the field of quality. It is very important that the values measured by the relevant devices correspond to reality even after a certain period of use of the measuring instrument. It is advisable for organizations to use adequate measuring instruments, appropriate measurement and monitoring methods, and also to use the necessary documentation. This consists of operational procedures that precisely indicate and standardize how it is necessary to proceed in the individual steps when performing a measuring operation.

Any deviation or inaccuracy from the required values can be detected by measuring products. Whether the product is satisfactory can then be determined according to the tolerances given. If it is not, it is necessary to suspend production and take the necessary measures so that customer satisfaction is not jeopardized.

In the article, we focused on the measurements of gears and their tooth runout. The runout of the tooth flanks results in uneven gearing, uneven engagement, noise and vibration of the system. Therefore, together with the quality requirements, zero or as little runout as possible is most appropriate. This deviation is caused by improper clamping of the workpiece during gearing or machine instability.

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Използване на MathCAD за решаване на проблеми из областта на земната механика и фундирането

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Резюме: В настоящия доклад се разглежда използването на MathCAD за решаване на задачи от областта на земната механика и фундирането. Добре известен факт е, че повечето задачи свързани със земната основа предлагат прилагането на сложни и дълги аналитични формули. Традиционно изчислителната тежест се редуцира за сметка използването на готови таблици и номограми. Този подход обаче не изглежда напълно естествен за 21 век. Настоящата разработка има за цел да покаже предимствата при използването на Системи за компютърна алгебра пред традиционно консервативните методи на използване на таблици и номограми.

Ключови думи: Системи за компютърна алгебра, математика, земна механика

Using MathCAD to solve problems in the field of soil mechanics and foundations

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Abstract: This paper discusses the use of Mathcad for solving problems in the field of soil mechanics and foundations. It is well known that most problems solved in soil mechanics offer very complex and long analytical solutions. Traditionally, the computational complexity is reduced by using tables and nomograms. However, this still traditional approach seems a bit unnatural for the 21st century. The present work aims to show some advantages of using Computer Algebra Systems over the traditional approach of using tables and nomograms.

Keywords: COMPUTER ALGEBRA SYSTEMS, MATHCAD, SOIL MECHANICS

1. Въведение

Настоящият доклад има за цел да демонстрира използването на системите за компютърна алгебра при решаване на проблеми из областта на земната механика и фундирането. В исторически план системите за компютърна алгебра (СКА) се разработват и използват от около четири десетилетия. Повечето от тях се използват широко в инженерната практика, заради широките им възможности както за числени така и за символни пресмятания и построяване на графики. Измежду множеството СКА за настоящата разработка е предпочетена системата MathCAD. Изборът ѝ е продиктуван от няколко обстоятелства. Първо MathCAD позволява въвеждането на формули така, както се пишат на хартия, използвайки стандартни математически символи. Освен това програмата предлага интуитивен интерфейс съчетан с големи изчислителни възможности.

Поради строежа и поведението на земната основа изчислителните формули използвани в земната механика често са доста сложни. Обикновено земния масив се разглежда, като еластично полупространство, което позволява прилагането на методите на теорията на еластичността. Много често за да се заобиколи изчислителната сложност се използват таблици и номограми. Този подход обаче вече не отговаря на съвременните тенденции. Бурното развитие на компютърната техника позволява бързото и точно изчисляването на много сложни аналитични изрази. Целта на настоящият доклад е да демонстрира точно тези възможности с конкретни примери на приложение.

2. Решение на конкретни задачи с MathCAD

Както вече бе споменато MathCAD може да се използва успешно в решаване на редица инженерни проблеми. В [1], [2] и [3] проследяваме използването на MathCAD за решаване на задачи от областта на земната механика и фундирането. По-общо приложение в инженерното обучение е разгледано в [4], [5], [7], [8], [9], [11]. В [12] и [14] се представя прилагането на други СКА и приложното програмиране на езици с общо предназначение в обучението по строително инженерство.

Решаването на конкретни практически инженерни проблеми се разглежда в [6] и [13]. Тук ще разгледаме по-конкретно възможностите за използването му в задачи свързани със земната механика и фундирането. Ще се спрем на няколко задачи за демонстрация на възможностите на СКА и в частност на MathCAD.

3.1. Определяне на напреженията в почвата

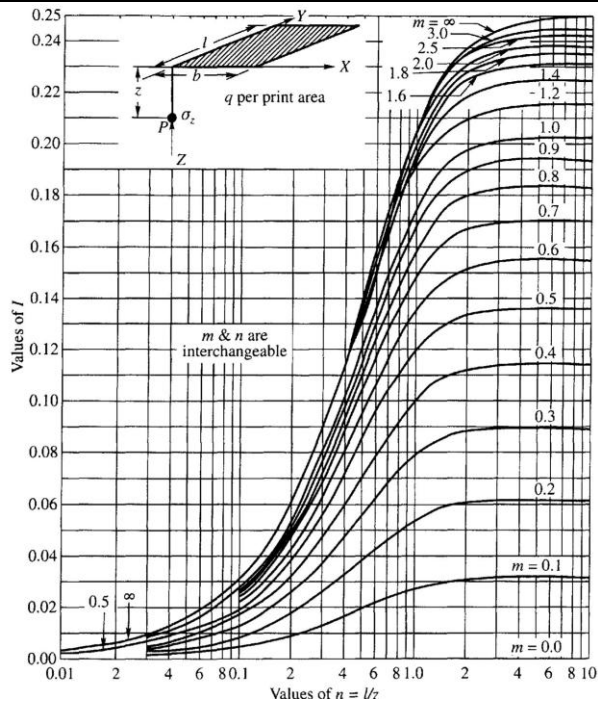
Една от задачите, които ще разгледаме е определянето на напреженията в почвите. Ще се спрем първо на определяне на напреженията в полупространството от съсредоточен в точка товар. Решението на тази задача е дадено за първи път от Boussinesq през 1885 г. Това е основна задача и служи за изходна точка при определяне на напреженията от различни по вид товари. В инженерната практика често се налага определянето на напреженията в почвата под действие на равномерно разпределен товар върху правоъгълна плоскост. Най-прости изрази за напреженията се получават, когато се разглеждат точки лежащи на вертикалата минаваща през ъглова точка. Обикновено се използва метода на Steinbrenner. На фиг 1 е представена диаграмата на Steinbrenner.

Изразът за напрежението, което основно ни интересува се дава с формулата:

$$(1) \sigma_z = \frac{q}{2\pi} \left[\frac{LBz(L^2 + B^2 + 2z^2)}{R(R^2 z^2 + L^2 B^2)} + \arctg \frac{LB}{zR} \right],$$

където q интензитета на равномерно разпределения товар, L и B са страните на правоъгълника, z е дълбочината на разглежданата точка, а $R = \sqrt{L^2 + B^2 + z^2}$.

Както се вижда от фиг.1 отчета по номограмата е свързан с наличието на известна неточност, а използването на формулата е свързано с разход на време за изчисление. Това може да се избегне успешно чрез използване на СКА. Освен това СКА предлага и възможности за параметрично изследване, които в случая биха били много удачни.



Фиг. 1 Диаграма на Steinbrenner

4.2. Определяне на земния натиск

Другата задача, която ще разгледаме е свързана с определянето на земен натиск. Ще се спрем на теорията на Coulomb и произлизащите от нея формули за коефициентите на активен и пасивен земен натиск. В съвременния си вид те са изведени от Muller-Breslau:

$$(2) K_a = \left[\frac{\frac{\sin(\theta - \varphi)}{\sin \theta}}{\sqrt{\sin(\theta + \delta) + \frac{\sqrt{\sin(\varphi + \delta) \sin(\varphi - \alpha)}}{\sin(\theta - \alpha)}}} \right]^2,$$

$$(3) K_p = \left[\frac{\frac{\sin(\theta + \varphi)}{\sin \theta}}{\sqrt{\sin(\theta - \delta) - \frac{\sqrt{\sin(\varphi + \delta) \sin(\varphi + \alpha)}}{\sin(\theta - \alpha)}}} \right]^2,$$

5.3. Задача за определяне на изчислителната носимоспособност на земната основа

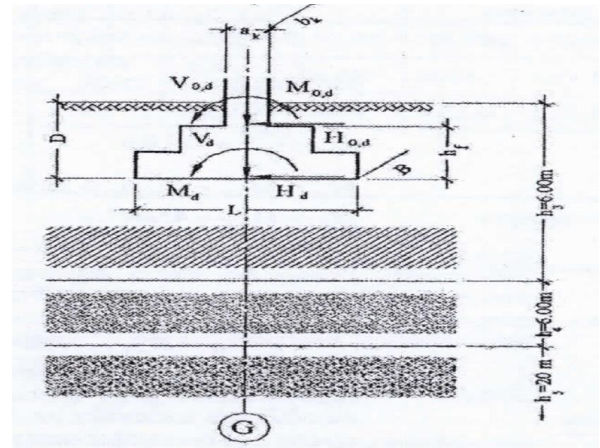
Проверка на носимоспособността на земната основа. Извършва се на база на следното неравенство:

$$(4) V_d \leq R_d,$$

където V_d е изчислителната стойност на вертикалната сила на нивото на основната плоскост на фундамента. Последната се получава по формулата:

$$(5) V_d = V_{0,d} + 0,85 \gamma_{b,d} LBD,$$

където V_d е изчислителната с $\gamma_{b,d}$ е означено осредненото обемно тегло на бетона на фундамента и обратната засипка. Останалите означения са дадени на фиг. 2. Последната е взимствана от [10], както и условието на решаваната по-долу задача. Част от нужните ни данни са представени в таблица 1.



Фиг. 2 Данни за геотехническо проектиране

Таблица. 1 Почвени показатели

Характеристична стойност	γ_M	Изчислителна стойност
III почвен пласт – плиоценска глина, номер на диаграма на слягане :10		
$\varphi_k = 21^\circ$	1.0	$\varphi_d = 21^\circ$
$c_k = 16 \text{ kN/m}^2$	1.0	$c_d = 16 \text{ kN/m}^2$
$\gamma_k = 16.9 \text{ kN/m}^3$	1.0	$\gamma_d = 16.9 \text{ kN/m}^3$
$w_l = 45\%, w_p = 25\%, w_u = 33\%$		
$e = 0.85$		

Изчислителната носимоспособност на земната основа се изчислява по:

$$(6) R_d = \frac{A'}{\gamma_{R,y}} \left(c N_{c s i b c} + q N_{q s i b q} + 0,5 \gamma B' N_{\gamma s i b \gamma} \right),$$

където:

$$A' = L' B'$$

$$L' = L - 2e_L$$

$$B' = B - 2e_B$$

$$N_q = e^{\pi \tan \varphi} \tan^2 \left(45^\circ + \frac{\varphi}{2} \right)$$

$$N_c = (N_q - 1) \tan \varphi$$

$$N_\gamma = 2(N_q - 1) \tan \varphi$$

$$s_q = 1 + \frac{B'}{L'} \sin \varphi$$

$$s_\gamma = 1 - 0,3 \frac{B'}{L'}$$

$$s_c = \frac{s_q N_q - 1}{N_q - 1}$$

$$i_c = i_q - \frac{1 - i_q}{N_c \tan \varphi}$$

$$i_q = \left[1 - \frac{H_d}{V_d + A' c \cot \varphi} \right]^m$$

$$i_\gamma = \left[1 - \frac{H_d}{V_d + A' c \cot \varphi} \right]^{m+1}$$

$$m = m_L = \frac{2 + \frac{L'}{B'}}{1 + \frac{L'}{B'}}$$

$$b_q = b_\gamma = (1 - \alpha \cdot \varphi \tan \varphi)^2$$

$$b_c = b_q - \frac{1 - b_q}{N_c \tan \varphi}$$

Въвеждането на формулите в MathCAD изисква спазването на определена последователност. Всяка използвана променлива трябва вече да е определена преди да се ползва в дадена изчислителна формула. Така например за да получим

$$i_c = i_q - \frac{1 - i_q}{N_c \tan \varphi}, \text{ трябва преди това да имаме пресметнато}$$

$$i_q = \left[1 - \frac{H_d}{V_d + A' c \cot \varphi} \right]^m.$$

Ще се спрем по-подробно на последната задача. За целта ще използваме една от решените в [10] задачи и ще сравним получените резултати. Схематично предста на фиг. 3 е представено част от решението на третата конкретно поставена задача.

$s_q := 1 + \frac{B'}{L'} \cdot \sin(\varphi)$	$s_q = 1.351$
$s_\gamma := 1 - 0.3 \cdot \frac{B'}{L'}$	$s_\gamma = 0.706$
$s_c := \frac{s_q \cdot N_q - 1}{N_q - 1}$	$s_c = 1.409$
$i_q := \left(1 - \frac{H_d}{V_d + A' \cdot c \cdot \cot(\varphi)} \right)^m$	$i_q = 0.951$
$i_c := i_q - \frac{1 - i_q}{N_c \cdot \tan(\varphi)}$	$i_c = 0.942$
$i_\gamma := \left(1 - \frac{H_d}{V_d + A' \cdot c \cdot \cot(\varphi)} \right)^{m+1}$	$i_\gamma = 0.919$

Фиг. 3 Решение с MathCAD

От фигурата е видно, че начина на записване максимално наподобява писането при „ръчни“ изчисления. Освен това последните версии на софтуера поддържат много добре кирилица и имат разширена функционалност за работа с текстови елементи. Това прави окончателното оформяне на проектната или учебна документация в един единствен документ с помощта на един единствен софтуер. На фиг. 4 са

представени, както възможностите за работа с текст, така и възможностите за писане на програмен код в MathCAD.

$$R_d := \frac{A'}{\gamma R} \cdot (c \cdot N_c \cdot s_c \cdot i_c \cdot b_c + q \cdot N_q \cdot s_q \cdot i_q \cdot b_q + 0.5 \cdot \gamma \cdot B' \cdot N_\gamma \cdot s_\gamma \cdot i_\gamma \cdot b_\gamma)$$

$$R_d = 1.82 \cdot 10^3$$

Проверка := if $R_d > V_d$

|| "плоският фундамент е осигурен на загуба на носимоспособност на земната основа"
 ||
 || "плоският фундамент не е осигурен на загуба на носимоспособност на земната основа"
 ||

Проверка = "плоският фундамент е осигурен на загуба на носимоспособност на земната основа"

Фиг. 4 Възможности за програмиране с MathCAD

Бихме могли да разширим обхвата на разглеждания проблем и с използване на богатия нагледен набор от графически възможности на програмата.

Сравнението на резултатите с [10], дава пълно съвпадение. Тук обаче изчисленията се извършват буквално за секунди и можем многократно да варираме с входните данни без да губим допълнително време за това.

3. Заключение

Предимството на използването на MathCAD е от една страна свързано с лесното провеждане на изчисленията, които биха отнели много време при извършването им с калкулатор. От друга страна можем да извършваме многократно решаването на еднотипни задачи при различни входни данни. И не на последно място бихме могли да използваме с незначителни изменения готовия MathCAD файл за изготвяне на проектна документация.

Освен при решаване на конкретни инженерни задачи СКА могат твърде успешно да се използват и като инструмент в професионалното обучение.

Друго голямо предимство на СКА е възможността за параметрично изследване на даден проблем, както и лесното изготвяне на графични презентационни материали.

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Preparation and investigation of zr–ti–sm–nd–al oxide coatings on glass via sol–gel method and dip-coating technique

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Abstract: In the present study, multicomponent Zr–Ti–Sm–Nd–Al oxide coatings were successfully synthesized via the sol–gel method and deposited on glass substrates using the dip-coating technique. The preparation procedure involved the formation of stable precursor sols and oxides based on zirconium, titanium, samarium, neodymium, and aluminum compounds, followed by controlled hydrolysis, aging, multilayer deposition, and thermal treatment at 430 °C. The obtained coatings were investigated with respect to their structural, compositional, and optical properties using X-ray diffraction (XRD), energy-dispersive X-ray fluorescence spectroscopy (XRF), and UV–VIS–NIR spectroscopy. The experimental results demonstrated the successful formation of uniform and transparent oxide layers with thicknesses ranging from approximately 39 to 57 nm, depending on the number of deposited layers. XRD analysis revealed the presence of nanocrystalline monoclinic ZrO₂ as the dominant crystalline phase, while no separate crystalline phases related to Ti, Sm, Nd, or Al oxides were detected, suggesting homogeneous incorporation of the dopants into the oxide matrix. Optical characterization showed high transmittance in the visible and near-infrared spectral regions, close to that of the untreated glass substrate, indicating the suitability of the coatings for optical and photovoltaic applications. The incorporation of rare-earth and aluminum-containing species contributes to improved structural stability and functional performance of the coatings. The obtained results confirm that the combined sol–gel and dip-coating approach is an effective route for the fabrication of multifunctional transparent oxide coatings with potential application as durable self-cleaning and protective layers for photovoltaic panels and related optical systems.

Keywords: SOL–GEL, DIP–COATING, MULTICOMPONENT OXIDE COATINGS, ZrO₂, TiO₂, RARE-EARTH OXIDES, UV–VIS–NIR SPECTROSCOPY, XRD, SELF-CLEANING COATINGS, PHOTOVOLTAICS

1. Introduction

In recent decades, the development of advanced multifunctional oxide coatings has become an important research field due to the increasing demand for materials with enhanced optical, thermal, mechanical, and chemical properties. Thin oxide films are widely used in optics, photovoltaics, catalysis, sensors, microelectronics, corrosion protection, and self-cleaning surfaces [1]. Among the numerous fabrication techniques, the sol–gel method has emerged as one of the most attractive approaches for the preparation of multicomponent oxide coatings because of its simplicity, low processing temperature, compositional homogeneity, and excellent control over the microstructure and thickness of deposited films [1, 2].

The sol–gel process enables the synthesis of inorganic and hybrid materials through hydrolysis and polycondensation reactions of metal alkoxide or inorganic salt precursors [2, 3]. Compared with conventional ceramic processing methods, sol–gel technology offers several advantages, including high purity of the final products, molecular-level mixing of components, reduced energy consumption, and the possibility of depositing uniform coatings on substrates with complex geometries [2]. In addition, the process allows easy incorporation of dopants and modifiers, enabling precise tailoring of the physicochemical properties of the resulting materials [3].

Among various oxide systems, titanium dioxide (TiO₂) and zirconium dioxide (ZrO₂) have attracted considerable scientific attention because of their excellent functional characteristics. TiO₂ is widely known for its high photocatalytic activity, optical transparency, chemical stability, non-toxicity, and hydrophilic behavior [1,4]. These properties make TiO₂-based coatings particularly suitable for self-cleaning surfaces, photocatalytic purification systems, optical devices, and photovoltaic applications [1]. Sol–gel-derived TiO₂ thin films have been extensively investigated due to their controllable crystalline structure and surface morphology [4].

ZrO₂, on the other hand, exhibits excellent thermal stability, high hardness, low thermal conductivity, superior wear resistance, and remarkable chemical durability [2, 5]. Zirconia-based coatings are widely used in thermal barrier systems, corrosion-resistant

layers, and high-temperature structural applications [5]. However, pure zirconia undergoes phase transformations during heating and cooling, which may affect its structural stability. The incorporation of additional oxides or rare-earth elements can stabilize the zirconia structure and improve its mechanical and thermal properties [5].

The combination of TiO₂ and ZrO₂ in binary or multicomponent oxide systems has demonstrated significant synergistic effects. TiO₂–ZrO₂ mixed oxides often exhibit improved thermal stability, enhanced surface acidity, better mechanical performance, and modified crystallization behavior compared to the individual oxides [4]. Furthermore, mixed oxide systems can suppress grain growth and delay phase transitions, resulting in coatings with improved structural homogeneity and durability [4]. Previous studies have shown that TiO₂–ZrO₂ coatings synthesized by sol–gel methods remain amorphous at temperatures where pure TiO₂ and ZrO₂ already crystallize, indicating strong interactions between both oxide phases [4].

Rare-earth elements are increasingly incorporated into oxide coatings because of their ability to modify optical, luminescent, dielectric, and catalytic properties [5, 6]. Samarium (Sm) and neodymium (Nd) are among the most promising rare-earth dopants due to their unique electronic configurations and characteristic f-electron transitions [6]. Rare-earth ions can create localized energy levels within the oxide matrix, influence charge carrier dynamics, inhibit grain coarsening, and enhance thermal stability [6, 7]. In TiO₂-based systems, rare-earth doping has been reported to improve photocatalytic efficiency by reducing electron–hole recombination and extending light absorption into the visible spectral region [6, 7].

In zirconia-containing systems, rare-earth oxides contribute to phase stabilization, increased ionic conductivity, and improved resistance to thermal degradation [5]. Co-doping with mixed rare-earth oxides has also been shown to refine the microstructure and improve sintering behavior of zirconia-based materials [5]. Such modifications are particularly important for advanced coatings operating under aggressive thermal or environmental conditions.

The incorporation of aluminum-containing species into multicomponent oxide systems can additionally improve coating adhesion, hardness, chemical resistance, and structural integrity. Aluminum oxide phases are known for their excellent mechanical strength and resistance to corrosion and wear [2]. The presence of

Al species within Ti–Zr-based matrices may also influence densification processes, pore structure, and thermal stability of the coatings [2,3].

Among the available deposition techniques, dip-coating remains one of the most effective and economical methods for applying sol–gel-derived thin films. The technique allows precise control of coating thickness through adjustment of withdrawal speed, solution viscosity, and processing conditions [1]. Dip-coating is especially suitable for large-area substrates and provides uniform coatings with relatively simple experimental equipment [1,3].

Despite the growing number of investigations on binary and rare-earth-doped oxide systems, studies focused on multicomponent Zr–Ti–Sm–Nd–Al oxide coatings remain relatively limited. The simultaneous incorporation of transition-metal and rare-earth oxides into a single sol–gel-derived coating may provide synergistic improvements in structural, optical, thermal, and surface characteristics. However, the complexity of hydrolysis, condensation, and crystallization processes in multicomponent systems requires detailed investigation in order to optimize synthesis conditions and understand the interactions between the different oxide phases.

There are also many studies on the synthesis and properties of sol-gel coatings deposited on hybrid materials and other coatings [9-13].

Therefore, the present study aims to prepare Zr–Ti–Sm–Nd–Al oxide coatings using the sol–gel method combined with the dip-coating technique. Particular attention is focused on the synthesis procedure, formation of homogeneous oxide films, and investigation of the structural and surface properties of the obtained coatings. The influence of the multicomponent oxide composition on the morphology, phase formation, and potential functional performance of the coatings is also discussed.

2. Experimental procedures

2.1. Materials

Each chemical used for this study were analytical reagent grade and were not further purified before use. Zirconium oxychloride octahydrate ($\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$), samarium oxide (Sm_2O_3), aluminum oxide (Al_2O_3), neodymium oxide (Nd_2O_3), titanium(IV) butoxide ($\text{Ti}(\text{OBu})_4$), nitric acid (HNO_3), acetylacetone (AcAc), diethanolamine (DEA), ethanol ($\text{C}_2\text{H}_5\text{OH}$) and deionized water were used as received without further purification. Microscope-grade soda–lime glass slides were used as substrates /26x76 mm/.

2.2. Preparation of Sols

2.2.1. Preparation of Sol 1 (Zr–Sm–Al–Nd system)

The first sol was prepared by dissolving 7.297 g $\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$ in ethanol under continuous stirring. Subsequently, 0.518 g Sm_2O_3 , 0.255 g Al_2O_3 and 0.515 g Nd_2O_3 were added. The mixture was acidified with nitric acid to promote hydrolysis. Ethanol acted as the solvent, while DEA stabilized the sol. The mixture was stirred for 5 h.

2.2.2. Preparation of Sol 2 (Zr–Sm–Al–Ti system)

In a similar process, 8.048 g $\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$, 0.527 g Sm_2O_3 and 0.255 g Al_2O_3 were dissolved in ethanol. Then 1.1 mL $\text{Ti}(\text{OBu})_4$ was added dropwise under vigorous stirring. AcAc was used as a chelating agent to control Ti(IV) hydrolysis.

2.3. Combined Sol Preparation and Hydrolysis Control

The two sols stayed 30 days and were mixed and stirred for 30 min. Hydrolysis was initiated by adding: 85 mL ethanol, 65 mL deionized water, 10 mL HNO_3 and 2.5 mL AcAc. The molar ratios were:

- Zr : Ti = 27.3 : 1
 - Zr : Sm = 43 : 1
 - Zr : Al = 87 : 1
 - Zr : Nd = 27 : 1
 - $\text{Ti}(\text{OBu})_4$: AcAc $\approx$ 1 : 1.7
 - H_2O : (Zr + Ti) $\approx$ 16 : 1
 - EtOH : (Zr + Ti) $\approx$ 72 : 1
- The final sol was aged for 24 h.

3. Substrate Cleaning

Glass substrates were ultrasonically cleaned in acetone, ethanol and deionized water.

2.4. Dip-Coating Deposition

The sol was filtered (0.45 μm). Films were deposited using dip-coating at 25 °C and 40–50% RH with withdrawal rates. The prepared sols were coated onto glass substrates using the dip-coating technique at a draw speed of 5 cm/min. After each layer, films were dried at 100 °C. Typically 3–5 layers were applied.

2.5. Thermal Treatment

Films were heated to 430 °C at 2 °C/min (1–2 h hold), yielding transparent multioxide coatings.

2.6. Characterization - XRD, UV-Vis spectroscopy.

3. Results and Discussion

3.1. XRD analysis of Zr–Ti–Sm–Nd–Al oxide coatings

The samples were examined using a Philips X-ray diffractometer PW 1030, with an X-ray source of Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) and θ –2 θ Bragg-Brentano geometry. The scan step size was 0.025°, 10 s in the range 25–65° 2 θ . The diffractograms were analysed using the PDF-2 2022 database.

The thickness of the layer and its elemental composition were measured using energy-dispersive X-ray fluorescence spectrometry (EDXRF) with an EPSILON 1 spectrometer (PANalytical, Malvern, UK). The Omnian and Stratos software modules were used for quantitative and layer thickness analysis respectively.

The size of the crystallites is calculated according to the Scherrer formula:

$$D = 0.9\lambda/B.\cos\theta$$

D - average crystallite size /Average Crystallite size/
 λ - wavelength (in angstroms) - 1.54178 $\text{\AA}$ /X-Ray wavelength/
 θ - Bragg angle (degrees) - 2 θ /Bragg angle/

B - line broadening FWHM (2 θ), /Line broadening/ must be of dimension radians (rad=2 θ * π /180)

The table1 presents the elemental composition and thickness of the obtained ZSATN coatings determined by energy-dispersive spectroscopy (EDS). The results reveal the presence of the main elements characteristic of the investigated multicomponent oxide system — Ti, Zr, Sm, Nd, and Al — confirming the successful formation of Zr–Ti–Sm–Nd–Al oxide coatings on the silicate substrate.

Table 1

Samples	Elements [wt %]						
	Al	Si	S	Cl	K	Ca	Ti
ZSATN-1	1.42	70.24	0.2 2	0.2 1	2.69	23.92	0.16
ZSATN-3	1.55	72.30	0.2 3	0.1 6	2.48	21.97	0.18
ZSATN-5	1.52	71.43	0.2 3	0.1 8	2.57	22.67	0.19
Samples	Fe	Sr	Zr	Ba	Nd	Sm	
ZSATN-1	0.29	0.13	0.1 4	0.1 1	0.19	0.28	
ZSATN-3	0.26	0.12	0.1 4	0.1 1	0.20	0.31	
ZSATN-5	0.27	0.12	0.1 6	0.1 1	0.22	0.34	

Table 2

Samples	Layer
	Thickness [nm]

ZSATN-1	39.47
ZSATN-3	53.97
ZSATN-5	57.29

Observed that the contents of Si and Ca are the highest for all samples, which is associated with the influence of the glass substrate and the relatively small thickness of the deposited coatings. In table2 is show with increasing number of deposited layers from ZSATN-1 to ZSATN-5, a gradual increase in coating thickness from 39.47 nm to 57.29 nm is observed, indicating successful accumulation of the oxide layer during the consecutive dip-coating deposition process.

The concentrations of Ti, Zr, Nd, and Sm remain relatively stable for the different samples, demonstrating good homogeneity of the sol-gel system and uniform distribution of the components within the coating structure. The slight increase in the concentrations of the rare-earth elements Nd and Sm in the ZSATN-5 sample may be related to the increased coating thickness and the higher amount of deposited oxide material.

The presence of small amounts of K, Sr, Fe, Cl, and S most likely originates from the composition of the glass substrate or from residual impurities associated with the precursors and technological process. Nevertheless, the low concentrations of these elements indicate relatively high purity of the obtained coatings.

The obtained results confirm that the applied sol-gel technology combined with the dip-coating technique enables the formation of relatively uniform and thin multicomponent oxide layers with controllable thickness and stable chemical composition.

Figures 1-3 present the results of XRD analyses of the surface of the glass samples.

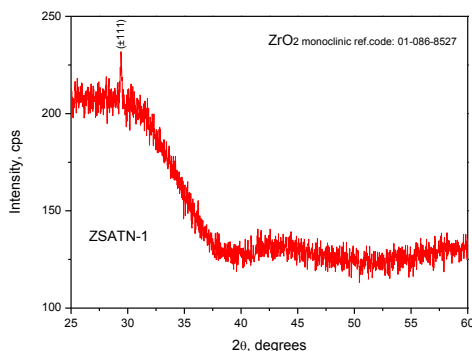


Figure 1. XRD analyses of the surface of the coating on glass /ZSATN-1/

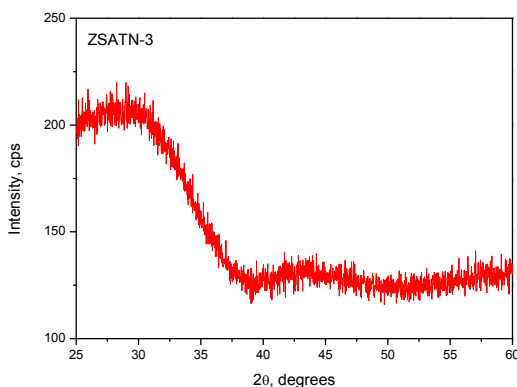


Figure 2. XRD analyses of the surface of the coating on glass /ZSATN-3/

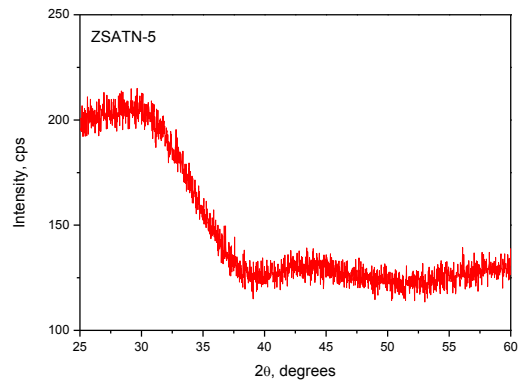


Figure 1. XRD analyses of the surface of the coating on glass /ZSATN-5/

The crystalline structure of the synthesized Zr-Ti-Sm-Nd-Al oxide coatings was examined using X-ray diffraction. Figure X presents the diffraction patterns of the three samples, designated as **ZSATN-1**, **ZSATN-3**, and **ZSATN-5**. All diffractograms exhibit characteristic reflections corresponding to **monoclinic zirconia**, as confirmed by comparison with the reference pattern:

“ZrO₂ monoclinic ref.code: 01-086-8527”.

The presence of these peaks indicates that the sol-gel synthesis followed by thermal treatment successfully induces crystallization of ZrO₂ within the multicomponent oxide matrix.

A progressive increase in peak intensity is observed from ZSATN-1 to ZSATN-5. The **ZSATN-1** sample displays the lowest peak intensities, suggesting either a lower degree of crystallinity or a thinner deposited layer. In contrast, **ZSATN-3** shows more pronounced reflections, while **ZSATN-5** exhibits the highest peak intensities among the three samples. This trend indicates that increasing the number of dip-coating cycles (or sol concentration, depending on the experimental design) leads to enhanced crystallinity and/or increased coating thickness.

No additional crystalline phases associated with Ti, Sm, Nd, or Al oxides were detected. This implies that these dopants are either incorporated into the ZrO₂ lattice without forming separate crystalline phases or remain in an amorphous state within the coating. Such behavior is typical for multicomponent sol-gel systems, where dopants can act as structural stabilizers, inhibit grain growth, and promote homogeneous distribution within the oxide network.

The dominance of the monoclinic ZrO₂ phase is consistent with the thermodynamically stable structure at room temperature. The gradual increase in crystallinity with layer buildup suggests improved structural ordering during heat treatment, which is beneficial for mechanical stability, thermal resistance, and long-term durability of the coatings.

Overall, the XRD results confirm that the applied sol-gel and dip-coating procedures yield well-crystallized ZrO₂-based coatings, with structural properties strongly influenced by the number of deposited layers. These findings correlate with the expected behavior of sol-gel derived oxide films, where repeated deposition cycles enhance film density, crystallinity, and structural uniformity.

3.2. Optical characterization of Zr-Ti-Sm-Nd-Al oxide coating

Optical characterization was performed with UV-VIS-NIR Shimadzu 3600 double-beam spectrophotometer (Shimadzu Corporation, Kyoto, Japan) in the spectral region of 240-1800 nm. The transmittance spectra of the samples were taken against air. The reflectance spectra were measured by using the specular reflectance attachment (5° incidence angle) and Al coated mirror as reference. On the figures 4,5 present the results of optical characterization.

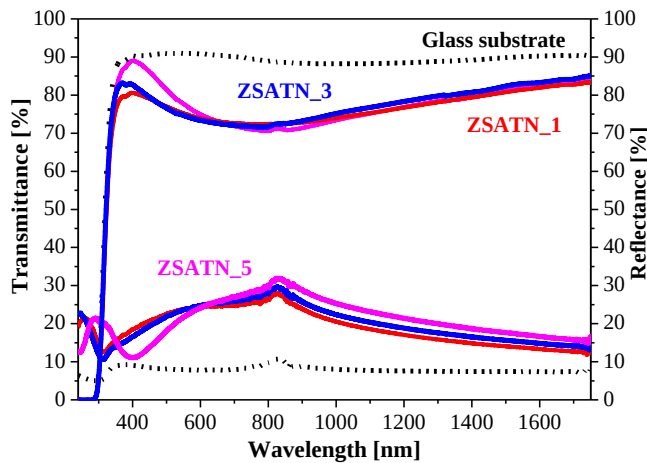


Figure 4. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 400 - 1800 nm / ZSATN-1, ZSATN-3 and ZSATN-5 /

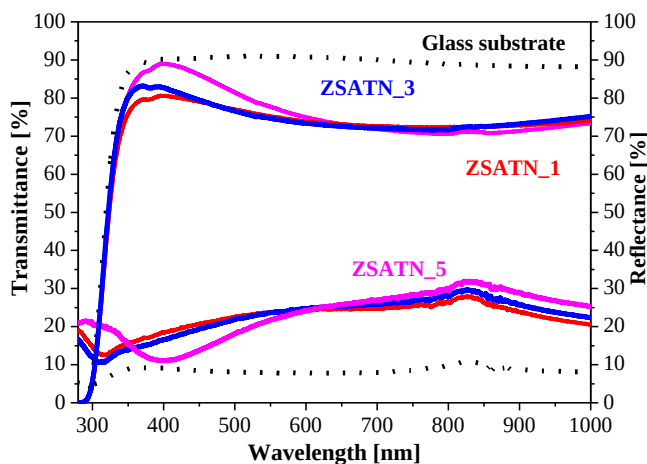


Figure 5. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 300 - 900 nm / ZSATN-1, ZSATN-3 and ZSATN-5 //

4. Conclusions

This study preparation and investigation of Zr-Ti-Sm-Nd-Al oxide coatings via sol-gel method.

1. The coatings are prepared by sol gel method with Dip Coating.

2. The coatings are dense and nanocrystalline, according to XRD and XRF analyses.

3. The coatings of ZSATN-1, ZSATN-3 and ZSATN-5 samples show good transmittance by UV-VIS-NIR spectrophotometer examination.

The experimental results represent a prerequisite for the development of a series of additional compositions and a detailed technological regime for obtaining various modifications of resistant, long-lasting self-cleaning coatings, potentially applicable to photovoltaic panels.

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Electrochemically Assisted Sol–Gel Synthesis of $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ Coatings Derived from TEOS-Based Systems

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Abstract: In the present study, a combined approach for the synthesis of multicomponent coatings in the $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ system was developed using a sol-gel process combined with electrochemically assisted deposition. Tetraethylorthosilicate (TEOS), calcium nitrate ($\text{Ca}(\text{NO}_3)_2$) and citric acid ($\text{C}_6\text{H}_8\text{O}_7\cdot\text{H}_2\text{O}$) were used as precursors. The obtained materials were characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM). The formation of amorphous-crystalline structures characteristic of bioactive silicate-calcium-phosphate systems was established. The combined approach demonstrates effective control over the structure formation processes and allows the preparation of multicomponent oxide coatings with potential for application in bioactive and functional surface systems.

Keywords: COATINGS, $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$, SOL-GEL, CEM, XRD

1. Introduction

Bioactive silicate-based coatings have attracted considerable scientific interest due to their ability to improve the surface properties of metal implants and to promote the formation of a stable bond between the implant and biological tissues. Among the studied bioactive systems, $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ -type systems occupy a particularly important place, since they combine the mechanical stability of the silica network with the biological activity induced by the calcium- and phosphorus-containing phases. These materials have the ability to form a hydroxyapatite-like layer in a physiological environment, which is considered a key factor for successful osseointegration and long-term operation of implants [1-5]

The sol-gel method is widely recognized as one of the most flexible approaches for the synthesis of silicate-based bioactive materials. Compared to conventional melt-based methods, the sol-gel process allows the synthesis to be carried out at lower temperatures, provides better compositional homogeneity, controlled porosity, and high specific surface area. In addition, the hydrolysis and condensation reactions of the alkoxide precursors allow for precise control over the structural evolution of the oxide network. Tetraethyl orthosilicate (TEOS) is among the most commonly used silica precursors due to its high purity, controllable reactivity, and the ability to form stable silicate structures via hydrolytic-condensation mechanisms [3, 4]

In the ternary systems $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$, calcium oxide acts as a modifier of the silicate network, disrupting its connectivity and facilitating ion exchange processes, while phosphorus-containing components promote the nucleation and growth of calcium-phosphate phases. The inclusion of CaO and P_2O_5 in the silicate matrix has a significant impact on the microstructure, degradation behavior and bioactivity of the resulting coatings. Previous studies have shown that the relative concentrations of calcium and phosphorus significantly affect the gelation processes, thermal stability, crystallization behavior and the ability to form an apatite layer [5, 6]

In recent years, electrochemically assisted sol-gel deposition has emerged as a promising method for obtaining homogeneous oxide coatings on electrically conductive substrates. The application

of an external electric field during deposition can accelerate hydrolysis and condensation reactions near the electrode surface, improve adhesion, and influence the morphology and thickness of the formed layers. In addition, electrochemical assistance allows local control over film growth and facilitates the formation of coatings on metallic substrates such as titanium, which is widely used in biomedical applications due to its high corrosion resistance and good biocompatibility [7]

Despite the considerable number of studies on sol-gel synthesized bioactive glasses, the combined effect of electrochemical assistance and TEOS-based ternary systems $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ on the morphology and compositional distribution of the coatings is still not sufficiently understood. Therefore, the present study is focused on the electrochemically assisted sol-gel synthesis of coatings from the system $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$, deposited on titanium substrates using TEOS-based precursor systems. Particular attention is paid to the relationship between the synthesis conditions, the microstructural evolution and the elemental distribution in the resulting coatings.

2. Experimental part

The precursors used are tetraethylorthosilicate (TEOS), calcium nitrate $\text{Ca}(\text{NO}_3)_2\cdot 4\text{H}_2\text{O}$, 0.2g $\text{C}_6\text{H}_8\text{O}_7\cdot\text{H}_2\text{O}$ (citric acid), $(\text{NH}_4)_2\text{H}_2\text{PO}_4$ ammonium hydrogen phosphate, ethyl alcohol ($\text{C}_2\text{H}_5\text{OH}$). 15ml $\text{C}_2\text{H}_5\text{OH}$ was mixed with distilled water in a ratio of 1:0.5. Calcium nitrate was previously prepared from 0.58g CaO and 10ml HNO_3 (Solution 1). 2.75ml TEOS and 0.15g citric acid (Solution 2) were added to the $\text{C}_2\text{H}_5\text{OH}$ solution. The two solutions were homogenized for 40 min on a magnetic stirrer until complete homogenization. Solution 1 was slowly added dropwise to solution 2. The total solution had a pH of 3. The duration of homogenization was 2 hours. $(\text{NH}_4)_2\text{H}_2\text{PO}_4$ was added to the solution thus obtained. The resulting sol had a pH of 3.5. The deposition of the layers was performed on Ti (Ti-6Al-4V) with dimensions of 30x20 mm. (fig.1) They were cleaned with acetone in an ultrasonic bath and dried. The layers were deposited by the immersion method. The total layers are 7, and after each layer the sample is dried in a dryer at 60°C for 20 min.



Fig. 1 Experimental setup for layer deposition using the immersion method

The next stage is electrochemical support. The sol solution is used as the electrolyte. The anode of the experimental setup is a stainless steel plate, and the cathode is the test sample. The set amperage is 1.2 A with a duration of 10 min. This process is followed by drying in a dryer at 100°C for 2 hours and heat treatment at 400°C with a hold of 1 hour.

3. Results and discussion

3.1. X-ray structural analysis

XRD analysis of a coating from the $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ system was carried out using an apparatus Bruker D8 Advance.

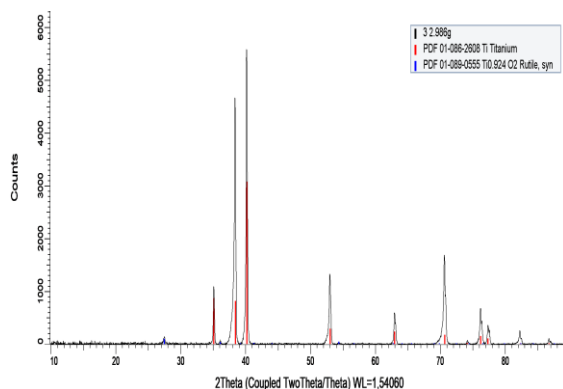


Fig.2 X-ray diffraction analysis of electrochemically assisted sol-gel coatings from the $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ system

The X-ray diffraction analysis (Fig. 2) of the electrochemically assisted sol-gel coatings of the $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ system deposited on titanium substrates shows the presence of mainly diffraction maxima belonging to the metallic Ti substrate. The main peaks at approximately 35°, 38–40°, 53°, 63°, 70° and 76° (2θ) are attributed to the hexagonal α -Ti phase. Additionally, weak peaks characteristic of the rutile phase of TiO_2 were found, suggesting partial oxidation of the titanium surface during the heat treatment.

No distinct crystalline reflections corresponding to silica, calcium phosphate or calcium silicate phases are observed. This indicates that the resulting coating is predominantly amorphous or has a low degree of crystallinity. The lack of sharp diffraction peaks is typical of TEOS-based sol-gel bioactive coatings processed at relatively low temperatures.

SEM/EDS analysis of a titanium substrate with a deposited coating of $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ by electrochemically assisted sol-gel method.

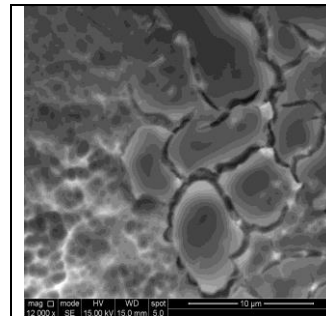


Fig. 3 SEM images of the electrochemically assisted sol-gel coating in the $\text{CaO--SiO}_2\text{--P}_2\text{O}_5$ system

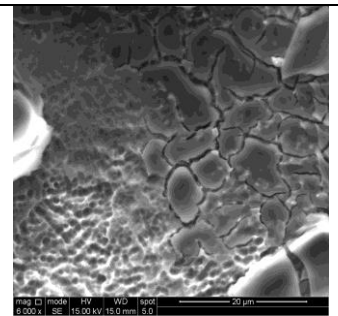
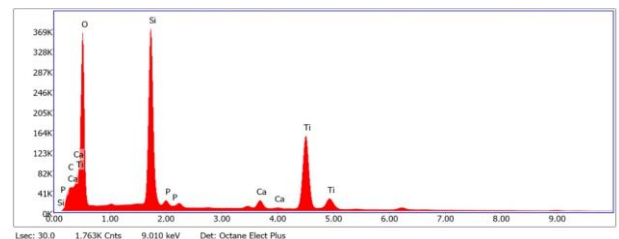
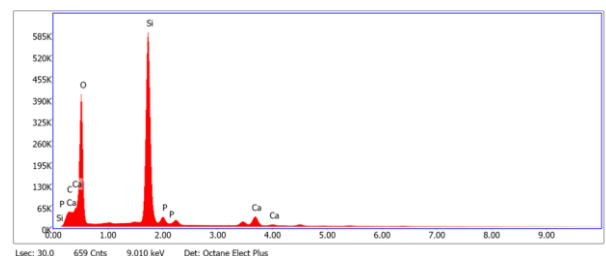


Fig. 4 SEM images of the electrochemically assisted sol-gel coating in the $\text{CaO--SiO}_2\text{--P}_2\text{O}_5$ system

SEM images (Fig. 3 and Fig. 4) of the electrochemically assisted sol-gel coating in the $\text{CaO--SiO}_2\text{--P}_2\text{O}_5$ system on a titanium substrate reveal a heterogeneous morphology. The porous finoglobular region is associated with the silica matrix formed during the sol-gel condensation. The compact flaky agglomerates probably represent regions enriched in calcium and phosphorus, due to local agglomeration and partial crystallization of calcium phosphate phases. The presence of microcracks between the agglomerates is associated with compressive stresses during drying and heat treatment. The bright smooth areas are interpreted as locally exposed titanium substrate, indicating uneven surface coverage.



a)



b)

Fig.5 EDS analysis of the electrochemically assisted sol-gel coating $\text{CaO--SiO}_2\text{--P}_2\text{O}_5$ on a Ti substrate

SEM/EDS analysis (Fig. 5) of the sample shows the formation of a heterogeneous microstructure. The porous regions with fine globular morphology are enriched in Si and are associated with the

silica matrix of the coating. The compact agglomerated domains probably represent locally enriched in Ca and P regions, associated with calcium phosphate segregation. The presence of microcracks between the agglomerates is due to compressive stresses during drying and heat treatment. In separate areas, a high Ti signal is observed, which indicates partial exposure of the titanium substrate and uneven thickness of the coating.

4. Conclusion:

Electrochemically assisted sol-gel synthesis was successfully applied to prepare coatings of the $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ system on titanium substrates using TEOS-based precursor systems. The resulting coatings are characterized by a heterogeneous microstructure composed of porous SiO_2 -rich regions and compact Ca/P-rich agglomerates distributed on the titanium surface.

SEM analysis revealed the formation of a porous globular morphology, typical of sol-gel synthesized silicate materials, as well as the presence of local compact domains and microcracks, resulting from the drying and heat treatment processes. EDS analysis confirmed the presence of Si, Ca and P in the composition of the coatings, while the locally recorded Ti signal indicates partial exposure of the metal substrate as a result of uneven layer thickness and shrinkage processes. Elemental distribution shows that the silicon phase forms the main matrix of the coating, while calcium and phosphorus are included in the form of dispersed Ca/P-rich regions in the amorphous silicate network.

X-ray diffraction analysis shows that after heat treatment the coatings retain a predominantly amorphous character. The diffraction patterns are dominated by reflections belonging to the titanium substrate, while weak peaks of rutile TiO_2 phase indicate partial oxidation of the surface during heat treatment. The lack of clearly defined crystalline calcium phosphate or calcium silicate phases suggests that the calcium and phosphorus components are mainly incorporated into the amorphous SiO_2 matrix, without the formation of separate crystalline compounds.

The combined results of SEM/EDS and XRD analysis indicate that the electrochemically assisted sol-gel approach allows the preparation of porous bioactive oxide coatings with high surface heterogeneity and amorphous nature, which are favorable for potential biomedical applications. The resulting $\text{SiO}_2\text{--CaO--P}_2\text{O}_5$ coatings possess structural features that facilitate ion exchange and surface bioactivity, making them promising for functional modification of titanium implant materials.

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Additive manufacturing of Ti/TiB titanium matrix composites using X-Beam 3D printing

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Abstract: Titanium matrix composites reinforced with titanium borides (TiB) represent a promising class of advanced structural materials due to their high specific strength, hardness, wear resistance, and thermal stability. The combination of titanium alloys with ceramic TiB reinforcing phases enables the development of lightweight materials with improved mechanical and *експлуатаційними* characteristics for aerospace, biomedical, and engineering applications.

