

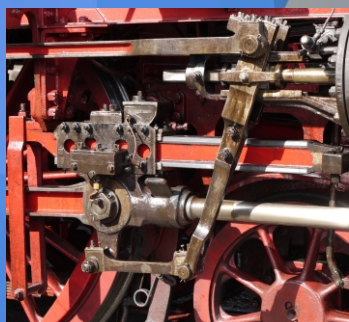
INTERNATIONAL SCIENTIFIC JOURNAL

INDUSTRY 4.0

ISSN (PRINT) 2534-8582

ISSN (WEB) 2534-997X

YEAR XI ISSUE 3/2026



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PUBLISHED BY
SCIENTIFIC TECHNICAL UNION OF MECHANICAL ENGINEERING
“INDUSTRY 4.0”, BULGARIA

INTERNATIONAL SCIENTIFIC JOURNAL

INDUSTRY 4.0

YEAR XI, ISSUE 3 / 2026
ISSN (PRINT) 2534-8582, ISSN (WEB) 2534-997X

PUBLISHER
**SCIENTIFIC TECHNICAL UNION OF MECHANICAL
ENGINEERING “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.

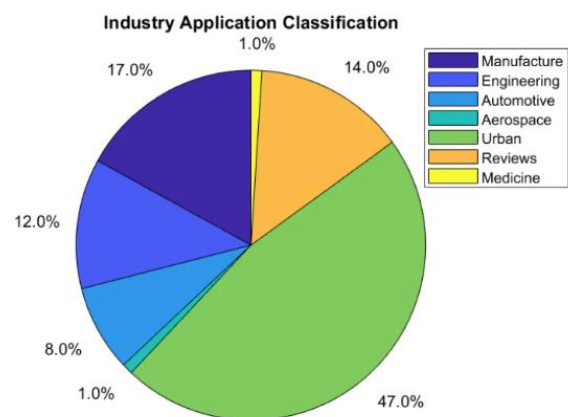


Fig.3 The publications on digital twin by use case/ application [13]

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].

Acknowledgment

This work was supported by KEGA project No. 012ŽU-4/2025 Implementation of methods and proposal of educational modules for the design of automated and robotic production systems with an aspect related to safety and risk elimination.

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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

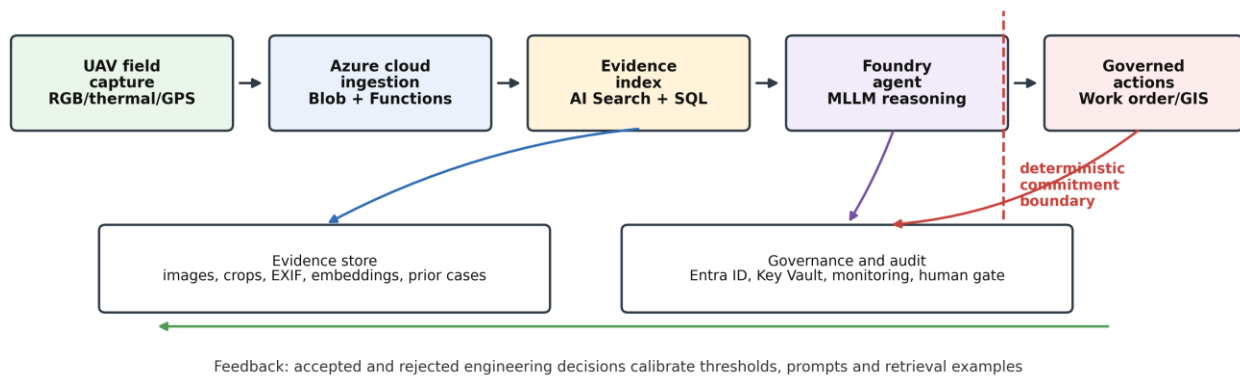


Fig. 1. Azure and Microsoft Foundry solution architecture for autonomous structural inspection.

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.