This study investigates the fabrication of Ti/TiB titanium matrix composites using X-Beam 3D printing technology. The process is based on electron-beam additive manufacturing under vacuum conditions, which ensures stable melting conditions, reduced oxidation, and controlled heat input during layer-by-layer deposition. Special attention was focused on the in situ formation of TiB reinforcing phases and their influence on the microstructure evolution of the composite material.

Microstructural analysis was carried out using scanning electron microscopy and metallographic techniques. The obtained results demonstrated the formation of dense composite structures with relatively low porosity and homogeneous distribution of reinforcing phases within the titanium matrix. TiB particles and whisker-like precipitates were observed to form during solidification, contributing to microstructure refinement and strengthening effects.

The fabricated Ti/TiB composites exhibited improved structural uniformity and enhanced hardness compared with unreinforced titanium materials. The morphology and distribution of TiB phases were found to depend on the thermal conditions and processing parameters of X-Beam printing. The results confirm the potential of X-Beam additive manufacturing for producing advanced titanium matrix composites with tailored microstructure and improved performance characteristics.

Keywords: TITANIUM HYDRIDE, MICROSTRUCTURE, POWDERS, MMC, HOT PRESSING.

Introduction.

Titanium and its alloys possess an outstanding combination of high specific strength, corrosion resistance, and thermal stability, which makes them attractive materials for aerospace, automotive, marine, and biomedical applications [1–3]. Nevertheless, their relatively low hardness and limited wear resistance restrict the use of titanium-based materials in components subjected to intensive friction and abrasive conditions. One of the most effective approaches to overcoming these limitations is the development of titanium matrix composites (TMCs) reinforced with high-strength ceramic phases.

Among various reinforcement phases, titanium monoboride (TiB) is considered particularly attractive due to its high elastic modulus, excellent thermal stability, and strong interfacial bonding with the titanium matrix. The incorporation of TiB whiskers into titanium matrices significantly improves hardness, wear resistance, and mechanical performance while maintaining relatively low density. However, the enhanced hardness and brittleness of TiB-reinforced composites complicate their processing using conventional manufacturing technologies.

Additive manufacturing (AM) provides a promising route for producing near-net-shape titanium matrix composites with complex geometries and reduced material waste. Among various AM technologies, the xBeam electron-beam wire-feed process has demonstrated considerable potential for manufacturing titanium-based materials. The hollow electron beam used in this process enables precise control of the thermal conditions, melt pool geometry, cooling rate, and resulting microstructure, which are critical factors for obtaining high-quality titanium products.

The fabrication of conventional solid wires from TiB-reinforced composites is difficult because of their limited ductility. An alternative solution is the use of cored wires consisting of powder mixtures enclosed within a ductile metallic sheath. Such feedstock materials make it possible to introduce reinforcing components directly during the printing process and provide flexibility in tailoring the composition of titanium matrix composites.

Despite the growing interest in titanium matrix composites produced by additive manufacturing, the microstructure formation, phase evolution, and processing characteristics of TiB-reinforced materials fabricated using cored wires in the xBeam process remain insufficiently studied. Therefore, further investigation is required to evaluate the feasibility of this approach and to establish the

relationships between processing conditions, phase composition, and microstructural features of the printed composites.

The aim of the present study is to evaluate the potential of cored wires as feedstock materials for xBeam additive manufacturing of TiB-reinforced titanium matrix composites and to investigate the resulting phase composition and microstructural characteristics of the fabricated products.

Materials and experimental procedure.

The advanced directed energy deposition (DED) technology known as xBeam 3D Metal Printing, developed by the company "Chervona Hvylya" [4,5], has demonstrated significant potential for manufacturing titanium alloy components with controlled microstructure, precise chemical composition, and consequently predictable mechanical properties [6–10]. Unlike conventional wire-fed DED processes, xBeam employs a hollow conical electron beam to generate the melt pool while the wire feedstock is supplied coaxially through the center of the beam (Fig. 2) [7].

This unique deposition configuration, combined with the relatively low power density of the hollow electron beam, reduces overall heat input and minimizes thermal gradients within the deposited material and surrounding regions. As a result, solidification conditions can be effectively controlled, suppressing the formation of the coarse columnar microstructures commonly observed in many metal additive manufacturing processes. Previous studies have shown that Ti–6Al–4V components produced by the xBeam process and subjected to appropriate post-processing heat treatment can exhibit microstructures comparable to, or even superior to, those of conventionally wrought materials [7–10]. Consequently, the mechanical properties of the printed material satisfy the requirements of relevant industrial standards [10]. Additional advantages of the xBeam technology include its combination of high deposition rates, good dimensional accuracy, and relatively low production costs, largely due to the use of commercially available wire feedstock.

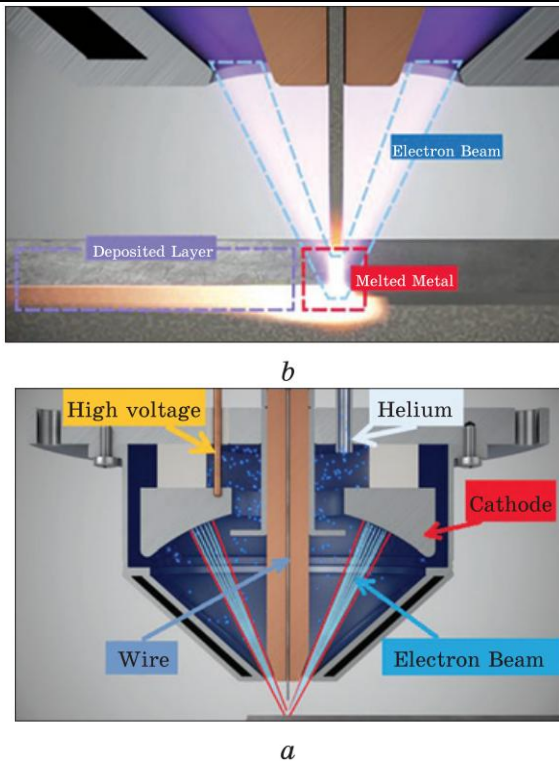


Fig. 1. Principle of the xBeam 3D Metal Printing process: (a) general arrangement of the deposition system and (b) spatial distribution of electron-beam power in the deposition area [26].

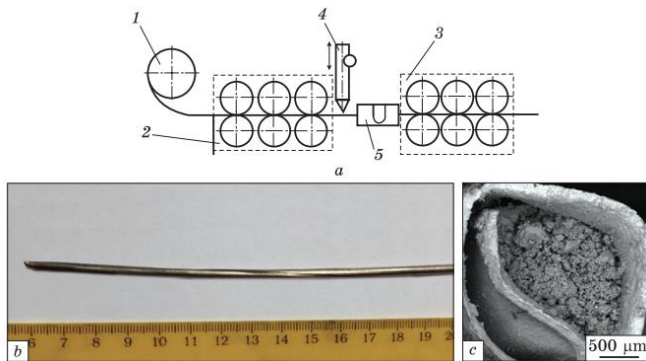


Fig. 2. Fabrication of Ti-TiB composite cored wire: (a) schematic of the manufacturing setup (1—powder hopper, 2 and 3—forming rollers, 4—powder feeder, 5—spinning unit); (b) appearance of the fabricated cored wire; and (c) cross-sectional view showing the metallic sheath filled with the powder mixture.

An important feature of the xBeam process is the possibility of using cored wire feedstock owing to its coaxial wire-feeding configuration. A cored wire consists of a metallic sheath filled with powdered materials designed to achieve a required chemical composition. Such feedstock offers a practical route for introducing alloying or reinforcing constituents directly into the melt pool during deposition. To ensure the desired composition of the deposited material, it is necessary to achieve complete transfer of the powder filler into the molten pool. In electron-beam-based processes, direct interaction between the electron beam and the powder should be avoided because it may cause electrostatic dispersion of powder particles under vacuum conditions. This requirement can be satisfied when the powder reaches the melt pool before the metallic sheath is fully melted, thereby shielding the powder from direct beam exposure. The coaxial feeding arrangement of the xBeam process provides favorable conditions for such powder transfer, although several additional processing requirements must also be fulfilled, as discussed in the experimental section.

In contrast to ductile titanium alloys, the production of wire feedstock from titanium matrix composites reinforced with ceramic

phases is challenging because of their limited ductility and increased brittleness. Conventional wire-manufacturing techniques, such as rolling, drawing, or extrusion, are generally unsuitable for such materials. Therefore, the development of alternative feedstock concepts capable of delivering the desired composite composition into the additive manufacturing process is of considerable practical interest.

The aim of the present study was to develop a processing route for the fabrication of cored wire feedstock with a prescribed titanium matrix composite composition, to evaluate its applicability in the xBeam additive manufacturing process, and to investigate the resulting microstructure, phase composition, and properties of the fabricated composite materials.

The microstructure of the fabricated composites was examined using an Olympus IX-70 optical microscope and a VEGA 3 TESCAN scanning electron microscope (SEM) equipped with a Bruker energy-dispersive X-ray spectroscopy (EDS) system for local chemical analysis. The crystallographic characteristics and local texture of the constituent phases were investigated by electron backscatter diffraction (EBSD) using a MIRA 3 TESCAN microscope. Vickers hardness measurements were performed using a Wolpert Wilson Instruments 452 SVD hardness tester.

Results and discussion.

In the present study, a processing route was developed to produce a cored wire feedstock corresponding to a titanium matrix composite reinforced with TiB. The fabricated wire was subsequently employed in the xBeam additive manufacturing process to investigate the feasibility of producing TiB-reinforced titanium composites and to establish the fundamental relationships between processing conditions, microstructure evolution, and material properties.

The cored wire was manufactured at the E.O. Paton Electric Welding Institute using a specially developed technology [11-12]. A powder mixture containing commercially pure titanium powder and boron-containing precursor powders was encapsulated within a titanium foil sheath (commercially pure Ti Grade 1, 0.2 mm thickness). The relative amounts of the powder core and titanium sheath were selected to achieve the target composite composition after deposition. During fabrication, the titanium foil was continuously formed and drawn using a dedicated wire-manufacturing device (Fig. 3a) while simultaneously being filled with the powder mixture, producing a straight cored wire with a diameter of approximately 3 mm (Fig. 3b). The filling ratio of the internal wire volume was approximately 62% (Fig. 3c). The wire was manufactured at a drawing speed of 30–35 m h⁻¹, while a series of spinners was used to gradually reduce the wire diameter, with each reduction step corresponding to approximately 0.1 mm.

The produced cored wire was subsequently used as feedstock material in the xBeam electron-beam additive manufacturing process [6-10]. Composite specimens with lateral dimensions of 10–20 mm and heights of up to 12 mm were fabricated layer-by-layer on Ti-6Al-4V substrates. The printed samples were used to investigate the microstructure development, phase formation, and mechanical characteristics of the deposited material.

Titanium matrix composites reinforced with TiB were fabricated using a powder cored-wire feedstock via the xBeam additive manufacturing process. The feedstock consisted of a titanium sheath filled with a powder mixture designed to form TiB reinforcement during electron-beam deposition. The composites were produced directly by layer-by-layer melting of the cored wire on a Ti-6Al-4V substrate using a coaxial hollow electron beam.

The results confirm that the xBeam process enables stable fabrication of Ti-TiB composite structures from powder cored wire. During deposition, in situ formation of TiB occurs within the molten pool, leading to the development of a composite microstructure consisting of a titanium matrix reinforced with TiB phases. The rapid solidification conditions inherent to the process govern the morphology and distribution of the reinforcing phase.

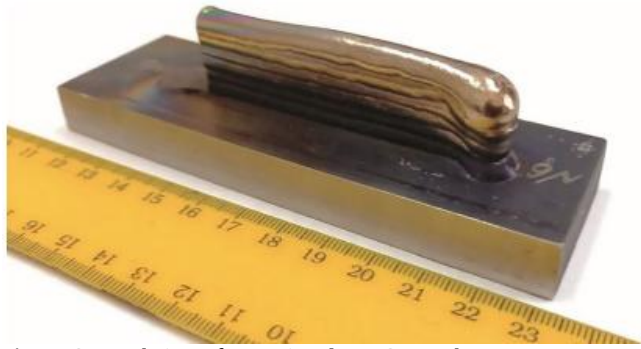


Fig. 3. General view of 3D-printed MMC sample.

The X-ray diffraction patterns and microstructural features of the Ti–40% TiB MMC fabricated using cored wire with raw TiB₂ additions are presented in Figs. 4 and 5. Notably, no residual TiB₂ phase was detected by XRD analysis (Fig. 4), indicating that the Ti + TiB₂ → TiB reaction was either fully completed or proceeded nearly to completion during the additive manufacturing process. The diffraction patterns reveal the presence of α (hcp) titanium matrix and TiB monoboride reinforcing phase, with a clear increase in the TiB phase fraction toward the upper regions of the build.

In addition, minor amounts of β (bcc) titanium were identified in the lower part of the deposit, which can be attributed to the influence of vanadium originating from the Ti–6Al–4V substrate. The printed composite exhibits a lamellar titanium matrix microstructure reinforced with TiB precipitates of non-uniform morphology and size along the build height.

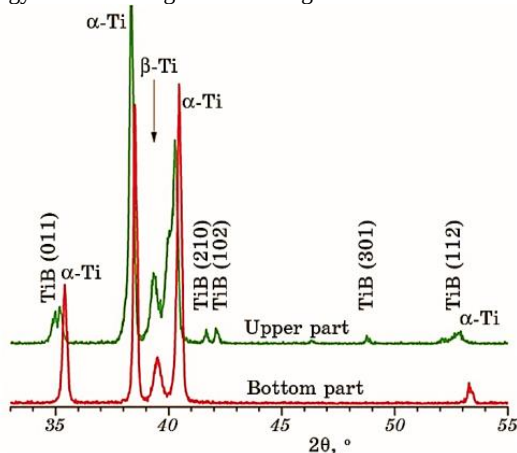


Fig. 4. X-ray diffraction patterns of the upper and bottom sections of the MMC produced by 3D printing with Ti + 40% TiB₂ cored wire.

The lower region of the MMC (Figs. 5a, b) is characterized by relatively fine needle-like TiB precipitates with widths in the range of 1–10 μm, while the interfacial zone between the MMC and the Ti–6Al–4V substrate contains even finer boride particles, typically 1–4 μm in size. A well-defined and sharp interface between the deposited composite and the substrate is observed in all microstructural images.

For the middle region of the MMC (Fig. 5c, d), fine boride particles coexist with coarser boride precipitates reaching up to 20 μm in width and 100–150 μm in length. In cross-section, these coarse features exhibit a hollow hexagon-like morphology. The spatial distribution of coarse and fine precipitates within the CP-Ti matrix is highly non-uniform; in particular, regions adjacent to coarse boride formations are largely depleted of fine particles (Fig. 5d).

The upper part of the MMC contains boride precipitates with a broad size distribution. The largest boride needles reach lengths of up to 1 mm and widths of approximately 50 μm, while finer precipitates are present between them (Fig. 5e, f).

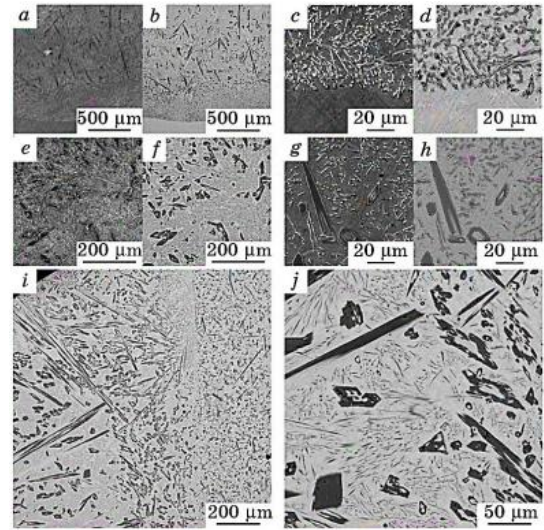


Fig. 5. Microstructural evolution of the TiB-reinforced MMC across the build height: bottom region adjacent to the Ti–6Al–4V base plate (a–d), central region (e–h), and upper region (i, j). SE mode (a, c, e, g); BSE mode (b, d, f, h, i, j).

Despite the pronounced microstructural heterogeneity, EDX analysis indicates a slight increase in the overall boron content in the upper region of the MMC compared to the bottom part (Table 2). Minor aluminium contamination is detected primarily in the lower region, attributed to diffusion from the Ti–6Al–4V substrate, whereas only trace amounts are observed in the upper part.

A clear variation in hardness is observed along the build height. The lowest hardness values (399–406 HV) are recorded at the MMC/substrate interface. The bottom region exhibits higher hardness levels in the range of 432–447 HV. The upper region shows the highest but also most scattered hardness values, varying between 430 and 541 HV.

Conclusions.

Titanium matrix composites reinforced with TiB were successfully fabricated using cored-wire feedstock via the xBeam electron-beam additive manufacturing process. The approach ensured stable layer-by-layer deposition and formation of dense near-net-shape structures on a Ti–6Al–4V substrate.

X-ray diffraction confirmed in situ formation of TiB, with no residual TiB₂ detected, indicating near-complete transformation of the precursor during processing. The resulting material consists of a titanium matrix reinforced with TiB phases formed during solidification.

The microstructure is heterogeneous along the build height, with variations in TiB morphology and distribution governed by local thermal conditions. This structural gradient leads to corresponding variations in hardness, with increased values compared to unreinforced titanium.

Overall, the results demonstrate that xBeam processing with cored-wire feedstock is an effective route for producing TiB-reinforced titanium composites with enhanced mechanical properties.

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LOW-POWER INDUCTION MOTOR FOR PUMPING SYSTEM APPLICATIONS

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Abstract: Paper deals with a newly designed low-power three-phase induction electric motor for continuous duty cycle operation with application mainly in pumping system. The main features are presented. The problems and solutions related to the sizing and optimization of the motors during design according to different criteria and conditions are analyzed, with energy efficiency being the main determinant. Numerous graphical results obtained during the design are presented.

Keywords: ELECTRIC MACHINES, INDUCTION MOTOR, WATER PUMPS, OPERATING CHARACTERISTICS, PRODUCT DESIGN

1. Introduction

To set working machines in motion, the main engine is the electric motor and, therefore, the main type of drive is the electric drive.

Currently, there is a widespread orientation towards energy-efficient technical solutions globally in the world and Europe and in this regard the development of this direction in terms of electricity consumption with a view to optimizing electricity costs. The application of an optimal in this regard electric drive, the main component of which is an electric motor, guarantees not only the energy-efficient operation of entire systems, but also low electricity costs for the industry. In other words – the most expensive energy in the industry is the unnecessarily consumed and the optimal electric drive will guarantee not only the energy-efficient operation of a given system, but also low electricity costs [1].

The creation of any mechanical unit is currently directly related to the design of electrical equipment. In this case, one must have a good knowledge of mechanical equipment and technologies, methods of speed regulation, calculation of transient processes of electric drives, and selection of the power of electric motors. The appropriate design of rotating electrical machines is the basis for achieving local and global electrical energy efficiency.

2. Some considerations

Caproni JSC – Kazanlak is a leading manufacturer of hydraulic components and systems for use in mobile and stationary industrial equipment. One of the company's innovations is the development of AC electric motors with the possible application of frequency regulation and vector control to them [2].

Modern electric drive is developing mainly in the following direction – simplification of the transmission mechanism between the electric motor and the working machine. This is achieved mainly by using electric motors that allow regulation of the rotational frequency, which avoids the complication of the transmission mechanisms. In this case, things such as the steady-state torque-speed curve, the dynamic performance required, the inertia of the load, the pattern of operation (continuous or intermittent), etc. are important [3].

Speed control is the forced change in the speed of an electric drive. The term 'speed control' should not be confused with the natural change in speed that occurs in an electric drive due to changes in the load on the shaft of a running machine. Speed regulation is achieved by additional action on the driving electric motor or the gear system of the production mechanism. This action can be performed by a person or by a special automatic device. For induction motors, pulse width modulation (PWM) inverters are suitable for control. Voltage source PWM inverters are popular because they are readily applied to different types of motor and load. That's why they are called 'the industrial work horse' and are the most widely used drives. Method of torque/speed control can

be Field Oriented Control (FOC) or Direct Torque Control (DTC), as well as Simpler Scalar (V/f) variant [3].

In the historical development of drives, mechanical control methods were the first step in the transition from unregulated to regulated drives. Currently, electrical control prevails, which has a number of advantages in terms of technical and economic indicators. In electrical control, the aim should be to ensure that the characteristics across the entire range have high rigidity and that the electric motor has sufficient overload capacity. The electrical method of regulation creates broad opportunities for automation of the regulation process and allows to eliminate mechanical regulating devices and thus to increase the reliability of the operation of the installations and to simplify their design.

By the way, it should be noted that for self-ventilated electric motors, the reduction in speed must correspond to the reduction in permissible losses in them. At low speeds, these electric motors must operate at currents lower than the nominal, and therefore the permissible torque is reduced in proportion to the reduction in speed.

Dynamic loads occurring during starting and stopping of electric drives increase losses in the motor, but since they are short-term compared to the duration of operation in a fixed mode, their influence on the heating of the electric motor is negligible. Therefore, in many cases, under the conditions of heating, it can be assumed for a short time that the torque of the electric motor is much greater than the rated one.

In addition to heating, there are other factors that limit the permissible overload of electric motors – for each there is a limit value of the moment, permissible under the conditions of normal operation of the electric motor, which should not be exceeded even briefly. It is this ratio of the maximum permissible moment to the nominal one that is called the overload capacity of the electric motor.

The peculiarity of the ATM range of AC electric motors (manufactured by Caproni JSC) is that maximum unification of the equipment used has been achieved in the implementation of products in the usual IE1 (Standard Efficiency) and IE2 (High Efficiency) energy class. The already available designs for the various types of products from the basic range are a prerequisite for implementing the IE3 energy class (Premium Efficiency). Electric motors with the ATM designation are available in standard and special designs according to their intended purpose, with the different combinations not changing the connection dimensions of the basic designs. In all products, the body and bearing shields are cast from aluminum alloy. All versions are ventilated except those operating immersed in an oil tank. More special versions are also possible, such as:

- tropical performance;
- with protection degree IP55 or IP56;
- for other supply voltage and frequency;
- for operating modes other than S1;
- with parameters different from those of the basic versions;
- with second output shaft end;
- for operation immersed in hydraulic oil.

The International Electrotechnical Commission (IEC) is an organization based in Geneva that publishes and promotes worldwide mechanical and electrical standards for electric motors, among other documents. IEC uses duty cycle (mode) designations (categories) S1 ... S10 to describe the operating conditions of electric motors – IEC 60034-2-1:2024 [4]. The modes of electric motors, in addition to specifying their operating parameters and duty cycles, also determine the temperature rise (insulation class), frame size (the physical dimensions of the electric motor), housing type, service factor, etc. In typical modes, serial electric motors should operate while the reliable operation of the machine is guaranteed by the manufacturer if the electric motor is operated in the mode specified in its passport at the rated load. Rapid failure is usually due to the fact that the electric motor is selected without taking into account the required rated mode.

It is necessary to clarify that the standards are recommended, i.e. they are not mandatory. A given manufacturer declares that his products comply with relevant standards, but this is for the purpose of seeking and selling his products. However, the ordinances in Bulgaria, as well as the regulations, directives and decisions created by the European Commission, are mandatory for implementation..

Electric motors for applications in pumps, fans, compressors, conveyors, operate in S1 mode (continuous duty cycle). This mode is characterized by operation at a constant load without interruption and with a sufficient duration to reach thermal equilibrium (thermal equilibrium is the state reached when the temperature rise of the machine does not vary by more than 2 degrees on the Kelvin scale per hour) [4].

3. Specifics of the designed electric motor

The induction motor under consideration is designed for operating mode S1 according to IEC, cooled by self-ventilation – code IC01, thermal protection is implemented with a Pt1000 thermistor in the stator winding (equipment upon customer request), and the insulation of the stator winding has a heat resistance class H (180°C). Parameter values and general view of an electric motor ATM are given in Table 1 and Figure 1, respectively.

The design is carried out with specified inner and outer diameters of the blades, with a certain number and dimensions of the stator and rotor channels. The possibilities for varying the independent variables are limited by the conditions for minimum dimensions and mass, as well as technological factors. Regarding the moment of inertia of the rotor - it is known that higher rotor inertias increase energy consumption when changing speed, with more compact dimensions the rotor inertia is smaller [1].

Partial optimization tasks have been solved with a maximum efficiency criterion and constraints on the current density in the stator and rotor windings. These constraints are imposed to achieve permissible winding temperatures. The parameters of the equivalent circuit, the currents in the windings, losses, powers, etc. have been determined. The results obtained allow us to estimate the distribution of magnetic induction in the sections of the magnetic circuit, to determine the magnetic flux through the air gap and the electromagnetic moment.

For the rated speed, the overload capacity of the electric motor is determined by the maximum torque factor. The maximum torque factor is usually greater than 2, where the stator current is more than twice the rated motor current. The air gap has the greatest influence on the value of the magnetizing current of induction motors. In turn, the magnetizing current determines the current and losses in the stator winding and the power factor. The production of induction motors with an optimal air gap depends on the design of the bearing and the level of the manufacturing process.

Table 1: Parameter values for the considered induction motor

Parameters	
Description	Data
Type	ATM 0.55-1500-L70
Duty cycle	S1
Connection (stator)	Y
Rated power	0.55 kW
Stator terminal phase voltage	230 V
Line-line supply voltage	400 V
Fundamental frequency	50 Hz
Number of pole pairs	4
Airgap	0.25 mm
Shaft diameter	25 mm
Copper diameter	0.63 mm
Synchronous rotational frequency	1500 rpm
Shaft rotational frequency	1427 rpm
Rated slip	0.04493
Rotor moment of inertia	0.0010668 kgm ²
Rated torque	3.68 Nm
Starting torque	1.73 p.u.
Maximum torque	2.68 p.u.
Phase current	1.3368 A
Starting current	4.54 p.u.
Maximum current	3.2 p.u.
Rated efficiency	80.514%
Phase resistance	11.30 Ω
Line-line resistance	22.60 Ω
Referred rotor resistance	10.74 Ω
Stator leakage reactance	7.35 Ω
Referred rotor leakage reactance	25.43 Ω
Magnetizing reactance (saturated)	274 Ω
Airgap flux density (mean)	0.5618 T
Stator copper losses (analytic on load)	60.58 W
Rotor copper losses (analytic on load)	29.15 W
Stray load losses (analytic on load)	17.01 W
Stator iron losses (total, analytic on load)	25.91 W
Rotor iron losses (total, analytic on load)	0.4707 W
Total losses (analytic on load)	133.10 W

The selected design scheme and the precision in machining the stator and rotor packages, bearing shields and shaft create the possibility of achieving a small and uniform air gap in the motors.

The machine winding and laying of the sections, the channel filling factor and the quality of the impregnation of the stator winding largely determine the heat dissipation and the temperature state of the winding. The resistance of the winding, the losses in it and the efficiency depend on the temperature.



Fig. 1 General view of an electric motor ATM.

The considered induction motor can be used to drive pumps designed for household use at home and garden, for fixed installation and pumping water from wells and other passive waters. Such pumps are designed to handle clean, clear or moderately contaminated water with solid particles at the declared maximum volume and are suitable for the following applications [5]:

- irrigation and watering of lawns, beds and vegetable gardens;
- the pumping of water reservoirs and ponds;
- for water-drainage from wells, tanks and rainwater tanks;
- the pump is suitable for pumping clean water, rain water and chlorinated water (water pools).

Figure 2 presents an example diagram for using a pump driven by an induction motor [5].

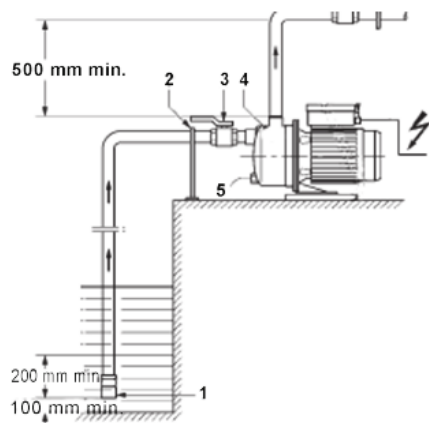


Fig. 2 General diagram of a pump with an induction motor (depicted elements: 1- suction with filter and check valve; 2 – suction pipe support; 3 – suction pipe slide valve; 4 – water filling plug (bleeding valve); 5 – pump water drain plug).

4. Results obtained

Below in Fig. 3 ÷ Fig. 12 are presented in graphical form the results for the designed induction electric motor. An appropriate software toolkit for electrical machines has been used – Ansys® Motor-CAD [6].

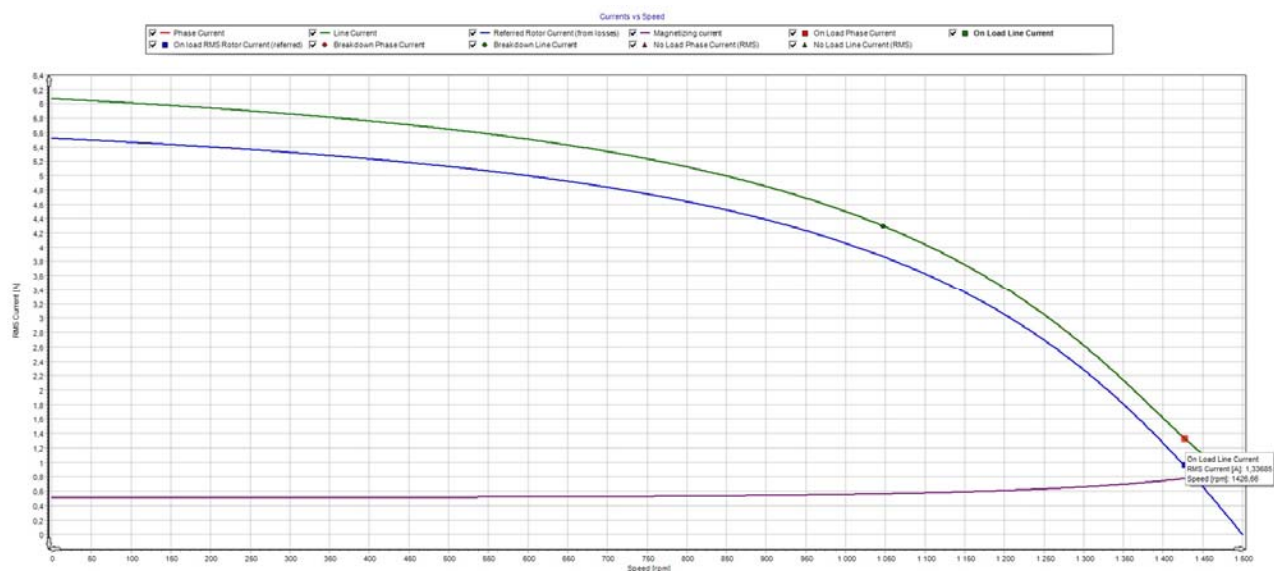


Fig. 3 Currents vs speed characteristics (green colored – line current, blue colored – referred rotor current, purple colored – magnetizing current).

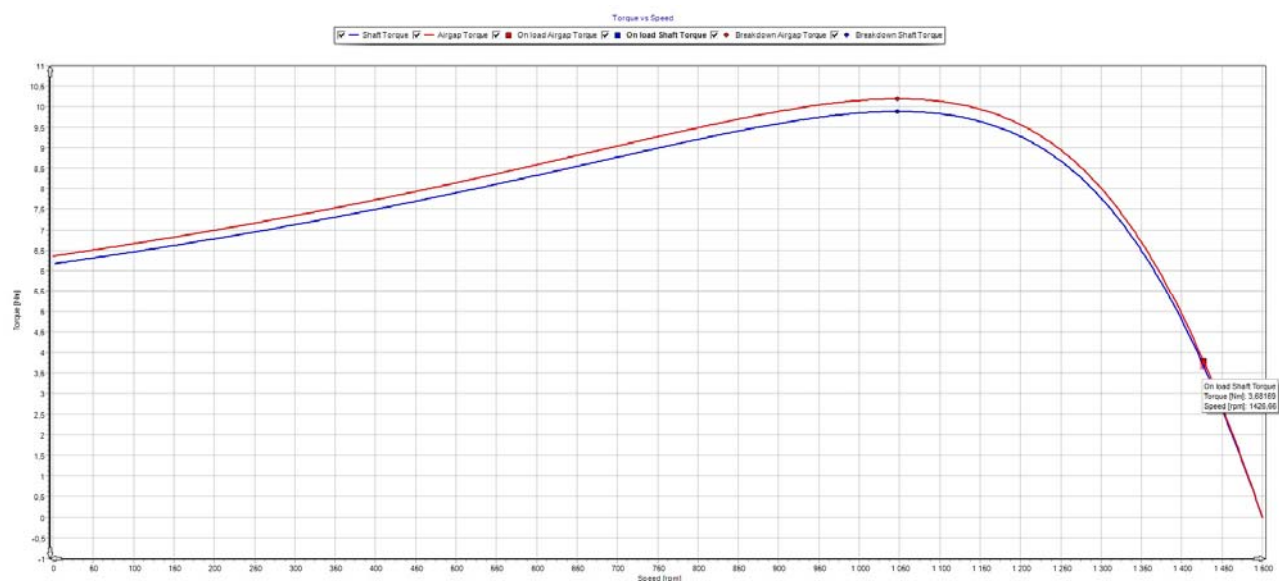


Fig. 4 Torque vs speed characteristics (red colored – on load airgap torque, blue colored – on load shaft torque).

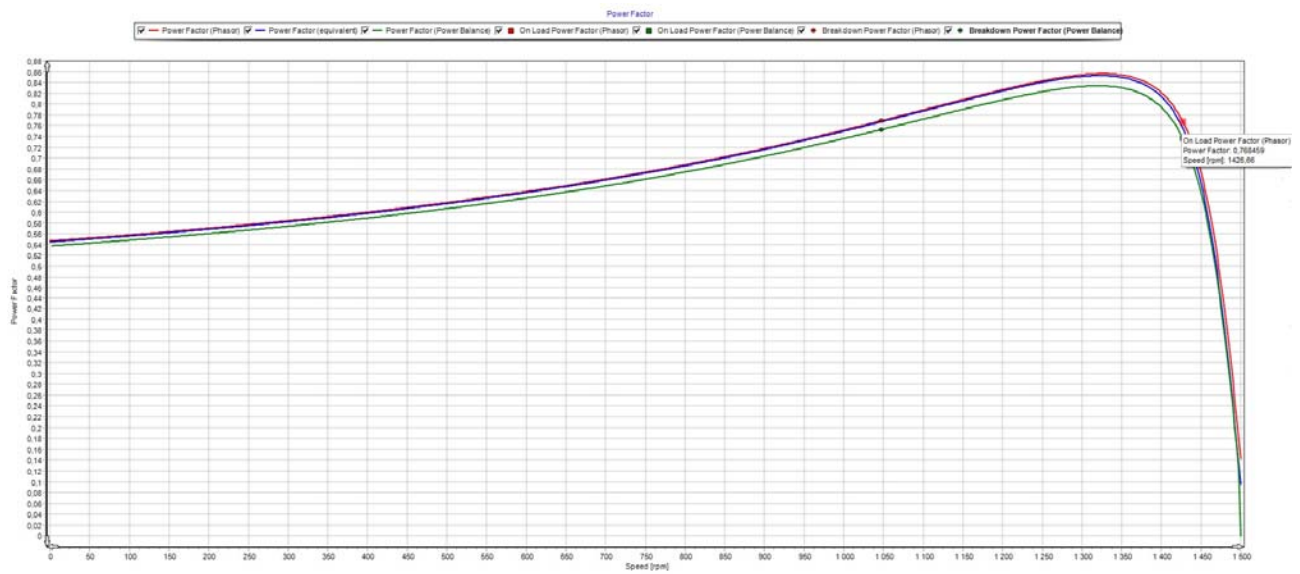


Fig. 5 Power factor vs speed characteristics.

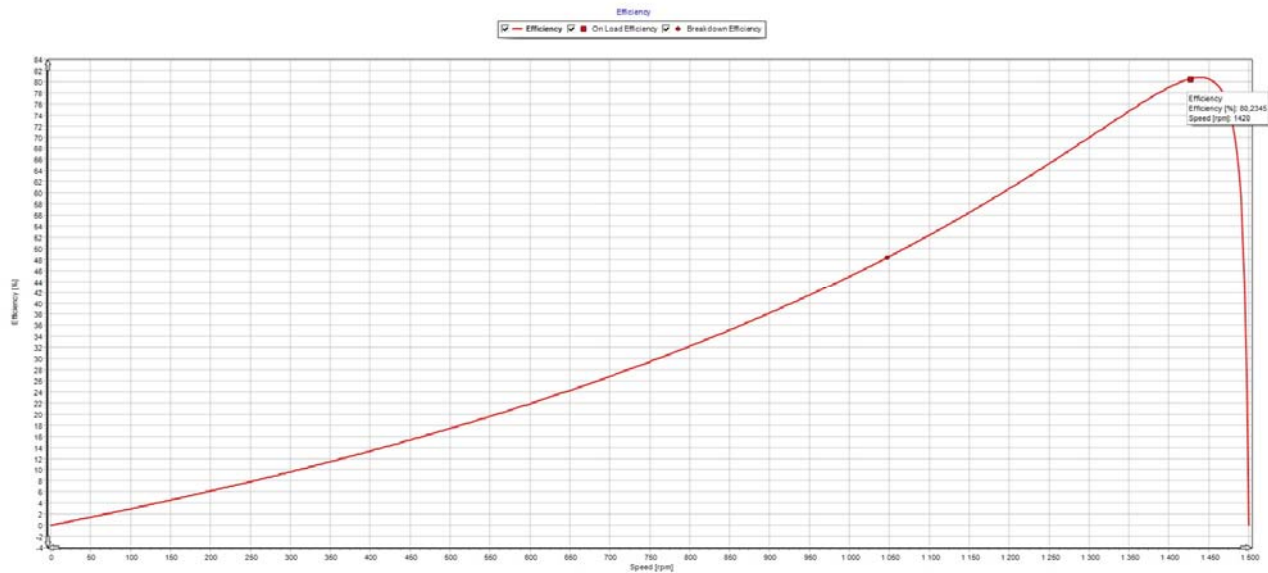


Fig. 6 Efficiency vs speed characteristic.

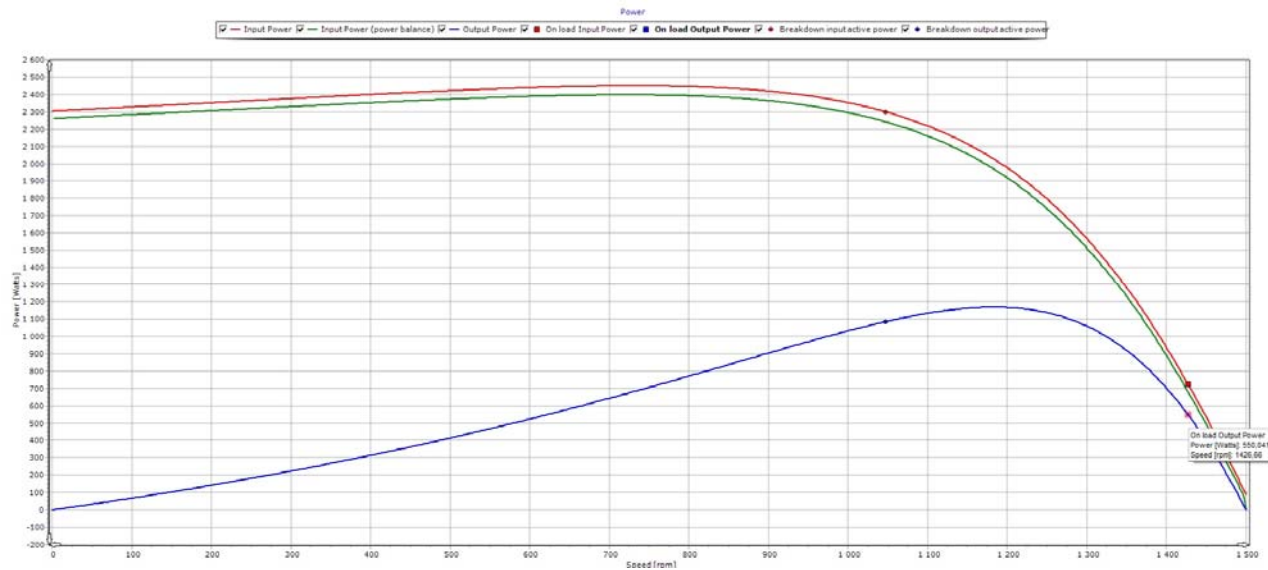


Fig. 7 Power vs speed characteristics
(red colored – input power consumed, green colored – input power consumed, power balance, blue colored – output power).

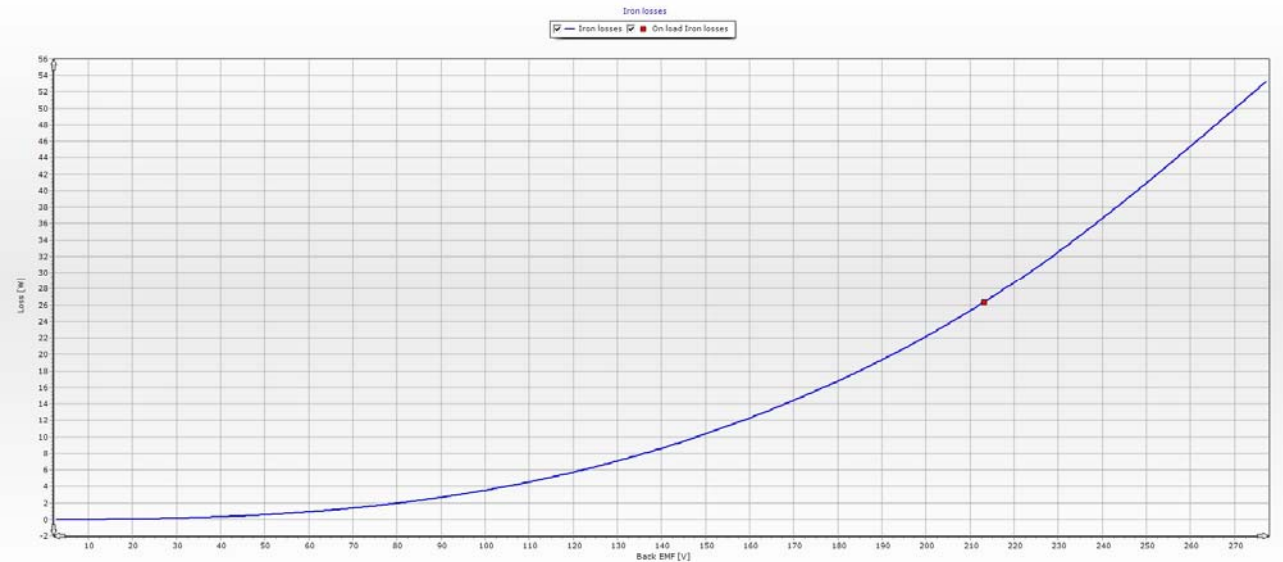


Fig. 8 Iron losses vs back e.m.f.

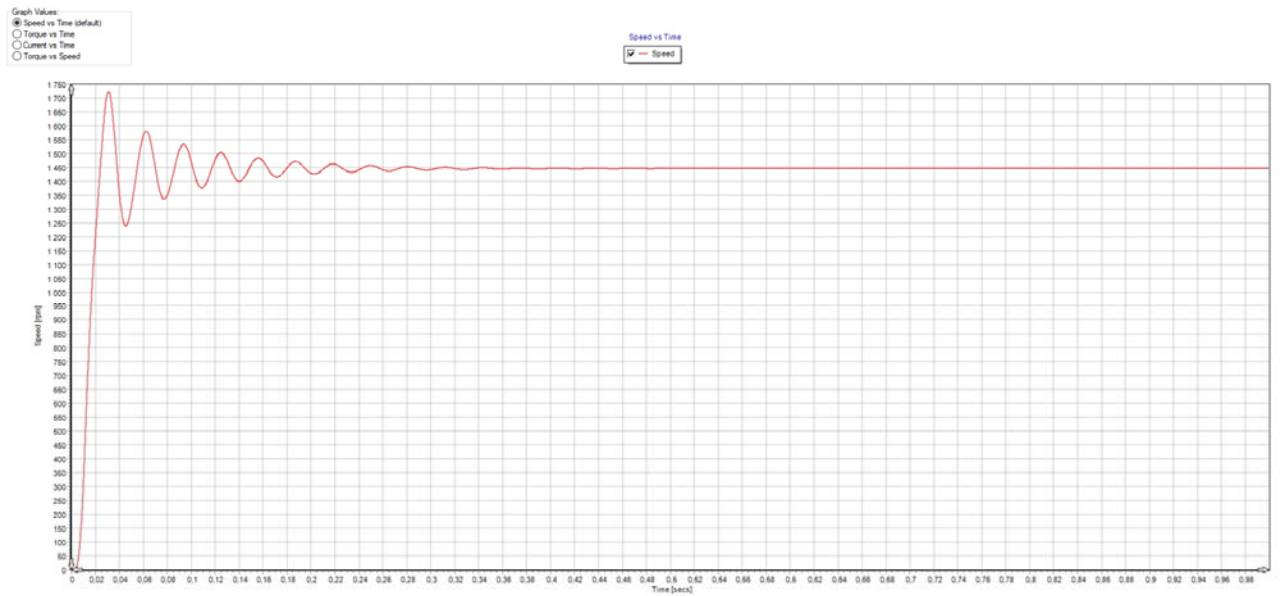


Fig. 9 Speed vs time characteristic.



Fig. 10 Torque vs time characteristic.

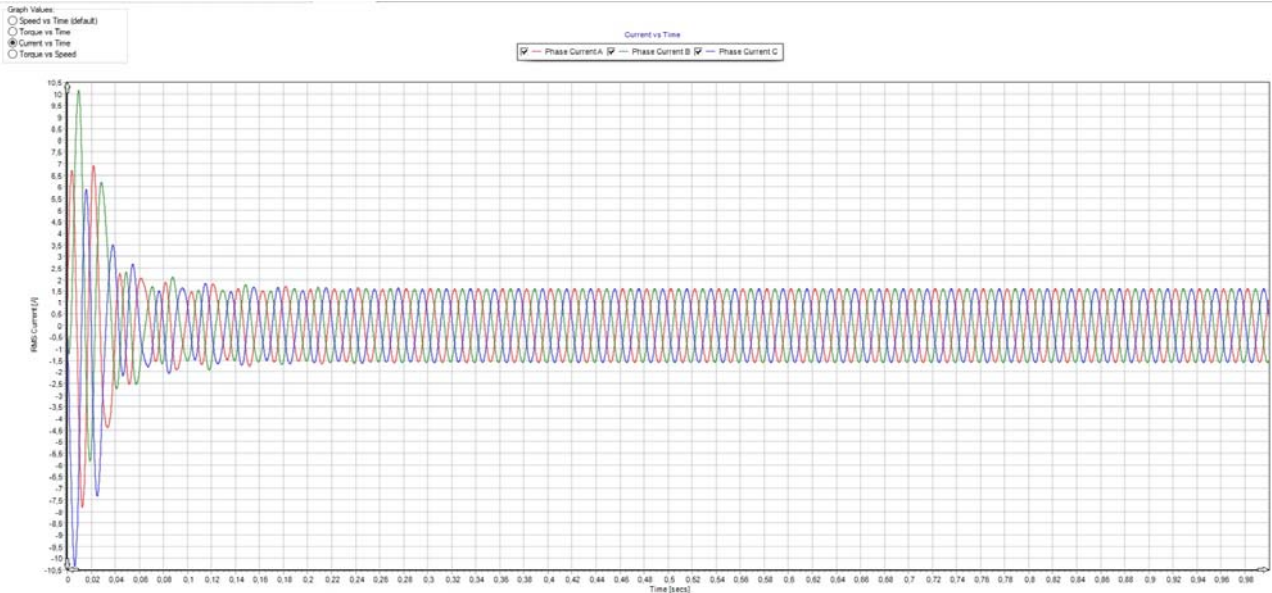


Fig. 11 Currents vs time characteristics
(red colored – phase current A, green colored – phase current C, blue colored – phase current C).