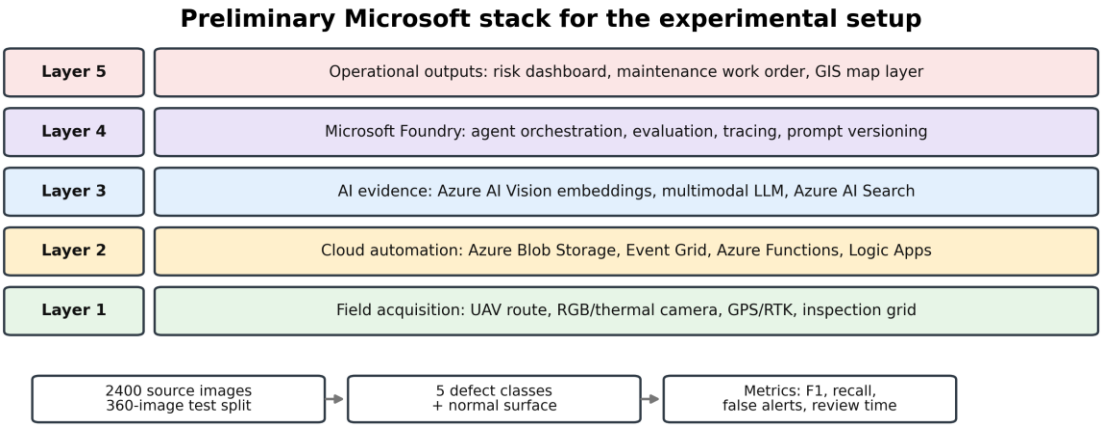


Fig. 2. Preliminary Microsoft stack used for the simulated experiment.

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.

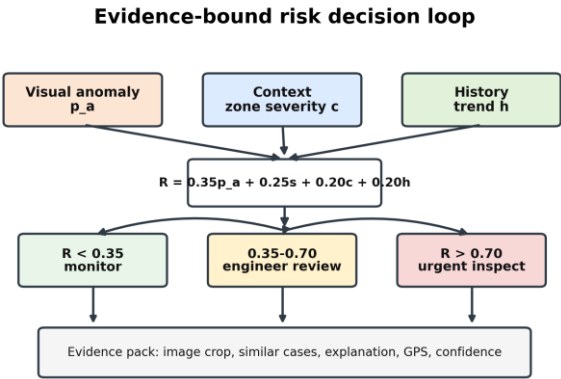


Fig. 3. Evidence-bound risk decision loop.

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

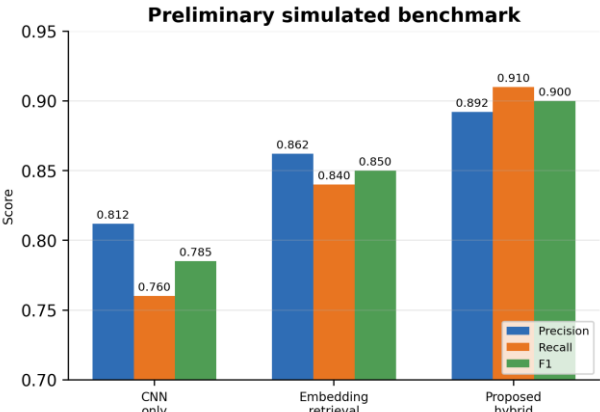


Fig. 4. Simulated comparison of precision, recall and F1.

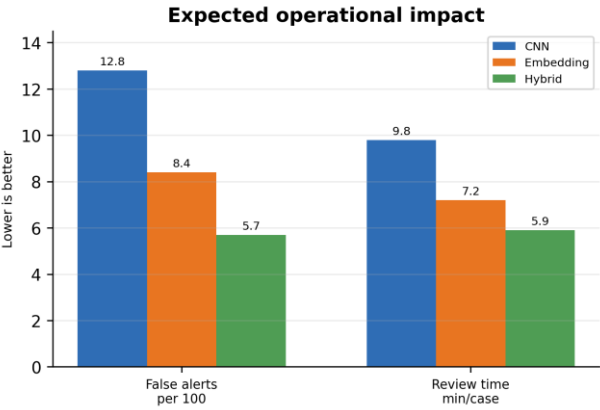


Fig. 5. Expected operational impact of the hybrid architecture.

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

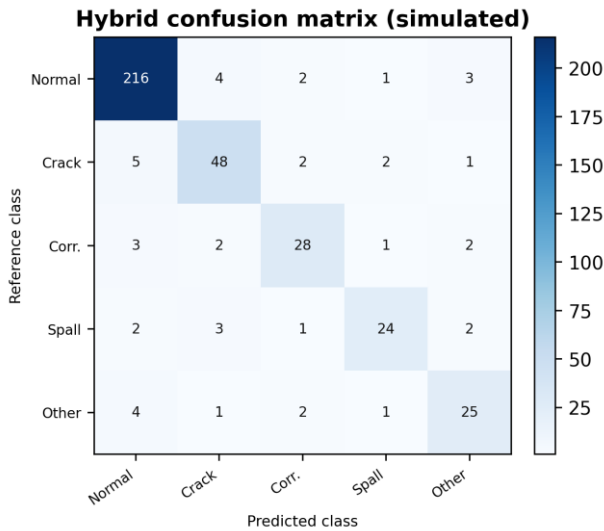


Fig. 6. Simulated confusion matrix for the hybrid model.

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

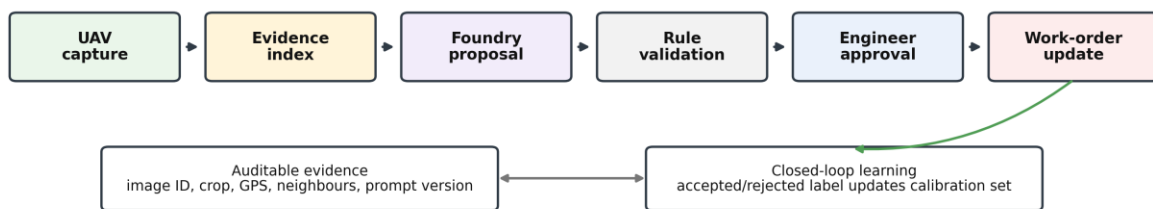


Fig. 7. Digital thread from inspection evidence to maintenance action

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]

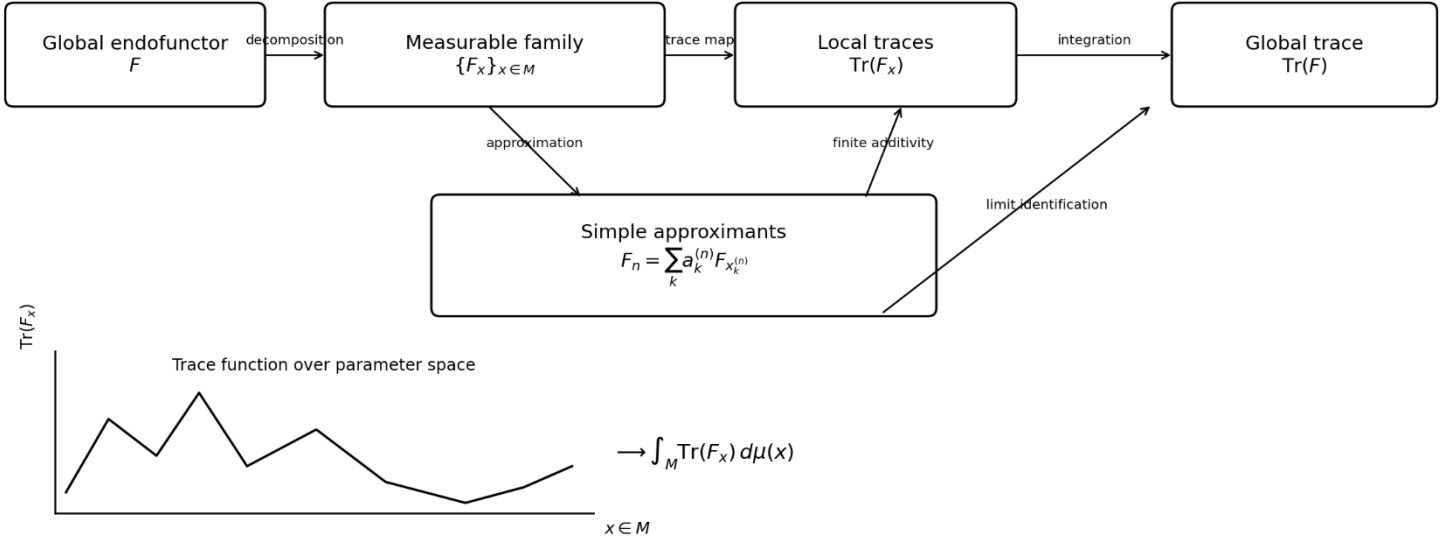
$$\text{Tr}\left(\sum_k F_k\right) = \sum_k \text{Tr}(F_k) \quad (10)$$