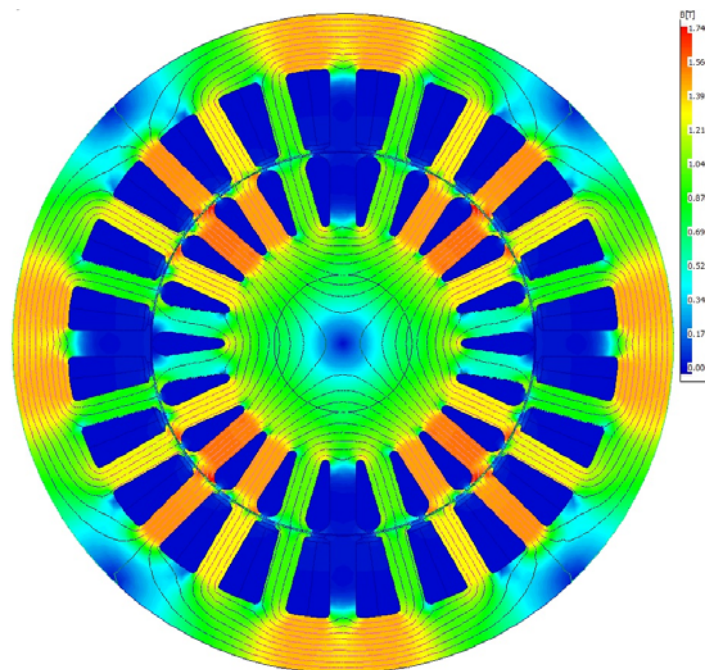


Fig. 12 Flux density [T].

5. Conclusions

Based on the research carried out, the following summary notes are formed. Models for different degrees of loading have been created. It should be noted that the experimental results are of great value, since as a result of their analysis it can be established how correctly the electric motor is designed, to clarify the reserves for improvement and possible shortcomings. This is actually planned as future work - testing with different loads on the shaft of the motor under consideration.

The selection of an electric drive should not end with considering only the possibility of obtaining certain mechanical characteristics. It is also necessary to evaluate the dynamic qualities, economic indicators, reliability and ease of maintenance.

6. Acknowledgments

The implementation of this paper is thanks to the support from the Project BG16RFPR002-1.014-0005 Competence Center 'Intelligent Mechatronic, Eco- and Energy-Saving Systems and Technologies' financed by the Operational Program 'Science and Education for Intelligent Growth' of the European Regional Development Fund.

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On the Geometric Role of the Distribution Parameter in Conic Spatial Rack Drives

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Abstract: This paper presents a study of some geometric characteristics of conic spatial rack drives with linear helicoids. Three variants of the conic configuration are considered — with convolute, involute, and Archimedean helicoids — and their action surface properties are analyzed in relation to the distribution parameter. The role of the distribution parameter in determining the geometry of the action surface and the position of each variant in the design parameter space is discussed.

Keywords: RACK DRIVES, SLIDING VELOCITY, ANALYTICAL CONDITIONS, DISTRIBUTION PARAMETER

1. Introduction

The transformation of rotational motion into rectilinear translation, and vice versa, represents a fundamental kinematic function in a wide range of mechanical systems — from industrial machinery and robotics to precision actuators and mechatronic devices. Spatial rack mechanisms occupy a special place among such devices: unlike conventional plane rack-and-pinion systems, they operate with non-orthogonal axis configurations, introduces additional geometric freedom in the design process. This freedom enables more compact drive layouts, customized force transmission paths, and better adaptation to the spatial constraints typical of modern robotic and mechatronic applications [1 -4].

The theoretical foundations for spatial gear mechanisms are established by Olivier [5] through formulation of generation principles, and later they are systematized by Litvin and Fuentes [6]. The geometry of helical surfaces and hyperboloid gear mechanisms has been studied extensively by Litvin [6], Minkov [4], and Abadjiev [2], providing the theoretical foundation for spatial rack drive analysis. Early studies on spatial conic rack configurations are presented by Trahanov and Ilinski [8], who treat a specialized conic rack enabling variable velocity ratio transformation, and by Watanabe and Maki [9], who analyze a Wildhaber-Novikov rack mechanism from a contact stress perspective. Systematic geometric synthesis methodologies for spatial rack drives with linear helicoids are developed in [1, 2, 7], establishing action surface equations and mesh region characterization for conic, cylindrical, and face configurations.

The present paper examines the role of the distribution parameter in the classification of conic linear helicoid variants and shows its connection to the geometry of the action surface and the position of each variant in the geometric parameter space.

2. Kinematic Scheme and Sliding Velocity Vector

2.1 Kinematic Configuration

The spatial rack mechanism is considered as a three-link system in which link $i=1$ rotates with angular velocity ω_1 (value of the angular velocity vector $\bar{\omega}_1$) around a fixed axis $1-1$, while link $i=2$ performs rectilinear translation with velocity (value of the translation velocity vector $\bar{V}_2$) (see Fig. 1).

The motions transformation of type $(R \leftrightarrow T)$ and vice versa is realized through high kinematic joints $(\Sigma_1 : \Sigma_2)$ which elements Σ_1 and Σ_2 at any moment have a conjugate instantaneous contact points P (the points of tangential contact P can belong to the conjugate instantaneous contact line). The motions transformation is characterized by the following conditions [1]:

$$\begin{aligned} \omega_1 &= \text{constant}, \quad V_2 = \text{constant}, \\ \delta_r &= \angle(\bar{\omega}_1, \bar{V}_2) = \pi - \Sigma_r = \text{constant}, \\ j_{12} &= \frac{\omega_1}{V_2} = \frac{1}{j_{21}} = \text{constant}, \end{aligned} \quad (1)$$

where with δ_r it is a crossed angle between the motion transformation vectors and with Σ_r it is noted an angle between the motion directions of the rack drive; j_{12} , j_{21} - velocity ratio of motion transformation of type $R \leftrightarrow T$.

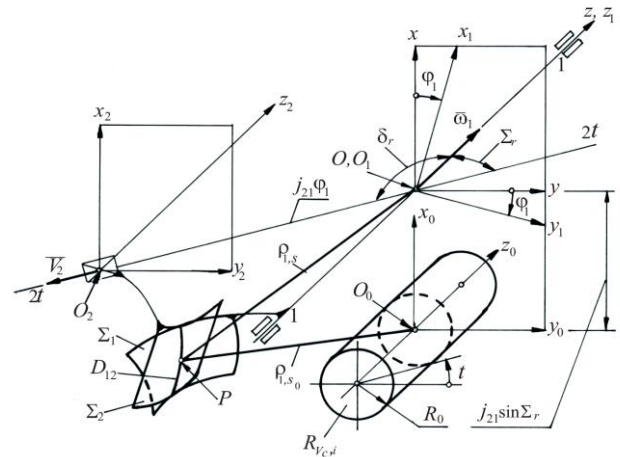


Fig 1. Kinematic configuration of spatial rack mechanism, where $S(O, x, y, z)$ is fixed coordinate system; the coordinate system $S_1(O_1, x_1, y_1, z_1)$ and $S_2(O_2, x_2, y_2, z_2)$ are connected to the movable links $i=1$ and $i=2$ correspondingly

For the rack mechanism in every moment of motion transformation, more than one high kinematic joints $(\Sigma_1 : \Sigma_2)$ takes part in the process of transformation. When rotation with angular velocity $\bar{\omega}_1$ is applied to the link $i=1$, the second motion link $i=2$ obtains a translation velocity $\bar{V}_2$. According to (1) the condition $V_2 = j_{21}\omega_1$ is accomplished for the value of $\bar{V}_2$. Hence, the joints $(\Sigma_1 : \Sigma_2)$ shown in Fig. 1 are kinematically conjugated, and the rack mechanism, respectively.

From the kinematic configuration shown in Fig. 1, link $i=1$ obtains rotational velocity at any contact point P , while link $i=2$ realizes translational velocity as defined in (1). The sliding velocity at P is the difference between the two velocity components [1]:

$$\bar{V}_{12} = \bar{V}_1 - \bar{V}_2 = \bar{V}_{r,2} - \bar{V}_{r,1}, \quad (2)$$

where $\bar{V}_{12}$ is relative (sliding) velocity vector of the contact point P ; $\bar{V}_i$ - transference velocity vector of P , joined to surface Σ_i ; $\bar{V}_{r,i}$ - relative velocity vector of point P , when P moves on the surface Σ_i . For the kinematic conjugation of the high kinematic joints $(\Sigma_1 : \Sigma_2)$, the sliding velocities displacement $\bar{V}_{12}$ at the common contact points P of the geometrical elements Σ_1 and Σ_2 is of a great importance.

2.2 Sliding Velocity Vector and Scalar Field Analysis

According to the condition of transformation (1) and the kinematic configuration shown in Fig. 1, for the function (2), written in the coordinate system $S(O, x, y, z)$, it is obtained [1]:

$$\bar{V}_{12} = \bar{V}_{12}(x, y, z) = \bar{V}_1 - \bar{V}_2 = \bar{\omega}_1 \times \bar{\rho}_{1,s} - \bar{V}_2. \quad (3)$$

By taking into account (1) and (3) in the fixed coordinate system $S(O, x, y, z)$ and symbols shown in Fig. 1[1] it is obtained:

$$\begin{aligned} \bar{V}_{12} &= \bar{V}_{12}(x, y, z) = V_{12,x}\bar{i} + V_{12,y}\bar{j} + V_{12,z}\bar{k}, \\ V_{12,x} &= -y, \quad V_{12,y} = x + j_{21}\sin\Sigma_r, \quad V_{12,z} = j_{21}\cos\Sigma_r, \end{aligned} \quad (4)$$

where coordinates of $\bar{V}_{12}$ in the coordinate system S are $V_{12,x}$, $V_{12,y}$, $V_{12,z}$ and $\bar{i}$, $\bar{j}$, $\bar{k}$ are unit vectors of the axes of the coordinate system $S(O, x, y, z)$.

In equation (4) without disturbing the community of arguments is accepted $\omega_1 = 1$ rad/s and therefore $V_2 = j_{21}$ m/s. The scalar magnitude of the relative velocity vector $\bar{V}_{12}$ (4) of the conjugate tooth surfaces Σ_1 and Σ_2 in their common contact points P defines a scalar vector field [1]:

$$V_{12} = V_{12}(x, y, z) = \sqrt{V_{12,x}^2 + V_{12,y}^2 + V_{12,z}^2}, \quad (5)$$

The family of surfaces satisfying:

$$V_{12}(x, y, z) = V_c, \quad V_c = \text{constant}, \quad (6)$$

constitutes the surfaces of level of the scalar field (5) they define it geometrically. Their canonical type is determined in the coordinate system $S_0(O_0, x_0, y_0, z_0)$. From (4), (5) and (6) it follows [1]:

$$\begin{aligned} x_0^2 + y_0^2 &= R_0^2, \quad z_0 = H, \quad H \in (-\infty, +\infty), \\ x_0 &= x + j_{21}\sin\Sigma_r, \quad y_0 = y, \quad z_0 = z, \\ R_0 &= \sqrt{V_c^2 - (j_{21}\cos\Sigma_r)^2}. \end{aligned} \quad (7)$$

Equation (7) shows that the surfaces of level represent a family of coaxial cylinders — named *kinematic cylinders of level* [1] — with family parameter V_c whose axis coincides with the axis O_0z_0 of the coordinate system $S_0(O_0, x_0, y_0, z_0)$. The surfaces of level will exist if:

$$V_c \geq j_{21}\cos\Sigma_r. \quad (8)$$

When equality holds in (8), the cylinder transforms into the axis O_0z_0 — the zero kinematic cylinder of level — which is the locus of points of minimum sliding velocity.

Substituting the transformation (7) into the components of (4), the sliding velocity vector in $S_0(O_0, x_0, y_0, z_0)$ takes the form:

$$V_{12,x_0} = -y_0, \quad V_{12,y_0} = x_0, \quad V_{12,z_0} = j_{21}\cos\Sigma_r. \quad (9)$$

From equation system (9) for the sliding velocity in $S_0(O_0, x_0, y_0, z_0)$ follows:

$$V_{12,s_0} = \sqrt{x_0^2 + y_0^2 + (j_{21}\cos\Sigma_r)^2}. \quad (10)$$

In every point of the axis O_0z_0 , the sliding velocity vector $\bar{V}_{12}$ obtains its minimum value:

$$V_{12,\min} = V_{12,z_0} = p_{z_0} = j_{21}\cos\Sigma_r \quad (11)$$

3. Conic Linear Helicoids and Distribution Parameter

The kinematic analysis establishes the spatial distribution of the sliding velocity field and identifies the geometric locus corresponding to minimum relative sliding. However, the actual sliding conditions in a spatial rack mechanism additionally depend on the geometry of the contacting tooth surfaces. In conic rack

drives, these active surfaces are generated as linear helicoids whose geometric structure determines both the orientation of the contact lines and consequently the geometry of the action surface within the kinematic field [1]. Therefore, the following analysis focuses on the geometric characteristics of conic linear helicoids and, in particular, on the role of the distribution parameter in relation to the sliding conditions established above.

3.1 Generation of Conic Helicoids and Active Tooth Surfaces- Parametric Representation

The helicoids and especially the linear helicoids are widely used as active tooth surfaces of spatial gears with crossed axes, in both working meshing conditions and instrumental meshing conditions. Such choice of the active tooth surfaces for these gears is determined by the technological manufacturing, especially when their synthesis is performed in accordance with the second Oliver's principle [3, 7].

Fig. 2 shows the generation of right-handed conic convolute helicoids $\Sigma_1^{(j)}$ ($j = 1, 2$) determined by different geometrical characteristics of the helical teeth (treads) of the particular gear mechanism. The process of helical surfaces generation is considered in fixed coordinate system $S_p^{(j)}(O_p^{(j)}, x_p^{(j)}, y_p^{(j)}, z_p^{(j)})$ and it is as

follows. The generatrix $L^{(j)}$ does not cross the axis $O_p^{(j)}z_p^{(j)}$ which coincides with the geometric axis of the gear. $L^{(j)}$ and $O_p^{(j)}z_p^{(j)}$ conclude an angle $0,5\pi < \xi^{(j)} < \pi$. The line $L^{(j)}$ belongs to plane $T^{(j)}$, which is tangential to the directed circled cylinder $C^{(j)}$. The generation of the $\Sigma_1^{(j)}$ by the line $L^{(j)}$ is realized by two generatrix motions: axial helical motion along the longitudinal axis $O_p^{(j)}z_p^{(j)}$ with parameter $p_s^{(j)} = \text{const.}$; crossed helical motion in the plane $T^{(j)}$, perpendicular to the axis $O_p^{(j)}z_p^{(j)}$ with parameter $p_t^{(j)} = \text{const.}$ Here it should be noted that $\Sigma_1^{(1)}$ is the conic convolute helical surface that is turned to the positive direction of the axis $O_p^{(j)}z_p^{(j)}$, and $\Sigma_1^{(2)}$ is the helicoid, turned along the negative direction of the $O_p^{(2)}z_p^{(2)}$.

The vector equation of the conic convolute helical surface $\Sigma_1^{(1)}$, in accordance with Fig. 2, has the form [1]:

$$\bar{\rho}_1^{(j)} = r_0^{(j)} + s^{(j)}\bar{s}^{(j)} + t^{(j)}\bar{t}^{(j)} + u^{(j)}\bar{u}^{(j)}, \quad (12)$$

where $\bar{\rho}_1^{(j)}$ is a radius-vector of point $N^{(j)}$ that belongs to the conic convolute helicoid $\Sigma_1^{(j)}$; $r_0^{(j)}$ - radius-vector of the directed cylinder $C^{(j)}$; $\bar{s}^{(j)}$, $\bar{t}^{(j)}$, $\bar{u}^{(j)}$ - coordinates of the helical surface $\Sigma_1^{(j)}$; $s^{(j)} = p_s^{(j)}g^{(j)}$ - axial motion of the generatrix $L^{(j)}$; $t^{(j)} = p_t^{(j)}g^{(j)}$ - crossed displacement (tangential to the directed cylinder $C^{(j)}$) of the generatrix line $L^{(j)}$.

If (12) is written in coordinate system $S_p^{(j)}$, then:

$$\begin{aligned} x_p^{(j)} &= r_0^{(j)}\cos g^{(j)} \pm (u^{(j)}\sin \xi^{(j)} - p_t^{(j)}g^{(j)})\sin g^{(j)}, \\ y_p^{(j)} &= r_0^{(j)}\sin g^{(j)} \mp (u^{(j)}\sin \xi^{(j)} - p_t^{(j)}g^{(j)})\cos g^{(j)}, \\ z_p^{(j)} &= p_s^{(j)}g^{(j)} \pm u^{(j)}\cos \xi^{(j)}; \end{aligned} \quad (13)$$

For the equation systems (13) the upper signs and $j = 1$ refer to the $\Sigma_1^{(1)}$, and the lower and $j = 2$ refer to the $\Sigma_1^{(2)}$.

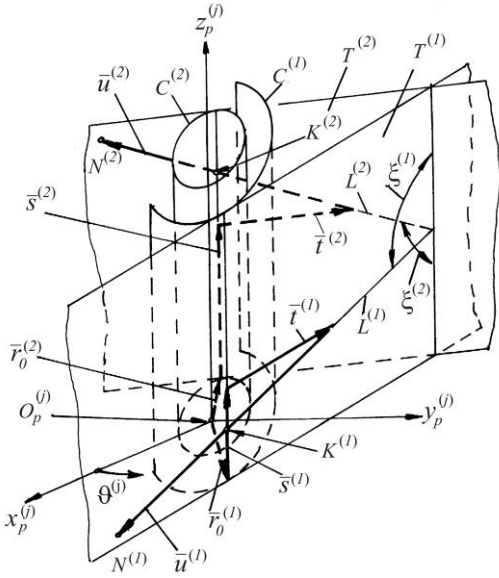


Fig. 2. Conic convolute helicoids generation

After a substitution in (13)

$$R_0^{(j)} = u^{(j)} - \frac{p_t^{(j)} g^{(j)}}{\sin \xi^{(j)}} \text{ and } p^{(j)} = p_s^{(j)} \pm p_t^{(j)} \cot \xi^{(j)}, \quad (14)$$

it is obtained

$$\begin{aligned} x_p^{(j)} &= r_0^{(j)} \cos g^{(j)} \pm R_0^{(j)} \sin \xi^{(j)} \sin g^{(j)}, \\ y_p^{(j)} &= r_0^{(j)} \sin g^{(j)} \mp R_0^{(j)} \sin \xi^{(j)} \cos g^{(j)}, \\ z_p^{(j)} &= p^{(j)} g^{(j)} \pm R_0^{(j)} \cos \xi^{(j)}; \end{aligned} \quad (15)$$

Equations (15) represents the conic convolute helical surface $\Sigma_1^{(j)}$ as a cylindrical one with helical parameter $p^{(j)} = \text{const}$ and coordinates $g^{(j)}$ and $R_0^{(j)}$.

Conic involute helical surfaces generation. It is known [10] that each developable surface is cylindrical one, conic one or locus of the tangential lines to an arbitrary curve and vice versa - each cylindrical, conic or surface representing the locus of tangential lines to a curve is a developable surface.

The specific for each developable surface is, that the parameter of distribution is equal to zero, i.e.

$$h^{(j)} = p^{(j)} + r_0^{(j)} \cot \xi^{(j)} = 0, \text{ or } \cot \xi^{(j)} = -\frac{p^{(j)}}{r_0^{(j)}}. \quad (16)$$

Following the condition (16), the equation (15) describes the conic involute helicoid as:

$$\begin{aligned} x_p^{(j)} &= r_0^{(j)} \cos g^{(j)} \pm R_0^{(j)} \cos \lambda_0^{(j)} \sin g^{(j)}, \\ y_p^{(j)} &= r_0^{(j)} \sin g^{(j)} \mp R_0^{(j)} \cos \lambda_0^{(j)} \cos g^{(j)}, \\ z_p^{(j)} &= p^{(j)} g^{(j)} \mp R_0^{(j)} \sin \lambda_0^{(j)}, \end{aligned} \quad (17)$$

where $R_0^{(j)} = u^{(j)} - \frac{p_t^{(j)} g^{(j)}}{\cos \lambda_0^{(j)}}$, $p^{(j)} = p_s^{(j)} \mp p_t^{(j)} \tan \lambda_0^{(j)}$ and

$\lambda_0^{(j)} = \xi^{(j)} - \pi/2$ is spiral angle [11] for the directed helical line on the cylinder $C^{(j)}$. For this case the cylinder $C^{(j)}$ is named basic cylinder.

Conic Archimedean helical surfaces generation. The conic Archimedean helicoid is generated when the generatrix $L^{(j)}$ (see Fig. 2) crosses the axis $O_p^{(j)} z_p^{(j)}$, i.e. when $r_0^{(j)} = 0$.

Then from (13) it is obtained:

$$\begin{aligned} x_p^{(j)} &= \pm (u^{(j)} \sin \xi^{(j)} - p_t^{(j)} g^{(j)}) \sin g^{(j)}, \\ y_p^{(j)} &= \mp (u^{(j)} \sin \xi^{(j)} - p_t^{(j)} g^{(j)}) \cos g^{(j)}, \\ z_p^{(j)} &= p_s^{(j)} g^{(j)} \pm u^{(j)} \cos \xi^{(j)}. \end{aligned} \quad (18)$$

The curvilinear coordinate $g^{(j)}$ in (18) represents the angle on which the normal vector $\bar{r}_0^{(j)}$ rotates to the axial plane (determined by the $L^{(j)}$ and $O_p^{(j)} z_p^{(j)}$). If it is noted with $g_a^{(j)} = g^{(j)} + \pi/2$, the angle, that the plane $(L^{(j)}, O_p^{(j)} z_p^{(j)})$ concludes with the plane $(O_p^{(j)} x_p^{(j)} z_p^{(j)})$, then the equation systems (18) turn into:

$$\begin{aligned} x_p^{(j)} &= \mp [u^{(j)} \sin \xi^{(j)} - p_t^{(j)} (g_a^{(j)} - \pi/2)] \cos g_a^{(j)}, \\ y_p^{(j)} &= \mp [u^{(j)} \sin \xi^{(j)} - p_t^{(j)} (g_a^{(j)} - \pi/2)] \sin g_a^{(j)}, \\ z_p^{(j)} &= p_s^{(j)} (g_a^{(j)} - \pi/2) \pm u^{(j)} \cos \xi^{(j)}. \end{aligned} \quad (19)$$

4. Action Surface Geometry

The action surface, considered as a locus of the lines of the tooth contact in the fixed space, defines conjugate tooth surfaces of the second movable link – tooth rack.

The offered here study is realized with shown in Fig. 3 symbols.

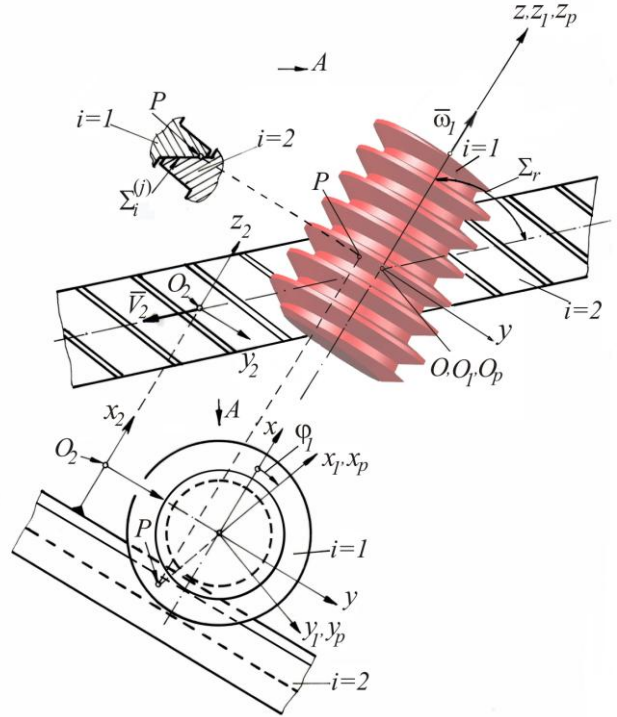


Fig. 3. Geometric-kinematic scheme of spatial rack drive having rotating linear conic helicoids

Conic convolute rack mechanism. The equations (15) of the linear helicoid $\Sigma_1^{(j)}$ are shown as:

$$\begin{aligned} x_p^{(j)} &= r_0^{(j)} \cos g^{(j)} \pm U^{(j)} \sin g^{(j)}, \\ y_p^{(j)} &= r_0^{(j)} \sin g^{(j)} \mp U^{(j)} \cos g^{(j)}, \\ z_p^{(j)} &= p^{(j)} g^{(j)} \pm U^{(j)} \cot \xi^{(j)}, \end{aligned} \quad (20)$$

where $U^{(j)} = R_0^{(j)} \sin \xi^{(j)} = u^{(j)} \sin \xi^{(j)} - p_t^{(j)} g^{(j)}$, $p^{(j)} = p_s^{(j)} \pm p_t^{(j)} \cot \xi^{(j)}$.

The set of equations (20) describes the conic convolute helicoid as a cylindrical one with helical parameter $p^{(j)}$.

The normal vector in an arbitrary point of $\Sigma_1^{(j)}$ is described by equations system:

$$\begin{aligned} n_{1,x_p}^{(j)} &= \mp h^{(j)} \sin \xi^{(j)} \cos \vartheta^{(j)} - U^{(j)} \cos \xi^{(j)} \sin \vartheta^{(j)}, \\ n_{1,y_p}^{(j)} &= \mp h^{(j)} \sin \xi^{(j)} \sin \vartheta^{(j)} + U^{(j)} \cos \xi^{(j)} \cos \vartheta^{(j)}, \\ n_{1,z_p}^{(j)} &= U^{(j)} \sin \xi^{(j)}. \end{aligned} \quad (21)$$

It is known [1, 12] that conic helicoids $\Sigma^{(j)}$ are cylindrical helical surfaces with constant helical parameter $p^{(j)} = \text{const}$.

Hence, for these surfaces is valid the equation of meshing [1, 12]:

$$\tan \Delta = \frac{n_{1,y}}{n_{1,z}} = \frac{p + j_{21} \cos \delta_r}{j_{21} \sin \delta_r} = \text{constant}. \quad (22)$$

Then the action surface of the conic convolute helicoid is described by using the equations (20) and (21) (written in the fixed coordinate system S) and the analytical type (22) of meshing equation (see Fig. 4), i.e.

$$\begin{aligned} x^{(j)} &= r_0^{(j)} \cos \theta^{(j)} \pm U^{(j)} \sin \theta^{(j)}, \\ y^{(j)} &= r_0^{(j)} \sin \theta^{(j)} \mp U^{(j)} \cos \theta^{(j)}, \\ z^{(j)} &= p^{(j)} g^{(j)} \pm U^{(j)} \cot \xi^{(j)}, \\ \frac{\mp h^{(j)} \sin \xi^{(j)} \sin \theta^{(j)} + U^{(j)} \cos \xi^{(j)} \cos \theta^{(j)}}{U^{(j)} \sin \xi^{(j)}} &= \frac{p^{(j)} - j_{21} \cos \Sigma_r}{j_{21} \sin \Sigma_r}, \end{aligned} \quad (23)$$

where $\theta^{(j)} = \vartheta^{(j)} + \varphi_1$, $U^{(j)} = u^{(j)} \sin \xi^{(j)} - p_t^{(j)} g^{(j)} \neq 0$, $p^{(j)} = p_s^{(j)} \pm p_t^{(j)} \cot \xi^{(j)}$, $h^{(j)} = p^{(j)} + r_0^{(j)} \cot \xi^{(j)}$.

The tooth surfaces $\Sigma_2^{(j)}$ ($j=1, 2$) of the tooth rack $i=2$, conjugated with $\Sigma_1^{(j)}$, are obtained from (23), after it is written in the fixed coordinate system S_2 , firmly connected with link $i=2$:

$$\begin{aligned} x_2^{(j)} &= r_0^{(j)} \cos \theta^{(j)} \pm U^{(j)} \sin \theta^{(j)}, \\ y_2^{(j)} &= r_0^{(j)} \sin \theta^{(j)} \mp U^{(j)} \cos \theta^{(j)} + j_{21} \varphi_1 \sin \Sigma_r, \\ z_2^{(j)} &= p^{(j)} g^{(j)} \pm U^{(j)} \cot \xi^{(j)} + j_{21} \varphi_1 \cos \Sigma_r, \\ \frac{\mp h^{(j)} \sin \theta^{(j)} + U^{(j)} \cot \xi^{(j)} \cos \theta^{(j)}}{U^{(j)}} &= \frac{p^{(j)} - j_{21} \cos \Sigma_r}{j_{21} \sin \Sigma_r}. \end{aligned} \quad (24)$$

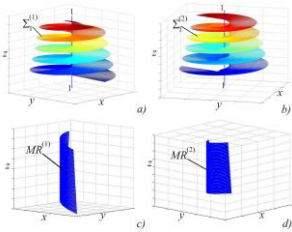


Fig. 4. Spatial conic convolute mechanism with velocity ratio $j_{21} = 2,29$; number of the teeth $z_1 = 1$: a) conic convolute worm $\Sigma_1^{(1)} \Rightarrow \xi^{(1)} = 98^\circ$, b) $\Sigma_1^{(2)} \Rightarrow \xi^{(2)} = 120^\circ$, c) region of mesh $MR^{(1)}$; d) $MR^{(2)}$

Conic Archimedean rack mechanism. The analytical representation of the action surface of the conic Archimedean rack drive (see Fig. 5) is obtained from the (23) after a substitution $r_0^{(j)} = 0$, whence $h^{(j)} = p^{(j)}$, i.e.

$$\begin{aligned} x^{(j)} &= \pm U^{(j)} \sin \theta^{(j)}, \\ y^{(j)} &= \mp U^{(j)} \cos \theta^{(j)}, \\ z^{(j)} &= p^{(j)} g^{(j)} \pm U^{(j)} \cot \xi^{(j)}, \\ \frac{\pm p^{(j)} \sin \theta^{(j)} + U^{(j)} \cot \xi^{(j)} \cos \theta^{(j)}}{U^{(j)}} &= \frac{p^{(j)} - j_{21} \cos \Sigma_r}{j_{21} \sin \Sigma_r}. \end{aligned} \quad (25)$$

Active tooth surfaces $\Sigma_2^{(j)}$ ($j=1, 2$) of the tooth rack of the Archimedean rack drive are obtained from the system (25):

$$\begin{aligned} x_2^{(j)} &= \pm U^{(j)} \sin \theta^{(j)}, \\ y_2^{(j)} &= \mp U^{(j)} \cos \theta^{(j)} + j_{21} \varphi_1 \sin \Sigma_r, \\ z_2^{(j)} &= p^{(j)} g^{(j)} \pm U^{(j)} \cot \xi^{(j)} + j_{21} \varphi_1 \cos \Sigma_r, \\ \frac{\mp p^{(j)} \sin \theta^{(j)} + U^{(j)} \cot \xi^{(j)} \cos \theta^{(j)}}{U^{(j)}} &= \frac{p^{(j)} - j_{21} \cos \Sigma_r}{j_{21} \sin \Sigma_r}. \end{aligned} \quad (26)$$

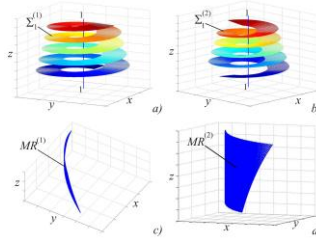


Fig. 5. Spatial conic Archimedean drive with velocity ratio $j_{21} = 2,29$; number of the teeth $z_1 = 1$: a) conic Archimedean right-handed worm $\Sigma_1^{(1)} \Rightarrow \xi^{(1)} = 98^\circ$; b) conic Archimedean right-handed worm $\Sigma_1^{(2)} \Rightarrow \xi^{(2)} = 120^\circ$, c) mesh region $MR^{(1)}$; d) mesh region $MR^{(2)}$

Conic involute rack mechanism. From equations systems (23) after substituting $h^{(j)} = 0$, it is obtained the analytical form of action surfaces (see Fig. 6):

$$\begin{aligned} x^{(j)} &= r_0^{(j)} \cos \theta^{(j)} \pm U^{(j)} \sin \theta^{(j)}, \\ y^{(j)} &= r_0^{(j)} \sin \theta^{(j)} \mp U^{(j)} \cos \theta^{(j)}, \\ z^{(j)} &= p^{(j)} g^{(j)} \pm U^{(j)} \cot \xi^{(j)}, \\ \cot \xi^{(j)} \cos \theta^{(j)} &= \frac{p^{(j)} - j_{21} \cos \Sigma_r}{j_{21} \sin \Sigma_r}. \end{aligned} \quad (27)$$

Bellow (27) is written in the fixed coordinate system, connected with the link $i=2$. Hence, the active tooth surfaces $\Sigma_2^{(j)}$ ($j=1, 2$) of the spatial involute conic rack drive are:

$$\begin{aligned} x_2^{(j)} &= r_0^{(j)} \cos \theta^{(j)} \pm U^{(j)} \sin \theta^{(j)}, \\ y_2^{(j)} &= r_0^{(j)} \sin \theta^{(j)} \mp U^{(j)} \cos \theta^{(j)} + j_{21} \varphi_1 \sin \Sigma_r, \\ z_2^{(j)} &= p^{(j)} g^{(j)} \pm U^{(j)} \cot \xi^{(j)} + j_{21} \varphi_1 \cos \Sigma_r, \\ \cot \xi^{(j)} \cos \theta^{(j)} &= \frac{p^{(j)} - j_{21} \cos \Sigma_r}{j_{21} \sin \Sigma_r}. \end{aligned} \quad (28)$$

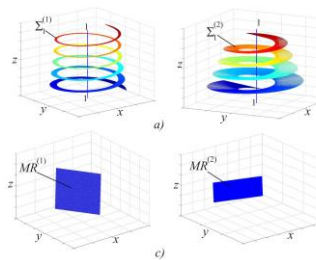


Fig. 6. Spatial conic involute mechanism with velocity ratio $j_{21} = 2,29$; number of the teeth $z_1 = 1$: a) conic involute right-handed worm $\Sigma_1^{(1)} \Rightarrow \xi^{(1)} = 98^\circ$, b) conic involute right-handed worm $\Sigma_1^{(2)} \Rightarrow \xi^{(2)} = 120^\circ$; c) mesh region $MR^{(1)}$; d) mesh region $MR^{(2)}$

5. Helicoid types and distribution parameter

The distribution parameter $h^{(j)}$ establishes a geometric relationship between the angle inclination $\xi^{(j)}$ and the directed cylinder radius $r_0^{(j)}$ which uniquely determines the types of conic helicoid. For conic helicoids, $h^{(j)}$ is defined as [1]:

$$h^{(j)} = p^{(j)} + r_0^{(j)} \cot \xi^{(j)} \quad (29)$$

where $p^{(j)}$ is the helical parameter, $r_0^{(j)}$ is the radius of the cylinder radius, and $\xi^{(j)} \in (90^\circ, 180^\circ)$ is the angle between the generatrix $L^{(j)}$ and the longitudinal axis of the helicoid. When dimensionless geometric ratio $\rho = r_0^{(j)} / p_t^{(j)}$, is introduced, the three variants occupy distinct regions in the (ξ, ρ) parameter space:

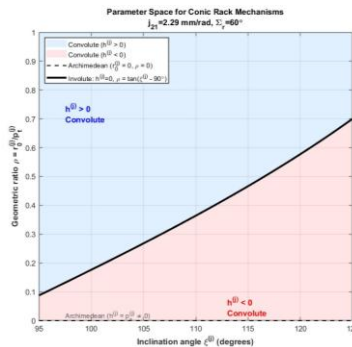


Fig. 7. Parameter space $(\xi^{(j)}, \rho)$ for conic rack drive ($j_{21} = 2, 29$ mm/rad, $\Sigma_r = 60^\circ$). Black curve: involute curve $h^{(j)} = 0$; blue region: convolute $h^{(j)} > 0$; pink region: convolute $h^{(j)} < 0$; dashed line: Archimedean $\rho = 0$.

- *Conic involute helicoid* ($h^{(j)} = 0$): the condition $h^{(j)} = 0$ gives $r_0^{(j)} \cot \xi^{(j)} = -p^{(j)}$, which for the resultant helical parameter $p^{(j)} = p_s^{(j)} \pm p_t^{(j)} \cot \xi^{(j)}$ obtains the curve $\rho = \tan(\xi^{(j)} - 90^\circ)$. This is the black curve in Fig. 7. For this configuration the action surface is of plane type.

- *Conic convolute helicoid* ($h^{(j)} \neq 0$, $r_0^{(j)} > 0$): lies above ($h^{(j)} > 0$) or below ($h^{(j)} < 0$) the involute curve. The action surface is convolute.

- *Conic Archimedean helicoid* ($r_0^{(j)} = 0$, $h^{(j)} = p_s^{(j)} \neq 0$): lies on the boundary $\rho = 0$, shown as the dashed line in Fig. 7. The action surface is Archimedean type.

The involute curve thus separates the parameter space into regions of positive and negative $h^{(j)}$. For a given inclination angle $\xi^{(j)}$, the type of conic helicoid is uniquely determined by the ratio ρ : a scientist or designer can take from Fig. 7 which configuration corresponds to their geometric parameters and what action surface geometry to expect. Thus, the distribution parameter connects the geometry of the active tooth surfaces to the sliding conditions of the mechanism — the type of action surface geometry, determined by $h^{(j)}$, defines the contact line orientation and consequently the conditions under which relative sliding between the tooth surfaces is realized.

6. Conclusion

The paper presents a study of the geometric characteristics of conic spatial rack drives with linear helicoids. The kinematic analysis establishes the sliding velocity field and its theoretical minimum, which depends only on the kinematic parameters of the mechanism. The three variants of conic linear helicoids — convolute, involute, and Archimedean — are characterized by the distribution parameter, which determines the geometry of their action surface.

The design parameter space, defined by the inclination angle $\xi^{(j)}$ and the geometric ratio $\rho = r_0^{(j)} / p_t^{(j)}$, provides a unified geometric framework in which the position of each variant is uniquely determined by $h^{(j)}$. The involute configuration is located on a well-defined curve that separates the convolute regions, while the Archimedean configuration lies on the boundary $\rho = 0$. This classification allows a designer to identify directly, from the geometric parameters of the mechanism, which helicoid type is

realized and what action surface geometry to expect — without additional computation.

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Determination of the stress-strain state of an aircraft wing twisted around its spar

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Abstract: This paper examines an improved method for calculating the stiffness and strength of a pre-twisted wing for special-purpose aircraft. These wings represent a type of adaptive wing, the development of which is the subject of active research in many industrialized countries due to the pressing need for improved aerodynamic performance. Such wings are intended for use in experimental aircraft to determine the influence of their aerodynamic parameters over a wide range of angles of attack during twisting during takeoff, landing, and, most importantly, during cruising flight for complex missions. For example, during rescue operations in hard-to-reach areas or the use of military aircraft for special defense missions.

Such variable-geometry wings require comprehensive research using modern methods of strength of materials and elasticity theory. In this regard, the problem being solved is one of the main fundamental issues of structural mechanics of special-purpose aircraft.

Keywords: WING, TWIST, DISPLACEMENT, SECTION, BENDING MOMENT.

1. Introduction

Efficient flight requires changing the aerodynamic characteristics of an aircraft depending on the mission and the corresponding flight modes. The traditional approach to designing new aircraft currently allows only a slight (up to 5%) increase in lift-to-drag ratio and improvement in takeoff and landing performance.

Wing high-lift devices in the form of simple deflectable leading and trailing edge elements, as well as changes in wing sweep, do not allow for achieving high maximum lift coefficients under varying flight modes.

In recent years, due to the development of technical know-how and the emergence of new aviation materials, increasing attention has been paid to improving aircraft aerodynamic performance by changing wing geometry depending on flight modes, i.e., by using an adaptive wing (Fig.1-2).

Adaptation of aircraft load-bearing components can be achieved by changing the span and sweep of the wing, as well as the shape and size of the wing, and the twist of the wing relative to its spar. We performed a strength and rigidity calculation for such a wing in a previous study; however, this was insufficient to address more complex issues and fully describe the stress-strain state of the structure under consideration.

Therefore, in this study, we attempted a more detailed investigation of this issue and additionally performed a calculation to determine the rotation angles of the wing's free edge cross-section. This allowed us to gain a more complete understanding of the structural deformation of the unit under consideration.

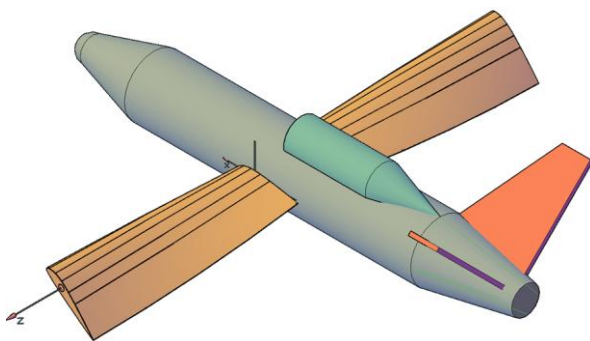


Fig. 1 General axonometric view of an aircraft with twisted wings.

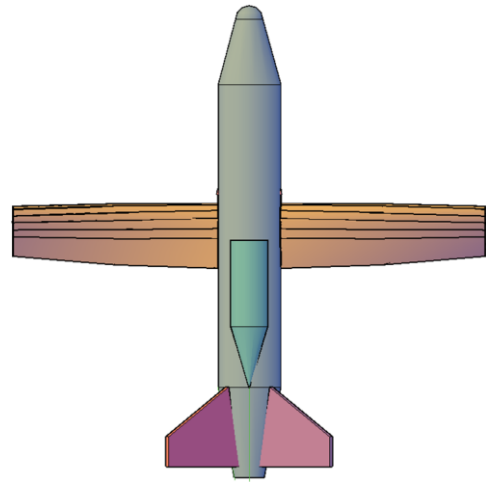


Fig. 2 Aircraft diagram, top plan view.

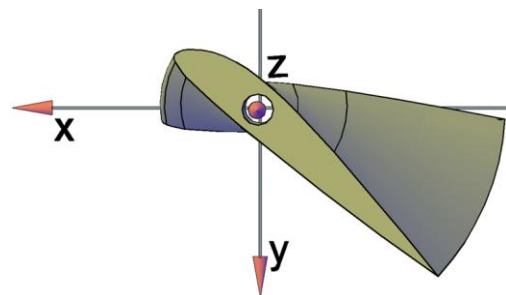


Fig. 3 View of a twisted wing from the free edge.

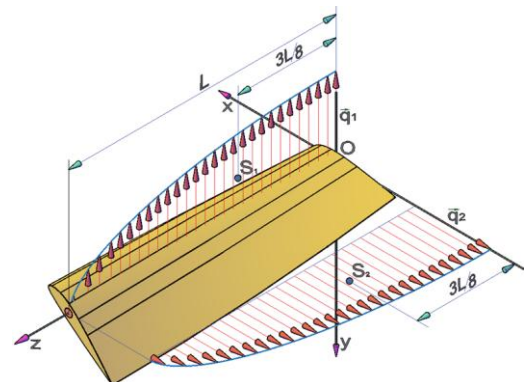


Fig. 4 Diagram of distributed loads acting on the wing, which change according to a parabolic law.

A twisted wing with a lenticular cross-section (Fig. 3) is loaded along its span by two distributed loads acting in mutually perpendicular planes Oxz and Oyz , which vary according to a parabolic law (Fig. 4). Its geometric shapes and dimensions, as well as the mechanical parameters of its cross-section, are predetermined: I_x, I_y are the moments of inertia of the section, l is the wing length, E is the modulus of elasticity of the rod material, q_1 is the parabolically distributed load acting in the Oyz plane, and q_2 is the parabolically distributed load acting in the Oxz plane [1, 3, 9].

To determine the displacements of the twisted wing tip, we use Mohr's formula. First, we obtain the dependences of the bending moments in an arbitrary cross-section on the action of applied parabolically distributed loads q_1 and q_2 and unit forces $F_{1x}=1N$, $F_{1y}=1N$ applied to the end section (Fig. 5). In an arbitrary cross-section, oblique bending occurs in all loading cases [6, 8, 17].

The bending moment from a distributed load in an arbitrary cross-section is determined by the formula:

$$M_q = \omega \cdot \frac{3z}{8} = \frac{2qz^2}{3\sqrt{l}} \cdot \frac{3z}{8} = \frac{q \cdot z^2}{4\sqrt{l}} \quad (1)$$

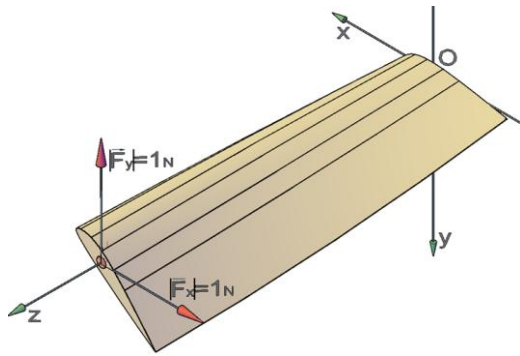


Fig. 5 Scheme of application of unit forces to the free end of the wing.

On the coordinate axes associated with the wing section, the bending moment from the external load acting in this section is projected using the following formulas:

$$\begin{aligned} M_{1xi} &= M_1 \cdot \cos\varphi + M_2 \cdot \cos(90^\circ - \varphi) = \\ &= M_1 \cdot \cos\varphi + M_2 \cdot \sin\varphi = \frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \cos\varphi + \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \sin\varphi; \end{aligned} \quad (2)$$

$$\begin{aligned} M_{yi} &= M_1 \cdot \cos(90^\circ - \varphi) + M_2 \cdot \cos(180^\circ - \varphi) = \\ &= \frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \sin\varphi + \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot (-\cos\varphi) = \\ &= \frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \sin\varphi - \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \cos\varphi; \end{aligned} \quad (3)$$

Bending moments from unit loads applied at the end of the wing are projected onto the same axis (Fig. 6-7) associated with the section using the following formulas:

$$M_{1xi}^h = z \cdot \cos\varphi; \quad M_{1yi}^h = z \cdot \sin\varphi; \quad (4)$$

$$M_{1xi}^v = z \cdot \sin\varphi; \quad M_{1yi}^v = z \cdot (-\cos\varphi); \quad (5)$$

To determine the displacement along the Oy axis, we write Mohr's formula in the following form:

$$\Delta_y = \int_0^l \frac{M_{xi} M_{1xi}^h}{EI_{xi}} dz + \int_0^l \frac{M_{yi} M_{1yi}^h}{EI_{yi}} dz; \quad (6)$$

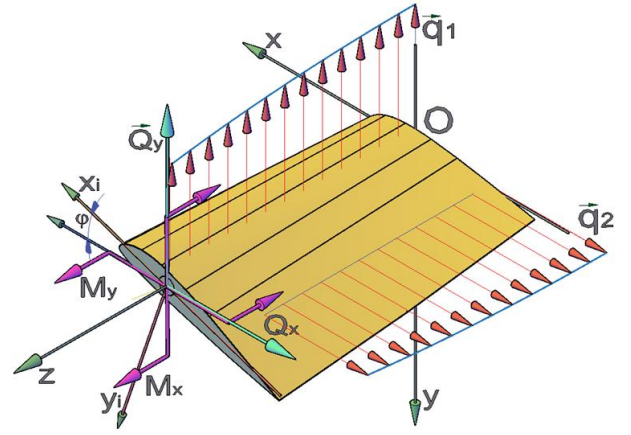


Fig. 6 Diagram of internal and external force factors acting on the cut-off part of the wing.

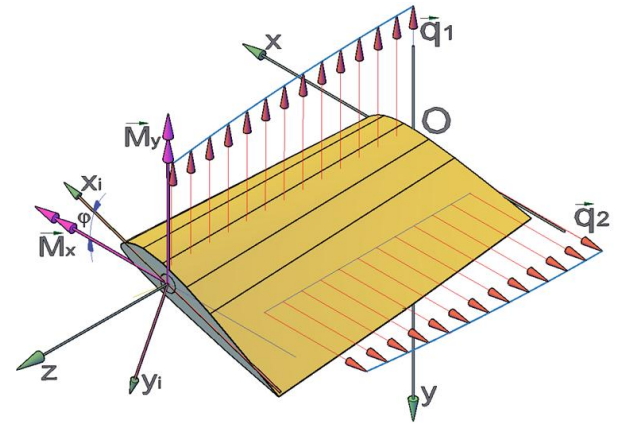


Fig. 7 Scheme of application of internal moments acting in an arbitrary section of the wing.