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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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.

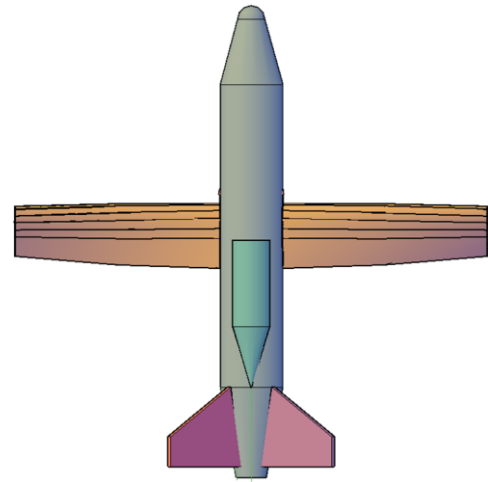


Fig. 2 Aircraft diagram, top plan view.

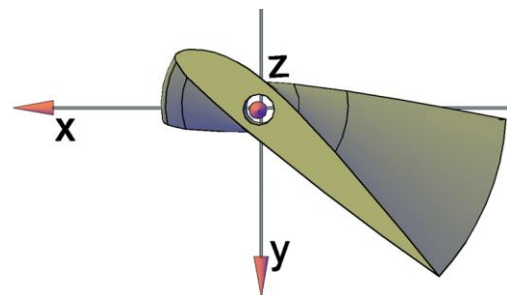


Fig. 3 View of a twisted wing from the free edge.

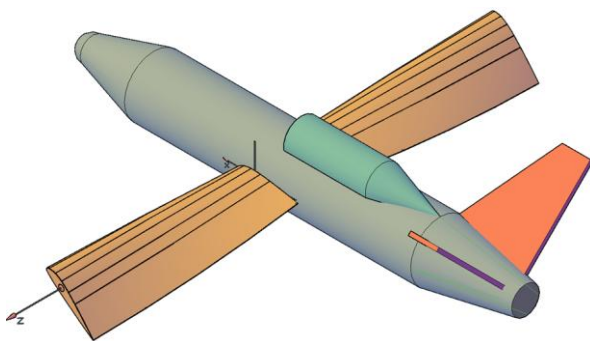


Fig. 1 General axonometric view of an aircraft with twisted wings.

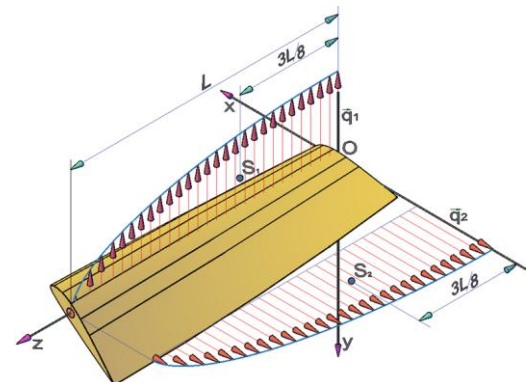


Fig. 4 Diagram of distributed loads acting on the wing, which change according to a parabolic law.