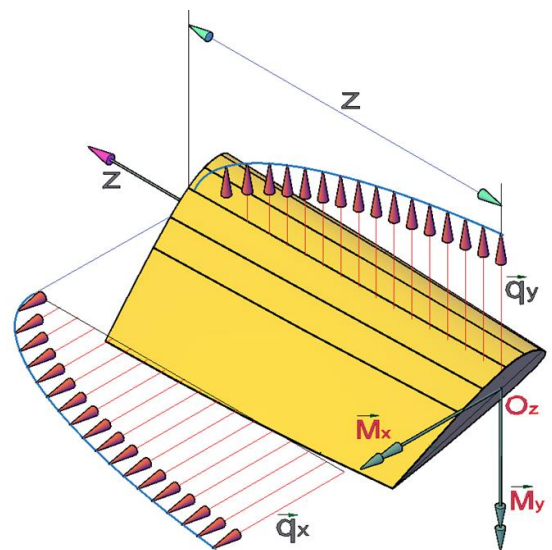


Fig. 8 Scheme of application of internal moments acting in a section at a distance Z from the free edge of the wing.

To solve this expression, the integrals included in it must be solved separately, for which it is necessary to replace the variable according to the following formulas:

$$z = \frac{6l}{\pi} \varphi, \quad dz = \frac{6l}{\pi} d\varphi; \quad (7)$$

Since the wing tip rotates by 30° at maximum twist in the case we are considering, the integration limits are taken from 0 to $\pi/6$ (Fig.8)

Then the first integral from expression (6) is calculated as follows:

$$\begin{aligned} \int_0^l \frac{M_{x_i} M_{1x_i}^h}{EI_{x_i}} dz &= \int_0^l \left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \varphi \right] \cdot z \cdot \cos \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^l \frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos^2 \varphi + \frac{q_2 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{7}{2}} \cdot q_1}{4\sqrt{l}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{7}{2}} \cdot q_2}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot \varphi^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi \cdot d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot \varphi^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot d\varphi = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi \cdot d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi \cdot d\varphi \end{aligned} \quad (8)$$

Solving the second integral from expression (6) we obtain:

$$\begin{aligned} \int_0^l \frac{M_{y_i} M_{1y_i}^h}{EI_{y_i}} dz &= \int_0^l \left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \varphi - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi \right] \cdot z \cdot \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^l \frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \sin^2 \varphi - \frac{q_2 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \sin^2 \varphi \cdot d\varphi - \\ &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi \cdot d\varphi \end{aligned} \quad (9)$$

By summing up the obtained results of these integrals, we obtain an expression for determining the displacement of the end of a twisted wing along the Oy axis [4, 6]:

$$\begin{aligned} \Delta_y &= \int_0^l \frac{M_{x_i} M_{1x_i}^h}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y_i}^h}{EI_{y_i}} dz = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi \cdot d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi \cdot d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \sin^2 \varphi \cdot d\varphi - \\ &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi \cdot d\varphi = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} 0,0099 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} 0,0045 + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} 0,0021 - \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} 0,0045; \end{aligned} \quad (10)$$

To determine the displacement along the Ox-axis, we write Mohr's formula in the following form:

$$\Delta_x = \int_0^l \frac{M_{x_i} M_{1x_i}^v}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y_i}^v}{EI_{y_i}} dz; \quad (11)$$

Proceeding in a similar manner to the previous one, calculations are made for the first integral of the expression:

$$\begin{aligned}
 \int_0^l \frac{M_{x_i} M_{1x_i}^v}{EI_{x_i}} dz &= \int_0^l \frac{(M_1 \cdot \cos \varphi + M_2 \cdot \sin \varphi) \cdot z \cdot \sin \varphi}{EI_{x_i}} dz = \\
 &= \int_0^l \frac{q_1 \cdot z^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi + q_2 \cdot z^{\frac{7}{2}} \cdot \sin^2 \varphi}{EI_{x_i}} dz = \\
 &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi d\varphi + \\
 &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \sin^2 \varphi d\varphi
 \end{aligned} \quad (12)$$

For the second integral of expression (11) we will have:

$$\begin{aligned}
 \int_0^l \frac{M_{y_i} M_{1y_i}^v}{EI_{y_i}} dz &= \int_0^l \frac{[M_1 \cdot \sin \varphi + M_2 \cdot (-\cos \varphi)] \cdot z \cdot (-\cos \varphi)}{EI_{y_i}} dz = \\
 &= \int_0^l \frac{\left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \varphi - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi \right] \cdot z \cdot (-\cos \varphi)}{EI_{y_i}} dz = \\
 &= \int_0^l \frac{\frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot (-\cos \varphi \sin \varphi) + \frac{q_2 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos^2 \varphi}{EI_{y_i}} dz = \\
 &= - \int_0^{\pi/6} \frac{\frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi}{EI_{y_i}} \cdot \frac{6l}{\pi} d\varphi + \\
 &+ \int_0^{\pi/6} \frac{\frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^3 \cdot q_{2x}}{4} \cdot \cos^2 \varphi}{EI_{y_i}} \cdot \frac{6l}{\pi} d\varphi = \\
 &= - \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi d\varphi + \\
 &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi d\varphi
 \end{aligned} \quad (13)$$

By summing up the results obtained from these integrals, we obtain an expression for determining the displacement of the end of a twisted wing along the Ox axis:

$$\begin{aligned}
 \Delta_x &= \int_0^l \frac{M_{x_i} M_{1x_i}^v}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y_i}^v}{EI_{y_i}} dz = \\
 &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi d\varphi + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \sin^2 \varphi d\varphi - \\
 &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi d\varphi + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi d\varphi = \\
 &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} 0.0045 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} 0.0021 - \\
 &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} 0.0045 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} 0.0099
 \end{aligned} \quad (14)$$

The total displacement of the end of a twisted wing is obtained by summing the displacements found:

$$\Delta = \sqrt{\Delta_x^2 + \Delta_y^2} \quad (15)$$

To determine the rotation angles of a twisted wing tip, bending moments equal in magnitude to unity must be applied to the free end. Substituting these moments into Mohr's formula yields expressions determining the rotation angles of the free wing tip (Fig. 9) [10, 20].

First, we apply a unit moment around the Ox axis, $M_{1x}=1$ N/mm, and determine its projections onto the axes $O_i x_i$ and $O_i y_i$ associated with the section:

$$M_{1x(x_i)} = M_{1x} \cdot \cos \varphi = 1 \cdot \cos \varphi = \cos \varphi \quad (16)$$

$$M_{1x(y_i)} = M_{1x} \cdot \cos(90^\circ - \varphi) = 1 \cdot \sin \varphi = \sin \varphi \quad (17)$$

After this, we apply $M_{1x}=1$ N/mm - around the Oy axis and determine its projections onto the same axes $O_i x_i$ and $O_i y_i$

$$\begin{aligned}
 M_{1y(x_i)} &= M_{1y} \cdot \cos(90^\circ - \varphi) = \\
 &= M_{1y} \cdot \sin \varphi = 1 \cdot \sin \varphi = \sin \varphi
 \end{aligned} \quad (18)$$

$$\begin{aligned}
 M_{1y(y_i)} &= M_{1y} \cdot \cos(180^\circ - \varphi) = \\
 &= M_{1y} \cdot (-\cos \varphi) = 1 \cdot (-\cos \varphi) = -\cos \varphi
 \end{aligned} \quad (19)$$

The angles of rotation of the wing tip relative to the axes Ox, Oy are determined using Mohr's formulas:

$$\varphi_x = \int_0^l \frac{M_{x_i} M_{1x(x_i)}}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1x(y_i)}}{EI_{y_i}} dz \quad (20)$$

$$\varphi_y = \int_0^l \frac{M_{x_i} M_{1y(x_i)}}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y(y_i)}}{EI_{y_i}} dz \quad (21)$$

First, we calculate each integral separately, and then we sum them up [20, 26].

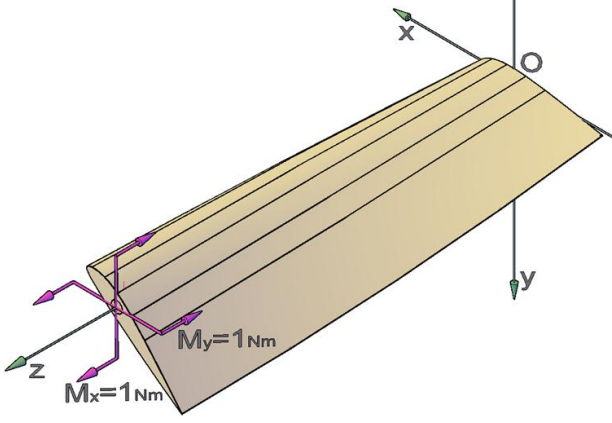


Fig. 9 Scheme of application of single moments of a pair of forces to the free end of a wing.

For the first integral of expression (20), the following calculations are performed:

$$\begin{aligned}
 \int_0^l \frac{M_{x_i} M_{1x(x_i)}}{EI_{x_i}} dz &= \int_0^l \frac{\left[\frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \cos \varphi + \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \sin \varphi \right] \cdot \cos \varphi}{EI_{x_i}} dz = \\
 &= \int_0^l \frac{\frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \cos^2 \varphi + \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi}{EI_{x_i}} dz = \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{5}{2}} \cdot q_1 \cdot \cos^2 \varphi}{4\sqrt{l} EI_{x_i}} \cdot \frac{6l}{\pi} d\varphi + \\
 &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{5}{2}} \cdot q_2 \cdot \cos \varphi \sin \varphi}{4\sqrt{l} EI_{x_i}} \cdot \frac{6l}{\pi} d\varphi = \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{5}{2}} \cdot q_1}{4EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi + \\
 &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{5}{2}} \cdot q_2}{4EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \varphi^{\frac{5}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi d\varphi + \\
 &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \varphi^{\frac{5}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi d\varphi =
 \end{aligned}$$

$$\begin{aligned}
 &= \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos^2 \varphi d\varphi + \\
 &+ \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos \varphi \sin \varphi d\varphi; \quad (22)
 \end{aligned}$$

For the second integral of this expression we will have:

$$\begin{aligned}
 \int_0^l \frac{M_{y_i} M_{1x(y_i)}}{EI_{y_i}} dz &= \int_0^l \frac{\left[\frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \sin \varphi - \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \cos \varphi \right] \cdot \sin \varphi}{EI_{y_i}} dz = \\
 &= \int_0^l \frac{\frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \sin^2 \varphi - \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi}{EI_{y_i}} dz = \\
 &= \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \sin^2 \varphi d\varphi - \\
 &- \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos \varphi \sin \varphi d\varphi \quad (23)
 \end{aligned}$$

After calculating the first integral of expression (21), we obtain:

$$\begin{aligned}
 \int_0^l \frac{M_{x_i} M_{1y(x_i)}}{EI_{x_i}} dz &= \\
 &= \int_0^l \frac{\left[\frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot (-\sin \varphi) + \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot (-\cos \varphi) \right] \cdot (-\cos \varphi)}{EI_{x_i}} dz = \\
 &= \int_0^l \frac{\frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi + \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \cos^2 \varphi}{EI_{x_i}} dz = \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{5}{2}} \cdot q_1}{4\sqrt{l} EI_{x_i}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi + \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{5}{2}} \cdot q_2}{4\sqrt{l} EI_{x_i}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi = \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{5}{2}} \cdot q_1}{4EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi + \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{5}{2}} \cdot q_2}{4EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi = \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \varphi^{\frac{5}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi d\varphi + \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \varphi^{\frac{5}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi d\varphi = \\
 &= \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos \varphi \sin \varphi d\varphi + \frac{\left(\frac{6l}{\pi} \right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos^2 \varphi d\varphi; \quad (24)
 \end{aligned}$$

For the second integral of this expression we will have:

$$\begin{aligned} \int_0^l \frac{M_{y_i} M_{1y(y_i)}}{EI_{y_i}} dz &= \int_0^l \frac{\left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos\varphi + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\sin\varphi) \right] \cdot (-\sin\varphi)}{EI_{y_i}} dz = \\ &= \int_0^l \frac{\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\cos\varphi \sin\varphi) + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin^2\varphi}{EI_{y_i}} dz = \\ &= -\frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos\varphi \sin\varphi d\varphi + \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \sin^2\varphi \cdot d\varphi; \quad (25) \end{aligned}$$

After substituting the solutions of these integrals into formulas (20) and (21), we finally obtain expressions for the angles of rotation of the wing tip relative to the Ox and Oy axes:

The rotation relative to the Ox axis is determined by the expression [12, 16]:

$$\begin{aligned} \varphi_x &= \int_0^l \frac{M_{x_i} M_{1x(x_i)}}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1x(y_i)}}{EI_{y_i}} dz = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos^2\varphi d\varphi + \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos\varphi \sin\varphi \cdot d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \sin^2\varphi d\varphi - \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos\varphi \sin\varphi \cdot d\varphi = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} 0,0347 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} 0,0098 + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} 0,0031 - \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} 0,0098 \quad (26) \end{aligned}$$

The rotation about the Oy axis is determined by the expression:

$$\begin{aligned} \varphi_y &= \int_0^l \frac{M_{x_i} M_{1y(x_i)}}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y(y_i)}}{EI_{y_i}} dz = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos\varphi \sin\varphi d\varphi + \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \sin^2\varphi \cdot d\varphi - \\ &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos\varphi \sin\varphi d\varphi + \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos^2\varphi \cdot d\varphi = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} 0,0098 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} 0,0031 - \\ &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} 0,0098 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} 0,0347; \quad (27) \end{aligned}$$

To determine the normal stress in any section of the wing in the formulas for bending moments from transverse loads relative to the axes $O_i x_i$ and $O_i y_i$, it is necessary to replace the variable in the following way [9, 20, 22]:

$$z = \frac{6l}{\pi} \varphi; \quad \varphi = \frac{z\pi}{6l}; \quad (28)$$

Relative to the $O_i x_i$ - axis, the bending moment will have the form:

$$M_{1x_i} = M_1 \cdot \cos\varphi + M_2 \cdot \sin\varphi = \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos\frac{z\pi}{6l} + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin\frac{z\pi}{6l} \quad (29)$$

The formula determining the moment of inertia of the wing section relative to the axis $O_i x_i$ will be:

$$J_{npx_i} = \sum_{i=1}^n F_{inp} \cdot x_i^2 \quad (30)$$

The formula determining the moment of resistance of the wing section relative to the same axis $O_i x_i$ will be:

$$W_{x_i} = \frac{\sum_{i=1}^n F_{inp} \cdot x_i^2}{y_{max}} \quad (31)$$

The normal stress from this bending moment is found using the formula [4, 6]:

$$\sigma_{x_i} = \frac{M_{x_i}}{W_{x_i}} = \frac{\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cos\frac{z\pi}{6l} + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \sin\frac{z\pi}{6l}}{\frac{\sum_{i=1}^n F_{inp} \cdot x_i^2}{y_{max}}} = \frac{y_{max} \left(\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cos\frac{z\pi}{6l} + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \sin\frac{z\pi}{6l} \right)}{\sum_{i=1}^n F_{inp} \cdot x_i^2}; \quad (32)$$

Relative to the $O_i y_i$ - axis, the bending moment will have the form:

$$\begin{aligned} M_{y_i} &= M_1 \cdot \sin\varphi + M_2 \cdot (-\cos\varphi) = \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin\varphi + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\cos\varphi) = \\ &= \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin\varphi - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos\varphi; \quad (33) \end{aligned}$$

The formula determining the moment of inertia of the wing section relative to the $O_i y_i$ axis will be:

$$J_{npy_i} = \sum_{i=1}^n F_{inp} \cdot y_i^2 \quad (34)$$

The formula determining the moment of resistance of the wing section relative to the same axis $O_i y_i$ will be:

$$W_{y_i} = \frac{\sum_{i=1}^n F_{inp} \cdot y_i^2}{x_{max}} \quad (35)$$

The normal stress from this bending moment is found using the formula:

$$\sigma_{y_i} = \frac{M_{y_i}}{W_{y_i}} = \frac{M_1 \cdot \sin\frac{z\pi}{6l} - M_2 \cdot \cos\frac{z\pi}{6l}}{\frac{\sum_{i=1}^n F_{inp} \cdot y_i^2}{x_{max}}} = \frac{x_{max} \left(\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \sin\frac{z\pi}{6l} - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cos\frac{z\pi}{6l} \right)}{\sum_{i=1}^n F_{inp} \cdot y_i^2}; \quad (36)$$

The total normal stress acting in an arbitrary section of a twisted wing is obtained by summing the previously obtained stresses:

$$\sigma_z = \sigma_{x_i} + \sigma_{y_i} = \frac{M_{x_i}}{W_{x_i}} + \frac{M_{y_i}}{W_{y_i}} =$$

$$= \frac{x_{max} \cdot \left(\frac{q_2 \cdot z^2}{4\sqrt{l}} \sin \frac{z\pi}{6l} - \frac{q_2 \cdot z^2}{4\sqrt{l}} \cos \frac{z\pi}{6l} \right)}{\sum_{i=1}^n F_{imp} \cdot x_i^2} + \frac{y_{max} \cdot \left(\frac{q_1 \cdot z^2}{4\sqrt{l}} \cos \frac{z\pi}{6l} + \frac{q_2 \cdot z^2}{4\sqrt{l}} \sin \frac{z\pi}{6l} \right)}{\sum_{i=1}^n F_{imp} \cdot y_i^2}; \quad (37)$$

2. Conclusion

Based on the results of the analysis of design options and preliminary corresponding aerodynamic calculations for the proposed special-purpose aircraft, it has been established that:

1. Future experimental aircraft, in principle, could be equipped with variable-geometry wings, since these wings can practically change their shape during flight, allowing them to adapt to changing conditions at different stages of flight. These measures enable the aircraft under consideration to become more efficient, safer, and easier to control.
2. Particularly noteworthy are the advantages that allow the aircraft to more easily respond to turbulence, strong cross-currents, and unexpectedly changing and extreme flight conditions.
3. A critical step in the design of such wings is strength and rigidity calculations, based on the fact that large wing deformations can cause additional normal and shear stresses in structural components that may exceed their permissible values. This can lead to component failure, including the failure of the entire wing and, ultimately, the entire aircraft.
4. We deemed it necessary to perform not only strength calculations but also calculations to determine the lateral displacements and rotation angles of the entire wing. A preliminary solution to these issues is presented in our proposed work.
5. After the development and implementation of modern automatic control system methods, the effectiveness of the above solutions will be significantly increased.

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Model for implementing blockchain in the supply chain for product traceability in support of industry 4.0

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Abstract: Blockchain technology is primarily implemented in the supply chain for disintermediation to reduce transactional fees. A secondary use case is for product traceability. A key element in achieving Industry 4.0 within the supply chain includes the use of blockchain for product traceability. To do this, questions arise concerning critical success factors for implementation and their interaction. This research evaluates a potential relationship between identified critical success factors and uses those relationships to design a model for successfully implementing product traceability in the supply chain through blockchain. This research also evaluates the impact certain factors, such as organization size, revenue, or type of industry may have on which critical success factors are most important for implementing blockchain in the supply chain.

Keywords: SUPPLY CHAIN, BLOCKCHAIN, PRODUCT TRACEABILITY

1. Introduction

Blockchain was originally designed for cryptocurrency. Initially focused on financial transactions blockchain found success when applied to other types of transactions. This creates possibilities for other blockchain applications, including supply chain traceability. Using blockchain in the supply chain has been advocated in recent years [1].

Purchasing goods in a modern supply chain involve third parties such as a banks or brokers. This process incurs bank transaction fees. Satoshi Nakamoto's 2008 paper, which first proposed a distributed ledger, eliminated the need for a trusted third-party payment system [2]. Blockchain technology allows for peer-to-peer payments using a digital currency across a public ledger system which avoids transaction fees. These small transaction fees add up to large sums of money when hundreds, thousands, or tens of thousands of transactions are processed.

In addition to avoiding transactional fees, there are other use cases that make the implementation of distributed ledger technology a growing trend [3]. The use case of interest here is that of product traceability. Traceability is always a concern for companies.

2. Prerequisites and means for solving the problem

2.1 Prerequisites

There is a lot of discussion around traditional traceability systems and their improvement. Methods of improving current systems include bar codes and Radio Frequency Identification (RFID) tags [4]. While these methods provide improvements, they do not fundamentally change the process. Current processes around product traceability, and established technologies for improvement, cannot fundamentally support achievement of Industry 4.0. There are five common types of issues experienced in traceability systems:

1. Real time information [5] – The ability to retrieve information in a timely manner. The inability to have timely information is not only a frustration for companies and consumers, it can also be a legal requirement.
2. Easy availability [6] – The ability to access information. When a blockchain established on the supply chain has the traceability information included, the information becomes easily available at every stage of the supply chain.
3. Long term storage [4] – Retaining information for extended periods of time. Traditional filing systems (i.e. paper) create difficulties including, physical storage space, degradation of materials, and reliance on master

copies. Storing the same data on the blockchain alleviates the need of physical storage space, degradation of materials, and reliance on master copies. Inclusion on a distributed ledger, by definition, contains multiple copies and protects against data corruption.

4. Security [7] – Preventing the data from being compromised. A public ledger system is solved in blocks making it almost impossible to forge. These blocks cannot be altered but only added to, which creates a chain of blocks. Thus it was titled block chain. Short of a 51% attack it is impossible to change an entry after it has been codified as part of the blockchain.
5. Accuracy [7] – The data does not contain errors. Systems designed to automatically enter traceability information mitigates risks associated with human data entry. Sharp estimates that data entry, even among skilled typists, contains one mistake for every 300 characters [33]. Conversely, automated systems have approximately one mistake per 1 million characters.

Blockchain is well suited to handle the issues associated with traditional traceability systems. Improving upon the limitations of traditional traceability systems presents a powerful support for the use case of blockchain for product traceability in the supply chain.

2.2 Research Problem

It is clear that Blockchain has the capacity to solve many issues associated with traceability systems and support the transition to Industry 4.0. The question now concerns the implementation of blockchain in the supply chain for product traceability. There are many factors influencing blockchain implementation. Which factors have the greatest influence on implementation of blockchain in the supply chain?

2.3 Research Questions

Research question 1: What factors most influence blockchain implementation in the supply chain for product traceability?

Research question 2: Do organization size, revenue, or type of industry have an impact on which critical success factors are considered most important for implementing blockchain in the supply chain?

2.4 Analysis

Two types of analyses were used to complete the study, with all data being collected from one survey instrument. The research design was a quantitative non-probabilistic study using a

convenience sample of supply chain professionals at the Association for Supply Chain Management (ASCM) national conference and LinkedIn ASCM group members.

The analysis for research question 1 was correlational using stepwise regression. The analysis for research question 2 was causal comparative using t-tests.

The quantitative survey instrument used a Likert-type scale based on the research questions enumerated above and the critical success factors given by Clohessy [8]. The critical success factors from Clohessy under consideration were:

Technological

- Perceived Benefits
- Complexity
- Compatibility
- Data Security
- Smart Contract Coding
- Maturity
- Relative Advantage
- Disintermediation
- Permissions (public vs private)
- Architecture

Organizational

- Organizational/Value Chain Readiness
- Top Management Support
- Organizational Size
- Business Model Readiness
- Technology Readiness
- Innovativeness
- Participation Incentives
- Blockchain Knowledge

Environmental

- Regulatory Environment/Regulation
- Market Dynamics/Competitive Pressure
- Industry Pressure/Standards
- Government Support
- Business Use Cases
- Trading Partner Support
- Critical User Mass

The 25 factors identified by Clohessy were categorized in two groups. The first category is factors that influence the decision to implement blockchain as compared to the second category which are those factors that influence how well blockchain is implemented.

Decision factors are those a company would consider when deciding whether or not to implement blockchain. A company should consider the compatibility, complexity, data security, regulatory environment/regulation, participation incentives, maturity, business model readiness, critical user mass, technology readiness, government support, perceived benefits, trading partner support, organizational/value chain readiness, innovativeness, disintermediation, relative advantage, and market dynamics/competitive pressure. These are factors companies use to determine if they are ready for blockchain implementation.

Implementation factors are those that help determine how well blockchain is implemented. These include architecture, permissions (public vs private), industry pressure/standards, top management support, blockchain knowledge, organizational size, smart contract coding, and business use cases. These factors help predict successful implementation.

2.5 Research Hypotheses

To answer research question 1, implementation factors were analysed using a stepwise regression in Minitab to build the statistical model. This method ensured all variables were considered.

Three groups were compared to answer research question 2. Comparisons of groups were organization size, revenues, and industry. Small to Medium Enterprises (SMEs) are defined as those with 500 or fewer employees. Large organizations are defined as those with more than 500 employees [9]. Revenue used two categories – low and high revenue. Low revenue was defined as less than 250 million US dollars annually and more than 250 million US dollars annually for high revenue. The third comparison was industry. Broad categories of manufacturing and service were used.

Using these categories, the following research hypotheses were established:

H₀1: There is no significant difference on the critical success factors between small and large organizations for implementing blockchain in the supply chain.

H_a1: There is a significant difference on the critical success factors between small and large organizations for implementing blockchain in the supply chain.

H₀2: There is no significant difference on the critical success factors between low and high revenues for implementing blockchain in the supply chain.

H_a2: There is a significant difference on the critical success factors between low and high revenues for implementing blockchain in the supply chain.

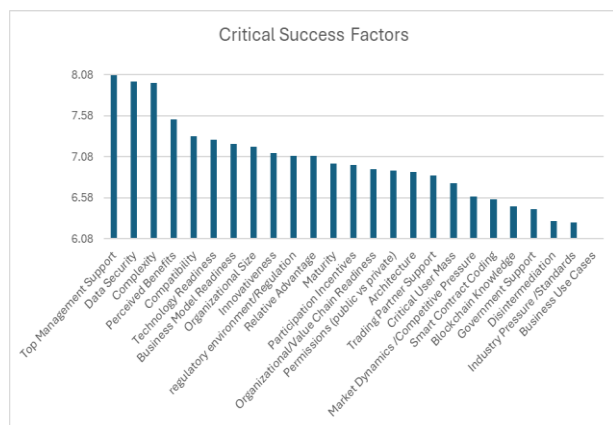
H₀3: There is no significant difference on the critical success factors between manufacturing and service industry for implementing blockchain in the supply chain.

H_a3: There is a significant difference on the critical success factors between manufacturing and service industry for implementing blockchain in the supply chain.

3. Solution of the examined problem

3.1 Research Question 1

The survey instrument asked the respondents to rank to what extent the critical success factors influence implementation of blockchain in the supply chain. They were asked to rate how much the listed factor will influence blockchain implementation in the supply chain. A rating of 1 is no influence on implementation and a rating of 10 is extremely high influence on implementation. These rankings were averaged across all responses and the following bar chart was created.

Figure 1. Bar Chart of Critical Success Factor Rankings

Top management support, data security, and complexity (how complicated blockchain will be to implement) represented the top three factors with average rankings of 8.07, 8.00, and 7.98 respectively. It is worth noting the large drops in relative rankings after complexity and again after perceived benefits. With only a 1.98 difference between the average ranking of the top critical success factor and the lowest average ranked critical success factor, a drop of 0.446 from complexity to perceived benefits and another drop of 0.202 to compatibility represents 22.5% and 10.2% of the total difference. Roughly one-third of the difference.

Research question 1 asked which factors most influence the implementation of blockchain in the supply chain for product traceability. Simplistically this can be answered by the bar chart shown in figure 1. A more complete answer includes evaluating a relationship that might exist between the identified critical success factors and using those relationships to design a model for the successful implementation of blockchain in the supply chain as it relates to product traceability.

Successful implementations and unsuccessful implementations were compared using stepwise regression to generate a model. The regression model for implementing blockchain in the supply chain is written as:

$$\text{Success} = 0.286 + 0.1512 \text{ Permissions} + 0.0745 \text{ Organizational Size} + 0.1589 \text{ Blockchain Knowledge}.$$

It is interesting to note that in the simple bar chart, the top 3 factors are Top Management Support, Data Security, and Complexity, while in the model none of these factors are represented.

Permissions in the model refers to the two basic formats for the implementation of a block chain; public and permissioned (sometimes called private). Public blockchains are exactly as the name sounds. They are open to the public. Anyone with network access can become a node on the network. Once on the network, the node has full permissions to read, transact, and create blocks. In a permissioned blockchain, someone must receive permission from the network owner to access the blockchain network. The network “owner” can set permissions on who can read information on the blockchain, who can transact on the blockchain, and who can write new blocks to the chain [10].

3.2 Research Question 2

For organizational size there are two critical success factors that have a statistically significant difference at the .05 level. Trading Partner Support, with a p value of 0.036, shows a clear difference in

responses for organizational size. Participation Incentives is also statistically significant with a p value of 0.05.

The null hypothesis for organizational size is that there is no significant difference between the critical success factors between small and large organizations for implementing blockchain in the supply chain. With two critical success factors having a statistically significant differences between small and large organizations, this study rejects the null hypothesis at the .05 significance level for those two factors. There is a significant difference between the critical success factors among small and large organizations for implementing blockchain in the supply chain. The means of the critical success factors are not the same between small and large organizations. This can be interpreted that the organization size may affect the level of influence of critical success factors.

The next comparison of the data was by revenue.

Based on the α of 0.05, there are no critical success factors that have a statistically significant difference.

The null hypothesis for organizational revenue is that there is no significant difference between the critical success factors between low and high revenues for implementing blockchain in the supply chain. With no critical success factors having a statistically significant difference between low and high revenues, this study fails to reject the null hypothesis at the .05 significance level for those two factors. This can be interpreted that the organization revenue does not affect the level of influence of critical success factors.

The final comparison of the data was by industry.

Based on the a priori $\alpha = 0.05$, there is one critical success factor that has a statistically significant difference. Organizational/Value Chain Readiness, with a p value of 0.014, shows a clear difference in responses from manufacturing and service.

The null hypothesis for industry is that there is no significant difference between the critical success factors between manufacturing and service industry for implementing blockchain in the supply chain. With one critical success factor having a statistically significant difference between manufacturing and service industry, this study rejects the null hypothesis at the .05 significance level for those two factors. There is a significant difference between the critical success factors among industries for implementing blockchain in the supply chain. The means of the critical success factors are not the same between industries. This can be interpreted that type of industry affects the level of influence of critical success factors.

4. Results and discussion

4.1 Research Question 1

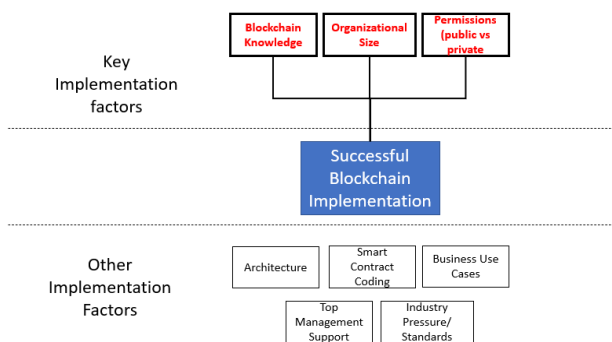
To answer research question 1, the 25 critical success factors had to first be divided into implementation factors and decision factors. The implementation factors are what were considered in developing the model for implementation. The findings for research question 1 indicate that of the eight implementation factors, only three are needed to model successful implementation. A multiple linear regression was calculated to predict successful implementation of blockchain (the dependent variable) based upon the independent variables of the implementation factors ((blockchain knowledge, organizational size, permissions (public vs private), architecture, smart contract coding, business use cases, top

management support, and industry pressure/standards)). A significant regression equation was found ($F(3,5) = 47.29$, $P < .000$), with an R^2 of .966. Participants' predicted successful implementation of blockchain is equal to $0.286 + 0.1512$ Permissions + 0.0745 Organizational size + 0.1589 Blockchain knowledge, where permissions, organizational size, and blockchain knowledge is measured as a 1 to 10 ranking. Permissions, organizational size, and blockchain knowledge were significant predictors of successful implementation.

The R^2 value predicts 96.6% of the variability of its response data around its mean. This is not to say that the factors not included in the model are not important to implementation. It is to say that these 3 best represent the regression line.

To represent the mathematical model in a visual way, only the implementation factors are presented. When thought of this way, a visual representation of the model becomes apparent. Figure 2 represents the visual model.

Figure 2. Model of Factors Influence on Implementing Blockchain



4.2 Research Question 2

Blockchain knowledge, organizational size and permissions (public vs private) are the primary factors predicting successful implementation of blockchain. Though, the other five implementation factors in the model (Top management support, industry pressure/standards, architecture, smart contract coding, and business use cases) should also be considered.

By failing to reject the second null hypothesis, the model would apply in organizations of different revenue levels. The implication of rejecting the first and third null hypothesis is whether or not the implementation model still applies in organizations of different size and different industries. On its face, the model would not apply to different organizational sizes or different industries. Looking deeper, the critical success factors that had a statistically significant difference are those that are not in the model. It is further shown that the critical success factors that had a statistically significant difference are decision factors and not implementation factors. Based on this further examination, the model would still apply to organizations of different sizes and different industries.

5. Conclusions

Investment is ongoing as companies work to develop blockchain technology. An example of this is Catena-X in the automotive industry. One of the main goals of the technology is disintermediation. By removing banks and brokers from the payment process in the supply chain, transactional costs can be eliminated. By eliminating the transactional costs, the benefits are monetary. Standardized data exchange across a supply chain can improve transparency, efficiency, and sustainability[11]. One of the

identified advantages of blockchain beyond disintermediation is to incorporate traceability. This immutable database of provenance makes traceability a natural fit with blockchain technology.

Companies want to be successful when implementing blockchain in the supply chain. Of the 25 critical success factors determined by Clohessy [8], companies should primarily consider the factors of blockchain knowledge, organizational size, and permissions. Secondly, architecture, smart contract coding, business use cases, top management support, and industry standards should also be considered.

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Elements of the Risk Management Process in a Seaport

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Abstract: Having as an initial motive a very high level of importance of the risk related parameters and their relevance for the overall decision making, in this paper are taken into consideration some elements of the risk management process in a seaport. In order to establish bases for the research, a literature overview was carried out with special attention on different approaches to defining phases of the risk management process in a port, variety of classification manners of risks, techniques for assessing risk, national (in Montenegro) and international regulation used as a base for structuring and functioning of a risk management system in the field of safety and health on work. Using DEA CCR input oriented method, intensity of impact of the risk related inputs (number of workers directly engaged in the cargo handling process, berth length, water depth, operation costs) on the berth efficiency is analyzed, having as a base data series from a concrete dry bulk cargo terminal in a seaport. Results indicate that risk related input parameters, of various characters, causing intensive variations in berths efficiency scores. An approach proposed in this paper can be implemented in other ports as well as in other systems for investigating intensity of impact of risk related influential factors on parameters which characterize their functioning.

Keywords: SEAPORT, RISK MANAGEMENT, IMPACTS, RISK RELATED INPUTS.

1. Introduction

The risks faced by the ports are larger than ever before. They could lead to interruptions of the working process in a port itself, with negative impacts on local, regional and global economies due to the role ports have in the supply chain.

In the available literature are taken into consideration different aspects of the risk management in the ports (terminals) as well as

the risk management in the logistic chain as a whole or some of its elements (ships, customs, ...). The priority is given to structure of the risk management process, risks' classification and recognition of their criticality ranks, etc.

Available literature contains different approaches to defining phases of the risk management process in a port, as shown with the following table (Table 1).

Table 1: Some approaches to defining phases of the risk management in a port

Approach	Reference
A risk management process consists of risk identification, assessment, prioritization, implementation, and tracking.	[1]
There are four steps of the risk management procedures, which are: identification, classification, analysis and estimation and control.	[2]
The risk management process consists of six steps: System identification (Port); Risk identification (what go wrong?) Risk assessment (investigation of important risks); Risk control options (measures to mitigate risks); Cost/benefit assessment (cost/benefit of measures); Decision-making (recommendation);	[3]
The risk management process is usually structured around five phases: (1) Identification of risks; (2) Risk Analysis; (3) Planning and scheduling preventive and corrective actions; (4) Monitoring and implementation of action plans; (5) Effectiveness monitoring of measures;	[4]
Risk management process can be structured according to following model: establish the context, identify risks, analyze risks, evaluate risks, treat risks, all connected with communication, consulting and monitoring and review.	[5]
The risk management process can be structured as follow: establishing the context, collection of information and intelligence, risk assessment (risk identification, risk analysis, risk evaluation and prioritization), risk treatment, monitoring and review, documentation, communication and consultation;	[6]

(source: authors)

Classification of risks – With the available literature are proposed numerous approaches to classification of risks. In Table 2

are presented some characteristic classifications, with a description of identified categories.

Table 2: Classification of risks

Risk classification (1)	Description of risks (2)	Reference (3)
internal risks	the risks generated within a port: ship collisions, lack of personnel, irresponsibility, document interpretation problems, ...	[7-10]
external risks	the risks originate from external sources: fuel price, traffic jam, monopoly, electricity blackout, old shipping lane, storms, ...	
hidden risks	the risks are generated by smaller separate threats related to a local scale (within a port) or to a larger scale (over the supply chain).	
natural risks	the risks which cannot be connected with the human actions: strong winds, hurricane, earthquake, volcano eruption, floods, high temperature during working hours, heavy rain.	[11]
man-made risks	a man-made risk occurs mainly as a consequence of one or more intentional or negligent human actions.	[12]
liability risks and associated	third-party property damage; loss or damage to vessels or cargo; wreck removal errors and omissions; fines and duty;	
property and handling equipment risks	loss or damage to port's assets, including handling equipment or property; damage to sea walls, piers, and wharves, from natural hazards or vessel impact;	
revenue stream risks	strikes; denial of access or transportation incidents; damage that incapacitates critical cargo handling equipment; damage to key customers' or suppliers' premises;	
cyber risks	loss of availability, integrity, or confidentiality related to critical systems or data; ...	
environmental risks	can arise at all stages of a port life cycle [13]; ship emissions, dredging, oils spills, chemical contaminants, ballast waters, noise pollution, alien species, ... [14];	[16]
construction risks	dredging, removal and disposal of contaminated material, ...	
health and safety risks	port safety is affected by multiple factors related to design, installation, operation and maintenance [15];	
country risks	the risk of investing in a country (in a port), financial factors such as currency controls, devaluation or regulatory changes, or stability factors such as mass riots, civil war;	
business risks	the externally driven uncertainties which can impact any subject within or outside a port.	

organisational risks	lack of clarity over roles and responsibilities, inadequate or inaccurate information, poor staff selection procedure, inappropriate decision making, performance failure (people or equipment).	
operational risks	lack of management supervision, errors, malice, fraud, poor health and safety procedures and environmental compliance failures, physical disasters, and poor internal controls; the risks generated during: operational planning process, loading/unloading and storage of cargo, ... [17]; the risk of loss arising from the failure or inadequacy of internal processes, poor work culture, poor occupational safety and health, etc. [18];	
port safety risks	people safety: port workers, customers, service providers, ship`s crew, ...	
contract related risks	the risks generated with the inadequate contracts with port customers.	
human related risks	here belong following risks` factors: people - knowledge, skill, ability, decision making, safety culture, performance, training and communication...	
technical risks	inadequate maintenance policies, caused by: absence of preventive and corrective maintenance, lack of qualified maintenance personnel, lack of adequate stocks of spare parts, insufficient standardization of equipment types, ...	
climate risks	The entry and exit of vessels into and from a port, including pilot transfer operations, are sensitive to wind and wave conditions. Within the port, changes to wind conditions and precipitation patterns can interrupt cargo operations, potentially even risking damage during extreme weather events. According to researchers from the Massachusetts Institute of Technology Supply Chains Initiative, freight transportation contributes approximately 8 % of global greenhouse gas emissions. If the warehousing operations are added, this figure increases to 11 % [20]. In the first European Climate Risk Assessment report [21] are identified the many different economic and social risks that Europe will need to manage over the next decade due to the climate crisis. Managing climate risks is a necessary condition for improving living standards, fighting inequality and protecting people [22]. Projected increases in global temperatures are expected to cause or intensify several climate-related hazards that can pose considerable physical risks to the shipping and port industries: sea level rise; severe tropical storms; inland flooding; drought; extreme heat events, etc. [23-24].	[19]

(source: authors)

Some additional categories of risks, not mentioned in the Table 2 are recognized in the available literature: risks caused by national and international regulation, risks generated by multiple jurisdiction [2,5], security risks [14], financial risks [18,25], commercial risks [18], risk associated with physical flows, risks associated with payment flow, risks associated with information flows [26], , etc.

Techniques for assessing risk - EC 31010:2019 provides guidance on the selection and application of techniques for assessing risk in a wide range of situations [27]. The methods used for risks assessment are [28]: brainstorming, check-lists, hazard analysis and critical control, scenario analysis, business impact analysis, failure mode effect analysis (FMEA), failure mode effect and criticality analysis (FMECA), fault tree analysis, cause-and-effect analysis, Markov analysis, Monte Carlo simulation, ...

In the process of risk assessment, the Data envelopment analysis (DEA) cross-efficiency method is used to evaluate a set of risk factors obtained from the FMEA [29]. DEA is initially employed to prioritize risk factors, and based on obtained results, optimal response strategies are determined [30].

For example, FMECA is widely used in order to assure that all potential failure modes have been considered and the proper provisions have been made to eliminate these failures [31-32].

Regulation - In general, risk management in a port has to be based on the international and national – domain specific – regulation. In order to illustrate complexity and very wide range of risk related regulation in this section are summarized some elements of the national and international regulation which is used as a base for structuring and functioning of a risk management system in the field of safety and health on work.

National regulation (in Montenegro) – The Law on Safety and Health at Work [33], states that safety and health at work is ensured and implemented by applying modern technical-technological, organizational, health, social and other measures and means of protection in accordance with this law, other regulations, ratified and published international agreements. The Law defines occupational health and safety as the process of ensuring working conditions that do not lead to work injuries, occupational diseases and work-related illnesses and that create conditions for full physical and psychological protection of employees.

International regulation – here are summarized some elements of the European Union regulation in the field of safety and health on work.

Framework Directive 89/391/EEC requires employers to carry out a risk assessment to enable them to take the appropriate measures to protect workers' safety and health. The Directive introduces as a key element the principle of risk assessment [34-35]. Individual directives tailor the principles of the Framework

Directive to [36]: specific tasks (e.g. manual handling of loads); specific hazards at work (e.g. exposure to dangerous substances or physical agents); certain work-related aspects (e.g. organisation of working time).

The EU Strategic Framework on Health and Safety at Work 2021-2027, announced in the European Pillar of Social Rights action plan, sets out the key priorities and actions necessary for improving workers' health and safety [37-38].

The European Commission has announced its top three occupational safety and health actions in its Communication Safer and Healthier Work for All - Modernisation of the EU Occupational Safety and Health Legislation and Policy [36].

Relevant directives and regulations from the domain of health and safety on work [39-42]: Directive 2009/104/EC – use of work equipment; Directive 92/58/EEC - safety and/or health signs; Directive 89/654/EEC - workplace requirements; Regulation 2023/1230/EU - machinery; Regulation (EU) 2016/425 on personal protective equipment; Directive 2003/88/EC - working time etc.

European directives set out the minimum standards for safety and health in the workplace [43].

Although a very wide group of topics are treated in the available literature on risk management in the ports, there is a lack of references related to quantification of influence of risks on port efficiency. It is a main motive of the authors to select the central theme of this paper: to measure intensity of influence of risk related inputs on the berth efficiency, as one of metrics of a port efficiency, using DEA CCR method.

2. A description of a port where the analysis is performed

The Port of Bar [44] is a multipurpose port, situated at the south of the Adriatic sea, established at the beginning of the last century (1906). The Port is managed according to the landlord port management model. Within the Port area are functioning two terminal operators: Port of Bar JSC, where major shareholder is The State of Montenegro, owning 78.55% of shares, and the Port of Adria JSC, where majority of shares – 62% are owned by the Turkish Company Global Ports Holding. There are several specialized terminals in the Port of Bar: Terminal for dry bulk and liquid bulk cargo, Container terminal, General cargo terminal, Ro-Ro terminal and Passenger terminal.

Concrete results presented in this paper are related to the Terminal for liquid bulk and dry bulk cargo, managed by the Terminal Operator Port of Bar JSC. Basic characteristics of the Terminal are given in the Table 3.

Table 3: Basic characteristics of the Terminal

Volujica Quay - berths: 01, 02, 03)	Total length: 554 m; Water depth: 14 m;
Old Quay - berths: 04, 05, 06	Total length: 280 m; Water depth: 5.00 m – 7.20 m;
New Tanker Berth (NPV)	Maximal ship's LOA: 200 m; Water depth: 13.50 m;

(source: [44])

3. An analysis of impact of risk related inputs on berth efficiency

Port efficiency is the capability of a port (terminal) to fit the optimum number of inputs to a given output level [45].

The efficiency of port operations directly influences the speed, cost, and reliability of global shipping [46]. Port efficiency is depending on different influential factors: the various technological

advancements, including, digitalization, advanced analytics and sustainable technologies [46], adaptation to climate changes (especially for the coming years) [47], security procedures according to ISPS Code [48], etc. Port efficiency was researched in some additional references, too, as shown with the next table (Table 4).

Table 4: Additional references on port efficiency

Object of research/Findings	Reference
Object of research: A new methodology to quantify the efficiency dynamics of a port over time. / Findings: An optimization-based approach for efficiency measurement under uncertainty and a risk-based index to measure the efficiency of any operating unit.	[49]
Object of research: Risk management in the maritime supply chain. / Findings: When supply chain risk increases, efficiency significantly goes down even when the maritime supply chain is very good.	[50]
Object of research: The importance of port efficiency and service quality. / Findings: Exporting firms have a positive willingness-to-pay for a reduction in the handling time. Findings emphasize the importance of trade facilitation measures in improving port efficiency and service quality.	[51]
Object of research: Determinants of effective high-risk cargo (HRC) handling at seaports. / Findings: The study confirmed the correlation between HRC training and the level of knowledge of risk mitigation and emergency procedures, documentation understanding and regulations adherence.	[52]

(source: authors)

In general, there are three required elements for measuring efficiency in ports: decision making unit (DMU), output variables, and input variables [45]. In the available literature related to measuring port efficiency are used different methods (techniques): original least squares (OLS), corrected original least squares (COLS), data envelopment analysis (DEA), stochastic frontier analysis (SFA), etc. [53].

Efficiency in a port can be measured in different manners, using various metrics: efficiency of whole port (in comparison with other ports), efficiency of terminals in the same port or among different ports, efficiency of berths within a terminal, etc.

As defined before, in this paper will be analyzed impacts of risk related inputs (elements directly generated by the risk management system) on berth efficiency, using DEA CCR method (input oriented).

3.1 Methodology

Data Envelopment Analysis (DEA), developed by Charnes et al. in 1978, is a linear programming based method for evaluating performance of organizational units called decision-making units (DMUs) [54-55]. There are two basic DEA models, DEA-CCR (Charnes–Cooper–Rhodes) and DEA-BCC (Banker–Charnes–Cooper) [56]. DEA approach has been used in numerous domains, including ports [45,54].

DEA-CCR model has its two versions: the first - input-oriented and the second - output-oriented. The objective of the first is to minimize inputs for reaching outputs, while the second attempts to maximize outputs [53,57].

The original DEA-CCR model problem formulation for assessing efficiency was defined as a task of fractional programming (FP), while the solution procedure consists of linear programming (LP) usage for each of the units under assessment [57]. The mathematical interpretation of the DEA-CCR model for the chosen entity “o” is analyzed in [57-58].

An analysis of impacts of risk related inputs on berth efficiency will be performed through following steps: STEP 1: selection of input and output variables, decomposition of input variables (where applicable) and recognition of risk related components; STEPS 2: calculation of efficiency scores in two variants: V1-using total values of input parameters; V2-using values of input parameters

after deduction (isolation) of risk related components; STEPS 3: a comparison between efficiency scores in variant V1 and variant V2.

3.2 Selection of input and output variables

The assessment of port efficiency using DEA method begins with the adequate selection of input and output variables [59]. The most frequently used inputs are resources such as land, human resources, and equipment as well as the total quay length (m); net berth productivity (t/h); operation costs; maximal allowed ship draft (m); etc. [54,56,59-61]. The measurement of the output is done by: throughput (t); terminal capacity (t); number of ships; number of passengers; number of containers; berth occupancy; vessel turnaround time [53,60-62], etc.

There is no universal rule (no consensus) on selection of the input/output variables, which could be recognized from the available literature [59,63]. In the following parts of this section are defined DMUs, input/output parameters and period taken into consideration.

Decision Making Units (DMUs): berths (seven berths) at the Terminal for dry bulk and liquid bulk cargo in the Port of Bar JSC (Table 5).

Table 5: Decision Making Units (DMUs)

DMU _i	Purpose/Main activities carried out
DMU ₁ – berth 01	loading/unloading operations with dry bulk cargo
DMU ₂ – berth 02	loading/unloading operations with dry bulk cargo
DMU ₃ – berth 03	loading/unloading operations with dry bulk cargo
DMU ₄ – berth 04	unloading operations with dry bulk cargo
DMU ₅ – berth 05	loading operations with liquid bulk cargo
DMU ₆ – berth 06	loading/unloading operations with liquid bulks
DMU ₇ – berth 07	unloading operations with liquid bulks

(source: [44])

Input variables: input - number of workers directly engaged in the cargo handling process, N_w , berth length, B_i (m), water depth (by a berth), D_w (m), operation costs, C_o (€);

Output: annual cargo throughput by berths (DMU_s), Q_{bi} (t);

Period taken into consideration: 2021 – 2024.

Description of the input parameters per variants is given in the Table 6.

Table 6: Description of the input parameters

Input parameters: Variant 1 (V1),	Input parameters: Variant 2 (V2)
Total number of workers, directly engaged in the cargo handling process – N_{w1} : a group of workers engaged for realization a loading/unloading operation, consists of: foreman, port machinery operator(s), stevedores, fireman, ... depending on the type of cargo and type of operation;	Number of workers – risk related, N_{w2} - engaged in the cargo handling process, after deduction (isolation) of risk related workers; risk related workers whose engagement is determined by the requirements of the risk management process: signal man, fireman, ... depending on the type of cargo and type of operation;
Berth lenght, B_{11} (m)	Berth lenght – risk related, B_{12} (m) - available berth lenght after deduction (isolation) of the lenght of a part which was under maintenance (risk related activities) in the analyzed period;
Water depth (by the berth), D_{w1} (m)	Water depth (by the berth) – risk related, D_{w2} (m) – there were no differences in values of this parameter in both variants within the analyzed period.
Direct operation costs, C_{o1} (€): <i>-daily wages, C_{01-1}(€)</i> - related to the workers (from a group of engaged workers for realization a loading/unloading operation, consists of: foreman, port machinery operator(s), stevedores, fireman, depending on the type of cargo and type of operation), calculated based on the average productivity per shift, period of effective work in a shift, total number of workers in a engaged group, average gross salary per month of a worker in the port, average working hours per employee (per month), average costs per hour (per worker); <i>-port machinery costs, C_{01-2}(€)</i> – related to used port machinery, depending on the type of the cargo handling operation and type of the cargo; costs are sum of following components (depending on the type of port machinery): fuel costs, electric power costs, depreciation costs and cost of periodical inspection by authorized external body (fulfillment of safety requirements), calculated based on fuel consumptions per effective working hour, average price of the fuel, electric energy costs per unit, number of effective working hours per year, etc.; <i>-costs of personal safety equipment, C_{01-3}(€)</i> , calculated based on costs of personal safety equipment per year, total number of working hour of a employee per year, number of effective working hour necessary to handle annual total cargo quantity per berth, ...; <i>-costs of fire truck, C_{01-4}(€)</i> , calculated based on fuel consumptions per effective working hour, average price of the fuel, number of effective working hours per year, depreciation costs, ...; <i>-costs of insurance of engaged workers, C_{01-5}(€)</i> , calculated based on annual insurance costs per employee, total annual fund of working hour per employee, average insurance costs per hour, period of effective work necessary for handling total annual quantity of cargo per berth, ...; <i>-costs of using protective dam, C_{01-6}(€)</i> , against spilages of oil derivates during handling operation with that cargo type, calculated based on costs of usage protective dam per hour and number of effective working hours used for loading/unloading total annual quantity of cargo per berth. ----- Direct operation costs related to Variant V1: $C_{o1} = C_{01-1} + C_{01-2} + C_{01-3} + C_{01-4} + C_{01-5} + C_{01-6}$	Direct operation costs – risk related, C_{o2} (€) – after deduction (isolation) of risk related components: <i>-daily wages-risk related, C_{02-1}(€)</i> – is calculated based on the value of the component C_{01-1} reduced for costs of the risk related workers (signal man, fireman), depending on the type of cargo and type of operation. <i>-port machinery costs, C_{02-2}(€)</i> – is calculated based on the value of the component C_{01-2} reduced for the cost of periodical inspection by authorized external body (fulfillment of safety requirements). ----- Direct operation costs related to Variant V2: $C_{o2} = C_{02-1} + C_{02-2}$ Remark: All other cost components are risk related and are not taken into account in the Variant V2.

(source: author)

In both variants, the same output parameter values were used.

3.3 Data series

In the Table 7 are presented data series for selected DMUs (berths at the Terminal for dry bulk and liquid bulk cargo in the Port

of Bar JSC), selected input and output variables - variants V1 and V2 - for the period from the year 2021 to the year 2024. Sources of data were official reports from the Port of Bar JSC Information System [44].

Table 7: Data series

DMU _i	Year	Output Annual throughput (t) (x 10 ³)	Inputs							
			Number of directly engaged workers (x 10 ³)		Berth length (m) (x 10 ³)		Water depth (m) (x10 ³)		Direct operation costs (€) (x10 ³)	
			V1	V2	V1	V2	V1	V2	V1	V2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Berth 01	2021	156.74	0.49	0.37	0.185	0.185	0.014	0.014	34.31	29.00
	2022	182.68	0.58	0.43	0.185	0.185	0.014	0.014	39.98	33.80
	2023	343.07	1.08	0.81	0.185	0.185	0.014	0.014	75.09	63.48
	2024	306.10	0.97	0.72	0.185	0.185	0.014	0.014	67.00	56.64
Berth	2021	662.58	1.08	0.72	0.185	0.185	0.014	0.014	175.68	160.89

02	2022	1,084.76	1.76	1.18	0.185	0.145	0.014	0.014	287.62	263.41
	2023	323.60	0.53	0.35	0.185	0.145	0.014	0.014	85.80	78.58
	2024	204.59	0.33	0.22	0.185	0.185	0.014	0.014	54.25	49.68
...										
Berth 07	2021	50,471.23	0.027	0.014	0.198	0.198	0.013	0.013	2.87	0.49
	2022	83,110.87	0.045	0.022	0.198	0.198	0.013	0.013	4.73	0.81
	2023	30,315.94	0.016	0.008	0.198	0.198	0.013	0.013	1.73	0.29
	2024	20,140.00	0.011	0.005	0.198	0.198	0.013	0.013	1.15	0.20

(source: [44])

3.4 Berth efficiency scores

Based on values of input and output variables given in the Table 7, efficiency scores for defined DMUs (berths at the Terminal for dry bulk and liquid bulk cargo in the Port of Bar JSC), per defined variants (V1 and V2) and years of the analyzed period from 2021 to 2024, are calculated using appropriate software (based on DEA

CCR input oriented model). Having in mind that throughput per years related to the berths 01, 02 and 03 had the biggest share in the total throughput achieved by Port of Bar JSC, per analyzed years [44], considerations are focused on the berths 01, 02 and 03. Calculated efficiency scores per analyzed variants V1 and V2 are presented with the next tables (Table 8 for Variant V1; Table 9 for Variant V2).

Table 8: Efficiency scores related to Variant V1

Berths	2021		2022		2023		2024	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
01	0.4447	2	0.5115	3	0.8300	2	0.7078	2
02	1	1	1	1	0.8078	3	0.5770	3
03	0.2548	3	0.6119	2	1	1	1	1

(source: authors)

Table 9: Efficiency scores related to Variant V2

Berths	2021		2022		2023		2024	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
01	0.4678	2	0.5177	3	0.8390	3	0.9146	2
02	1	1	1	1	0.8898	2	0.7010	3
03	0.4557	3	0.6241	2	1	1	1	1

(source: authors)

A comparison of efficiency scores per analyzed variants is done in the Table 10.

Table 10: A comparison of efficiency scores per analyzed variants V1 and V2

Berths	2021		2022		2023		2024	
	V1	V2	V1	V2	V1	V2	V1	V2
01	0.4447	0.4678	0.5115	0.5177	0.8300	0.8390	0.7078	0.9146
02	1	1	1	1	0.8078	0.8898	0.5770	0.7010
03	0.2548	0.4557	0.6119	0.6241	1	1	1	1
	2021		2022		2023		2024	
01-V2/V1	1.0519		1.0121		1.0108		1.2921	
02-V2/V1	1		1		1.1015		1.2149	
03-V2/V1	1.7884		1.0199		1		1	

(source: authors)

4. Discussion of results

The results presented in the Table 10 enable quantification of impact of risks` related inputs on the efficiency scores for analyzed DMUs (berths at the Terminal for dry bulk and liquid bulk cargo):

* Variations of efficiency scores for the year 2021:

- in the variant V2, efficiency score for the berth 01 is bigger for 5.19% than in Variant V1: as the length of the berth and water depth by the berth were the same for both variants, changes in the efficiency score were caused by reduction in number of engaged workers (after deduction of number of risk related workers for 24.49%) and reduction of operation costs (after deduction of risk related components of costs for 15.47%); efficiency score for the berth 02 are the same for both variants; in the variant V2, efficiency score for the berth 03 is bigger for 78.84% than in Variant V2, what was caused by the reduction of number of workers in an engaged

group of workers for 12% (after deduction of the number of risk related workers), reduction of the berth length for 67.58% (deduction of the part of the berth which was under maintenance) and reduction of operation costs for 12.55% (deduction of risk related components of costs);

* Variations of efficiency scores for the year 2022:

- in the variant V2, efficiency score for the berth 01 is bigger for 1.21% than in Variant V1; as the length of the berth and water depth by the berth were the same for both variants, changes in the efficiency score were caused by reduction in number of engaged workers (after deduction of number of risk related workers for 25.86%) and reduction of operation costs (after deduction of risk related components of costs for 15.46%); efficiency scores for the berth 02 are the same for both variants; in the variant V2, efficiency score for the berth 03 is bigger for 1.99% than in Variant V1, what was caused by the reduction of number of workers in an engaged group of workers for 14.42% (after deduction of the number of risk

related workers) and reduction of operation costs for 12.57% (after deduction of risk related components of costs);

* Variations of efficiency scores for the year 2023:

- in the variant V2, efficiency score for the berth 01 is bigger for 1.08% than in Variant V1; as the length of the berth and water depth by the berth were the same for both variants, changes in the efficiency score were caused by reduction in number of engaged workers (after deduction of number of risk related workers for 25%) and reduction of operation costs (after deduction of risk related components of costs for 15.47%); in the variant V2, efficiency score for the berth 02 is bigger for 10.15% than in Variant V1, what was caused by the reduction of number of workers in an engaged group of workers for 33.96% (after deduction of the number of risk related workers), reduction of berth length for 21.62% (after deduction of a part of the berth which was under maintenance) and reduction of operation costs for 1.17% (after deduction of risk related component of the costs); efficiency score for the berth 03 is the same for both variants;

* Variations of efficiency scores for the year 2024:

- in the variant V2, efficiency score for the berth 01 is bigger for 29.21% than in the Variant V1; as the length of the berth and water depth by the berth were the same for both variants, changes in the efficiency score were caused by reduction in number of engaged workers (after deduction of number of risk related workers for 25.77%) and reduction of operation costs (after deduction of risk related components of costs for 15.46%); in the variant V2, efficiency score for the berth 02 is bigger for 21.49% than in the Variant V1, what was caused by the reduction of number of workers in an engaged group of workers for 33.33% (after deduction of the number of risk related workers) and reduction of operation costs for 8.57% (after deduction of risk related components of the costs); efficiency score for the berth 03 is the same for both variants;

* Influences on efficiency scores for selected DMUs (berths) were generated by changes in number of workers in a group of engaged workers per analyzed variants, variations in the available length of the berths due to maintenance works and variations in values of operation costs per analyzed variants.

5. Conclusions

Presented results directly confirm a high level of importance of the risk management system for functioning of a port and existence of correlations between the elements generated in the risk management system and level of a port efficiency. As well, results indicate that risk related input parameters, of various characters, caused intensive variations in berths efficiency scores. In addition, results suggest additional interdependencies among values of risk related input parameters, type of handled goods and implemented cargo handling technology.

An approach proposed in this paper can be implemented in other ports as well as in other systems for investigating intensity of impact of risk related influential factors and can be used as a reliable base for further engagement of the author in this domain.

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Quality management in SMEs as a factor for green transition and circular economy: an empirical study in the context of industry 5.0

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Abstract: The paper investigates the specific role of quality management systems (QMS) as a factor for green transition and circular economy in small and medium-sized enterprises (SMEs) within the context of Industry 5.0. Based on a sub-sample of 209 SMEs (from $n = 250$ Bulgarian industrial enterprises), a targeted statistical analysis was conducted. Results show that QMS maturity in SMEs is significantly lower than in large enterprises, but the effect of its growth on the Green Transition Index (GTI) is proportionally stronger. The regression model for SMEs explains 61.4% of GTI variation ($R^2 = 0.614$), with integrated ISO 9001 + ISO 14001 systems remaining the strongest predictor ($\beta = 0.271$; $p < 0.001$). Specific barriers facing SMEs are identified and targeted recommendations are formulated.

Keywords: SME, quality management, green technologies, circular economy, Industry 5.0, ISO 9001, ISO 14001, GTI

1. Introduction

Small and medium-sized enterprises (SMEs) represent the backbone of the European and Bulgarian economy — over 99% of all enterprises in the EU are SMEs, providing nearly 65% of employment and generating approximately 55% of added value [1]. Nevertheless, SMEs face the most serious challenges in the transition to sustainable production: limited financial resources, weaker access to technology and specialized competencies, and greater vulnerability to regulatory changes.

In the context of Industry 5.0, which emphasises sustainability, humanisation, and innovation [2], [1], quality management acquires strategic significance as a mechanism for systemic transformation. The ISO 9001 and ISO 14001 standards provide a structured approach to continuous improvement, performance measurement, and integration of environmental goals into day-to-day management [3], [4].

This report fills an existing gap in the literature: while research on QMS and sustainability in large enterprises is well developed, the specific context of SMEs — particularly in Central and Eastern Europe — remains underexplored [5]. The aim of the report is to analyse the impact of QMS maturity on the green transition in SMEs and to identify the specific drivers, moderators and barriers.

2. Theoretical Framework

2.1. SMEs and Sustainable Transformation – Specific Context

SMEs differ fundamentally from large enterprises in their organisational characteristics: flatter structures, greater dependence on key individuals, limited budgets for investment and certification, and weaker regulatory pressure [6]. These features define a specific readiness profile for green transition — different from the corporate model on which most research is focused.

Despite their limitations, SMEs also possess unique advantages: flexibility in organisational change, faster communication between management levels, and higher sensitivity to market signals for sustainability. Research shows that SMEs with formalised quality management systems are able to compensate for scale limitations through more efficient resource use [7], [8].

2.2. QMS as a Catalyst for Green Transition in SMEs

Quality management systems, and in particular their integration with environmental management under ISO 14001, provide SMEs with a structured mechanism for identifying, measuring, and reducing their environmental footprint [4]. The process approach and the principle of continuous improvement embedded in ISO 9001:2015 create an institutional foundation for the gradual, measurable, and cost-effective adoption of green practices [9].

In the context of the circular economy, the quality of products and production processes is critically important for ensuring durability and reuse [10]. Publications in the Journal of Cleaner Production confirm that SMEs with an implemented QMS demonstrate a greater inclination to adopt circular business models [11].

2.3. Barriers Facing SMEs in the Green Transition

The literature identifies three main categories of barriers facing SMEs. Financial barriers include high upfront costs for certification, implementation of green technologies, and staff training. Human capital barriers manifest as a lack of specialised competencies. Regulatory barriers stem from the unequal application of requirements to SMEs and from the complexity of reporting under ESG standards [5].

3. Research Hypotheses

The main research hypothesis is: "In SMEs, the effect of QMS maturity on the green transition is statistically significant and proportionally stronger than in large enterprises, despite the lower starting position of SMEs."

H1-SME: ISO 9001 certification in SMEs is positively associated with the adoption of green technologies, with the effect being stronger in small enterprises (10–49 employees) than in micro-enterprises.

H2-SME: ISO 14001 certification in SMEs is positively associated with circular economy principles (CEI), with a particularly pronounced effect in medium enterprises (50–249 employees).

H3-SME: The integration of QMS and EMS (ISO 9001 + ISO 14001) generates a synergistic effect on GTI in SMEs, exceeding the sum of the individual contributions.

H4-SME: Industry 5.0 readiness moderates the relationship between QMS and GTI in SMEs more weakly due to a lower degree of digitalisation.

H5-SME: Enterprise size (micro/small/medium) is a significant moderator in the adoption of green technologies.

4. Methodology

The present study uses a sub-sample of 209 SMEs drawn from the overall sample of the main study ($n = 250$ Bulgarian industrial enterprises). SMEs are defined in accordance with the European Commission classification: micro-enterprises (1–9 employees, $n = 42$), small enterprises (10–49 employees, $n = 78$), and medium enterprises (50–249 employees, $n = 89$). The structure is presented in Table 1.

Table 1. Structure of the SME Sub-Sample by Category

SME Category	n	% of SMEs	ISO 9001 (%)	ISO 14001 (%)
Micro (1–9 employees)	42	20.1%	38%	9%
Small (10–49 employees)	78	37.3%	61%	29%
Medium (50–249 employees)	89	42.6%	74%	52%
Total SMEs	209	100 %	60.3%	33.5%

Note: Data extracted from the main study ($n = 250$). Developed by the author.

The statistical analysis includes: descriptive statistics and a comparative analysis of SMEs vs. large enterprises; correlation analysis (Pearson r); multivariate regression analysis (MRA) with a separate model for SMEs; and moderation analysis with enterprise category as the moderating variable. Reliability was verified using Cronbach's α coefficient [12], and statistical power was assessed following the methodology of Cohen [13].

5. Conceptual Model

Based on the theoretical review and the specific SME context, a conceptual model — "Three Pillars of Sustainable Transition in SMEs" — has been adapted (Fig. 1). Unlike the corporate model, the SME version places emphasis on the accessibility and gradualism of the transformation.

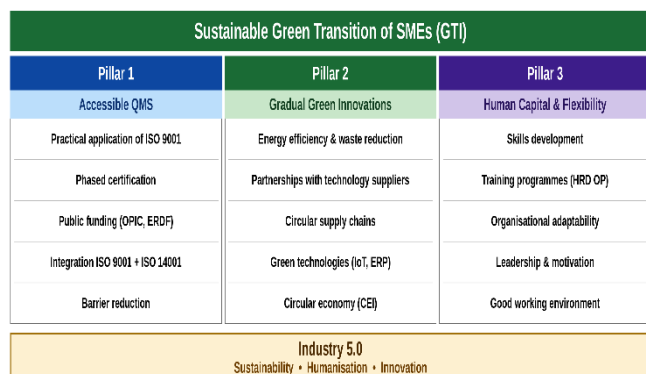


Fig. 1. Conceptual Model "Three Pillars of Sustainable Transition in SMEs in the Context of Industry 5.0"

Note: Adapted by the author for the specific SME context.

The model is structured around three interconnected pillars: Pillar 1 — Accessible Quality Management System (pragmatic application of ISO 9001, phased certification, public funding); Pillar 2 — Gradual Green Innovations (energy efficiency, circular supply chains); Pillar 3 — Human Capital and Organisational Flexibility (multifunctional competencies, HRD Operational Programme schemes).

6. Results and Analysis

6.1. Comparative Profile: SMEs vs. Large Enterprises

The comparative analysis reveals significant differences in QMS maturity between SMEs and large enterprises (Table 2). The mean QMS index for SMEs is 2.81 (SD = 0.94) compared to 4.23 (SD = 0.61) for large enterprises — a difference of 1.42 points ($t(248) = 11.47$; $p < 0.001$). The analysis shows that a 1-unit increase in the QMS index for SMEs is associated with a 0.31-unit increase in GTI — comparable to the effect of 0.28 units for large enterprises.

Table 2. Comparative Profile: SMEs vs. Large Enterprises ($n = 250$)

Indicator	SMEs (n=209)	Large (n=41)	p-value
QMS Index (mean)	2.81 (SD=0.94)	4.23 (SD=0.61)	< 0.001
ISO 9001 cert. (%)	60.3%	93.2%	< 0.001
ISO 14001 cert. (%)	33.5%	80.5%	< 0.001
GTI (green transition)	0.512 (SD=0.21)	0.731 (SD=0.14)	< 0.001
CEI (circular economy)	34.1 (SD=16.3)	58.7 (SD=11.2)	< 0.001
I5.0 Readiness Index	2.64 (SD=0.88)	3.91 (SD=0.72)	< 0.001

Note: Developed by the author based on own research.

6.2. Correlation Analysis for the SME Sub-Sample

The correlation matrix (Table 3) reveals significant positive associations between all studied constructs ($p < 0.01$). The strongest correlation is observed between green technologies and GTI ($r = 0.821^{**}$), followed by circular economy–GTI ($r = 0.774^{**}$). Correlations for SMEs are moderately lower than for the overall sample ($r = 0.836$ and $r = 0.791$), reflecting the greater heterogeneity within the SME segment.

Table 3. Correlation Matrix for the SME Sub-Sample ($n = 209$, $**p < 0.01$)

Construct	QMS	EMS	Green tech.	Circ. econ.	GTI
QMS (ISO 9001)	1.000	—	—	—	—
EMS (ISO 14001)	0.598**	1.000	—	—	—
Green Technologies	0.511**	0.658**	1.000	—	—
Circular Economy	0.463**	0.601**	0.698**	1.000	—
GTI (Green Transition)	0.548**	0.681**	0.821**	0.774**	1.000

Note: Developed by the author based on own research.

6.3. Regression Analysis for SMEs

The regression model for the SME sub-sample explains 61.4% of the variation in GTI ($R^2 = 0.614$; $F(4, 204) = 81.3$; $p < 0.001$). The EMS index remains the strongest predictor ($\beta = 0.271$), followed by the QMS index ($\beta = 0.221$). SME category is a significant moderator ($\beta = 0.134$; $p = 0.006$). The I5.0 Readiness Index has a weaker effect ($\beta = 0.158$) compared to the overall model ($\beta = 0.187$), confirming H4-SME (Table 4).

Table 4. Results of the Regression Analysis for SMEs ($n = 209$)

Predictor	B	SE	Beta	t	p
Constant	0.387	0.201	—	1.925	0.055
QMS Index (ISO 9001)	0.261	0.071	0.221**	3.676	< 0.001
EMS Index (ISO 14001)	0.318	0.079	0.271**	4.025	< 0.001
I5.0 Readiness Index	0.162	0.062	0.158**	2.613	0.009
SME Category (moderator)	0.148	0.053	0.134**	2.792	0.006

$R^2 = 0.614$; $F(4, 204) = 81.3$; $p < 0.001$

Note: $**p < 0.01$. Developed by the author based on own research.

6.4. Hypothesis Testing

All five hypotheses are confirmed (Table 5), including H5-SME, which in the overall sample was only partially confirmed ($\Delta R^2 = 0.031$). This confirms that enterprise size is a more significant differentiating factor within the SME category.

Table 5. Summary of Hypothesis Testing for the SME Sub-Sample

Hyp.	Statement	Method	Result	Status
H1	ISO 9001 and green technologies in SMEs	Pearson r ; MRA	$r = 0.511$; $p < 0.001$	✓ Confirmed
H2	ISO 14001 and CEI in SMEs	Pearson r ; MRA	$r = 0.601$; $p < 0.001$	✓ Confirmed

H3	QMS+EMS synergistic effect in SMEs	SEM	$\beta = 0.271$; $p < 0.001$	✓ Confirmed
H4	I5.0 weakly moderates QMS-GTI in SMEs	Moderation analysis	$\beta = 0.158$; $p = 0.009$	✓ Confirmed
H5	Category is a significant moderator	Hier. MRA	$\Delta R^2 = 0.041$; $p = 0.006$	✓ Confirmed

Note: Developed by the author based on own research.

6.5. Specific Barriers Facing SMEs

Financial constraints are identified as the most significant barrier (mean score 4.21), followed by the lack of specialised personnel (3.87) and the complexity of regulatory requirements (3.64). Lack of information is rated comparatively low (2.93), suggesting that SMEs are aware of the requirements but encounter practical obstacles in meeting them (Fig. 2).

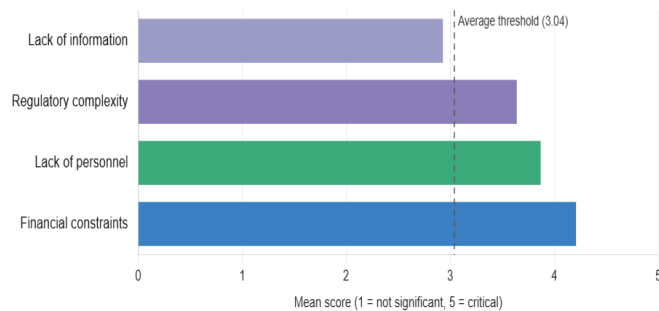


Fig. 2. Significance of Barriers to Green Transition in SMEs (mean score on a scale of 1–5)

Note: Developed by the author based on own research.

7. Conclusions and Recommendations

The present paper confirms that quality management functions as a significant catalyst for the green transition also in SMEs. The regression model ($R^2 = 0.614$) demonstrates that integrated ISO 9001 + ISO 14001 systems are the strongest predictor of GTI. The key original contribution is the identification of a specific SME effect: investment in QMS yields a higher relative return in smaller enterprises.

Targeted recommendations include: (1) phased certification with public funding; (2) sectoral clusters for ISO 14001; (3) digitalisation following baseline QMS maturity (IoT, ERP); (4) a simplified national QMS + EMS light scheme for SMEs; (5) competency development through industry chambers and HRD Operational Programme.

Limitations include the cross-sectional study design, the self-reported nature of the indicators, and the focus on Bulgaria. Future research should include longitudinal observations, regional comparative analyses in CEE, and sector-specific models.

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Общехозяйственные стратегические решения: влияние государственной поддержки на выбор производственного портфолио в сельском хозяйстве Северного Казахстана

Whole-farm strategic decision-making: impacts of government support on portfolio choice in North-Kazakhstani agriculture

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Аннотация. В данной работе рассматривается влияние фактора неприятия риска, а также субсидий на выбор направления и структуры производства сельскохозяйственных предприятий в природно-экономических условиях Северного Казахстана. Использовались данные обследования хозяйств за период с 2020 по 2024 годы для построения математической модели, эффективной с точки зрения полезности. Гипотеза состояла в том, что субсидирование оказывает существенное влияние на отношение фермера к рискованным решениям, на формирование производственной структуры предприятия, а также способствует более полному использованию экономических ресурсов сельскохозяйственных предприятий. Полученные результаты подтверждают эту точку зрения. На основе расчетов по риск-модели делается вывод, что растениеводство в регионе обладает относительным экономическим преимуществом в сравнении с животноводством. Поэтому сколь-нибудь значительное развитие мясо-молочного скотоводства в регионе возможно лишь при наличии соответствующих правительственных субсидий. Также делается вывод, что развитие только двух или трех отраслей в хозяйстве может быть достаточным для заметного снижения экономического риска.

Ключевые слова: АГРОБИЗНЕС, РИСК, СУБСИДИИ, МОДЕЛЬ, ФУНКЦИЯ ПОЛЕЗНОСТИ, ПРОИЗВОДСТВЕННАЯ СТРУКТУРА, ПРИНЯТИЕ РЕШЕНИЙ.

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Abstract. This study examines the influence of risk aversion and subsidies on the choice of production direction and structure of agricultural enterprises under the natural and economic conditions of Northern Kazakhstan. Data from a survey of farms conducted between 2020 and 2024 were used to formulate a utility-based mathematical model. The hypothesis was that subsidies have a significant impact on farmers' attitudes toward risky decisions and on the formation of a farm's production structure, and that they also contribute to a more efficient use of agricultural enterprises' economic resources. The results obtained confirm this view. Based on calculations using the risk model, it is concluded that crop production in the region has a relative economic advantage over livestock production. Therefore, any significant development of meat and dairy cattle farming in the region is possible only with the availability of appropriate government subsidies. It is also concluded that the development of just two or three sectors in the economy may be sufficient to significantly reduce economic risk.

Key words: AGRIBUSINESS, RISK, SUBSIDIES, PROGRAMMING MODEL, UTILITY FUNCTION, PRODUCTION STRUCTURE, DECISION-MAKING.

1. Введение

В сельском хозяйстве развивающихся и транзитных экономик наиболее часто используемым инструментом противодействия риску является биодиверсификация [1]. Меры, которые основаны на использовании биоразнообразия сельского хозяйства в ответ на резкие изменения климата и экономической среды, можно разделить на две большие категории: выращивание большего числа видов и диверсификация фермерских хозяйств в целом; внедрение или расширение масштабов выращивания более адаптированных культур и сортов, а также домашнего скота и пород. Развитие животноводства также рассматривается как стратегия диверсификации в ответ на изменение климата [2]. За последние десятилетия в засушливых регионах Казахстана фермеры сократили инвестиции в растениеводство и сосредоточились на разведении более устойчивых к засухе животных, таких как овцы, лошади и верблюды. Подобные тенденции наблюдаются и в других странах [3]. Диверсификация растениеводства и интеграция растениеводства и животноводства часто сочетаются с корректировкой методов ведения сельского хозяйства, внедрением методов сохранения плодородия почв и водных ресурсов, а также использованием более адаптированных сортов сельскохозяйственных культур [4]. Вместе с тем в ряде случаев фермеры продолжают выращивать традиционные сорта благодаря их способности адаптироваться к новым климатическим условиям [5].

Основной вывод из анализа публикаций по рассматриваемой теме состоит в том, что эффективное и адекватное применение методов системного анализа для прогнозирования экономического развития агроэкосистем возможно лишь при тщательном учете специфических местных природно-

экономических условий и особенностей поведения предпринимателей в условиях неопределенности хозяйственной среды.

Климатические особенности Северного Казахстана существенно ограничивают возможности сельского хозяйства. При этом сохраняется значительная изменчивость уровня маржинального дохода, связанная с колебаниями урожайности, качества продукции и рыночных цен.

В вероятностной модели планирования важно учитывать отношение фермеров к риску. Неприятие риска оказывает существенное влияние на выбор общехозяйственного производственного плана [6,7]. Однако в указанных работах (кроме [7]) анализу подвергались условия, сильно отличающиеся от казахстанских по своему содержанию.

В классической экономической литературе утверждается, что функция полезности должна демонстрировать положительное, но убывающее абсолютное неприятие риска [8], эмпирические исследования указывают на отсутствие согласия в данном вопросе [9]. Практически все исследования основывались на полезности богатства (за редким исключением – см., например, [10]). Между тем, агробизнес имеет целью извлечение дохода.

В исследовании представлена вероятностная модель задачи общехозяйственного планирования и оптимизации структуры многоотраслевого сельскохозяйственного производства, включающего растениеводство и животноводство. При этом используется функция полезности с последовательной корректировкой параметра неприятия риска. Разработанная модель отражает условия предприятия, функционирующего в типичных сельскохозяйственных условиях степной черноземной зоны, занимающей 96,3% всех пахотных земель Северо-Казахстанской области. Природно-климатические условия данной зоны позволяют заниматься растениеводством

и животноводством. Задача заключается в эмпирическом изучении влияния субсидий и отношении фермеров к рискованным решениям на формирование общехозяйственного плана и структуры производства.

2. Методы и материалы

Структурно модель состоит из взаимосвязанных блоков: первый блок представляет собой запись условий по товарному растениеводству, второй - по ведению животноводства, включая кормопроизводство, третий - записи условий, связывающих блоки растениеводства и животноводства в единый комплекс. В модели реализуется сценарный подход с соответствующими вероятностями. В качестве сценариев взяты погодные и экономические условия в каждый из последних пяти лет.

Основные переменные представляют собой размер посевов культур товарного и нетоварного растениеводства, а также поголовье крупного рогатого скота и лошадей. Ключевые ограничения модели отражают условия использования земельных, трудовых и кормовых ресурсов, требования к севооборотам и структуре рационов животных, условия по финансированию текущих производственных затрат, выполнению контрактных обязательств, емкости рынка продукции, страховым взносам и выплатам. Меры финансовой поддержки государства учитываются через их влияние на уровень дохода в разрезе культур и животных, а также на стоимость основных и оборотных средств. Нормы потребления животными кормов по видам учитываются в кормовых единицах. Соотношение между взрослым поголовьем и молодняком определялось продолжительностью выращивания животных и межотельным периодом. Имеет смысл также ввести в модель ограничения по вместимости ферм для скота.

Цель в рассматриваемой задаче состоит в том, чтобы с учетом указанных условий максимизировать ожидаемую полезность маржинальных доходов по сценариям (исходам):

$$(1) E(U) = \sum_{s \in S} p^s U(z_s, r) = \sum_{s \in S} p^s [1/(1-r)z_s^{1-r}],$$

где $E(U)$ – ожидаемая полезность; r – коэффициент относительного неприятия риска; s – исход (природно-экономические условия года); S – множество исходов (природно-экономических состояний); z_s – суммарный маржинальный доход в исход s ; p^s – вероятность исхода s .

В качестве функции полезности взята степенная функция вида $U = \left(\frac{1}{1-r}\right) z^{1-r}$, где z – суммарная стоимость активов, r –

коэффициент относительного неприятия риска. Чем больше значение r , тем выше степень неприятия риска. При $r = 0$ функция принимает линейную форму, соответствующую нейтральному отношению к риску. При $r = 1$ степенная функция превращается в логарифмическую. Поскольку в модели коэффициент неприятия риска оценивается в отношении маржинального дохода (а не общей стоимости сельскохозяйственных активов), то необходимо провести расчет коэффициента относительного неприятия риска по маржинальному доходу с помощью формулы:

$$(2) r(z) = (z/W)r(W),$$

где z – среднегодовой доход; W – среднегодовая общая стоимость активов предприятия (вывод указанной формулы приводится в работе [11]).

Поиск наилучшего решения по модели проводится с использованием встроенного в MS Excel приложения Solver.

Планирование общехозяйственного дохода в многоотраслевых производствах имеет ряд особенностей, связанных с наличием и характером стохастической связи между уровнями различных производственно-экономических показателей, а также неопределенностью производственно-рыночных условий планового периода. Поэтому для расчета ожидаемых величин показателей применяется метод, в котором используются принципы экспертной оценки в сочетании с вероятностным анализом исторических данных. При этом предварительно проводится корректировка исторических данных на тренд и инфляцию.

В анализе и построении модели использовались исторические данные по урожайности сельскохозяйственных культур и продуктивности животных, переменным расходам и ценам реализации продукции в период с 2020 по 2024 г.г. Этот период охватывает полный набор типов погодных и рыночных условий региона. Все данные по урожайности и продуктивности были пересчитаны с учетом трендов (на основе методики из работы [12]).

Стоимостные исторические данные пересчитывались с помощью индекса потребительских цен (в качестве базового для пересчета был взят 2024 год).

В таблице 1 представлены исходные данные по урожайности культур, продуктивности естественных угодий и сельскохозяйственных животных за 2020-2024 г.г. Кумыс в анализируемом хозяйстве не производится с целью реализации.

Таблица 1. Урожайность сельскохозяйственных культур и продуктивность животных по годам (состояниям среды), ц/га

Год (состояние среды)	Пшеница	Ячмень	Рапс	Лен	Многолетние травы		Однолетние травы			Естественные угодия		Пастбищная трава на зеленый корм	КРС		Лошади		Вероятность состояния среды
					на сено	на зеленую массу	на сенаж	на силос	на зеленую массу	на сено	на зеленую массу		молоко	мясо	кумыс	мясо	
2020	22,1	15,5	6,5	5,9	21,6	57,6	72,1	172,9	76,9	6,6	17,6	26,4	53,1	4,9	-	3,3	0,2
2021	30,0	13,6	7,3	4,9	12,4	33,2	41,5	99,6	76,9	3,8	10,1	15,2	60,7	4,2	-	4,3	0,2
2022	37,0	29,9	13,1	9,3	13,1	34,9	43,7	104,8	76,9	4,0	10,7	16,0	64,0	4,6	-	3,5	0,2
2023	18,0	30,0	14,7	5,5	11,5	30,6	38,2	91,7	76,9	3,5	9,3	14,0	53,1	4,9	-	3,3	0,2
2024	16,8	31,8	19,6	8,8	16,4	43,7	54,6	131	76,9	5,0	13,3	20,0	59,0	4,4	-	4,9	0,2

Данные по фактическим ценам реализации продукции растениеводства и животноводства представлены в таблице 2.

Однолетние и многолетние травы в хозяйстве используются в качестве ресурса для формирования кормовой базы.

Таблица 2. Цены реализации продукции растениеводства и животноводства по годам (состояниям среды), тыс. тенге/ц

Год (состояние среды)	Пшеница	Ячмень	Рапс	Лен	Крупный рогатый скот		Лошади	
					Молоко	Мясо	Кумыс	Мясо
2020	7,8	5,6	10,1	8,9	11,9	62,2	-	79,7
2021	9,9	7,9	18,9	14,2	13,7	72,1	-	111,3
2022	11,7	8,9	27,2	25,6	16,6	84,1	-	108,0

2023	9,2	6,5	18,2	17,1	18,6	94,4	-	111,8
2024	8,2	5,4	17,2	21,4	18,4	85,3	-	115,2

В анализируемом хозяйстве страхование посевов в указанный период не осуществлялось.

Размеры переменных расходов в животноводстве (кроме затрат на корма) и переменных расходов в растениеводстве, включающих в себя затраты на использование минеральных удобрений, горюче-смазочных материалов, средств защиты растений, заработную плату рабочих, страховые взносы, приведены в таблице 3.

Таблица 3. Переменные расходы в растениеводстве (тыс. тенге/га) и животноводстве (кроме затрат на корма, тыс. тенге/гол.)

Год (состояние среды)	Пшеница	Ячмень	Рапс	Лен	Многолетние травы		Однолетние травы			Трава естественных угодий		Пастбищная трава на зеленый корм	Крупный рогатый скот		Лошади		Вероятность состояния среды
					на сено	на зеленую массу	на сенаж	на силос	на зеленую массу	на сено	на зеленую массу		молоко	мясо	кумыс	мясо	
2020	80,7	59,6	21,8	29,1	18,1	15,4	16,9	36,5	14,4	3,3	2,8	0,8	261,2	117,5	323,5	388,2	0,2
2021	83,6	70,6	35,6	47,4	21,1	17,9	19,6	43	16,6	3,8	3,2	1,0	210,0	94,5	217,0	260,4	0,2
2022	121	121,5	33,7	44,9	24,4	20,8	23,1	50,5	19,6	4,4	3,7	1,1	337,7	151,9	446,1	535,3	0,2
2023	107	96,6	43,2	57,6	28,5	24,2	27,3	58	23,2	5,1	4,4	1,3	367,5	165,4	448,4	538,1	0,2
2024	103,2	100	40,5	50,6	32,6	27,7	30,8	65,5	26,2	8,0	5,0	2,0	371,5	167,2	310,5	372,6	0,2

Фактические цены на покупные корма в 2020-2024 годах составили: комбикорм - 5,4; 6,5; 7,5; 8,3 и 8,8 тыс. тенге/ц соответственно, кормовые добавки - 6,0; 7,5; 8,2; 9,0 и 10,3 тыс. тенге/ц соответственно. Нормы потребности животных в кормах, а также структуры рационов кормления животных в зависимости от продуктивности взяты из рекомендаций Северо-Казахстанского научно-исследовательского института животноводства и ветеринарии.

Оценка вероятности того, что в плановом периоде будут иметь место условия, сходные с теми, что были в период с 2020 по 2024 г.г., была проведена на основе опроса группы региональных экспертов. Оценки вероятности представлены в таблице 1.

В анализируемом хозяйстве участие в программах субсидирования по растениеводству не планируется, размер субсидии на производство молока составляет 4,5 тыс. тенге/т, на выращивание молодняка КРС на откорм - 30,0 тыс. тенге/гол.

Задача решалась в нескольких вариантах: без учета субсидий и с учетом субсидий при разных уровнях неприятия риска. Мы предположили, что коэффициент относительного неприятия риска по отношению к богатству, $r_r(w)$, находится в пределах от 0,5 (риск практически не принимается во внимание) до 4 (крайне высокая степень неприятия риска) (обоснование такой интерпретации указанных коэффициентов приведено в работе [13]). Соответствующие коэффициенты неприятия риска по отношению к доходу пересчитывались с использованием уравнения (2).

3. Результаты решения и обсуждение

В таблице 4 приведены результаты решения задачи. В варианте без учета субсидий при коэффициентах неприятия риска по богатству в промежутке от 0 до 1 (им соответствуют коэффициенты относительного неприятия риска по доходу от 0 до 0,4) структура производства претерпевает крайне незначительные изменения, а при коэффициентах от 1 до 2 (соответственно от 0,4 до 0,8) фермеры склонны придерживаться совершенно одинаковой производственной структуры.

Таблица 4. Производственный портфель предприятия без и с учетом субсидий при различных коэффициентах неприятия риска

Показатель	Единица измерения	Вариант без учета субсидий			Вариант с учетом субсидий		
		коэффициент неприятия риска					
		$r_r(w)=0$ $r_r(z)=0$	$r_r(w) \approx 1$ $r_r(z) \approx 0,4$	$r_r(w) \approx 2$ $r_r(z) \approx 0,8$	$r_r(w)=0$ $r_r(z)=0$	$r_r(w) \approx 2$ $r_r(z) \approx 0,8$	$r_r(w) \approx 4$ $r_r(z) \approx 1,7$
Маржинальный доход	тыс. тенге	1549080	1548841	1548841	1750932	1743339	1173829
Площадь посевов:							
Пшеница мягкая	гектары	4348	4309	4309	4348	3944	306
Ячмень на внутреннее потребление	гектары	259	167	167	259	286	1408
Ячмень на продажу	гектары	0	0	0	0	0	916
Рапс	гектары	2916	2916	2916	2916	2916	2123
Лен	гектары	0	0	0	0	0	793
Многолетние травы							
- на сено	гектары	1611	1611	1611	1611	1692	1844
- на зеленую массу	гектары	459	525	525	459	566	1215
Однолетние травы	гектары						
- на сенаж	гектары	672	794	794	672	789	1037
- на силос	гектары	514	514	514	514	566	658
- на зеленую массу	гектары	884	827	827	884	903	1013
Трава естественных угодий							
- на сено	гектары	207	207	207	207	207	182
- на зеленую массу	гектары	0	0	0	0	0	25
Пастбищная трава на зеленый корм	гектары	1361	1361	1361	1361	1361	211

Поголовье животных:							
- коровы	головы	600	600	600	600	663	776
- молодняк КРС	головы	400	400	400	400	442	517
- лошади взрослые	головы	250	250	250	250	250	250
- лошади молодняк	головы	250	250	250	250	250	250

При коэффициентах, превышающих 2, наблюдается уже неполное использование производственных ресурсов, прежде всего земельных. Это обстоятельство можно, помимо прочего, трактовать как уклонение от ведения бизнеса в силу высокой степени неприятия риска. Несколько иная картина складывается при расчетах с учетом субсидий. При коэффициентах относительного неприятия риска по богатству в пределах от 0 до 2 (по доходу соответственно от 0 до 0,8) наблюдается незначительные изменения в структуре производства. Заметные изменения в производственной структуре предприятия в пользу мясо-молочного животноводства имеют место в случаях, когда коэффициент неприятия риска превышает 2. Неполное использование ресурсов (уклонение от ведения сельскохозяйственного бизнеса) наблюдается при коэффициенте неприятия риска более 4. Полученные результаты свидетельствуют о том, что в природно-экономических условиях Северного Казахстана склонность сельскохозяйственного предпринимателя к рискованным решениям в значительной мере предопределяется наличием или отсутствием субсидий и других форм финансовой поддержки отрасли. При отсутствии финансовой помощи со стороны правительства агробизнесом в регионе занимаются индивидуумы с достаточно выраженной рисковой натурой. Наличие субсидий позволяет вовлекать в орбиту сельскохозяйственного предпринимательства также индивидуумов с более высоким уровнем неприятия риска.

В Северном Казахстане природно-экономические условия подталкивают фермеров формировать структуру производства в пользу выращивания зерновых и масличных культур. Иначе говоря, растениеводство в регионе обладает относительным экономическим преимуществом в сравнении с животноводством. Сколько-нибудь значительное развитие мясо-молочного животноводства в нынешних условиях возможно лишь при наличии соответствующих правительственных субсидий. Субсидии в значительной мере нивелируют влияние такого фактора как неприятие риска на формирование производственной структуры и способствуют более полному использованию экономических ресурсов сельскохозяйственных предприятий.

4. Заключение

В нашем анализе мы исходили из предположения о рациональности фермера в принятии управленческих решений. И хотя данное допущение в последнее время оспаривается некоторыми исследователями (см., например, [14]), следует иметь в виду, что большинство специалистов все же сходятся на мнении о том, что предприниматели в целом рациональны в выборе решений – хотя и с определенными оговорками.

Сельскохозяйственные предприниматели Северного Казахстана достаточно ограничены в подборе производственного портфолио, что объясняется специфическими географическими и климатическими условиями. Представляется, что в таких условиях развитие в хозяйстве только двух или трех отраслей часто оказывается достаточным для существенного снижения экономического риска в рассматриваемом регионе.

Построение и использование риск-моделей, в которых ставится цель максимизировать ожидаемую полезность конечного результата, представляет собой весьма непростую задачу. Вопрос в том, оправданы ли усилия по разработке таких моделей. Риск-модели с максимизацией ожидаемой полезности и последующий анализ результатов могут иметь теоретическую ценность. Однако, результаты некоторых специальных исследований показывают, что даже в развитых

экономиках такие сложные подходы находят себе практическое применение лишь в 5-10% случаев анализа бизнес-ситуаций [15].

Разработка моделей с максимизацией ожидаемой полезности требует весьма тщательной проработки проблемы, что в свою очередь предопределяет необходимость привлечения значительных ресурсов: интеллектуальных, финансовых, а также времени. Вместе с тем, обращение к таким моделям вполне оправдано в ситуациях, когда ставится задача прогнозирования и анализа последствий от реализации региональных и национальных сельскохозяйственных экономических программ. Значительные ресурсы, включая время, затрачиваемые на тщательную проработку проблемы, обосновываются масштабами, общественной значимостью и долгосрочным эффектом таких программ.

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Ways to stimulate the development of sustainable entrepreneurship

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Abstract : Sustainable entrepreneurship development meaning is a big challenge for scientific society and demands cooperation strengthening with entrepreneurs, princely states with structures and with youth who influence they make sustainable development in a new way on understanding and they need innovative approaches.

In this paper we have reviewed and investigated sustainable entrepreneurship development stimulates economic, social and environment dimensions which they form various prerequisites and certain circumstances are filled each other and hand promote in country sustainable entrepreneurial activity high level. It is important that countries they took obligation priority to be granted to advance, for which creativity, knowledge, technology and financial resources of society by addressed will be Sustainable Development Goals - SDGs to achieve all in context. This goals taking into account, by 2030 possible should to become all of a woman and of men complete and productive employment and decent of work achievement.

It is emphasized that countries should support the development of higher education, especially to increase the staff of higher professional education by expanding the educational balance, by increasing the financing of education for sustainable development, for the existence of more knowledgeable and qualified personnel.

KEYWORDS : SUSTAINABLE ENTREPRENEURSHIP, QUALITY EDUCATION, ENVIRONMENT, INNOVATION, INEQUALITY REDUCTION.

1. Introduction

The purpose of the research is to review and investigate the ways of stimulating the development of sustainable entrepreneurship, which includes three dimensions of economic, social and environmental protection, trends and certain circumstances. Also to establish the basic theoretical principles of research on how the various preconditions influencing sustainable entrepreneurship complement each other and contribute to a high level of sustainable entrepreneurial activity. This effort has significant potential to advance the field of entrepreneurship while promoting a cleaner planet.

The presentation of ways of stimulating the process of sustainable development of entrepreneurship and the theoretical analysis of factors made it possible from economic and social factors that education can better achieve high-quality sustainable development. Quality development can contribute to the efficient use of resources and energy, the construction of sustainable infrastructure, the green development of the environment, and the reduction of production and consumption waste and losses.

As a result of the research, the economic and social factors ensuring the development of sustainable entrepreneurship were determined, which, despite their contradictory nature, still provide significant incentives for environmental protection and the process of sustainable development in an environment of risk and uncertainty.

The paper establishes a theoretical analysis framework on ways to stimulate the development of sustainable entrepreneurship, which includes three dimensions of economic, social and environmental protection, thereby achieving sustainable development and efficiency of the world economy.