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:

$$M_q = \omega \cdot \frac{3z}{8} = \frac{2qz^2}{3\sqrt{l}} \cdot \frac{3z}{8} = \frac{q \cdot z^2}{4\sqrt{l}} \quad (1)$$

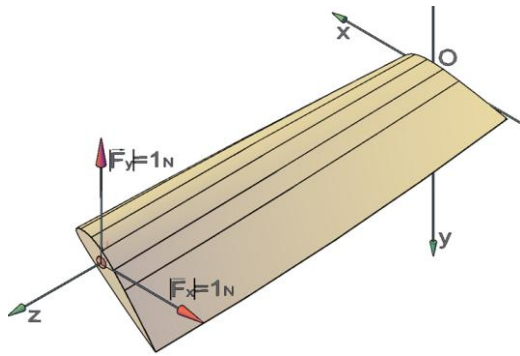


Fig. 5 Scheme of application of unit forces to the free end of the wing.

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:

$$\begin{aligned} M_{1x_i} &= M_1 \cdot \cos\varphi + M_2 \cdot \cos(90^\circ - \varphi) = \\ &= M_1 \cdot \cos\varphi + M_2 \cdot \sin\varphi = \frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \cos\varphi + \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \sin\varphi; \end{aligned} \quad (2)$$

$$\begin{aligned} M_{y_i} &= M_1 \cdot \cos(90^\circ - \varphi) + M_2 \cdot \cos(180^\circ - \varphi) = \\ &= \frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \sin\varphi + \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot (-\cos\varphi) = \\ &= \frac{q_1 \cdot z^2}{4\sqrt{l}} \cdot \sin\varphi - \frac{q_2 \cdot z^2}{4\sqrt{l}} \cdot \cos\varphi; \end{aligned} \quad (3)$$

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:

$$M_{1x_i}^h = z \cdot \cos\varphi; \quad M_{1y_i}^h = z \cdot \sin\varphi; \quad (4)$$

$$M_{1x_i}^v = z \cdot \sin\varphi; \quad M_{1y_i}^v = z \cdot (-\cos\varphi); \quad (5)$$

To determine the displacement along the Oy axis, we write Mohr's formula in the following form:

$$\Delta_y = \int_0^l \frac{M_{x_i} M_{1x_i}^h}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y_i}^h}{EI_{y_i}} dz; \quad (6)$$

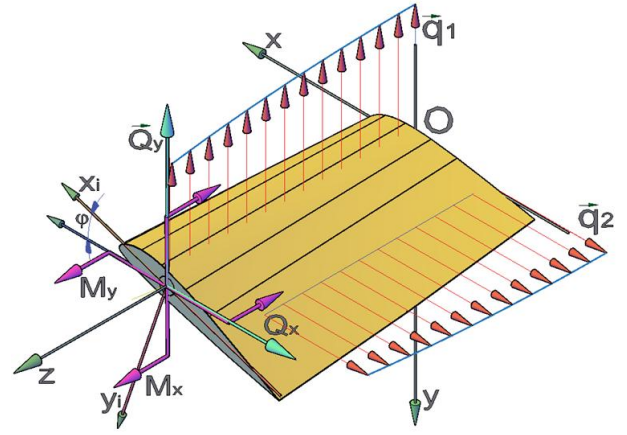


Fig. 6 Diagram of internal and external force factors acting on the cut-off part of the wing.

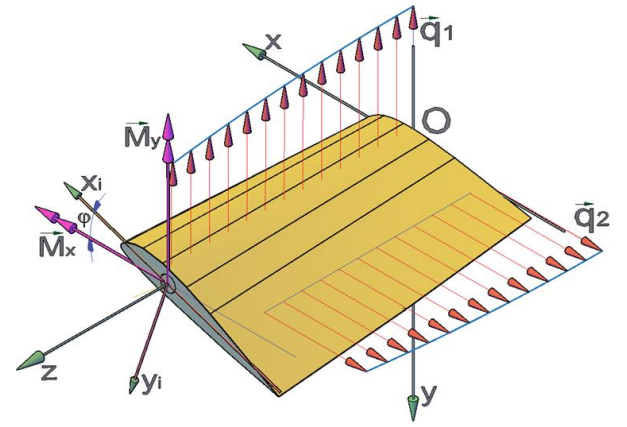


Fig. 7 Scheme of application of internal moments acting in an arbitrary section of the wing.