2. Sustainable Development Goals (SDGs)

Today, the world economy is characterized by high rates of development, but there are still often acute daily problems of political, economic and social security and well-being, such as poverty, climate protection and environmental degradation. To address these and other challenges, the United Nations adopted the Sustainable Development Goals (SDGs) in 2015 as a call to action to end poverty, protect the planet, and ensure that by 2030, all people enjoy peace and prosperity.¹

The Sustainable Development Goals, also known as the Global Goals, include 17 development goals such as: no poverty; zero hunger; good health and well-being; quality education; gender equality, clean water and sanitation; affordable and clean energy; decent work and economic growth; industry, innovation and

infrastructure; reducing inequality and others. They recognize that action in one area will affect outcomes in another and that development must balance social, economic and environmental sustainability.

Countries have committed to prioritizing progress so that creativity, knowledge, technology and financial resources can be channeled by society to achieve the SDGs in all contexts.

The SDGs promote sustainable economic growth, higher levels of productivity and technological innovation. Encouraging entrepreneurship and creating jobs is key to this. As well as effective measures to eliminate forced labour, slavery and human trafficking. Because of this, in the last ten years, entrepreneurship has been recognized as a potential lifeline for social inequality and environmental degradation [1]. Scholars have expanded this concept to include conventional entrepreneurship, its impact on society and the environment, and the emergence of a new form of entrepreneurship known as sustainable entrepreneurship [2].

Research by scientists has confirmed that sustainable entrepreneurship today faces many challenges, such as lack of funding, misinformation and government support. Because of this, national involvement of scientists, the state and entrepreneurs is necessary to identify and investigate ways to stimulate the development of sustainable entrepreneurship. This study is based on the ecological theory of sustainable entrepreneurship and establishes a framework for theoretical analysis that includes three dimensions: economic, social and environmental.

The economic dimension includes GDP and SDG9 - Industry, Innovation and Infrastructure; The social dimension includes SDG4 - quality education and SDG10 - reduced inequality; And the environmental dimension includes environmental quality and SDG12 - responsible consumption and production. Sustainable entrepreneurship systematically considers all elements of sustainability and pursues social, economic and environmental goals. [3] These three pillars are interconnected and interdependent.

Table 1: Gross domestic product (GDP) of Georgia

	2020	2021	2022	2023
Real GDP growth, percent	5.4	-6.3	10.6	6.9
GDP per capita (at current prices), USD	4 741.4	4 300.8	5 083.6	2 227.5
GDP at current prices, Billion USD	17.6	16.0	18.9	8.3

<https://www.geostat.ge/ka/modules/categories/23/mtliani-shida-produkti-mshp>

¹ <https://sdgs.un.org/goals>

The economic pillar means that in the process of sustainable development, economic growth should be sustainable and not at the expense of the environment and society. The social pillar implies that sustainable development should consider factors such as social justice, human well-being and social stability. The environmental pillar means that sustainable development must protect and improve the environment and achieve ecological balance in order to provide the necessary resources and foundations for future development of environmental protection, in the context of important global challenges and threats, such as global warming and the loss of non-renewable resources, all of which require broadening the research perspective from a narrow beyond economic considerations to include social and environmental dimensions. [4]

All this proves that it is not enough for entrepreneurs to focus on economic growth as the goal of business development, they also need to consider the long-term survival of the business and pay more attention to sustainability issues, which makes them pay more attention to the SDGs. Thus, sustainable entrepreneurship is not only a social responsibility, but also a business opportunity. Taking advantage of the business opportunities created as a result of sustainable development and using them requires more pragmatic actions by countries.

GDP per capita is considered as an indicator of the country's economic development potential. There is a correlation between entrepreneurship and economic development. In this context, a country's high GDP per capita, defined by purchasing power parity, indicates a high standard of living, improved conditions and opportunities for entrepreneurial activity. The positive impact of sustainable entrepreneurship and its advancement can be attributed to the level of economic development, and the measure of economic growth and development is GDP. Thus, sustainable entrepreneurship is related to GDP. Studies have shown that currently, countries around the world are trying to build resilient infrastructure and sustainable industries and promote innovation [5], thereby promoting sustainable entrepreneurship. Thus, sustainable entrepreneurship is linked to industry, innovation and infrastructure.

Education is one of the greatest drivers of sustainable development. In order to achieve quality education, countries should pay more attention to SDG4 - quality education.

Governments should support the development of higher education, especially the increase of higher vocational education personnel by expanding educational equality and increasing education funding for sustainable development to have more knowledgeable and qualified personnel.

Quality education focused on the values of sustainable development helps educated people develop the necessary scientific knowledge, learning competencies, values and behaviors for sustainable development and environmental protection. Quality entrepreneurship education fosters a sustainable entrepreneurial spirit, awareness and competence, enabling entrepreneurial candidates to create businesses that contribute to the sustainable development of humanity and society [6].

A higher level of education makes it easier for people to innovate, and allows entrepreneurs to identify possible market opportunities, and different tools can be used more effectively to carry out entrepreneurial activities. At the same time, students form an important pool of entrepreneurs, and a quality education can encourage them to solve social and environmental problems, as well as to make sustainable solutions a reality. Thus, sustainable entrepreneurship is linked to quality education.

Quality education helps reduce inequality. SDG10 works to reduce inequality between countries, which consists of various goals, which include the growth rate of household expenditures, equal opportunities by promoting social, economic and political participation and reducing inequality in results, universal sharing of the fruits of economic growth. This goal aims to meet the needs of all countries and people, especially women, youth and vulnerable groups. This requires the creation of more quality jobs and entrepreneurship. A reduction in social inequality and a stable environment encourage individuals to perceive and exploit new economic opportunities in the face of market uncertainty, thereby

engaging in entrepreneurship and promoting social well-being [7]. Thus, eliminating inequality and guaranteeing fair opportunities for individual development is an important prerequisite for achieving sustainable entrepreneurship. Thus, sustainable entrepreneurship is associated with reduced inequality.

To achieve economic growth and sustainable development, it is necessary to reduce the ecological footprint by changing the ways of production and consumption of goods and resources. This goal is served by SDG12 - Responsible consumption and production, which requires practical support for industry, business and consumers for responsible consumption and production. This is necessary because traditional consumption and production rely on resources from the natural environment, economic development takes place at the expense of the environment and human health [8]. Responsible consumption and production involves achieving higher levels of productivity and efficiency with limited resources, while breaking the link between economic growth and environmental degradation. From the perspective of sustainable entrepreneurship, this effort of sustainable development concerns firms involved in a wide range of entrepreneurial activities interested in and seeking economic and social returns due to the needs of responsible production. Because improving the quality of their environment requires a departure from traditional production methods and the use of clean production practices. Along with promoting responsible consumption, it is possible to diversify economic activities, conserve valuable resources and minimize waste. Thus, the way to stimulate sustainable entrepreneurship is responsible production and consumption.

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Digital Competencies of Healthcare Professionals in Healthcare Organizations: A PRISMA-Based Systematic Literature Review

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Abstract: The digital transformation of healthcare systems is significantly changing the way healthcare organizations operate and healthcare is delivered. The rapid development of digital technologies has increased the demand for digital competencies among healthcare professionals and managers. These competencies are essential for the effective implementation and use of digital technologies in healthcare. The aim of this study is to identify and analyze the key digital competencies required in healthcare organizations in the context of digital transformation. A systematic literature review was conducted using the PRISMA methodology to identify relevant scientific publications focused on digital competencies in healthcare. The analysis focuses on the digital skills and competencies of healthcare professionals and managers. The findings highlight the importance of digital literacy, data management, information security, and continuous professional development. The study contributes to an understanding of how healthcare organizations can better prepare their employees for digital transformation.

Keywords: DIGITAL COMPETENCIES, HEALTHCARE ORGANIZATIONS, DIGITAL TRANSFORMATION, HEALTHCARE MANAGEMENT, E-HEALTH, DIGITAL SKILLS, HEALTHCARE PROFESSIONALS, INDUSTRY 4.0

1. Introduction

Although the COVID-19 pandemic officially ended several years ago, its consequences continue to significantly impact the functioning of society [9, 10]. The coronavirus crisis, combined with the ongoing development of digital technologies, has accelerated the process of digital transformation across multiple sectors, and the healthcare sector was no exception. As a result of widespread lockdowns and efforts to minimize physical contact, healthcare facilities were forced to seek new ways of providing healthcare [6, 11].

This has significantly accelerated the transformation of healthcare delivery, but the implementation of changes in the healthcare sector continues at a slow pace [11, 14]. The digitization of healthcare brings several benefits, including remote patient monitoring, real-time data availability, the use of virtual assistants, telemedicine consultations, and electronic health records (EHR) [6, 9]. The positive impact of digital technologies is also evident in the work of healthcare staff, particularly through the elimination of human error, timely identification of anomalies, optimization of workflows, reduction of routine tasks, and support for faster decision-making [2, 12].

The goal of digital health is to provide safer, higher-quality, and more efficient healthcare services, while at the same time relieving healthcare professionals of administrative and routine tasks so that they can devote more time to strategic and professional activities [5, 7]. However, the digital skills and competencies of healthcare workers are key to achieving these benefits [15], [20]. Digital competencies are an essential prerequisite for the active participation of healthcare staff in the process of digitizing healthcare systems [6, 11]. Insufficient digital literacy can lead to the ineffective use of digital technologies and, consequently, to the failure to realize the potential of digital health. Therefore, managers should possess competencies in change management, strategic planning, and the creation of appropriate infrastructure to eliminate barriers that prevent the achievement of the desired level of digital skills [7, 19].

Digital competencies must be viewed holistically, as they encompass not only technical skills but also ethical, security, and information competencies related to the use of digital technologies [2], [12]. However, the implementation of digital solutions in healthcare is accompanied by several obstacles. One of these is resistance among healthcare staff to adopting and using new technologies, which is often linked to insufficient training, low levels of digital literacy, or limited knowledge of available technological solutions [1,7,8]. Other barriers include inadequate technological infrastructure, limited access to information

technology, high financial costs associated with implementing digital solutions, as well as insufficient institutional support [2, 19].

Systematic education and training of healthcare staff can be considered a key factor in the successful implementation of digital technologies [4, 6]. Managers should therefore place greater emphasis on the development of their healthcare staff. Planning educational activities is essential to ensure an adequate level of digital competencies, as the successful adoption of digital technologies depends on healthcare workers' readiness to use them effectively in practice [7]. Training programs should therefore be focused on developing practical skills and utilize diverse forms and methods of training [2, 6].

Based on the above, the digital competencies of healthcare professionals and managers appear to be a key prerequisite for the successful digital transformation of healthcare. The aim of this article was therefore to identify the digital competencies required of healthcare professionals and managers in the context of the digital transformation of healthcare.

2. Methods

The PRISMA methodology was applied to ensure a systematic literature review. The original version of the methodology was simplified for the purposes of this article, as the search for scholarly sources was conducted in only one database. The aim of the review was to answer the following research question: *What digital competencies are required for healthcare professionals and managers in healthcare organizations in the context of digital transformation*

The search for academic articles was conducted using the Web of Science database, which provides extensive access to peer-reviewed scientific publications in the fields of healthcare, management, and digital transformation. The following search string was used in the database: TS(("digital competenc*" OR "digital skill*" OR "digital literacy") AND ("healthcare professional*" OR "healthcare manager*") AND ("digital transformation" OR "digital health" OR e-health)).

Based on the search string provided, 145 records were identified. The filtering criteria listed in Table 1 were then applied.

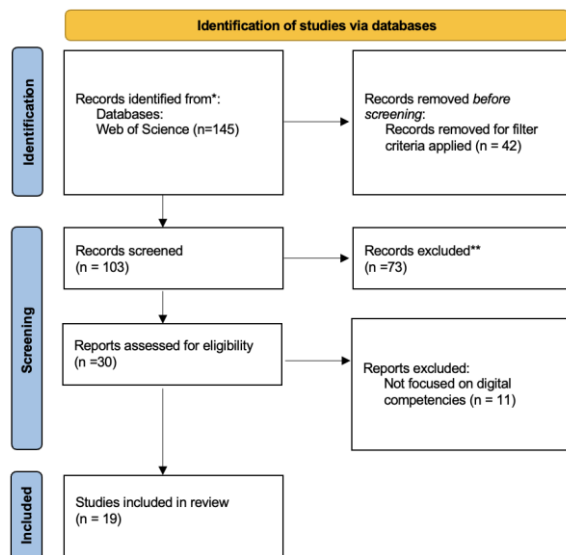
Table 1 Selection criteria

Criteria	Description
Publication years	2022 -2026
Language	English
Access type	Open access
Document types	Article, Review Article

Source: own elaboration

After applying the inclusion criteria and completing the screening process, 30 articles were assessed for relevance. Irrelevant studies, articles unrelated to the topic under investigation based on their title and abstract, as well as sources that did not meet the required quality criteria, were excluded from the dataset. Following the final evaluation and analysis of the full texts, 19 studies were included in the systematic review. The article selection process is illustrated using the PRISMA flow diagram in Fig. 1.

Figure 1 PRISMA flow diagram



Source: own elaboration, according to PRISMA 2020 methodology based on Page et al. (2021), <https://doi.org/10.1136/bmj.n71>

To enhance the relevance and practical value of the findings, the data from the systematic review were supplemented with statistical data from Eurostat and OECD databases, which provide an overview of digital competence levels.

3. Research results

To ensure greater clarity, the findings from the systematic review have been organized into three tables. The first two tables focus on the digital competencies of healthcare professionals and managers, while the third table highlights the challenges and barriers contributing to the insufficient level of digital competencies.

Table 2 Digital Competencies of Healthcare Professionals

Area	Description of competencies	Authors
Technical and ICT literacy	Ability to use hardware and software and solve other technical problems	(Erfani et al., 2025; Kulju et al., 2024)
Information and data literacy	Searching for, filtering, and evaluating information	(Esperança et al., 2026; Lee et al., 2023)
Digital communication and counseling	Video consultations, using applications, and email communication	(Guillari et al., 2024; Oudbier et al., 2024)
Ethics and Security	Cybersecurity, GDPR, and ethical decision-making	(Erfani et al., 2025; Kulju et al., 2024)

Source: own elaboration

We have identified the four most frequently recurring areas and competencies related to the digital transformation of healthcare personnel. One of the core competencies is technical proficiency, which in practice refers to the ability to effectively use information

and communication technologies [2]. At the same time, digitization enables the processing of large amounts of data, and healthcare professionals must have the ability to filter this data and identify the relevant information needed for decision-making and solving specific problems [3].

The digitization of healthcare is also giving rise to new forms of healthcare delivery, particularly remote counseling, telemedicine, and video consultations, which require healthcare personnel to possess sufficient digital skills [6, 17]. As the volume of data and its sharing increase, so does the importance of protecting sensitive data and ensuring information security to prevent unwanted data leaks [12].

Table 3 Digital Competencies for Healthcare Managers

Area	Description of competencies	Authors
Digital Leadership	Developing a digital vision and implementing innovations	(Erfani et al., 2025; Lee et al., 2023)
Change Management	Managing the transition to digital processes and staff adaptation	(Esperança et al., 2026)
Workforce Development	Planning training and organizing workshops	(Byungura et al., 2022; Navarro-Martínez et al., 2023)
Infrastructure Management	Ensuring connectivity and digital infrastructure	(Esperança et al., 2026; Hailu et al., 2026)

Source: own elaboration

Managers' competencies should be supplemented with managerial skills related to setting digital transformation strategies, as well as organizing and managing the transition from traditional forms of healthcare delivery to new digital solutions [2,3]. Workforce development is also emerging as a key area, as employees and their competencies are a significant factor in successful digital transformation.

According to Byungur et al. (2022), the training of healthcare professionals should take the form of blended learning, while Erfani et al. (2025) emphasize the importance of using a variety of educational methods. The main reason for this is the existence of a multigenerational work environment, which requires adapting training methods to different groups of employees [1, 2].

To ensure an effective and seamless digital transformation, it is also essential to establish an adequate digital infrastructure and ensure connectivity between existing and new digital solutions [3].

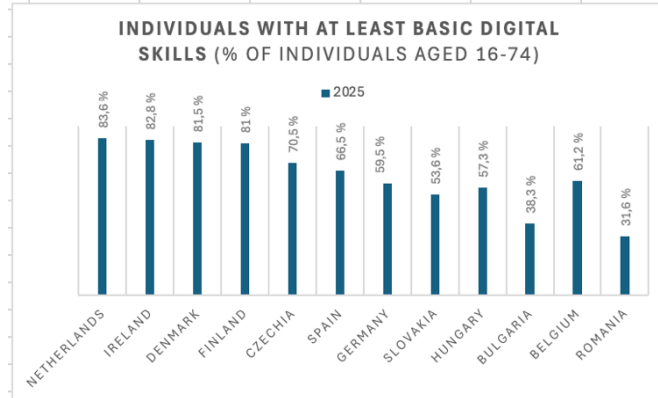
Table 4 Factors contributing to low levels of digital literacy

Challenge	Authors
Resistance to change, frustration	(Fernández-Luque & Ramirez-Montoya, 2024; Picón-Jaimes, 2024)
Lack of training and educational programs	(Esperança et al., 2026; Mikkonen et al., 2026)
Level of education	(Hengst et al., 2026; Kissi et al., 2022)
Age and generational differences	(Erfani et al., 2025; Mikkonen et al., 2026)
Inadequate infrastructure	(Hailu et al., 2026; Kulju et al., 2024)
Cybersecurity	(Kissi et al., 2022; McDevitt et al., 2025)

Source: own elaboration

Achieving an adequate level of digital skills is influenced by a number of factors and challenges that hinder or slow down the acquisition of the necessary digital competencies. Figure 2 also illustrates the slower progress in acquiring basic digital skills, highlighting differences in the level of basic digital skills among European countries. Several countries still do not meet the required level of digital literacy, which can pose a significant barrier to the effective implementation of digital technologies in healthcare [22].

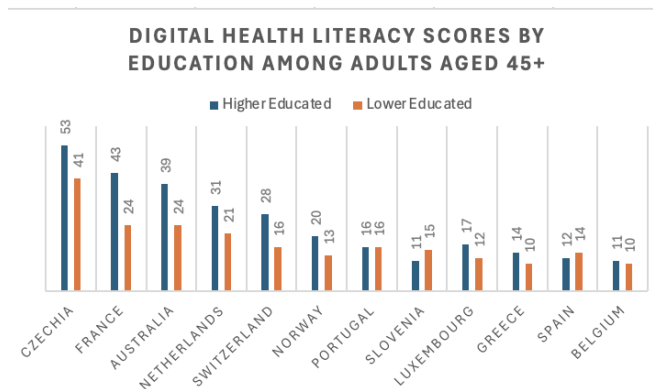
Figure 2 Individuals with at least basic digital skills



Source: own elaboration, According to Eurostat (2025), Available at: [doi:10.2908/isoc_sk_dskl_i21](https://doi.org/10.2908/isoc_sk_dskl_i21)

Figure 3 Digital health literacy scores by education

Source: own elaboration, According to OECD (2024), Available at: [OECD - Digital Health](https://oecd-digital-health.org/)



Other significant challenges include a lack of training and generational differences. Younger healthcare professionals generally have a more positive attitude toward adopting digital technologies, while older staff may be more resistant to change and the implementation of digital solutions. At the same time, OECD data (Figure 3) highlight differences in digital health literacy levels between higher- and lower-educated groups of the population aged 45 and older, supporting the claims of several authors that a higher level of education positively influences the adoption and effective use of digital technologies [2, 15].

To achieve the necessary level of digital literacy, it is essential to adapt training so that it is not only practice-oriented but also up-to-date, given the rapid evolution of digital technologies. Training should employ multi-method approaches, or methods such as “reverse mentoring.” This approach is based on the assumption that younger employees generally possess a higher level of digital skills, while older colleagues have more extensive professional and practical experience. The combination of this knowledge and experience has proven to be an effective model for developing the digital competencies of healthcare personnel [1, 2, 15].

4. Discussion

According to Esperança et al. (2026), digital competencies constitute a comprehensive set of knowledge, skills, and attitudes, and cannot be reduced merely to the technical use of information and communication technologies. This assertion is also supported by our findings, which indicate that digital competencies can be assessed across multiple domains. Several authors agree that one of the key prerequisites for the successful implementation of digital technologies is employee readiness and a sufficient level of digital literacy [2,7]. At the same time, the findings of several authors, as well as data published by Eurostat (2025), suggest that the level of digital competencies is still insufficient in many cases.

Education is emerging as a key factor in the development of digital competencies. Mikkonen et al. (2026) emphasize the need to continuously adapt competencies to the current demands of the digital environment, a view supported by Byungura et al. (2022), who argue that competencies must be continuously updated to reflect current technological developments. Guillari et al. (2024) and Kulju et al. (2024) also argue that the competence of healthcare personnel is key to realizing the full potential and benefits of healthcare digitization.

Some authors also emphasize the need for a multi-method approach to education, as digital competencies must be developed across various age and professional groups [2, 15]. Erfani et al. (2025) note that younger healthcare workers generally possess a higher level of digital skills and can pass this knowledge on to older colleagues. Conversely, older workers can pass on their professional and practical experience to younger colleagues. In this context, Mikkonen et al. (2026) highlight the importance of reverse mentoring.

At the same time, older workers may be more resistant to adopting digital technologies than younger generations. Hengst et al. (2026) add that higher levels of digital literacy are also associated with a more positive attitude and greater enthusiasm for using digital technologies.

5. Conclusion

Digital competencies are proving to be a key factor in the successful digital transformation of healthcare. Digital competence must be viewed from a multidimensional perspective, as it encompasses not only technical skills but also the ability to work with data, apply digital technologies in practice, ensure data protection, and effectively manage change within organizations. The results also highlight the need for continuous education and the development of digital competencies among healthcare workers and managers. Educational level, generational differences, and the availability of training and digital infrastructure also play a significant role. For the successful implementation of digital solutions, it is therefore essential to create conditions that support the development of digital readiness among healthcare personnel.

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Digital Profiling and 3D Representation of Traditional Bulgarian Belt Buckles (Pafti): A Cultural Data Approach in the Context of Industry 4.0

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Abstract: This study presents a framework for the digital profiling and online representation of traditional Bulgarian belt buckles (pafti) through the integration of structured cultural data and accessible 3D visualization approaches. The research is positioned within the context of Industry 4.0, where digital transformation, data-driven methodologies, and virtual representation increasingly influence the preservation and interpretation of cultural heritage. Traditional ethnographic artifacts are often documented through fragmented textual descriptions and static photographs, limiting their accessibility and analytical potential in digital environments. The proposed approach combines ethnographic documentation with data structuring and digital visualization techniques. Cultural attributes such as regional affiliation, ornamentation, material composition, decorative elements, and object form are organized into a structured descriptive model suitable for digital analysis and presentation. In parallel, the study applies a low-cost photogrammetry workflow for creating a digital representation of selected artifacts, supported by online visualization through a web-based environment and QR-based access. The results demonstrate how traditional cultural objects can be transformed into structured digital entities that support visualization, accessibility, and interactive exploration. The study highlights the potential of combining cultural heritage research with digital technologies in order to create accessible models for the preservation and presentation of ethnographic artifacts within contemporary digital ecosystems.

Keywords: CULTURAL HERITAGE, DIGITAL PROFILING, PHOTOGRAMMETRY, BELT BUCKLES (PAFTI), INDUSTRY 4.0, DIGITAL REPRESENTATION

1. Introduction

The rapid development of digital technologies has significantly transformed the ways in which cultural heritage is documented, preserved, and presented. Within the broader context of Industry 4.0, concepts such as digital transformation, data-driven methodologies, virtualization, and interactive access increasingly extend beyond industrial applications and find relevance in the fields of humanities, cultural heritage studies, and digital humanities. As a result, traditional cultural artifacts are gradually becoming part of new digital ecosystems that enable their structured representation, visualization, and long-term preservation.

In recent years, museums, researchers, and cultural institutions have increasingly explored digital approaches for documenting and presenting ethnographic objects through virtual collections, interactive platforms, and 3D visualization technologies [1]. Despite these developments, many traditional artifacts continue to exist primarily as static photographs or descriptive museum records, often lacking structured metadata and digital analytical representation. This limits both their accessibility and their potential integration into contemporary digital cultural environments.

Traditional Bulgarian belt buckles, known as pafti, represent an important element of women's traditional costume and material culture. Beyond their decorative function, they reflect regional identity, craftsmanship traditions, symbolic ornamentation, and cultural continuity across generations [2]. Due to their visual complexity and ethnographic significance, pafti provide a suitable case for exploring the possibilities of digital representation and structured cultural data organization.

The present study proposes a framework for the digital profiling and online representation of traditional Bulgarian belt buckles through the integration of structured descriptive attributes, photographic documentation, photogrammetry, and web-based visualization [3]. The research aims to demonstrate how accessible digital technologies and data-oriented approaches can support the preservation, accessibility, and interpretation of ethnographic artifacts within the technological paradigm of Industry 4.0.

The study is guided by the following research question:

How can structured cultural data, photogrammetry, and web-based visualization technologies be integrated into a digital framework for the representation and accessibility of traditional ethnographic artifacts?

2. Problem discussion

The digital representation of cultural heritage has become an increasingly important research direction within contemporary digital humanities and cultural preservation initiatives. Despite the growing use of digital technologies in museums, archives, and virtual heritage platforms, many ethnographic artifacts continue to be documented primarily through static photographs, descriptive inventories, and fragmented textual records. In many cases, this information remains unstructured and dispersed across museum catalogues, private collections, printed publications, and local historical archives, limiting the possibilities for systematic digital analysis and interactive representation.

Traditional ethnographic objects often contain complex visual, symbolic, and regional characteristics that are difficult to organize within conventional descriptive approaches. This is particularly evident in the case of traditional Bulgarian belt buckles (pafti), where variations in ornamentation, material composition, shape, decorative motifs, and regional stylistic features create a rich but highly heterogeneous body of cultural information. Although such artifacts possess significant ethnographic and historical value, they are rarely approached as structured cultural data objects suitable for integration into digital environments.



Fig. 1 Traditional embroidered belt from Central Northern Bulgaria

Figure 1 presents a traditional embroidered belt from Central Northern Bulgaria used as part of the ethnographic material examined in the present study. The artifact combines textile craftsmanship, decorative bead ornamentation, and leather structural elements characteristic of regional traditional costume accessories. The visual complexity and ornamental composition of the belt demonstrate the diversity of ethnographic objects that can be documented and represented through structured digital approaches.



Fig. 2 Traditional Gabrovo-style pafiti from a private ethnographic collection

Figure 2 illustrates traditional Bulgarian pafiti of Gabrovo style distinguished by detailed metallic ornamentation and sculptural decorative forms [4]. As representative elements of women's traditional costume, pafiti contain significant visual and symbolic characteristics that make them suitable objects for digital profiling and online cultural representation. Their structural complexity and decorative richness provide an appropriate basis for the application of photogrammetry and digital visualization techniques within contemporary cultural heritage environments.

The selected artifacts illustrate the diversity and visual complexity of traditional Bulgarian ethnographic objects. Their combination of textile craftsmanship, metallic ornamentation, symbolic decorative motifs, and regional stylistic characteristics demonstrates the rich informational potential embedded within traditional material culture. At the same time, such artifacts present significant challenges for digital documentation and representation due to the coexistence of visual, structural, and cultural attributes that are often difficult to organize within conventional descriptive models.

Another important challenge is the limited accessibility of many ethnographic artifacts outside museum exhibitions and private collections. Traditional forms of documentation are typically based on static photographs and descriptive records, providing restricted opportunities for interactive exploration and digital engagement. As a result, valuable cultural objects often remain insufficiently integrated into contemporary digital heritage environments and online cultural ecosystems [5].

Within the context of Industry 4.0, concepts such as digital transformation, virtualization, structured data processing, and online accessibility create new possibilities for the preservation and presentation of cultural heritage. In this regard, accessible digital workflows based on photogrammetry, structured cultural metadata, and web-based visualization technologies offer practical opportunities for transforming traditional ethnographic artifacts into interactive digital cultural objects. Such approaches support both the preservation and the broader accessibility of cultural heritage through contemporary digital platforms and mobile environments [3, 6].

3. Objective and research methodologies

The main objective of this study is to develop a framework for the digital profiling and online representation of traditional Bulgarian belt buckles (pafiti) through the integration of structured cultural data, photographic documentation, photogrammetry, and web-based visualization technologies. The proposed approach aims to transform traditional ethnographic artifacts into structured digital entities suitable for visualization, accessibility, and future integration into virtual cultural heritage environments.

The research methodology follows a structured multi-stage process that combines ethnographic documentation with digital technologies and data-oriented approaches (see Fig. 3). The workflow includes artifact documentation, cultural data structuring, digital representation, and online accessibility through interactive web-based environments.

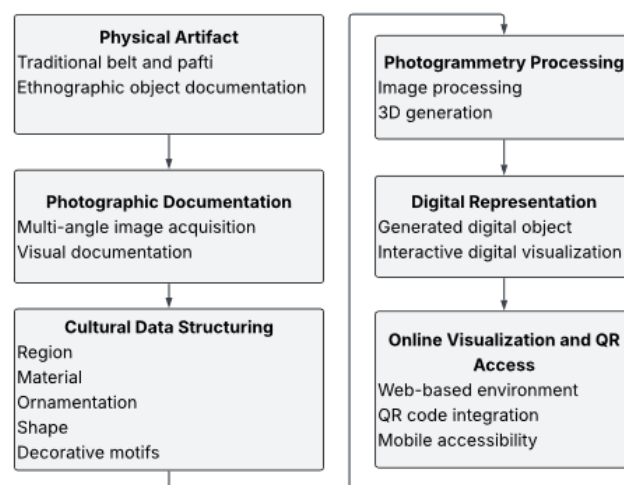


Fig. 3 Methodological framework for the digital profiling and online representation of traditional Bulgarian pafiti

The proposed methodological framework illustrates the sequential process used for the digital profiling and representation of the selected ethnographic artifacts. The workflow begins with the documentation of the physical object through photographic acquisition, followed by the structuring of cultural and descriptive metadata. The collected visual and descriptive information is subsequently used within a photogrammetry-based workflow for generating a digital representation of the artifacts. The final stage focuses on online accessibility through web-based visualization and QR-supported access, allowing users to explore the digital representation in an interactive environment. Each stage of the framework contributes to the transformation of traditional cultural objects into accessible digital cultural entities suitable for visualization and future digital preservation initiatives.

3.1 Data Collection

The study is based on the documentation of selected traditional Bulgarian belt buckles and belt elements originating from private ethnographic collections. The artifacts were photographed from multiple perspectives in order to capture their overall form, decorative structure, and visual characteristics. Additional ethnographic observations related to ornamentation, material appearance, stylistic features, and regional characteristics were also included during the documentation process.

The photographic documentation served both as a visual archival source and as the basis for the subsequent photogrammetry workflow used for digital representation. Particular attention was given to the visibility of decorative details and structural elements characteristic of traditional pafiti craftsmanship.

3.2 Data Structuring and Profiling

Following the documentation process, the collected information was organized into a structured cultural dataset describing the main characteristics of the artifacts. The profiling approach includes descriptive attributes such as object type, regional affiliation, material composition, ornamentation, decorative motifs, shape, and estimated historical period. The structured organization of cultural data allows the transformation of traditional ethnographic objects into digital entities suitable for classification, comparison, visualization, and future integration into digital cultural archives. This approach also supports the development of metadata-oriented models for cultural heritage representation and improves the accessibility and interpretability of ethnographic information [7].

The selected profiling attributes were defined in accordance with the visual, structural, and ethnographic characteristics of the examined artifacts. The attribute selection process aimed to include both descriptive and culturally significant elements that support digital identification, classification, and comparative analysis. Particular attention was given to attributes related to regional affiliation, material composition, ornamentation, decorative motifs, and object form, as these characteristics play a central role in the interpretation and representation of traditional ethnographic objects within digital cultural heritage environments.

Table 1: Comparative structured cultural attributes of the selected ethnographic artifacts

Attribute	Embroidered Belt	Belt Buckles
Object type	Traditional embroidered belt	Traditional belt buckles
Regional origin	Central Northern Bulgaria	Gabrovo region
Material	Textile, leather, beads	Metal alloy
Historical period	Late 19th – early 20th century	Late 19th century
Ornamentation	Embroidery and bead decoration	Relief metallic ornamentation
Shape	Elongated textile form	Oval
Decorative motifs	Floral motifs	Floral and animal motifs
Cultural function	Costume accessory	Women's costume accessory
Documentation methods	Photographic documentation	Photographic documentation
Digital processing	Photogrammetry workflow	Photogrammetry workflow
Digital accessibility	Web-based visualization and QR access	Web-based visualization and QR access

Table 1 presents a comparative overview of the structured cultural attributes used for profiling the selected ethnographic artifacts. The organization of the data into clearly defined descriptive categories supports consistent digital representation, comparative analysis, and future integration into digital cultural heritage environments. The profiling model also demonstrates the applicability of metadata-oriented approaches for the documentation and accessibility of traditional ethnographic objects.

3.3 Digital Representation and Online Accessibility

The digital representation process combines photogrammetry techniques with accessible online visualization technologies. A low-cost and accessible workflow based on photographic image processing was applied in order to generate a digital representation of the selected artifacts. The resulting visualization was integrated into a web-based environment developed for online presentation and interactive access.

In addition to static visual documentation, the study incorporates QR-based accessibility, enabling users to access the digital representation directly through mobile devices. This approach supports broader accessibility and demonstrates how traditional ethnographic artifacts can be integrated into

contemporary digital cultural ecosystems through practical and accessible technological solutions [6].

4. Results and visualization

The application of the proposed framework resulted in the creation of structured digital representations of the selected ethnographic artifacts. The implemented workflow combined photographic documentation, cultural data profiling, photogrammetry processing, and web-based visualization in order to provide accessible digital presentation of traditional Bulgarian cultural objects.

The digital processing stage enabled the transformation of the documented artifacts into interactive visual representations suitable for online exploration and future integration into digital cultural heritage platforms. Particular attention was given to preserving the visibility of decorative details, structural characteristics, and ornamental composition during the visualization process. The resulting digital representations retain the distinctive visual features of both the embroidered belt and the Gabrovo-style pafit while supporting accessibility through contemporary digital environments.

4.1 Technology Stack and Implementation Environment

The implementation of the proposed framework was based on a combination of accessible hardware and software technologies intended to support low-cost digital cultural heritage representation. The photographic acquisition process was performed using a smartphone camera, allowing multi-angle image capture of the selected ethnographic artifacts. The captured photographs were subsequently processed through a photogrammetry workflow for generating digital object representations.

The digital visualization environment was developed through a web-based platform supporting online presentation and mobile accessibility. QR code integration was additionally implemented in order to facilitate direct access to the digital representation from mobile devices. The selected technological workflow emphasizes accessibility, practical applicability, and the possibility for future adaptation within small museum collections, educational projects, and independent cultural heritage initiatives.

Table 2: Technology stack used in the digital representation workflow

Component	Technology	Purpose
Image acquisition	Smartphone camera	Artifact photography
Photogrammetry	Photogrammetry software	Digital object generation
Data structuring	Metadata profiling	Cultural data organization
Web visualization	Canva-based environment	Online presentation
QR integration	QR code generation	Mobile accessibility

Table 2 presents the main technological components integrated within the proposed digital representation workflow. The selected tools and technologies support the creation of accessible digital cultural environments through low-cost and widely available solutions suitable for independent cultural heritage initiatives and small-scale ethnographic digitization projects.

4.2 Digital Representation Results

Figure 4 presents the digital representation generated through the photogrammetry workflow applied in the present study. The visualization demonstrates the possibility of creating accessible digital cultural objects through low-cost and widely available technologies, without the necessity of specialized museum digitization infrastructure.



Fig. 4 Digital representation generated through photogrammetry processing

The generated digital representation preserves the main visual and structural characteristics of the examined ethnographic artifacts, including decorative motifs, ornamentation, and object form. The resulting visualization demonstrates the applicability of photogrammetry-based approaches for the digital preservation and presentation of traditional cultural objects within contemporary digital environments.

4.3 Web-based Visualization and QR Accessibility

The resulting digital object was subsequently integrated into a web-based visualization environment designed for interactive presentation and mobile accessibility. In addition to static visual documentation, the developed environment allows users to access the digital representation through QR-supported interaction, facilitating direct access from mobile devices and supporting broader public accessibility. Figure 5 illustrates the web-based visualization environment used for presenting the generated digital representation. The integration of QR access extends the accessibility of the artifacts beyond conventional museum documentation and creates opportunities for interactive digital engagement with ethnographic cultural heritage.



Fig. 5 Web-based visualization environment with QR-supported access

The presented results demonstrate that structured cultural profiling combined with accessible digital technologies can support the transformation of traditional ethnographic artifacts into interactive digital cultural entities. The proposed approach contributes to the broader integration of cultural heritage within contemporary digital ecosystems and illustrates the applicability of Industry 4.0 concepts in the field of ethnographic documentation and digital heritage representation.

5. Key findings and discussion

The results of the present study demonstrate that traditional ethnographic artifacts can be successfully transformed into structured digital cultural entities through the integration of cultural data profiling, photogrammetry, and web-based visualization technologies. The proposed framework illustrates how accessible digital workflows can support both the preservation and the online presentation of traditional Bulgarian cultural heritage within contemporary digital environments.

One of the main findings of the study is the applicability of structured metadata approaches in the organization and interpretation of ethnographic information. The use of descriptive attributes related to regional affiliation, material composition, ornamentation, decorative motifs, and object form allows the creation of consistent digital cultural datasets suitable for classification, comparison, and future expansion within larger digital heritage collections. This demonstrates the potential of data-oriented methodologies for improving the accessibility and interpretability of ethnographic artifacts. Another important outcome is the implementation of a low-cost digitization workflow based on accessible technologies. The study demonstrates that smartphone photography, photogrammetry, web-based visualization, and QR-supported access can support the digital transformation and broader accessibility of cultural heritage objects within small-scale projects and independent ethnographic research. Within the broader context of Industry 4.0, the proposed framework demonstrates how concepts such as digital transformation, virtualization, structured data processing, and online accessibility can be applied in the field of ethnographic documentation and digital heritage representation.

The study highlights the role of interdisciplinary approaches combining ethnographic knowledge and digital technologies for supporting cultural heritage preservation and accessibility. The full digital cultural heritage environment is available online at:

<https://shevitsa.my.canva.site/digitalculturalheritage>

6. Conclusion

The present study proposed a framework for the digital profiling and online representation of traditional Bulgarian ethnographic artifacts through the integration of structured cultural data, photogrammetry, and web-based visualization technologies. The research demonstrated how accessible digital workflows can transform traditional cultural objects into interactive digital entities suitable for visualization, accessibility, and future integration into digital cultural heritage environments. The implemented approach highlights the applicability of metadata-oriented profiling models and low-cost digital technologies, including smartphone photography, photogrammetry, web-based visualization, and QR-supported access. The study also demonstrates the relevance of Industry 4.0 concepts such as digital transformation, virtualization, and structured data processing within the field of cultural heritage preservation. Future research may expand the proposed framework through the inclusion of additional ethnographic artifacts and more advanced digital visualization environments suitable for integration into virtual museums and educational platforms.

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Contemporary Architecture and Urban Identity in a Rapidly Transforming City: The Case of Tirana

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Abstract: Contemporary architecture is crucial for post-socialist urban identity formation of cities in transition, and in particular of Tirana. During the last thirty years, the city has undergone a transition from the centralized socialist model into diverse, complex and ambivalent metropolitan space. This research examines the relationships between contemporary architecture and urban identity formation in Tirana using a mixed-methods approach, incorporating qualitative spatial analysis and quantitative data based on the citizens' perceptions analysis. The qualitative analysis explores three main urban interventions (Skanderbeg Square, the Pyramid of Tirana, the "Deshmoret e Kombit" Boulevard), and the quantitative analysis is based on the survey findings. The results suggest that Tirana's urban identity has become increasingly hybrid, through interaction of historical layers and global modern influences, and continues to develop new identities. But it is in tension with the forces that seek to preserve existing sources of urban identity and to modernise the city. This research increases the discussion on post-socialist cities and proposes an analytical framework of three perspectives, based on citizens' perceptions [7], [10], [14].

Keywords: CONTEMPORARY ARCHITECTURE; URBAN IDENTITY; URBAN TRANSFORMATION; POST-SOCIALIST CITIES; TIRANA; MIXED-METHOD APPROACH; PUBLIC PERCEPTION.

1. Introduction

Urban transformation is one of the major processes of the emerging contemporary city which is often among the most complex processes. Since globalization and liberalization processes the post-socialist cities experienced a fast and largely uncontrolled transition from the centrally operated cities to the market-oriented urban models [7], [9], [10]. These processes have represented a great change and had important implications not only over urban form but [also]social life, the spatial model and symbolic expression [5], [6].

The city that emerges as 'a paradigmatic example of a rapid urban change' in the group of above cities is Tirana. Since early 1990 the city has experienced a rapid pace of demographic growth, large-scale construction and a transformation of land-uses and land use patterns which have created a fragmented, heterogeneous urban fabric where different planning logics, planning practices, styles, and types coexist [17], [18] ranging from informal settlements, to mass new developments to aestheticised public spaces.

While the physical changes of the city are evident, the ongoing impact of contemporary architecture to urban identity is a critical issue that needs to be further studied. Many contemporary architectural interventions, from high-profile public projects to privatized projects, have imported new formal languages and used state of the art material and new spatial ideas that embodied contemporary architectural trends and socio-economic changes around the world[11], [15]. Nonetheless, such interventions created worries about the conservation of the urban layering, culture and history [2], [5].

Urban identity is thus seen as a dynamic and polycentric process emerging through the continuous interaction of spatial (re)formations, social practices and collective meanings [3], [4], [5]. The fast paced urban changes in Tirana have led to the integration of a hybrid urban identity in the city as many layers of history merge with the present [7], [10], [14]. This state of transition has led to debates on the disappearance of local identity and the simultaneous production of new global city representations.

Hence, this study intends to research on the association between people's perception and transformation of urban identity with the contemporary architectural interventions. In this respect, the research will attempt to answer the following research question: how do the contemporary architectural interventions affect the perception and transformation of urban identity of Tirana? By the answer of this question, this research intends to reveal the processes of change on urban identity in Tirana and to help architects take into consideration various local aspects to create more balanced urban development.

2. Literature review

The concept of urban identity is a highly debatable issue, which can not be summarized simply as a critical term. It reveals itself as a multi-dimensional idea, which contains physical, social, and symbolic components of the urban environment [1], [5]. Kevin Lynch emphasizes the importance of urban form and spatial legibility in shaping the imageability of the city [1]. Aldo Rossi considers the city as a repository of collective memory shaped through historical continuity and urban artifacts [2]. Relph and Tuan have formulated a phenomenological approach which emphasizes the significance of human life, perception and relationship to the place in the formation of identity [3] [4]. Urban identity in post-socialist cities has increasingly become a fluid and process of ongoing redefinition, shaped and redefined by globalization, market-oriented development and socio-spatial reordering [7], [8], [10], [14]. Transition also results in hybridities of identities that sit in between remnants of socialist history, urban compact and pressures of global economic integration [9], [10].

Urban identity, therefore, should not be considered as a tangible, static state, but an ongoing socio-spatial process influenced by political-economic-culturo-historical changes [14], [16].

3. Methodology

A methodology based on a mixed-methods qualitative and quantitative approach is utilized in this study to examine the relationship between contemporary architecture and urban identity in Tirana.

The analytical framework is built around three major axes that appear in both Urban theory and the urban design literature:

- (i) *the morphological dimension, consisting of the city shape, structures and types of space;*
- (ii) *the functional dimension, that is related to land use, urban uses and open space.*
- (iii) *The symbolic level or dimension which relates to meaning, collective memory and the development of identity* [1], [5], [11].

The form of this work is qualitative and features urban and visual analysis of three case studies, which show how three campaigns in Tirana: Skanderbeg Square, the Pyramid of Tirana, and the "Deshmoret e Kombit" Boulevard, interpret urban and architectural space for the city and the identity of its urban fabric.

Quantitative analysis is obtained from a questionnaire survey which was administered to the residents of Tirana on a 5-point Likert scale (1–5). The questionnaire examined citizens' opinions about urban processes, modern architecture, cultural heritage and urban identity. The responses were analyzed by means of descriptive statistics in order to grasp general trends about the citizens' view towards modern urban processes. Combining qualitative and quantitative

approaches produces a more holistic picture of urban change, providing a means to understand the spatial characteristics of architectural interventions in conjunction with the voices of the people [11], [12].

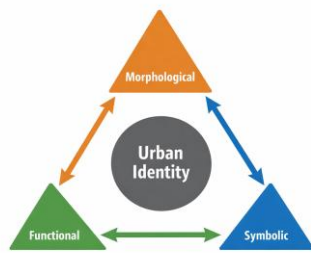


Figure 1: Conceptual framework of urban identity based on morphological, functional, and symbolic dimensions (author)

Diagram shows the relationship between the three analytical dimensions and their level of contribution to urban identity. Morphological dimension is related to the spatial form and urban morphology; also as the Functional dimension related to land uses, activities and the use of public spaces and symbolic dimension to the; meanings, collective memories and social perception.

4. Urban Transformation of Tirana

The modernization of Tirana is considered one of the most prominent examples of post-socialist urban evolution in Southeast Europe. During the past three decades the city has experienced massive population increase, spatial growth and architectural change as a result of the political transition, market liberalization and globalization dynamics [7], [10], [18].

The urban form of Tirana could be understood as a complex layered spatial arrangement, which has emerged from different historical-political phases of the city: the Ottoman city, the Italian planning, the socialist urbanism and the post-socialist periphery. Due to the coexistence of these layers, the city portrays an heterogeneous appearance in terms of architectural styles, planning principles and spatial arrangements [2], [7].

In socialist period, the urban form was mainly directed by centrally-planned control: modernization was implemented through high popular standardization, zoning of functions and monumentalized design in architectures and public spaces [7], [10]. Thus, the city formed a more uniform urban form dominated with collective housing blocks, monumental public places and pluralistic public institutions. Contrary to the socialist period, in the post-socialist era informal and unregulated processes of urban transformation emerged almost instantly. Migration, demographic increase, privatization and city deregulation, promoted informal construction, urban consolidation and dispersed spatial development [9], [16], [18]. As a result, the urban pattern of Tirana is a mixture of layers of historic urban fabric, modern architecture and global urban processes. This process of transformation has deeply impacted the way urban identity is perceived and constructed. Modern projects of architecture, public spaces regeneration and new urban developments have helped to develop a hybrid urban identity, somewhere between the past and the future [14], [15].

In order to have a better insight of these urban transformations and their contribution to the urban identity, the next section will focus on three case studies of each of them in Tirana, namely: Skanderbeg square, the Pyramid of Tirana and the “Deshmoret e Kombit” Boulevard.

4.1 Skanderbeg Square

Skanderbeg Square represents a significant urban intervention that has redefined the role of public space in Tirana. The redesign has enhanced accessibility, pedestrian connectivity, and functional flexibility, transforming the square into a central civic space [11],

[12]. It reflects an effort to construct a contemporary urban identity, while simultaneously incorporating elements that resonate with local context. However, the project also illustrates the influence of global design trends in shaping urban space.



Figure 2: Evolution of the Skanderbeg Square
a) View in 1990; b) View in 2020

Source: Google Earth Pro and authors' elaboration.

It shows how the Skanderbeg Square evolves from a traffic-dependent and monumental urban space to a civic square built for pedestrians. Morphologically, the intervention redefines the morphological shape of the city centre by enabling the enclosure of the square and intensifying pedestrian permeability. Functionally, the intervention transforms the square from circulation to two categories of use; vehicular circulation into public use and civic activities. Symbolically, the square now stands as a contemporary symbol of the transitional urban identity of Tirana.

4.2 Pyramid of Tirana

One of the most symbolic restructuring of architectural spaces since the end of socialist Albania is the pyramid of Tirana. The pyramid which was initially built as a museum for the Albanian communist leader Enver Hoxha, has been subjected to several interpretations symbolizing national political shifts, cultures and social changes [14]. The intervention reconfigured the Pyramid as a multifunctional civic and cultural institution that maintained its historic location within the city while also becoming a site for education, creativity and sociability. This form of adaptive reuse exemplifies an approach to contemporary architecture that appreciates and celebrates the value of historic monuments.



Figure 3: Evolution of the Pyramid of Tirana
a) View in 1990; b) View in 2025

Source: Google Earth Pro and authors' elaboration.

From the morphological point of view, the intervention retained the geometrical figure of the building as well as the original spatial identity of the structure, although it repackaged it with modern architectural language and a system of open access circulation. The new design produced a more permeable and accessible relation between the building and the urban context.

From the point of view of its use, the Pyramid became a publicly accessible and flexible building used for educational, cultural and recreational purposes and converted from a solely restricted symbolic monument. It had a fundamental impact on the city's social life.

The Pyramid keep the symbolic meaning of the reinterpretation of the collective memory in the post-socialist Tirana [2], [14] by managing to not delete the historic meaning of the building but in the same time to project its mean into a new one symbol, openness and transition towards a new urban identity.

4.3 “Deshmoret e Kombit” Boulevard

The “Deshmoret e Kombit” Boulevard functions as a major historical axis that embodies the continuity of Tirana's urban development [2], [7]. It connects different periods of the city's evolution, linking monumental structures, public institutions, and

open spaces. As a linear urban element, it reflects both the historical layering and the ongoing transformation of the city, serving as a key component in the construction of urban identity.



Figure 4: Evolution of the “Deshmoret e Kombit” Boulevard
a) View in 1990; b) View in 2025

Source: Google Earth Pro and authors' elaboration.

The visual comparison confirms that the “Deshmoret e Kombit” Boulevard has continued to be one of the main urban axes of the city. Morphologically, the boulevard keeps its original linear morphology even after recent densification and vertical urban growth. Functionally, the boulevard has shifted from an administrative and institutional corridor to a multifunctional urban space where cultural, commercial and public uses take place. Symbolically, the boulevard keeps standing as an important historical and political layer of the city, together with its image as a “new” part of the city where the current identity of Tirana is practically built.

4.4 Survey Results and Public Perception Analysis

A completed five-point scale on questionnaire survey was applied for the residents of Tirana in order to find out the public attitudes toward contemporary architecture, urban change, urban identity, and cultural heritage conservation. The survey was based on 186 respondents and focus on the citizens attitudes toward current architectural and urban change in place.

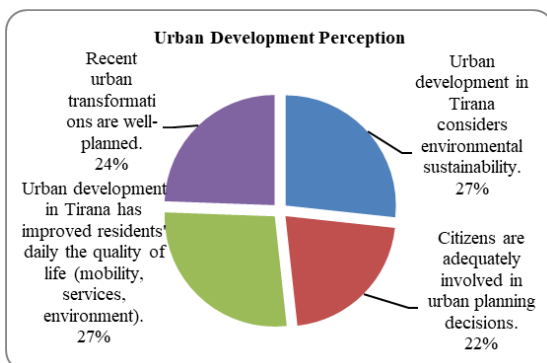


Figure 5. Urban Development Perception

Source: Authors' elaboration based on survey results (2026).

From the analysis it appears that residents view Tirana as a city in transitory dynamics between modernity and tradition. The most highly rated statement was “Tirana is a city in transition between tradition and modernity”, listed in the mid-range with an average score 3.30. This indicates that people perceive the city strongly in terms of a juxtaposition or hybrid places.

The survey also identified concerns about the preservation of local identity and cultural heritage. Preservation of historical buildings was regarded as crucial for the good identity of the city (Mean = 3.43). Conversely, urbanizations were perceived as not respecting cultural heritage (Mean = 3.21), which indicates an opinion that the fast expansion of the city and new developments may also threaten the historical and symbolic character of the city.

Also, respondents worried about the erosion of the identity of Tirana, as it is altering very quickly under urban development pressures and accelerated building activities, (Mean = 3.29). The above points to the fact that modern interventions are more likely to be welcomed within the cityscape but citizens do however feel more

hesitant about the maintenance of historical continuity and cultural identity [10], [14].

With respect to modern architecture, participants displayed neutral to somewhat positive attitudes toward it. The statement “Modern architectural projects follow international trends of design” obtained 3.20, suggesting that citizens are aware of the influence of international architectural trends on the urban image of Tirana [15]. Similar was the Citizens' evaluation of the statement “Modern architecture improve the city image”. This garnered an average score of 2.97.

On the other hand, the results for the integration of recent developments into the urban fabric were less positive (Mean = 2.22).

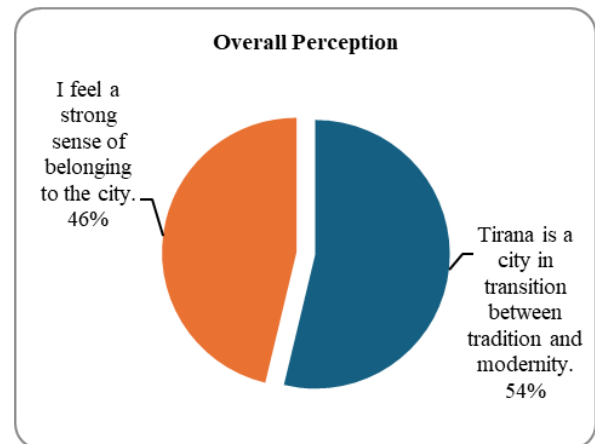


Figure 6. Public perceptions regarding urban transformation
Source: Authors' elaboration based on survey results (2026)

This highlights that a significant number of the respondents feel there is not a proper relation between current buildings and the historic fabric of the city.

Additionally, the survey data show the discontent with aspects of urban management and planning processes. There was -although many of the questions show high standard deviations- low public involvement with urban planning and decision-making procedures with the statement: “Citizens participate sufficiently in planning procedures” (Mean=1.80). Urban transformations, were, also perceived to have been insufficiently organized (Mean=2.04).

Other indicators that scored poorly included perceptions associated with environmental sustainability and quality of life. It appears that citizens are skeptical with respect to the degree to which urban development accommodates environmental sustainability (Mean=2.23) and enhances people's daily quality of life (services, mobility, environmental conditions) (Mean=2.28). These values imply that while urban development has reconfigured the face of the city of Tirana, citizens are not entirely satisfied that these changes have had a significant impact in terms of urban functionality and sustainability.

Public spaces, although, were rated a little more favorably. There was recognition that public spaces have improved in recent years (Mean=2.20) with regard to the ease of walkability and revival of the center of the city. In general, the findings indicated that Urban identity in the case of Tirana is an ongoing and dynamic process between the local influences and external ones, such as the global, in the present age and the imprint in time, heritage, history, urban context and urbanization, [4], [5], [10], [14]. These are the feelings and observations of the citizens about contemporary architecture's contribution to the redefinition of the city image, which coexists with worries towards the safeguarding of the existing cultural memory, local identity, urban cohesion and participative planning.

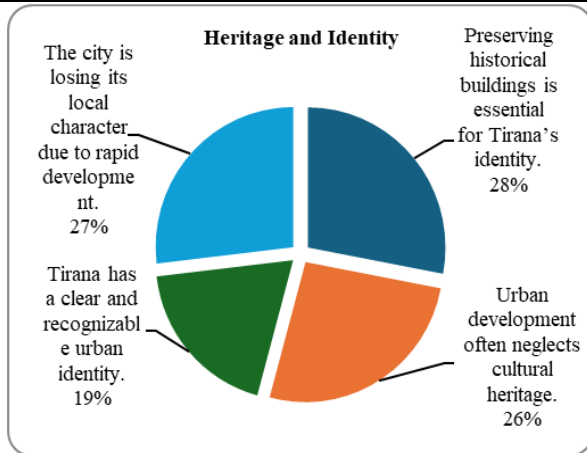


Figure 7. Public perceptions regarding heritage and urban identity
Source: Authors' elaboration based on survey results (2026).

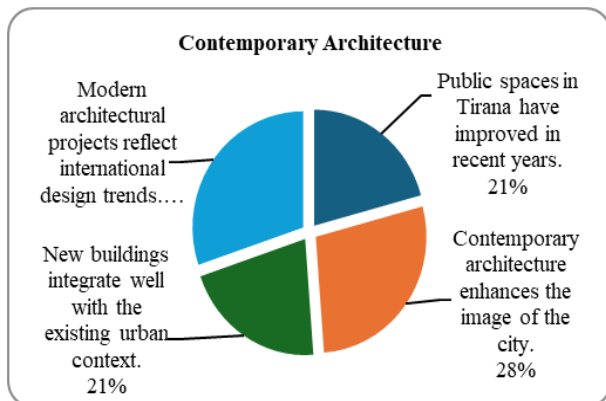


Figure 8. Public perceptions regarding contemporary architecture
Source: Authors' elaboration based on survey results (2026).

These findings concur with the qualitative findings described in this work and strengthen the argument for the hybrid urban condition to exist and that Tirana is a hybrid urban condition in which 'global contemporary influences and traditional urban memory coexist at some levels in a complex and, at times, contradictory relationship'.

5. Discussion

The conclusion that emerges from this study is that the City of Tirana, is constructing its hybrid urban identity through the process of interacting between past and present layers of city building interventions. This new urban identity appears to be a constitutive factor of the process of developing itself. Nevertheless, the process also involves with a bundle of tensions. These start from the dilemma between 'preservation of historic parts' and 'urban change' as high-rise developments threaten the continuity of the old structure; 'formal' vs 'informal' development which is derived from diverse planning principles that inform policy and regulations; and between 'local identity' and 'global images' as the city adopts global building trends and architecture while losing its sense of place.

Overall, the quantitative findings affirm the previous qualitative analysis. They show that urban identity in Tirana is not yet constituted, but remains in a process of ongoing formation. The citizens' perceptions demonstrate a dual attitude, as both chronicle the new changes while concern about the possible disregard of cultural and territorial identity.

On the whole, this discussion underpins the idea that Urban identity is a dynamic process of continuous 'negotiation', instead of a 'fixed' condition [5], [10], [14] with many different, and sometimes conflicting urban realities. It underpins the demand for a more pluralist, and contextually aware urban development policy framework that can reconcile innovation with continuity.

6. Recommendations

Based on the results of the present work, a few suggestions could be made in order to address the issue of a more balanced and sustainable urban development of Tirana. First, the role of cultural heritage should be more effectively integrated into urban development policies [2], [14] approaches which involve historic cities of numerous layers should be adopted. Second, stronger community participation in planning and decision-making processes is necessary [11], [17] and decision-making activities should be promoted with a hope of meeting citizens' needs and increasing their sense of ownership. Third, an enhanced control of informal urban development requires stronger regulation and governance mechanisms [9], [18] needs to be achieved through better regulations and more efficient urban governance; forth, a spurring of context-sensitive architectural approaches should be encouraged in order to preserve spatial continuity and local identity [15], [16] should be strongly supported, highlighting design strategies based on local contexts and spatial continuity over another model copied from the global context. Guidelines that follow are meant to serve the policy makers, planners and designers toward an integrated and identity centered approach.

7. Conclusions

The urban condition of Tirana is presented as a hybrid and multidimensional urban process [7], [10], [14] influenced both by the contemporary built environment and a wide range of socio-economic changes. The analysis indicates that the city is in the process of reflecting both its historical past and new developments. Yet, this process demands the existence of well-balanced policies to prevent the loss of cultural identity and heritage while leading the city to a more sustainable and inclusive urban development [17], [18] of the future. Urban planning becomes more successful when physical, social and symbolic considerations are equally addressed and incorporated. These findings overall enhance knowledge of post-socialist urban change, as well as demonstrate a need for holistic and context-sensitive urban approaches [11], [16], [17] in current urban processes.

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Парадигма и/или утопия на дигиталната прогресия на администрацията на местните власти в България

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Абстракт:

Технологичната адаптивност на администрацията на местните власти в България в дигиталната прогресия на съвременното създава дискусия относно разбирането и капацитета на публичния сектор за адекватно опериране и изпълнение на функциите си в онлайн среда. Усилията на публичната администрация в тази насока обуславят компилативна реалност от форми и модели на присъствие на публичния сектор онлайн, които отразяват творческа самоинициатива, неразбиране, неизпълнение на указания с препоръчителен характер за структуриране и експлоатиране на уеб-базираната инфраструктура на публичния сектор. Резултатът в повечето случаи е продукт, несъответстващ с изискванията за представителност на администрацията, носеща белезите на институционалния авторитет. Всеки сайт следва да притежава представителна стойност, актуалност и способност ефективно да достига до своите публики в изпълнение на целите на организацията и съответно комуникационните такива. В публичния сектор към тези характеристики се добавя и специфичното измерение на институционалността, защото сайтът е носител на авторитет и публична легитимност на институцията. В този смисъл онлайн присъствието на администрацията на местните власти в България носи не само информационна, но и обществена отговорност, свързана с гарантирането на прозрачност, достъпност и ефективна комуникация с аудиторията.

Ключови думи: ОНЛАЙН КОМУНИКАЦИИ, ПУБЛИЧНА АДМИНИСТРАЦИЯ, КОМУНИКАЦИИ, ИНСТИТУЦИОНАЛЕН САЙТ, ОБЩИНСКА АДМИНИСТРАЦИЯ, КОМУНИКАЦИОННА СТРАТЕГИЯ

1. Анотация

Настоящата статия разглежда състоянието на дигиталното представителство на администрациите на местните власти в България и поставя въпроса доколко дигиталната прогресия на публичния сектор се реализира като устойчива практика или остава в сферата на концептуалните намерения. Целта на изследването е да анализира степента на институционална представеност, достъпност и комуникационна ефективност на официалните интернет сайтове на общинските администрации в контекста на дигитализацията и електронното управление.

Изследването е проведено чрез комплексен методологически подход, включващ desk research, контент анализ и сравнителен анализ на интернет страниците на общините в административна област Благоевград. Анализиран са показатели, свързани с домейн структура, институционална идентичност, визуална организация, достъпност, прозрачност и наличие на електронни услуги.

Резултатите показват значителна нееднородност в онлайн представянето на местните администрации, ограничено използване на предоставените от държавата унифицирани решения и наличие на практики, които не съответстват на утвърдените насоки за институционална идентичност. Установява се, че липсата на нормативно задължителни стандарти води до различия в качеството и ефективността на дигиталното представителство на местната власт.

Изводът от изследването е, че успешната дигитална трансформация на администрацията изисква не само технологични решения, но и последователна политика за стандартизация, която да гарантира достъпност, прозрачност и разпознаваема институционална идентичност в онлайн среда.

2. Дигиталната администрация на местните власти в България – между унифицираната визия и институционалната автономност

Присъствието на администрацията на местните власти в България онлайн не е норматирана. Изготвените Правила за институционална идентичност и насоки за унифициране на визията и структурата на българските общини в интернет са с

препоръчителен характер, а експлоатацията на сайта е вторично вменено задължение от множество закони и нормативни актове. От изследвани общини в една административна област, според Единния класификатор на административно-териториалните и териториалните единици, по силата на Закона за административно-териториалното устройство на Република България, резултатите индикират проблем при представителството и работата на администрацията на местните власти онлайн. 35.7% от общините са с домейни, несъответстващи на установените стандарти, включително и с некоректна транслитерация на името, което е първи показател за достъпност. Едва 7.1% (или една от четирнадесет) от общините използват изготвения федериран портал за администрация на общини. Всички останали са продукт на дизайнерско виждане/недоглеждане. Резултатът е неунифицирано представяне и функциониране на администрацията на местната власт, от което следва ограничена достъпност за аудиторията и неизпълнение на целите и мисията на организацията.

Резултатите са от изследване, част от дисертационен труд на тема „Комуникациите в публичния сектор чрез институционалния сайт“, дефинирано с цел да анализира степента на институционална представеност, достъпност и комуникационна ефективност на интернет сайтовете на администрациите на местните власти в България в контекста на дигитализацията на публичния сектор. Специален акцент се поставя върху ролята на официалния уебсайт като инструмент за стратегическа комуникация, публична прозрачност и институционална идентичност.

Изследването се стреми да установи доколко онлайн присъствието на местните администрации съответства на утвърдените принципи за институционална комуникация, достъпност, унифицирана визуална идентичност и ефективно обслужване на гражданите. В този контекст се анализира и влиянието на липсата на нормативно регламентирани стандарти върху качеството, функционалността и публичната легитимност на дигиталното представителство на местната власт.

В изследването е приложен комплексен методологически подход, включващ desk research, контент анализ и сравнителен анализ. Проучени са нормативни документи, правила за

институционална идентичност, насоки за унифициране на общинските сайтове, стратегически документи в областта на дигитализацията и електронното управление, както и научни публикации, свързани с публичните комуникации и дигиталната администрация. Чрез контент анализ на официалните интернет страници на изследваните общини са анализирани елементи като домейн, структура, транслитерация, визуална идентичност, степен на унифицираност, актуалност на информацията, достъпност, навигация, наличие на електронни услуги и прозрачност на институционалната дейност. Изследването включва и сравнителен анализ между общините в рамките на конкретна административна област съгласно Единния класификатор на административно-териториалните и териториалните единици, като при анализа са използвани критерии, свързани с институционална идентичност, комуникационна ефективност, дигитална достъпност, функционалност, прозрачност, ориентация към потребителя и съответствие с добри практики в публичния сектор.

В началото на XXI век, с инициатива на Министерство на държавната администрация и административната реформа, се правят първи стъпки към установяване на правила за институционална идентичност в дигитална среда и унифициране на администрацията в публичния сектор. Създадени са Правила за унифициране на държавната администрация, разработени по проект с европейско финансиране – „Създаване на модерна и унифицирана визия на българската държавна администрация в контекста на членството на страната в ЕС“ с очакване за стандартизирано и модернизирано визуално и публично представяне на администрацията чрез Наръчник за прилагане на институционалната идентичност – правила за използването на графичните символи, изготвяне на документи, мултимедийно и интернет представяне. Разписът в документа е за създаване на институционална идентичност чрез съвременен и стилизиран дизайн, с консервативен подход за единна визия на българската администрация, без изключения. Така че да бъде разпознаваема, с авторитет, присъщ на държавността.

В първичния документ за стандартизиране на българската администрация и позициониране на публичния сектор в интернет, очакванията са за съчетаване на традициите и съвременността, чрез обобщаване на всичко налично, но на място, релевантно с потребностите на съвременното общество. Идеята за създаване на портал за институционална идентичност е служителна на министерства и агенции, на областни управы и на общински администрации да имат достъп до детайлна и изчерпателна информация за правилата и стандартите за употреба на държавните символи на Република България, както и за правилата и начина на оформление на печатните материали и електронните комуникации на администрацията. Фокус в разработката са правилата за разработването на интернет страниците на държавните институции – инструкции за достъпност, включително за незрящи хора, цветове и дизайнерски решения, улесняващи по-възрастните потребители. Създадена е общодостъпна за администрациите на местната власт платформа за изграждане на общински сайт.

Правилата за институционална идентичност са написани в духа на въвеждащи стандарти и при уеб представянето на администрацията, съобразено с изискванията на нормативната уредба за електронно управление и административно обслужване, както и с европейските норми за достъпност на уеб съдържанието. Документът е написан с увереността за установяване на нова политика за формирането на домейните и нови стандарти за визуално представяне според институционалната идентичност. Маркирани са и основните нормативни актове, с които се съобразява изработката и работата на сайта на администрацията – Административно-процесуален кодекс, Закон за електронното управление, Наредба за електронните административни услуги и други.

Създадените Правила и Наръчници остават указателни документи, без нормативна стойност и на практика – с препоръчителен характер. Такива остават и при последващата им актуализация от Държавната агенция „Електронно управление“, приемник на функциите на Министерство на държавната администрация и административната реформа. В улеснение на администрациите на местната власт, Държавната агенция „Електронно управление“ (ДАЕУ) актуализира и платформата за сайтовете на администрацията, достъпна за свободна употреба, включително актуализация и поддръжка. Разработен от Държавна агенция „Електронно управление“ е федериран портал на българските общини. Платформата отразява технологичния прогрес, като запазва основните насоки за институционална идентичност и структуро-организационна плътност на сайта. И представлява централизирано решение, с инициатива на правителствено ниво, за унифициране на визията на администрацията в интернет. Федерираните портали за общинска администрация, областна администрация и административни структури, създадени със закон, представляват облачно решение за изграждане на сайтове по предварително подготвен шаблон в рамките на единна инфраструктура. Шаблоните позволяват относителна персонализация на облика на сайта, но запазват структурата с цел улеснение на крайния потребител и създаване на единна визуална онлайн идентичност на държавните институции. Платформата се поддържа от екипите на Министерство на електронното управление (МЕУ) и Изпълнителна агенция „Инфраструктура на електронното управление“ (ИА ИЕУ), а съдържанието на федерирания портал – от екипите на съответната администрация, за която е създаден¹.

Федерираните портали се разглеждат като готови решения за е-администрация, с приоритет за значимостта в експлоатацията на Единния портал за достъп до електронни административни услуги, e-Плещания, Система за обмен на удостоверителна и справочна информация (RegiX), Система за сигурно електронно връчване (CCEB), Вътрешни електронни административни услуги. Сайтът като медиен пресцентър е в периферията на функциите му. По данни на МЕУ, пик в присъединяването на администрациите на местната власт към Единния модел има в годината на обновяване на платформата². От министерството остойностяват предимствата на Единния портал с липса на разходи за разработване и поддръжане на портал; липса на разходи за поддръжане на ИТ инфраструктура, в която функционира портала; не са необходими специфични ИТ компетентности; структурата е стандартизирана и визията на портала е еднотипна; както и отговарят на изискванията и Правилата за институционална идентичност, достъпност и мрежова и информационна сигурност.

В условия на все по-бързо развиваща се дигиталност и ускорено навлизане на все по-нови технологии и инструменти, администрациите на местните власти все още са представени в интернет със сайтове, разработени на платформи от преди 20 години - морално остарели и нефункционални за съвременните стандарти на интернет. „Най-възрастният“ общински сайт в област Благоевград е от 2006 година (община Гоце Делчев), както и сайтът на община Симитли от 2007 г., изграден на разработена от МДААР платформа, който приемник и последовател е федерираният портал на ДАЕУ, в последствие МЕУ. Към август 2023 година, едва 7,1% (или една от мониторираните четиринадесет общински административни области с административен център Благоевград) работи с федерирания портал на ДАЕУ – община Разлог. 13 от четиринайсетте общини в област Благоевград работят в

¹ <https://unifiedmodel.egov.bg/wps/portal/unified-model/for-administrations/federirani-portali/>

² <https://www.namrb.org/uploads/tinymceup/files/2022-GSMV/Prezentacii/Mestni-resursi/MEU.pdf>

интернет с платформа, продукт на разработчици на сайтове. Наличната инфраструктура онлайн дефинираме като многообразна. Наблюдението потвърждава определението на дивелъпъри (разработчици на сайтове), описващи тенденциите в развитието на интернет в България, за „шарения в интернет“ (данни от дълбочинно интервю). Във всички сайтове са налични ключовите компоненти за сайт и е депонирана информация. Но организацията не следва принципите на нормативните правила за унифициране на администрацията на местната власт.

Архитектурното решение, което Държавната агенция „Електронно управление“ (сега МЕРУ/ Министерство на електронното управление) използва за мащабиране на облачни услуги е INB - Integrated Business Network (Интегрирана бизнес мрежа). Мрежата се характеризира с централизирана архитектура, връзка с федерираните портали и технологичен стек. Тези характеристики на практика дават възможността за:

- ✓ Единна инфраструктура: Всички подсайтове (например тези на общините) се хостват върху обща мощна основа.
- ✓ Споделени ресурси: Използват се общи бази данни, защитни стени и сървърни капацитети.
- ✓ Бързо разгръщане: Нова община или държавна структура може да активира готов сайт за минути.
- ✓ Общи стандарти за сигурност: Всяко звено в мрежата е защитено от общия център за киберсигурност.
- ✓ Синхронизация на данни: Промени в нормативната уредба на централно ниво се отразяват автоматично във всички сайтове в мрежата.
- ✓ Оперативна съвместимост: Позволява на портала на една община да „комуникира“ директно с централните регистри на държавата.
- ✓ SaaS модел: Софтуер като услуга (Software as a Service).
- ✓ Multi-tenant поддръжка: Един софтуер обслужва много различни клиенти (общини), без данните им да се смесват.

Ползватели на федерираните портали съобщават за бавност при генериране на съдържание в сайтовете. Към май 2026 г. от Министерство на електронното управление е възложена актуализация на федерирания портал. Новата платформа се разработва от „Информационно обслужване“ и е в демо-тестова форма за администрацията на държавната/местната власт. Интерфейсът е по аналогия на WordPress – най-популярната платформа за управлението на съдържанието, която задвижва около 40% от сайтовете в световен мащаб. Разработваната нова платформа е с логична структура и тематична вертикална организация. Администраторският панел следва познатите от Word логика и инструментариум. Обновеният шаблон максимално се доближава до настоящия, с цел улеснение на администраторите, както и, приоритетно, свеждане до минимум неудобството от промяната в сайта за потребителите. От МЕРУ гарантират за цялостна миграция на данните при въвеждане на новата платформа.

Платформата на разработваното облачно решение за изграждане на сайтове по предварително подготвен шаблон в рамките на единна инфраструктура за държавната администрация копира въведената през 2020 година в системата на съдебната власт. С която паралел правим и в контекста на обосноваване на необходимостта от унифициране на администрацията онлайн, дори и в условията на задължителност.

При продължаващо неразбиране на препоръките за употреба на федерирания портал, логично и разумно е да се обмисли нормативане на употребата на унифицирания интерфейс. Общината е орган на местното самоуправление, но общината е административна единица в уредбата на административното делене в България и политиката за унифициране на държавната администрация е централизирана. По аналог на унифицираната визия и присъствие на съдебната система в интернет. Методологическата валидност на аналогичния подход

позволява извеждането на сравнителни зависимости. С яснотата за различията в същността, организацията на двете власти: в единия случай говорим за местно самоуправление, а в другия е налице единност на властта, дефинирана в основния закон на държавата – Конституцията на РБ, с разделението на властите. Но същевременно е налице професионализация на публиката в съдебната система, и широка аудиторност с различни нива на познания и възможности, както и образователен ценз, при местната власт. При унифицирана визия на администрацията на местната власт, от една страна е улеснен потребителя на услуги, постига се задоволство у публиките. От друга страна е постигната стратегическа цел в местното самоуправление. За разлика от съдебната система, в органите на местната власт има нормативно дефинирана самостоятелност и в този смисъл е напълно допустимо наличието на разнотилна информационна политика. Но унифицирането на платформата за представяне на информацията, независимо от информационната политика, облагодетелства както потребителите, така и източниците на информация. При създаден навик у потребителите за достъпване на конкретна информация в унифицирана структурно-организационна система, откриването на търсената информация е улеснено, което създава усещане на удовлетвореност и информационно задоволство.

Този резултат има добавена стойност за източника на информация, тъй като достъпността до информация по най-безпрепятствен начин води до усещането за откритост, а от там и до увеличаване на доверието, респективно одобрението на потребителите на услуги в цялост.

3. Заключение

Дигиталната трансформация на администрацията на местните власти в България е необходимост и стратегическа посока на развитие, но резултатите от настоящото изследване показват, че нейното практическо реализиране остава непоследователно и фрагментирано. Независимо от предприетите през последните две десетилетия институционални инициативи за стандартизиране на онлайн присъствието на публичния сектор, включително разработването на правила за институционална идентичност, унифицирани модели за интернет представяне чрез федерирани портали за общинските администрации, степента на тяхното реално приложение е ограничена.

Емпиричните данни от изследваните общини в област Благоевград показват значителни различия в домейн структурата, визуалната идентичност, архитектурата на съдържанието и комуникационната организация на общинските сайтове. Ниското ниво на използване на предоставените от държавата унифицирани решения и преобладаването на самостоятелно разработени платформи създават предпоставки за неравномерно качество на дигиталното представителство, затруднена достъпност и отслабване на институционалната разпознаваемост на местната власт в онлайн среда.

Изследването потвърждава тезата, че липсата на нормативно регламентирани и задължителни стандарти за уеб представянето на администрацията води до разминаване между концепцията за модерна, единна и разпознаваема публична администрация и реалното състояние на дигиталната инфраструктура на местната власт. В този смисъл дигиталната прогресия на администрацията в България се проявява едновременно като парадигма и като утопия – парадигма поради наличието на стратегическа визия, технологични решения и институционална воля за развитие, и утопия поради непълното им прилагане, липсата на задължителност и отсъствието на ефективни механизми за гарантиране на единни стандарти.

Анализът позволява да се направи изводът, че унифицирането на платформите за онлайн представяне не ограничава самостоятелността на местната власт, а напротив – създава предпоставки за по-висока прозрачност, по-добра потребителска ориентация, по-лесен достъп до информация и услуги и по-високо обществено доверие. Изграждането на предвидима и разпознаваема дигитална среда е в интерес както на гражданите, така и на самите институции, тъй като улеснява комуникацията и повишава ефективността на публичното обслужване, а от там и повишаване доверието у публиките.

Всичко посочено до тук предполага заключение, че бъдещето на дигиталната администрация на местните власти в България не зависи единствено от технологичните решения, а от способността на публичния сектор да превърне съществуващите добри практики и препоръчителни модели в устойчиви и последователно прилагани стандарти. Само при подобен подход дигиталната трансформация би могла да премине от сферата на желаното развитие към реално функционираща институционална практика.

Predictive security analysis based on new technologies

Предикативен анализ в сигурността, основан на новите технологии

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Summary: The paper examines how predictive analysis — the use of statistical algorithms, machine learning, and Big Data processing to forecast future threats — is transforming modern security. Rather than simply reacting to incidents, predictive systems aim to anticipate, prevent, and neutralize threats proactively. The paper highlights the convergence of AI + Blockchain + IoT + 5G/6G networks as the next frontier, alongside the looming challenge of quantum computing, which threatens existing cryptographic methods but also promises far more powerful predictive capabilities

Keywords: BLOCKCHAIN, BIG DATA, IoT, 5G/6G, SECURITY, AI

1. Въведение

Навлизането на цифровите технологии в почти всички сфери на общественения живот трансформира коренно разбирането ни за сигурност — физическа, кибернетична и национална. В центъра на тази трансформация стои предикативният анализ — съвкупност от методи, алгоритми и технологии, позволяващи не просто да се реагира на заплахи след тяхното настъпване, а да се предвиждат, предотвратяват и неутрализират проактивно. Наред с изкуствения интелект (ИИ) и машинното обучение, блокчейн технологията се утвърждава като трети стълб на тази архитектура — гарантирайки неизменност на данните, прозрачност на операциите и децентрализирано доверие, без което предикативните системи биха останали уязвими.

2. Теоретични основи и концептуална рамка

2.1 Определение и обхват на предикативния анализ

Предикативният анализ представлява клон на аналитичната наука, който използва статистически алгоритми, методи за машинно обучение и техники за обработка на големи данни (Big Data), за да идентифицира вероятността от бъдещи резултати въз основа на исторически данни. В контекста на сигурността той се прилага за прогнозиране на кибератаки, криминални дейности, терористични заплахи, физически пробиви и системни уязвимости.

Според изследователите от *Mesopotamian Journal of Big Data* (2024)¹, „предикативният анализ, интегриран с Big Data аналитиката, представлява нова парадигма за киберсигурност, при която заплахите се идентифицират и неутрализират преди да успеят да нанесат щети“ (Al-Mahmood et al., 2024)². Тази дефиниция акцентира върху проактивния характер на технологията — категорично разграничение от традиционните реактивни подходи. Рускоезичните анализатори описват предикативния анализ като „система от методи за машинно обучение, предназначени за предсказване на кибератаки и повишаване нивото на киберсигурността чрез алгоритми за класификация, клъстеризация и регресия“ (КиберЛенинка, 2024)³. Французката академична традиция допълва, дефинирайки *l'analyse prédictive* като способността да се „anticiper des incidents en se basant sur des données historiques“ — предвиждане на инциденти въз основа на исторически данни, като особен акцент се поставя върху интеграцията с интелигентни системи за наблюдение и

поведенчески анализ (Convergence Formation, 2024)⁴. В български контекст монографичното изследване „Изкуственият интелект в контекста на управлението и сигурността“ описва и анализира въпроса за ИИ и предикативните технологии като ключова академична разработка в националното научно пространство (ResearchGate, 2022)⁵.

2.2 Три стълба на съвременната предикативна сигурност

Съвременната архитектура на предикативната сигурност почива на три взаимозависими технологични стълба: Първият е **изкуственият интелект и машинното обучение** — инструментите за анализ и прогнозиране. Вторият е **Big Data инфраструктурата** — технологичната база за събиране, съхранение и обработка на масиви от данни. Третият, и нерядко подценяван, стълб е **блокчейн технологията** — гарантиращ, че данните, върху които се основават предвижданията, са непроменени, верифицируеми и защитени от манипулация. Публикация в *IEEE Computer Society* (2025) формулира тази взаимозависимост директно: „Блокчейн подобрява сигурността и поверителността на данните, осигурява децентрализирана верификация и гарантира прозрачни одитни следи (*immutable audit trails*) за AI системите“ (IEEE Computer, 2025)⁶. Проучване сред 608 специалисти, цитирано в същия текст, потвърждава, че организациите, интегрирали блокчейн в своите AI платформи, отчитат значително по-висока степен на доверие в резултатите на предикативния анализ.

2.3 Исторически контекст и еволюция

Корените на предикативния анализ в сигурността могат да бъдат проследени до статистическите методи за криминология от 1970–1980-те години, но истинският технологичен пробив настъпва с появата на машинното обучение в края на 1990-те и с демократизацията на изчислителната мощ след 2010 г. Периодът 2020–2026 г. е белязан от конвергенцията на генеративни AI модели, трансформационни архитектури, разпределени регистри и квантови изчисления, което качествено променя потенциала на предикативните системи. Пазарните прогнози сочат, че интеграцията на AI и блокчейн ще надхвърли 703 милиона USD пазарна стойност до 2025 г. (Blockware Solutions, 2025)⁷, което красноречиво илюстрира нарастващото значение на тяхната синергия.

3. Технологични инструменти и методи

3.1 Машинно обучение и дълбоки невронни мрежи

Машинното обучение е гръбнакът на съвременния предикативен анализ в сигурността. Изследване, публикувано в *ScienceDirect* (2024), сравнява ефективността на различни ML

¹ <https://mesopotamian.press/journals/index.php/bigdata/issue/view/33>

² <https://www.scirp.org/reference/referencespapers?referenceid=3763144>

³ <https://www.facebook.com/cyberleninka/>

⁴ <https://trustindigitallife.eu/event/convergence-2024/>

⁵ Иван Цанов, проф. д-р, „Изкуственият интелект в контекста на управлението и сигурността“ (2022), монографично изследване [ResearchGate](https://www.researchgate.net/publication/358111111).

⁶ <https://www.computer.org/about/year-in-review>

⁷ <https://www.blockwareolutions.com/research-articles/2025-market-forecast/>

алгоритми за изграждане на системи за засичане на прониквания, включително дървета на решенията, случайни гори (Random Forest), k-NN алгоритми, Support Vector Machines и невронни мрежи (ScienceDirect, 2024). Хибридният подход демонстрира особена ефективност — публикация в PMC/NLM описва „хибридна система за засичане на мрежови прониквания (NIDS), която интегрира множество алгоритми за машинно обучение и дълбоко обучение с цел засичане на аномалии, постигайки значително по-висока точност в сравнение с монолитните подходи" (PMC, 2025).

Руските автори, публикуващи в КиберЛенинка, анализират конкретни модели за предсказване на кибератаки: „Основното внимание се отделя на алгоритмите за класификация и способността им да разграничават нормалното от аномалното мрежово поведение в реално време" (КиберЛенинка, 2024).

3.2 Блокчейн технологията — архитектура и принципи за приложение в сигурността

Блокчейн (верига от блокове) представлява разпределен, децентрализиран регистър, при който всяка транзакция или запис се криптографски верифицира и добавя необратимо. Трите ключови характеристики — **неизменност (immutability)**, **прозрачност (transparency)** и **децентрализация (decentralization)** — правят технологията особено подходяща за осигуряване на интегритета на предикативните системи.

Публикация в *Rapid Innovation* (2024)⁸ формулира ролята на блокчейн по следния начин: „Блокчейн технологията значително подобрява интегритета на данните, осигурявайки децентрализирана и неизменна система за регистриране. Веднъж записани, данните не могат да бъдат модифицирани или изтрети без консенсус на мрежата" (Rapid Innovation, 2024). Това свойство е от фундаментално значение за предикативните системи за сигурност — всяка промяна в обучаващите данни или в моделите може да бъде незабавно детектирана.

Руският изследователски ресурс *Habr* допълва тази перспектива: „Изследват се ключовите предимства на блокчейна, включително повишаването на сигурността и поверителността на данните, възможността за децентрализирана верификация и одит на AI системи" (Habr.ru, 2025)⁹. LinkedIn публикация на руски език добавя, че „премахвайки централизираното управление, блокчейнът въвежда революционен подход към верификацията на данните и установяването на доверие" (LinkedIn RU, 2024).

Френският източник *OVHcloud France* дефинира AI-блокчейн интеграцията (*blockchain IA*) като синергия, при която „блокчейнът е технология на разпределен регистър, гарантираща сигурно, прозрачно и неизменно записване на данните, докато изкуственият интелект носи аналитичните и предикативни способности" (OVHcloud FR, 2024)¹⁰. Изданието *Alyra* (2025) констатира, че „блокчейнът и ИИ трансформират ключовите сектори, като създават нови възможности в сферата на сигурността, управлението и верификацията на данни" (Alyra, 2025).

От особено значение за правния контекст е решение от март 2025 г. на Трибунал дьо Марсей (Tribunal judiciaire de Marseille), с което за първи път се признава доказателствената

стойност на блокчейн данни в съдебен процес — прецедент с далечни последствия за употребата на блокчейн в системите за сигурност и наблюдение (Village Justice, 2025).

3.3 Смарт контракти и автоматизирана реакция при инциденти

Смарт контрактите представляват самоизпълняващи се програми, съхранени в блокчейн, чийто код автоматично прилага предварително зададени правила. В контекста на сигурността те отварят нова възможност — **автономна, незабавна и верифицируема реакция при засечени заплахи**.

Изследване в *ResearchGate* (2025), озаглавено „Leveraging Smart Contracts for Automated Incident Response in Cybersecurity Systems"¹¹, констатира, че „смарт контрактите могат да автоматизират процесите на реакция при инциденти в киберсигурностните екосистеми, позволявайки бърз, предварително програмиран отговор без нужда от човешка намеса" (ResearchGate, 2025). Това е качествен скок — от предикативен анализ, изискващ ръчна интервенция, към автономни системи, способни сами да изолират заразени сегменти от мрежата, да блокират подозрителни акаунти или да иницирират криптиране на компрометирани данни в рамките на секунди.

LinkedIn публикация за еволюцията на стандартите за сигурност на смарт контрактите (2025) предупреждава, че „до 2025 г. сигурността на смарт контрактите се превръща в крайъгълен камък на блокчейн екосистемата", включвайки комбинация от AI-управлявани технологии и квантово-устойчиви криптографски методи (LinkedIn, 2025). Изданието *Hacken* (2025) документира десетте най-критични уязвимости на смарт контрактите, подчертавайки, че тяхната сигурност изисква непрекъснат предикативен мониторинг.

3.4 Обработка на Big Data в контекста на сигурността

Big Data анализът е неотделим от предикативния анализ в сигурността поради огромните обеми данни, генерирани от мрежовия трафик, IoT устройства, системни журнали и сензори. Изследване в *ResearchGate* (2024), озаглавено „Big Data Analytics in Cybersecurity: Enhancing Threat Detection, Response and Prediction"¹², подчертава, че „интеграцията на Big Data анализа в операциите по сигурността подобрява не само ефективността на засичането на заплахи, но и цялостната организационна устойчивост" (ResearchGate, 2024). Блокчейнът допълва Big Data инфраструктурата, като гарантира, че събраните масиви от данни не могат да бъдат ретроактивно манипулирани — проблем, особено актуален при съдебно-технически разследвания.

3.5 Интернет на нещата (IoT), умни градове и блокчейн-базирана сигурност

Интеграцията на IoT устройства в критичната инфраструктура разширява значително повърхността на атака, но едновременно предоставя огромни масиви от сензорни данни за предикативен анализ. Ключовият въпрос е как да се гарантира, че тези данни са автентични и непроменени.

Изследване в *Nature Scientific Reports* (2025) предлага „децентрализирана рамка за доверие (*Decentralized Trust Framework*)"¹³, използваща блокчейн технология, AI-управлявано засичане на заплахи и адаптивен консенсусен механизъм", специално проектирана за умни градове. Публикация в *Springer* допълва с „интегрирана IoT-блокчейн лека рамка за сигурна комуникация" с акцент върху

⁸ Бързите иновации през 2024 г. се характеризират с ускорена конвергенция на изкуствения интелект, блокчейн и интернет на нещата, водеща до пробиви в диагностиката, устойчивите технологии и финансовите системи. Ключовите тенденции включват климатични решения, базирани на изкуствен интелект, диагностика в здравеопазването, подпомагана от изкуствен интелект, и появата на „екипи за бързи иновации" за ускорено реализиране на бизнес проекти. <https://www.rapidinnovation.io/post/ai-knowledge-management-in-2024>

⁹ <https://habr.com/en/feed/>

¹⁰ <https://corporate.ovhcloud.com/>

¹¹

https://www.researchgate.net/publication/397655619_Leveraging_Smart_Contracts_for_Automated_Incident_Response_in_Cybersecurity_Systems

¹²

https://www.researchgate.net/publication/386143147_Big_Data_Analytics_in_Cybersecurity_Enhancing_Threat_Detection_Response_and_Prediction

¹³ <https://www.nature.com/articles/s41598-025-06405-y>

автентикацията на устройствата (Springer, 2025). Изданието *MDPI Smart Cities* (2025) представя концептуална рамка, при която „синергичната интеграция на IoT и блокчейн служи като мощен катализатор за умните градове, осигурявайки разширени способности в сигурността на данните, поверителността и управлението" (MDPI, 2025). Руска публикация в LinkedIn (2024) обобщава: „Сливането на блокчейн и IoT в 2024 г. бележи ключова стъпка към по-сигурна, прозрачна и ефикасна цифрова екосистема, разрешавайки проблеми, пред които традиционните централизирани решения се оказват безсилни" (LinkedIn RU, 2024).

4. Приложни области

4.1 Кибернетична сигурност

Киберсигурността е водещото приложно поле на предикативния анализ. Инструментите включват системи за засичане на прониквания (IDS/IPS), платформи за управление на информация и събитията в сигурността (SIEM), анализатори на поведението на потребители и общности (UEBA) и платформи за разузнаване на заплахи (Threat Intelligence Platforms). Академично изследване от IACIS (2025), посветено на предикативния анализ в киберсигурността на здравеопазването, установява, че „предикативния анализ значително подобрява засичането на заплахи чрез усъвършенствани методи за анализ на данни".

Докладът на Световния икономически форум „Global Cybersecurity Outlook 2025"¹⁴ подчертава нарастващото неравенство в киберпространството и необходимостта от демократизиране на достъпа до предикативни инструменти за сигурност (WEF, 2025). *CrowdStrike Global Threat Report 2026*¹⁵ разкрива тревожна тенденция: „средното време за пробив е намаляло до само 29 минути — ускорение от 65% спрямо 2024 г.", което прави предикативните системи с реално-времеви отговор абсолютно необходими.

Интеграцията на блокчейн в кибер-сигурностните операции решава конкретен и стар проблем — доверието в одитните следи. Изследване в *MDPI Applied Sciences* (2025), озаглавено „AI-Blockchain Integration for Real-Time Cybersecurity"¹⁶, предлага „нова рамка за киберсигурност в реално време, интегрираща изкуствен интелект и блокчейн за засилена защита срещу заплахи", при което блокчейнът осигурява неизменна регистрация на всяко събитие, а AI провежда предикативния анализ (MDPI, 2025). LinkedIn публикация за комбинирането на AI и блокчейн директно обобщава: „AI, действайки като интелигентен пазач, носи несравними способности в проактивното засичане на заплахи, предикативната аналитика и автоматизирания отговор, докато блокчейнът осигурява неприкосновената основа от данни" (LinkedIn, 2024).

Руска публикация в LinkedIn (2024) анализира „ИИ в киберсигурността: предикативен анализ на защитата срещу заплахи", посочвайки, че „глобалният дефицит на кадри в сферата на киберсигурността е почти 4 милиона специалисти (по данни на ISC²), а AI агентите могат да автоматизират значителна част от тази работа" (LinkedIn RU, 2024). Публикацията в *scilead.ru* допълва: „С използването на машинно обучение AI системите могат да идентифицират заплахи, които не са били предварително известни, включително атаки от тип 'нулев ден'" (*scilead.ru*, 2024). Френският годишен доклад на *Recorded Future* (2024) „Analyse des menaces pour 2024 et prévisions pour 2025"¹⁷ установява, че „две ключови тенденции са определяли ландшафта на

киберсигурността: устойчивостта на киберпрестъпните мрежи въпреки предприетите мерки" и нарастващата употреба на AI от самите нападатели (Recorded Future FR, 2024).

4.2 Блокчейн като гарант за интегритет на доказателствата в разследванията

Един от най-значимите и нови приноси на блокчейн технологията е в сферата на цифровата криминалистика и управлението на доказателства. Изследване в *ResearchGate* (2025), озаглавено „Immutable Audit Trails Using Blockchain for AI-Driven Financial Fraud Investigations", описва подход, при който „AI моделите за засичане на измами се интегрират с регистриране на одитни следи чрез смарт контракти, позволявайки прозрачна верификация" (ResearchGate, 2025). Тази рамка гарантира, че доказателствата, събрани от предикативни AI системи, не могат да бъдат оспорени като манипулирани — ключово изискване при съдебно преследване на киберпрестъпления.

Широкомашабен преглед в *WJARR* (2025), „The Integration of AI and Blockchain Technologies for Secure Data Management in Cybersecurity", потвърждава, че „интеграцията на AI и блокчейн предоставя многопластова защита: AI обработва данните аналитично, докато блокчейнът осигурява тяхната неизменност и проследимост" (WJARR, 2025). Архитектурно проучване, публикувано в *OUCI* (2025), описва „блокчейн-базирана инфраструктура, при която блокчейнът функционира като слой за интегритет, засилващ сигурностния профил на AI-управляваните системи" (OUCI, 2025).

4.3 Предикативна полицейска дейност и публична безопасност

Предикативната полицейска дейност използва данни и анализи за предвиждане, предотвратяване и реакция спрямо престъпления. Изследване в *Minnesota Journal of Law, Science & Technology* (2024)¹⁸ анализира как „предикативната полицейска дейност, дава правомощия на правоохранителните органи да предсказват потенциални горещи точки на престъпност" (MJLST, 2024). Научна статия в *ScienceDirect* (2025) представя комплексен анализ на „предикативната полицейска дейност и предикативното правосъдие" в контекста на „етика, защита на данните и правни предизвикателства" (ScienceDirect, 2025). Блокчейнът може да изиграе решаваща роля и тук — верификацията на самоличностите, проследимостта на операциите и неизменността на записите от видеонаблюдение могат да бъдат гарантирани чрез разпределен регистър, предотвратявайки злоупотреби и постфактум манипулации на данни.¹⁹

4.4 Физическа сигурност и интелигентно видеонаблюдение

Французкото издание *FEND Security* (2024) отбелязва, че „компаниите приемат решения за поведенчески анализ в реално време, системи за предикативна сигнализация и интелигентни камери" като нова норма (FEND, 2024). Порталът *Access Protection* (2025) добавя, че иновациите в електронната сигурност включват „предикативен AI, биометрия и блокчейн за оптимална защита" — изрично признавайки блокчейна като неотделима компонента на съвременната физическа сигурност (Access Protection, 2025). Блогът на Националния институт за превенция в България описва как „за целите на киберсигурността ИИ може проактивно да идентифицира аномален мрежов трафик или злонамерен софтуер и да реагира на аномалното поведение преди то да причини щети" (НИПБ, 2023). Интегрирането на блокчейн в тези системи допълва картината, осигурявайки, че регистрираните инциденти не могат да бъдат заличени или модифицирани.

4.5 Здравеопазване и критична инфраструктура

¹⁴ <https://www.weforum.org/publications/global-cybersecurity-outlook-2025/>

¹⁵ <https://www.crowdstrike.com/en-us/global-threat-report/>

¹⁶ https://www.researchgate.net/publication/394707993_AI-Blockchain_Integration_for_Real-Time_Cyber_Security_-_System_Design_and_Evaluation

¹⁷ <https://www.recordedfuture.com/fr/research/2024-annual-report>

¹⁸ <https://scholarship.law.umn.edu/mjlst/>

¹⁹ Личева, Т. „Предиктивна полиция: интелигентна превенция на престъпността". В. Сб. Док. от IX Международна научна конференция по сигурност „CONFSEC 2025" 8 – 11 дек. 2025 г., стр. 18-20, ISSN 2603-2953

Предикативният анализ и блокчейн намират важно приложение в защитата на критичната инфраструктура. Руският изследователски ресурс *synaptik.ru* описва как „блокчейнът позволява безопасно събиране, съхранение и обмен на медицинска информация — лекарства, истории на заболявания — при едновременно прилагане на предиктивно обслужване" (*synaptik.ru*, 2024). Доклад от *Coherent Solutions* (2025) добавя, че „интеграцията на AI услуги и машинно обучение в здравната аналитика подобрява предикативните способности и повишава устойчивостта спрямо кибератаки" (*Coherent Solutions*, 2025).

5. Тенденции и перспективи

5.1 Квантови изчисления — заплахата и възможност

Квантовите изчисления представляват следващата граница — потенциална заплахата за съществуващата блокчейн криптография, но и инструмент за качествено по-мощен предикативен анализ. LinkedIn публикацията за еволюцията на стандартите за сигурност на смарт контрактите (2025) предвижда, че „комбинацията от AI-управлявани технологии и квантово-устойчиви криптографски методи ще определи следващото поколение блокчейн сигурност" (LinkedIn, 2025). Изданието *Cyberhoot* класира квантовите изчисления и тяхното влияние върху криптирането сред топ-10 стратегически предизвикателства на киберсигурността (*Cyberhoot RU*, 2024).

5.2 Конвергенция на AI, IoT, блокчейн и 5G/6G мрежи

Сливането на тези четири технологии ще създаде ново поколение предикативни системи, способни да анализират трилиони точки от данни в реално време, при пълна проследимост и неизменност. Публикацията на *TNGlobal* (2026) потвърждава, че „блокчейнът играе трансформираща роля в управлението на умните градове, подобрявайки сигурността, прозрачността и оперативната ефективност" (*TNGlobal*, 2026). Изданието *websoftshop.ru* (2024) на руски прогнозира, че „блокчейн проектите ще инвестират в надежди мерки за сигурност", допълнени от AI предикативен мониторинг (*websoftshop.ru*, 2024).

5.3 Декларативна блокчейн-AI архитектура за националната сигурност

Следващото еволюционно стъпало е изграждането на национални и наднационални инфраструктури за сигурност, при които блокчейн-базираните регистри служат като обща, взаимно верифицируема основа за споделено разузнаване на заплахата между държави и организации. Докладът на *Gartner* (2025) идентифицира трансформацията на управлението и нормализирането на AI като водещи приоритети (*Gartner*, 2025)²⁰, а *Trend Micro* (2025) на френски описва необходимостта от „усъвършенстване на засичането на заплахата чрез управлявани услуги за разпознаване и реакция, подкрепен от усъвършенстван анализ и автоматизация" (*Trend Micro FR*, 2025)²¹.

6. Заключение

Предикативният анализ в сигурността, основан на новите технологии, представлява едно от най-значимите технологични явления на нашето десетилетие. Синтезът на изследователската литература разкрива единодушие по следните ключови точки: AI и машинното обучение са незаменими инструменти за преддичане и засичане на заплахата; Big Data анализ е технологичният фундамент; IoT и умните градове са новото приложно поле; а блокчейн технологията е **необходимият слой за интегритет и доверие**, без който

предикативните системи остават уязвими към манипулация на данни, оспоримост на доказателства и липса на отчетност.

Блокчейнът не замества AI предикативния анализ — той го **легитимира**. Осигурявайки неизменност на данните, автоматизирана реакция чрез смарт контракти, децентрализирано управление на идентичността и прозрачни одитни следи, блокчейнът трансформира предикативните системи от технологични инструменти в **юридически значими, одитиреми и доверени инфраструктури** за сигурност.

България, в рамките на европейската и международната общност, стои пред предизвикателството да изгради собствен капацитет в тази конвергентна технологична екосистема — академичен, институционален и индустриален — като съчетае технологичния прагматизъм с ангажмента към правата на гражданите и демократичните ценности.

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IMPLEMENTATION OF BLOCKCHAIN IN COUNTERINTELLIGENCE

ВНЕДРЯВАНЕ НА БЛОКЧЕЙН В КОНТРАРАЗУЗНАВАНЕТО

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Abstract: The report explores the implementation of blockchain technology in counterintelligence as a tool for increasing security and protecting sensitive data. Based on decentralization and cryptography, the technology provides tamper-proof records and an audit trail that eliminates the risk of information manipulation. It has been successfully applied worldwide in the fields of intelligence, defense, and international cooperation against crime. In the counterintelligence cycle, blockchain protects against insider threats and provides a transparent, multilaterally approved decision-making process through smart contracts.

Keywords: BLOCKCHAIN, COUNTERINTELLIGENCE, DATA SECURITY, NATIONAL SECURITY, CRYPTOGRAPHY, SMART CONTRACTS, ZERO TRUST, HUMINT

1. Увод

Блоквата система създава структура от данни с присъщи качества за сигурност. Базира се на принципите на криптографията, децентрализацията и консенсуса, които гарантират доверие в трансакциите и истинност на данните. В повечето блокови вериги или технологии за разпределен регистър (DLT¹) данните са структурирани в блокове и всеки блок съдържа трансакция или пакет от трансакции. Всеки нов блок се свързва с всички блокове преди него в криптографска верига по начин, че е невъзможно да бъде подправен. Всички трансакции в рамките на блоковете се валидират и съгласуват чрез консенсусен механизъм, като по този начин се гарантира, че всяка трансакция е вярна и правилна².

Блокчейн позволява децентрализация чрез участието на членове в разпределена мрежа. Няма единична точка на отказ и един потребител не може да промени записа на трансакциите, а е необходимо съгласуване и одобрение на всички потребители от блоквата система. Технологиите се различават в някои критични аспекти на сигурността и за отделни дейности е необходимо да се подбере най-подходящата и отговаряща на нивото на сигурност на данните блоквата верига.

2. Интегриране на блокчейн в сигурността

Докато в световен мащаб се наблюдава активно експериментиране и внедряване на блокчейн в критични за сигурността сектори, България изостава в усвояването на този технологичен потенциал. В тази част от разработката ще анализирам както доказаните ползи и научени уроци от международния опит, така и предизвикателствата и необходимите стъпки за евентуалното бъдещо приложение на блокчейн в българските служби за сигурност.

- **Разузнавателен анализ:** Глобални компании като Cognite³ разработват специализирани

¹ Разпределителна или споделена книга (от англ. ез. Distributed Ledger Technology). Представява консенсус на репликирани, споделени и синхронизирани цифрови данни, които са географско разпределени в сайтове, институции или държави. Разпределителната книга не изисква централен администратор

² https://en.wikipedia.org/wiki/Distributed_ledger
³ https://www.ibm.com/topics/blockchain-security?x_tr_sl=en&x_tr_tl=bg&x_tr_hl=bg&x_tr_pto=sc

https://www.cognite.com/?utm_term=cognite&utm_campaign=Co+gnyte+--+KD+--+Brand+--+EMEA+--+Cognite+--+20220106&utm_source=adwords&utm_medium=ppc&hsa_acc=7164007194&hsa_cam=22465899263&hsa_grp=177035958126&hsa_ad=747631148588&hsa_src=g&hsa_tgt=kwd-1185607441640&hsa_kw=cognite&hsa_mt=e&hsa_net=adwords&hsa_ver=3&gad_source=1&gad_campaignid=22465899263&gbraid=0AAAAACpxrXtqw5B913_5nltjQISJaMuDI&gclid=Cj0KCCiArOvIBhDLARIsAPwJXOb9t0ukZRBvByrxEYindFCfYkJRRr_oWY7ruUduDJ7Ob0PQscxFCBYaAl_DEALw_wCB (последно посетен сайт на 20 окт. 2025 г.)

аналитични платформи, които използват изкуствен интелект и блокчейн анализ за проследяване на незаконни криптовалути трансакции, свързани с финансиране на тероризъм и финансови престъпления⁴.

- **Сигурност на веригата за доставки в сектор отбрана:** Министерството на отбраната на САЩ провежда множество пилотни проекти, често в партньорство с частни компании, за използване на частни блокчейн мрежи за проследяване на компоненти, управление на логистиката и гарантиране на автентичността на части в отбранителната индустрия⁵.
- **Доказателства и съдебна медицина:** Правоприлагащи органи в различни юрисдикции, включително в страни като Индия и Дубай, използват технологични решения, базирани на публични блокчейн системи, за създаване на неизменима верига на попечителство за криминални доказателства, като по този начин се повишават тяхната надеждност и достоверност в съда⁶.
- **Международно сътрудничество:** Международни организации експериментират с блокчейн-базирани системи. Пилотният проект „Сребърно известие“ има за цел да ускори трансграничното проследяване и възстановяване на активи, придобити от престъпна дейност, включително криптовалути⁷.

Интеграцията на блокчейн в службите за сигурност еволюира от теоретични концепции до конкретни оперативни проекта в рамките на по-малко от десетилетие. Този процес може да бъде разделен на три основни фази, отразяващи нарастващата зрялост на технологията и разбирането за нейния потенциал в сферата на националната сигурност.

3. Контраразузнаване

⁴ <https://itrade.gov.il/uae/2024/02/23/uniting-global-forces-for-a-safer-tomorrow-world-police-summit-2024-in-dubai/> (последно посетен сайт на 20 окт. 2025 г.)

⁵ <https://www.boozallen.com/insights/blockchain/blockchain-promise-for-defense-agency-supply-chains.html> (последно посетен сайт на 20 окт. 2025 г.)

⁶ <https://adapulse.io/securing-forensic-chain-of-custody-for-indian-state-govt-using-cardano-and-zero-knowledge-proofs/> (последно посетен сайт на 20 окт. 2025 г.)

⁷ <https://www.mishcon.com/news/interpol-publishes-the-first-silver-notice-targeting-criminal-assets-the-future-of-financial-crime-enforcement> (последно посетен сайт на 20 окт. 2025 г.)

Използването на блокчейн в контраразузнаването е насочено към едни от най-критичните уязвимости в тази сфера: риска от вътрешни заплахи, манипулация на данни и компрометиране на оперативната сигурност. Технологията предлага рамка за изграждане на високоустойчиви, поверителни и проследими системи за управление на контраразузнавателни операции.

Защита срещу вътрешни заплахи и манипулации

В същината на технологията, блокчейн осигурява среда с нулево доверие, която е от ключово значение за контраразузнаването. За разлика от разузнаването, където основният фокус е събирането на информация за външни субекти, контраразузнаването се бори и със заплахата от вътрешни компрометирания и вражеско проникване. Децентрализираната и криптографски свързана структура на блокчейн прави изключително трудно за вътрешен злонамерен агент да промени или изтрие вече въведени данни в блоковата верига, без това да бъде незабавно установено от цялата мрежа.

По този начин се създава неизменима и сигурна пътека на всяко действие – от постъпването на сигнал за потенциална заплаха до оторизацията на контра-операция. Това гарантира, че данните за източници, агенти и разследвания са защитени не само от външни атаки, но и от манипулации отвътре.

Повишена сигурност и оперативна дискретност

Блокчейн подобрява контраразузнавателния управленски цикъл чрез специфични механизми, които подсилват сигурността и дискретността на операциите и работните процеси.

- **Събиране и анализ на информацията:** Технологията позволява сигурно управление на данните от чувствителни източници. Чрез техники като доказателства с нулево доверие, може да се провери автентичността на информацията от даден източник, без да се разкрива неговата самоличност в регистъра⁸. Децентрализираният протокол за консенсус гарантира, че докладите от различни източници се валидират от множество страни, намалявайки риска от подаване на дезинформация.
- **Изготвяне на прогнози, прогнозни оценки, варианти за решение, взимане на решение**
решение и планиране: Многостраниното одобрение е ключово. Интелигентните договори могат да наложат правило, според което дадена контра-операция може да бъде одобрена само с цифровите подписи на няколко високопоставени служители. По този начин се предотвратява еднолични и нерегламентирани действия и взимане на решения.
- **Организиране, изпълнение, контрол и проверка на изпълнението с планираната цел:** Управлението на оперативни активи и екипи става по-сигурно. Анонимизирани цифрови самоличности могат да бъдат присвоявани на агенти и ресурси, като техните права и достъп се управляват чрез блокчейна, без да се разкриват реалните им

идентификации. Всяко действие се записва в неизменимия регистър, създавайки неопровержима одитна следа за целите на последващ анализ и контрол.

Таблица 1. Приложение на блокчейн в контраразузнаването по елементи на управленския цикъл

<i>Етап от управленския цикъл</i>	Приложение на блокчейн технологии в контраразузнаването
1. Събиране и анализ	Защита на чувствителни източници: Използването на прозрачност със селективна поверителност, която позволява верификация на данни от HUMINT източници без разкриване на тяхната самоличност. Времевите печати помагат за хронологичното поддръждане на събитията и засичането на аномалии в докладите.
2. Прогнозиране и решение	Автоматизирано засичане на заплахи: Интелигентните договори могат да изпълняват алгоритми за анализ на поведението, които автоматично оценяват и сигнализират за модели, индикиращи вътрешна заплаха или шпионаж. Междурегистровата обединяване позволява сигурен обмен на разузнавателна информация за заплахи със съюзнически служби, като същевременно се запазва строгата йерархия на ролеви достъп.
3. Взимане на решение	Устойчиво на компрометиране одобрение: Децентрализираният консенсус чрез мулти-подписни схеми гарантира, че решения за стартиране на чувствителни контраразузнавателни операции не могат да бъдат взети еднолично, а е необходимо одобрение от предварително определени лица. Криптографската сигурност осигурява строг контрол и проверка на лицата, вземащи решения.
4. Планиране	Секретни и неизменими оперативни планове: Интелигентните договори могат да генерират динамични оперативни планове, които се активират само при изпълнение на предварително определени условия. Параметрите на мисията се записват в неизменимия регистър, което гарантира възможност за преглед без риск от фалшификация.
5. Организиране	Сигурно управление на екипи: Токени за управление имат възможност да представляват правата на достъп на членовете на тайни екипи, като промените се записват прозрачно, но съдържанието остава криптирано в блокчейна.
6. Реализация	Сигурно задействане на тайни операции: Интелигентните договори служат като „мъртва ръка“ или кодиран автоматичен спусък, който активира оперативни действия, като задействане на средства за наблюдение, само при получаване на предварително уговорен криптографски сигнал.

⁸ <https://adapulse.io/securing-forensic-chain-of-custody-for-indian-state-govt-using-cardano-and-zero-knowledge-proofs/> (последно посетен сайт на 12 ян. 2026 г.)

7. Контрол

Неопровержима одитна следа: Вградената проследяемост на блокчейна предоставя пълна и неизменима следа на всички предприети действия, дори ако физически устройства или полевите системи бъдат компрометирани. Аномалиите, засечени от интелигентни договори, задействат незабавни сигнали за разследване.

4. Заключение

Контраразузнаването се фокусира върху вътрешния периметър на сигурността – защита от враждебно разузнаване, вътрешни заплахы, изтичане на класифицирана информация и компрометиране на критична инфраструктура. Тук управленският цикъл е наситен с чувствителни решения за започване на проверки, ограничаване на достъп, провеждане на операции и упражняване на строг вътрешен контрол. Прилагането на блокчейн в тези процеси има много голямо значение, като осигурява вериги на доказателствата, намалява риска от вътрешно манипулиране на данни и улеснява както вътрешния, така и външния надзор. Същевременно технологичният слой поражда и специфични рискове: концентрация на изключително чувствителни логове, опасност от елиминиране на анонимни източници чрез метаданни и необходимост строг контрол на достъп, криптографска защита и ясни правни рамки.

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Abstract: The report examines space as the fifth battlefield of modern geopolitics, where the United States, China, and Russia are engaged in intense technological competition. The main focus is on artificial intelligence as a key tool for processing intelligence data from satellites, SAR radars, and hyperspectral sensors. Special attention is paid to blockchain technology as a means of ensuring authenticity, security, and trust in sharing intelligence information between allies. The report outlines forecast trends for the period 2026–2035, including AI autonomy in orbit, quantum sensors, and the increasing independence of allied space programs. The overall conclusion is that processing speed and data reliability will be decisive factors in future conflicts and strategic decision-making.

Keywords: SPACE INTELLIGENCE, ARTIFICIAL INTELLIGENCE, GEOINT, BLOCKCHAIN, COUNTERINTELLIGENCE, NATIONAL SECURITY, CYBERSECURITY

1. Увод

Космическото пространство се е превърнало в петото бойно поле на съвременната война — наред с сушата, морето, въздуха и киберпространството. Геополитическото съперничество между САЩ, Китай и Русия катализира експоненциално технологично развитие в областта на космическото разузнаване, наблюдение и рекогносцировка. Интелигентност, наблюдение и разузнаване ISR¹.

Пазарът на геопропространствени отбранителни приложения (GEOINT) е оценен на около 128.29 млрд. USD за 2025 г. и се прогнозира да достигне 162.39 млрд. USD до 2032 г. Това е отражение на мащабното технологично и финансово инвестиране в сектора и неговото нарастващо значение за националната сигурност.

2. Ключови технологични системи и устройства

2.1 Синтетичен апертурен Радар (SAR)

Synthetic Aperture Radar (SAR) ² е революционна технология, която превръща движението в изключително детайлни изображения, работейки при всякакви метеорологични условия — облачност, тъмнина, валежи. За разлика от оптичните системи, SAR-сателитите осигуряват постоянно наблюдение независимо от осветеността или атмосферните условия.

Аерокосмическите и отбранителните сектори очакват **35% ръст** в приемането на SAR технологиите за разширено наблюдение. Ключови характеристики на съвременните военни SAR системи включват:

- **Многополяризационно изображение** – разграничаване между типове повърхности и обекти;
- **Интерферометрия (InSAR)** – картографиране на деформации на терена с милиметрова точност;
- **Coherent Change Detection (CCD)** – засичане на минимални промени между последователни снимки;

¹ Intelligence, Surveillance and Reconnaissance

² Синтетичният апертурен радар (SAR) е вид активно събиране на данни, при което инструмент изпраща енергиен импулс и след това записва количеството на тази енергия, отразено обратно, след като взаимодейства със Земята. За разлика от оптичните изображения, които са пасивна техника за събиране на данни, базирана на излъчена енергия, SAR изображенията се създават от реакцията на излъчен енергиен импулс с физически структури (като планини, гори и морски лед) и условия като почвена влажност. SAR се използва в широк спектър от приложения, включително изучаване на антарктически айсберги, проследяване на пътищата на нефтени разливи в чувствителни блатата и картографиране на влажните зони на Аляска, <https://www.earthdata.nasa.gov/learn/earth-observation-data-basics/sar>

- **Ground Moving Target Indication (GMTI)** – проследяване на движещи се наземни цели

Германската система SARah е показателен пример. Оперативната разузнавателна система е съставена от множество сателити и наземен сегмент, разработена за военни нужди. По оценката на SAAB, SAR-сателитите са „едни от най-мощните инструменти за идентифициране и локализиране на противника“.

2.2 Хиперспектрален анализ и оптика от висок клас

Хиперспектралните сензори разширяват обхвата на наблюдение далеч отвъд видимия спектър. Те способни да идентифицират:

- Химичен състав на почви и растителност;
- Прикрити военни съоръжения чрез топлинни и спектрални сигнатури;
- Тип и концентрация на промишлени емисии;
- Замаскирани обекти чрез спектрална диференциация

Системата Next Gen OPIR (Overhead Persistent Infrared)³ на Космическите сили на САЩ използва топлинни сигнатури за засичане на балистични ракети, хиперзвукови снаряди и нови заплахи. Първите два сателита от системата Next Gen OPIR GEO са насрочени за изстрелване през 2026 г.

2.3 Малки сателити и конотации (SmallSat Constellations)⁴

Революцията в миниатюризацията промени парадигмата на космическото разузнаване. Малките сателити (SmallSats) предлагат:

- **По-ниска цена на изстрелване** – до 100 пъти по-евтино от традиционните платформи;
- **По-висока честота на обновяване** – глобално покритие на всеки 1–3 часа;
- **Устойчивост** – загубата на единица не компрометира системата;
- **Бързо разгръщане** – „responsive launch“ при кризисни ситуации.

Показателен е проектът MILNET⁵ - партньорство между Космическите сили на САЩ и SpaceX за разработване на 480-

³ Следващото поколение въздушно-постоянна инфрачервена система (NG-OPIR) е съзвездие за предупреждение за ракети, разработано в Съединените щати като заместител на предшественика си, космическата инфрачервена система (SBIRS). Очаква се тя да бъде ключова част от оръжейната система „Златен купол“.

https://en.wikipedia.org/wiki/Next-Generation_Overhead_Persistent_Infrared

⁴ <https://www.capellaspace.com/resources/the-impact-of-small-satellite-constellations-on-earth-observation>

⁵ <https://satnews.com/2025/12/29/u-s-space-force-and-spacex-partner-to-develop-480-satellite-milnet-constellation/>

сателитна военна констелация. Първата партида е планирана за срездата на 2026 г., а пълна оперативна готовност се очаква в близко бъдеще.

2.4 Лазерни комуникационни линии (Laser Inter-Satellite Links)⁶

Прехвърлянето на разузнавателни данни в реално време е ключов оперативен проблем. Нов рекорд за скорост на предаване между сателити по лазерна линия – 400 Gbit/s е поставен през март 2025 г. между китайски апарати. Тази технология позволява:

- Незабавно предаване на данни към наземни станции;
- Оперативна разузнавателна картина в реален мащаб на времето;
- Намалена зависимост от наземни ретранслатори.

3. Национални програми и системи

3.1 Космически сили на САЩ

Космическите сили на САЩ (U.S. Space Force) са в процес на мащабна трансформация. В съответствие с Space Force Vector 2025⁷, основните направления са:

Програма SILENTBARKER⁸ - система за пространствено наблюдение на геостационарна орбита, проектирана за наблюдение на неприятелски сателити. Сателитите координират проследяването на цели и обмен на данни чрез допълващи се сензори. Space Force обявява намерение за преход към по-евтини комерсиални компоненти за SILENTBARKER.

Next Gen OPIR⁹ - следващото поколение инфрачервено наблюдение от орбита. Системата включва само 4 сателита (2 в GEO + 2 в полярна орбита), но с изключително разширени способности за засичане на ракетни изстрелвания.

Нова флота разузнавателни сателити. Космическите сили планират да издадат първите договори за следващо поколение разузнавателни сателити, като се целят за оперативна готовност около 2030 г.

⁶ EDRS Global позволява информация, събрана от нискоорбитални спътници и безпилотни летателни апарати, да бъде изпращана навсякъде по Земята в квазиреално време. Това се постига чрез предаване на информацията между геостационарните възли чрез лазер и предаване надолу към земята.

https://www.esa.int/ESA_Multimedia/Images/2016/02/Inter-satellite_laser_links

⁷ Документът синхронизира формиращата цел на Космическите сили и теорията за успеха – подход, насочен към поддържане на космическо превъзходство и предотвратяване на конфликти чрез проактивни и отговорни операции.

<https://www.spaceforce.mil/News/Article-Display/Article/4331082/space-force-releases-vector-2025/>

⁸ Космическите сили разработиха и изстреляха „Silent Barker“ съвместно с Националната разузнавателна служба. Мисията на космическия кораб е до голяма степен класифицирана, но службата заяви, че ролята му е да проследява обекти – и потенциално злонамерени дейности – в геосинхронна орбита, на около 35 000 километра над Земята.

<https://www.defensenews.com/space/2024/12/11/space-forces-first-silent-barker-satellites-to-be-live-in-early-2025/>

⁹ Next-Gen OPIR е част от по-голяма многоорбитална стратегия за осигуряване на възможности за предупреждение и проследяване на ракети от космоса. Наред с двата георобитални спътника, Космическите сили са сключили договор с Northrop Grumman за изграждането на два космически апарата в полярна орбита като част от Next-Gen-OPIR.

<https://www.defensenews.com/space/2025/06/11/space-forces-first-next-gen-missile-warning-launch-pushed-to-2026/>

NRO (National Reconnaissance Office) – провежда собствена паралелна програма за следващо поколение разузнавателни сателити, независима от Space Force. Двете системи работят в режим на „tip-and-cue“: сателитите за наблюдение насочват разузнавателните към конкретни цели.

3.2 Китай – най-бързо развиваща се космическа разузнавателна сила

Китай демонстрира зашеметяваща скорост на разгръщане на космически разузнавателни способности. По оценка на официален представител на Космическите сили на САЩ, „Китайското космическо развитие надминава очакванията и набира инерция“.

Серия Яогань (Yaogan)¹⁰ е военна серия „сателити за дистанционно наблюдение“, обхващаща оптически, SAR и сигнални разузнавателни апарати.

Към декември 2025 г. около 80 от 160 активни сателити Yaogan са потвърдени за извършващи оперативна дейност; Yaogan-45 е позициониран в средна земна орбита (MEO) на 7,497 км, т.е. 10 пъти по-висока от стандартните наблюдателни сателити, с разширено покритие; Yaogan-47 е изстрелян в края на 2025 г. от ракета Long March 4B.

Рекордно изстрелване от края на 2025 г. Китай извърши четири изстрелвания за 96 часа, демонстрирайки способност за бързо разгръщане на нови апарати при кризисни ситуации.

SIGINT способности. Институтът IISS публикува детайлен доклад за китайските разузнавателни способности от орбита, включително кораби за проследяване на космически апарати и ракети: Yuan Wang-3, -5, -6 и -7.

Лазерни комуникации. Китай установи световен рекорд от **400 Gbit/s** за предаване на данни между сателити.

3.3 Русия – Трансформация в условия на санкции

Русия изпълни **17 космически изстрелвания** за 2025 г. — стабилно ниво, постигнато чрез групови изстрелвания. Въпреки натиска от западни санкции, Русия поддържа оперативна разузнавателна констелация.

Руските малки сателити са идентифицирани като ключова технологична тенденция. Програмите за ДЗЗ (Дистанционно Зондиране на Земята) се развиват в посока: Групови изстрелвания за поддържане на орбитална плътност при ограничени ресурси; Двойна употреба за гражданска и военна функционалност в едни и същи платформи; Лазерни комуникационни линии за паралелно развитие с китайски и западни системи.

3.4 Европа – Нарастваща автономност

Европейската Космическа Агенция (ESA) стартира инициативата European Resilience from Space (ERS)¹¹, като

¹⁰ Серията сателити Яоган, известна още като китайската серия „Дистанционно наблюдение“, са изкуствени спътници, които използват технология и оборудване за дистанционно наблюдение, за да наблюдават земната повърхност. Тези сателити, оборудвани с камери с висока резолюция и друго оборудване за дистанционно наблюдение, могат да получават изображения и данни с висока резолюция на земната повърхност, предоставяйки важни информационни услуги

<https://spacemapper-cn.translate.google.com/show/constellation/yaogan>

¹¹ Предложената система ще интегрира дистанционно наблюдение, свързаност, PNT (позициониране, навигация и време), мониторинг на спектъра и системи за интернет на нещата, с цел да се предоставят на потребителите възможно най-сигурните, гъвкави и бързи възможности за реагиране.

https://www.esa.int/About_Us/Corporate_news/Europe_turns_to_space_to_boost_resilience

тригодишна прелюдия към по-широка ISR програма. Целта е намаляване на зависимостта от американски разузнавателни данни.

Японско-британското сътрудничество между **INI** и **SSTL** за японска ISR констелация е показателно за глобалната тенденция: съюзниците на САЩ вече не разчитат единствено на американски данни, а изграждат собствени независими способности.

4. Изкуствен интелект и анализ на разузнавателни данни

4.1 ИИ като мултипликатор на мощности

Изкуственият интелект е централен елемент на революцията в космическото разузнаване. Основните приложения включват:

Автоматична обработка на изображения (Automated Image Analysis)¹². ИИ системите могат да: Идентифицират военни обекти, превозни средства и съоръжения; Засичат промени между последователни снимки за секунди; Класифицират обекти по тип и потенциална заплаха; Прогнозират следващи действия на основа на исторически модели.

Геопространствен ИИ анализ. Изследователи от Stanford са разработили модели за машинно обучение, обучени на сателитни изображения за идентифициране на развиващи се показатели, скрити от официалната статистика.

Космически ИИ асистиенти. Пазарът на базирани в космоса ИИ асистиенти е оценен на 2.67 млрд. USD с прогноза за силен ръст до 2030 г. Изследователи от Stanford са внедрили машинно обучение в роботи на МКС за автономно планиране.

Google и машабируема ИИ инфраструктура в орбита. Google Research публикува концепция за модулна система от взаимосвързани малки сателити, носещи ИИ изчислителни способности директно в орбита. Тази концепция позволява обработката на данни да се извърши преди предаването на Земята. Това е изключително предимство за оперативност.

4.2 Мулти-доменен ISR и интеграция на данни

Конференцията за бъдещето на Multi-Domain ISR¹³ постави въпроса за интеграцията на разузнавателни данни от космос, въздух, суша, море и киберпространство в единна оперативна картина.

Основните технологични подходи: Fusion Intelligence – за обединяване на GEOINT, SIGINT, HUMINT в единна платформа; Predictive Analytics – за прогнозни модели за действия на противника; Real-time Processing – за обработка на данни в реално време без забавяне при предаването; Federated Learning – ИИ модели, обучавани на разпределени данни без централизиране на чувствителна информация.

¹² Автоматизиран анализ на изображения. Машабируемо решение за възпроизводими резултати., <https://www.arivis.cloud/home/>

¹³ Докато традиционните ISR системи разчитат предимно на ръчно управление и статични канали за данни, VISIONAIRY® ISR осигурява автономно събиране на разузнавателна информация в реално време с минимална човешка намеса. Активите могат независимо да откриват, класифицират и проследяват обекти от интерес във въздуха, на сушата и в морето. Той осигурява стабилни, адаптивни възможности за разузнаване, дори в условия на липса на GPS, ограничена комуникация или враждебна среда. VISIONAIRY® ISR осигурява непрекъснат поток от информация, подобрява скоростта на вземане на решения и предоставя машабируемо разузнаване там, където е най-важно. <https://www.spleenlab.ai/defense-isr>

4.3 Търговско-отбранителна Конвергенция¹⁴

Един от ключовите тренда за 2026 г. е **сближаването между търговския и отбранителния космически сектор**. Компании като Planet Labs, Maxar, BlackSky и Umbra предлагат търговски сателитни изображения с военна приложимост: Planet Labs предоставя ежедневни снимки на цялата Земя; Umbra предлага SAR изображения с <25 cm резолюция; Търговски GEOINT данни вече се интегрират директно в военни системи

5. Новите тактики и оперативни подходи

5.1 „Tip-and-Cue“¹⁵ - Многостепенно разузнаване

Съвременният подход замества монолитните разузнавателни платформи с многостепенна архитектура: Tier 1- (Широкообхватни сензори) – множества от малки сателити осигуряват постоянно глобално покритие, засичат аномалии; Tier 2 - (Насочване) – средни платформи получават „сигнал“ от Tier 1 и насочват вниманието към конкретни зони; Tier 3 (Детайлно изобразяване) – висококачествени разузнавателни сателити (NRO клас) осигуряват детайлни снимки на вече идентифицираните обекти. Именно тази архитектура описва взаимодействието между SILENTBARKER и NRO.

5.2 Разпределена устойчивост

Традиционните „exquisite satellites“ са скъпи, уникални платформи, но са уязвими. Новата доктрина предпочита: Голям брой малки сателити вместо единична скъпа платформа; Разпределени функции, всеки сателит изпълнява част от мисията; On-orbit servicing, с орбитално обслужване за удължаване на живота на платформите; Rapid reconstitution за бързо попълване при загуба на апарати.

5.3 Проактивно Космическо Позициониране

Китайският **Yaogan-45**, позициониран на нетипична МЕО орбита от 7,497 км., е пример за нов тактически подход: поставяне на разузнавателни апарати на нестандартни орбити за разширено покритие или затруднено засичане и проследяване.

6. Анализ и прогнозиране въз основа на космическото разузнаване

6.1 GEOINT-базирано стратегическо предупреждение

GEOINT (Geospatial Intelligence) е превърнало се в основен инструмент за стратегическо предупреждение.

Ключови аналитични способности: Засичане на военни натрупвания – броене на военна техника, оценка на логистични потоци; Мониторинг на ядрени съоръжения – засичане на промени в инфраструктурата; Икономическа разузнавателна дейност – анализ на пристанищна активност, промишлено производство; Хуманитарни кризи – ранно засичане на бежански движения и разрушения.

6.2 Шест ключови прогностични тренда (2026–2035)

ИИ автономия в орбита. Прогнозира се, че до 2030 г. значителна част от разузнавателните сателити ще обработват

¹⁴ Commercial-Defense Convergence

¹⁵ С постоянно нарастващия брой спътници за наблюдение на Земята (EO), сензори и честота на повторните им посещения, стратегията „tip and cue“ за проследяване и наблюдение на бързо движещи се обекти придобива все по-голям интерес. Комбинацията от допълващи се резолюции на изображението и спектрални ленти позволява рентабилно и ефективно идентифициране и проследяване на бързо движещи се обекти, дори на големи площи. <https://www.iceye.com/blog/tip-and-cue-technique-for-efficient-near-real-time-satellite-monitoring-of-moving-objects>

данни автономно в орбита, без да изпращат суровите данни на Земята. Това ще намали с порядъци латентността на разузнавателния цикъл.

Квантови сензори. Квантовите гравитационни и магнитни сензори от орбита ще позволят засичане на подводни съоръжения, подземни бункери и тунели – обекти, невидими за електромагнитни сензори.

Хиперзвукови мобилни цели. Развитието на хиперзвукови оръжия от Русия и Китай ще доведе до революция в системите за проследяване. Next Gen OPIR е директен отговор на тази заплаха.

Демократизация на GEOINT. Търговската наличност на сателитни снимки с висока резолюция размива монопола на правителствата върху разузнавателни данни. Журналисти, НПО-та и академични изследователи вече имат достъп до данни, резервирани само за разузнаването преди 10 години.

Космическо противодействие (Counter-Space). Китайските стотици разузнавателни сателити принуждават Space Force да премине към офанзивни космически способности. Това включва насочени енергийни оръжия, кинетични противосателитни ракети и кибератаки срещу космически системи.

Съюзническа автономност. Съюзниците на САЩ, Европа, Япония и Австралия, активно изграждат собствени ISR групирания, тъй като вече не могат да разчитат единствено на американски данни.

6.3 Геополитически приложения

Анализаторите предупреждават, че разширяващата се китайска сателитна мрежа представлява „главна заплаха за глобалната сигурност“, не само поради разузнавателните способности, но и поради потенциала за насочване (targeting) на американски военноморски и наземни сили в реално време.

Сателитните изображения вече играят ключова роля в разкриването на **китайското военно строителство в Южнокитайско море и Тихия океан**. Анализите на отворени източници (OSINT) редовно разкриват промени в базирането на самолетноносачи, строителство на ракетни позиции и движение на военноморски сили.

7. Блокчейн в космическото разузнаване

Космическото разузнаване генерира данни в безпрецедентен мащаб от стотици сателити, хиляди изображения на час, сигнали от множество сензори, предавани по глобални мрежи с множество участници. Критичният въпрос не е само „как да съберем данните“, а „как да гарантираме, че данните са истинни, непроменени и доверени“.

Именно тук блокчейн технологията се явява не като модерна приставка, а като основен архитектурен отговор на три съществени уязвимости:

Манипулация на данни: Противникът може да инжектира фалшиви сателитни изображения или да модифицира предадени данни в транзита.

Централизирана точка на отказ: Единната командна инфраструктура е уязвима на кибератаки, заглушаване и физическо унищожаване.

Доверие при многостранно споделяне: При коалиционни операции никоя нация не желае единна страна да контролира верификационната инфраструктура.

Ключови технически механизми на блокчейн в ISR

■ Неизменяемост и криптографска верификация

Блокчейн организира записите в **криптографски свързани блокове**, като всеки нов блок съдържа хеш на

предходния. Промяната на един запис прави невалидна цялата следваща верига, с което фалшификацията е математически доказуема. В контекста на космическото разузнаване това означава, че всяко сателитно изображение, всеки SIGINT запис, всяка телеметрична точка получава цифров отпечатък при генерирането, т.е. директно на борда на сателита и всяка последваща промяна може веднага да се засече.

■ Пространствен индекс и верификация на геоданни

Системата блокчейн се извежда като начин за пространствена верификация на данни от дистанционно наблюдение. Методът линеаризира пространствената информация на изображенията и я вписва в блокчейн структура, позволявайки: Криптографска проверка на географска точност; Доказателство за неизмененост на координатите; Одитируема верига на достъп до геопространствените данни.

■ Децентрализирана сигурна обработка на масиви от данни

Блокчейн предлага сигурни и децентрализирани стратегии за обработка на космически ресурси от данни. Верифицираните дистанционни данни могат да се обработват на разпределени възли без централизирана точка на уязвимост.

■ Конкретни приложения в космическото разузнаване

1. Верификация на автентичността на изображения в ерата на дийпфейкове.

Ерата на ИИ-генерирани медии поставя пред разузнаването екзистенциален проблем: как да се докаже, че дадено сателитно изображение е автентично и не е манипулирано или генерирано изкуствено?

Блокчейн осигурява пълна верига на произход за всеки разузнавателен медиен актив: Записва метаданните в момента на заснемане; Всяка последваща обработка и анализ се вписва в неизменяемия регистър; ИИ модели за засичане на дийпфейкове регистрират своите резултати и версия в блокчейна; Крайният потребител може криптографски да провери цялата история на изображението.

2. Сигурно многонационално споделяне на разузнавателни данни

В НАТО и коалиционни операции споделянето на разузнавателни данни е традиционно фрикционен процес – всяка нация се страхува от загуба на контрол върху чувствителни данни. Блокчейн предлага революционно решение.

NATO публикация (STO-MP-IST-209) представя Proof of Authority (PoA) базирана блокчейн архитектура специално за военни коалиции. PoA е идеален избор за военни приложения, тъй като: Само предварително авторизирани възли (нации, агенции) участват в консенсуса; Няма нужда от единна контролираща страна; Всяка нация вижда само данните, до които има разрешение; Цялата активност е одитируема и проследима.

Блокчейн е определен като инструмент за киберсигурност във федерирани мрежи и е основоположник за защита на активи и операционния интегритет в многонационални военни конфликтни зони.

3. Защита на сателитна комуникация от Спуфинг

Анализирани са директното приложение на блокчейн в космическото наблюдение и военните операции: технологията осигурява верификация на сателитни комуникации, значително намалявайки рисковете от GPS и сигнални спуфинг.

Умните договори автоматизират протоколите за сигурност и гарантират, че само оторизирани субекти могат да командват сателитни системи или да модифицират оперативни параметри.

Всяка команда към сателит се записва неизменяемо, като неупълномощена команда е криптографски невъзможна за изпълнение.

4. Верификация на веригата на доставките на сателитни компоненти

Блокчейн, големите данни и генеративен ИИ вече се използват за проследяване на военна помощ и логистика. В космическото разузнаване това е от критично значение: сателитните компоненти могат да бъдат компрометирани на ниво хардуер, ако не съществува верифицирана верига на произход.

Блокчейн проследява всеки компонент от производителя до интеграцията в сателита и създава цифровият паспорт на компонента прави невъзможно инсталирането на компрометиран хардуер без засичане.

5. Автономни решения и координация

При констелации от стотици малки сателити централизираното командване е практически невъзможно. Блокчейн и смарт контрактите позволяват автономна координация: Сателит А засича цел и автоматично задейства смарт контракт за пренасочване на Сателит Б; Условието за действие са предварително кодирани и криптографски верифицирани; Никой отделен сателит или наземна станция не може да наруши протокола

Блокчейн верификация на данни от дистанционно наблюдение показва, че интегрирането на блокчейн с облачно съхранение и системи за извличане на данни от дистанционно наблюдение изгражда проверима среда, която е необходимата архитектура за автономни групирания.

3. Заключение

Космическото разузнаване претърпява четирикратна революция: технологична, архитектурна групирания вместо единични апарати, търговска и геополитическа.

Китай е определен като най-динамично развиващия се участник, с нестандартни орбитални позиции, рекордни лазерни комуникации и способност за масови изстрелвания при кризи.

САЩ поддържат технологично превъзходство, но то се стеснява. Отговорът е MILNET, Next Gen OPIR и преход към по-евтини разпределени архитектури.

Русия поддържа оперативни способности, въпреки санкциите, чрез групови изстрелвания и двойна употреба на платформи.

Ключовата технология на следващото десетилетие е ИИ-базираната автономна обработка в орбита. Тя ще определи коя страна може да реагира на заплахи в рамките на минути, а не часове.

Блокчейн технологията не е алтернатива на съществуващите системи за космическо разузнаване, тя е доверителна инфраструктура, върху която тези системи могат да оперират надеждно в условията на активна противодействие. Forbes формулира стратегическия императив директно: „Следващото военно предимство няма да дойде от по-големи кораби, по-стелт самолети или по-бързи ракети. То ще дойде от по-бързи решения“, а бързите решения изискват доверени данни. Блокчейн осигурява точно това: математически доказуема достоверност на разузнавателните данни, от момента на заснемане до момента на вземане на решение и дори в условия на активни кибератаки, електронно заглушаване и многонационални операции без единен доверен

арбитър в процеси и етапи от управлението на контраразузнаването.

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Multimodal data fusion in the transition Health 4.0 to Health 5.0

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The transition from Health 4.0 to Health 5.0 represents a fundamental reorientation of digital healthcare—from a technology-centric, efficiency-driven paradigm to one centered on human flourishing, resilience, and sustainability. While Health 4.0 successfully deployed cyber-physical systems (CPS), the Internet of Things (IoT), big data analytics, and artificial intelligence (AI) to create interconnected and data-rich environments, its approach to data integration has proven insufficient for the complex demands of modern healthcare. Specifically, Health 4.0 has largely relied on centralized, siloed, and unimodal data processing strategies that prioritize volume and velocity over context, meaning, and shared decision-making. This paper argues that multimodal data fusion, the systematic integration of heterogeneous data sources including physiological signals, medical imaging, genomic profiles, electronic health records (EHRs), wearable sensor streams, environmental data, and patient-reported experience, serves as a critical technical and ethical bridge in the transition from Health 4.0 to Health 5.0.

In the Health 4.0 paradigm, data fusion has been predominantly technical. Architectures are centralized, with data streams aggregated into monolithic repositories for batch processing or real-time analytics. Fusion occurs at the data or feature level, often without transparency or interpretability. The primary goals are diagnostic accuracy, anomaly detection, and operational efficiency. For example, a Health 4.0 system might fuse vital signs from wearables with laboratory results to trigger an automated alert for sepsis. While clinically useful, such systems suffer from critical limitations: they cannot explain why a fusion decision was made, they do not incorporate patient values or preferences, they lack resilience when one data stream fails, and they treat the patient as a passive data source rather than an active participant.

Health 5.0 fundamentally reframes the purpose and process of multimodal data fusion. Drawing on the three intellectual traditions of Sociotechnical Systems Theory, Value-Sensitive Design, and Resilience Engineering, Health 5.0 envisions data fusion as a human-centric, transparent, and adaptive process. The guiding question shifts from "What patterns can we extract?" to "What should we enable for patients and providers together?" In this paradigm, data fusion operates at multiple levels—data, feature, decision, and value—integrating not only clinical measurements but also patient goals, cultural contexts, and clinician expertise. Multimodal fusion becomes a collaborative act rather than a purely algorithmic one.

Several key differences distinguish Health 4.0 from Health 5.0 approaches to multimodal data fusion. First, regarding data sources, Health 4.0 prioritizes quantifiable, objective signals (e.g., lab values, imaging pixels, vital signs), while Health 5.0 equally values subjective and qualitative data (e.g., patient narratives, pain descriptions, quality-of-life assessments, and shared decision-making preferences). Second, concerning fusion architecture, Health 4.0 relies on centralized, often black-box models (e.g., deep neural networks that fuse modalities without interpretability), whereas Health 5.0 adopts federated, patient-controlled architectures where data remains distributed, and fusion occurs through Explainable Artificial Intelligence (XAI) and collaborative algorithms. Third, regarding temporality, Health 4.0 focuses on real-time or retrospective fusion for immediate action or population analytics, while Health 5.0 emphasizes longitudinal, adaptive fusion that learns from individual trajectories and adapts to shocks (e.g., sudden illness, supply chain disruptions, or pandemics). Fourth, in terms of decision locus, Health 4.0 fuses data to generate algorithmic recommendations that clinicians may override. In contrast, Health 5.0 fuses data to support shared deliberation among clinicians, patients, and AI systems, preserving human judgment as the final arbiter.

The enabling technologies for Health 5.0 require substantial redesign to support this new vision of multimodal fusion. Explainable AI (XAI) becomes essential, allowing clinicians to ask "why did this fusion produce that conclusion?" and trace contributions from each modality. Federated learning with patient-controlled governance enables multimodal fusion without centralized data collection, preserving privacy and autonomy. Context-aware IoT sensing ensures that data fusion occurs only when meaningful—for example, alerting only when physiological changes combined with patient-reported distress exceed a personalized threshold. Collaborative digital twins simulate trade-offs across fused modalities, showing a patient how different treatment choices might affect not only clinical outcomes but also quality of life, financial burden, and family impact. Finally, patient-controlled data wallets using blockchain technology allow individuals to grant and revoke consent for which modalities are fused and for what purposes, transforming the patient from a data source into an active co-designer of their own information ecosystem.

The transition from Health 4.0 to Health 5.0 in multimodal data fusion faces significant challenges. Technical barriers include the lack of standardized ontologies for subjective health data, the difficulty of fusing sparse or irregularly sampled patient-reported outcomes with dense physiological streams, and the computational overhead of explainable fusion models. Ethical and regulatory barriers include ambiguous consent frameworks for dynamic data fusion, liability questions when fused information leads to harm, and the risk of algorithmic bias being amplified through multimodal integration. Workforce readiness remains a concern: clinicians must be trained to interrogate fusion outputs, and data scientists must learn value-sensitive design. Digital exclusion threatens to leave behind populations without access to wearable devices or high-bandwidth connectivity, potentially widening health inequities.

A priority research agenda emerges from these challenges. We need various metrics for human-centric fusion that evaluate not only accuracy but also explainability, patient satisfaction, clinician trust, and resilience under data loss. Governance models must be developed that balance patient control with public health needs, enabling dynamic consent and auditable fusion pipelines. Equity-focused design should ensure that multimodal fusion does not exacerbate bias; this requires diverse training datasets, fairness constraints, and community engagement. Implementation science is needed to understand how fusion systems transition from research settings into clinical workflows without increasing cognitive burden or displacing human connection.

Multimodal data fusion is not merely a technical subtask within Health 5.0 but rather a lens through which the entire paradigm shift can be understood. Health 4.0 fused data to optimize efficiency. Health 5.0 fuses data to enable human flourishing. The former asks "What can we predict?" while the latter asks "What should we enable together?" The successful transition requires simultaneous innovation across AI, ethics, regulation, and clinical training. Failure to reimagine data fusion risks perpetuating brittle, dehumanizing systems that treat patients as data sources rather than partners. Success, however, offers a future where multimodal fusion empowers clinicians and patients alike—where technology faithfully serves human judgment, adapts gracefully to shocks, and amplifies the best of compassionate care. The central question

moving forward is no longer "How much data can we fuse?" but rather "How can fused data help this patient and this provider make a better decision, together?"

Health 5.0 represents the evolutionary leap from reactive, hospital-centric care to a proactive, data-driven, and human-centric ecosystem. It also enables so-called precision medicine, which provides the technological engine—using multi-omics, AI, and real-time monitoring to decode individual variability in disease. Precision medicine, also known as personalized or individualized medicine, is an innovative approach that moves beyond the traditional “one-size-fits-all” model of healthcare. Instead of applying the same treatment to all patients, precision medicine uses information about a person’s genes, environment, and lifestyle to guide medical decisions, aiming to predict which prevention strategies and therapies will be most effective for specific individuals or groups of people. Precision medicine follows the 4P model (Predictive, Preventive, Personalized, Participatory). Predictive analytics from precision medicine identify risk before symptoms arise. Preventive interventions are tailored to each patient’s unique genomic and environmental profile. Personalized treatments replace the one-size-fits-all approach, maximizing efficacy and minimizing side effects. Participatory care empowers patients as active partners, leveraging digital tools for shared decision-making. Together, Health 5.0, precision medicine, and the 4P framework converge into a seamless, continuous loop: data from participatory individuals fuels predictive models, which enable precise prevention and personalization. The outcome is a resilient, equitable, and sustainable health system that treats not just the disease, but the person in their full biological and social context. That enables active and healthy ageing with a longer healthspan.