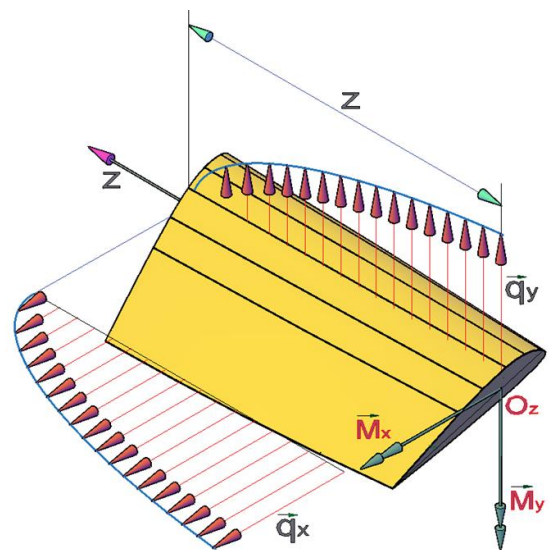


Fig. 8 Scheme of application of internal moments acting in a section at a distance Z from the free edge of the wing.

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:

$$\begin{aligned} \int_0^l \frac{M_{x_i} M_{1x_i}^h}{EI_{x_i}} dz &= \int_0^l \left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \varphi \right] \cdot z \cdot \cos \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^l \frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos^2 \varphi + \frac{q_2 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{7}{2}} \cdot q_1}{4\sqrt{l}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{7}{2}} \cdot q_2}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \varphi^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi \cdot d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \varphi^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot d\varphi = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi \cdot d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos \varphi \sin \varphi \cdot d\varphi \end{aligned} \quad (8)$$

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].

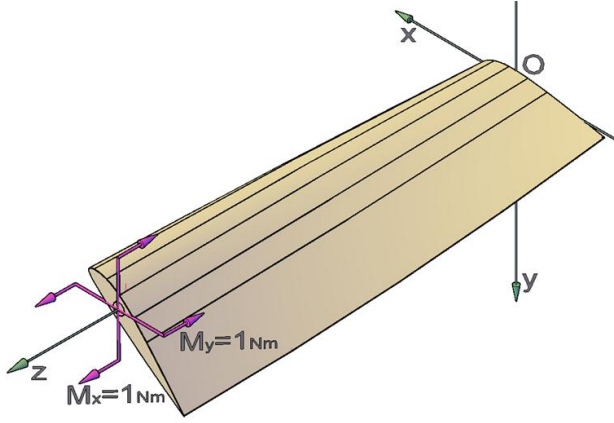


Fig. 9 Scheme of application of single moments of a pair of forces to the free end of a wing.

For the first integral of expression (20), the following calculations are performed:

$$\begin{aligned}
 \int_0^l \frac{M_{x_i} M_{1x(x_i)}}{EI_{x_i}} dz &= \int_0^l \left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \varphi \right] \cdot \cos \varphi \\
 &= \int_0^l \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos^2 \varphi + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{5}{2}} \cdot q_1}{4\sqrt{l} EI_{x_i}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi + \\
 &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{5}{2}} \cdot q_2}{4\sqrt{l} EI_{x_i}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi = \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \varphi^{\frac{5}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi d\varphi + \\
 &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \varphi^{\frac{5}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot d\varphi =
 \end{aligned}$$

$$\begin{aligned}
 &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos^2 \varphi d\varphi + \\
 &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos \varphi \sin \varphi \cdot d\varphi;
 \end{aligned} \quad (22)$$

For the second integral of this expression we will have:

$$\begin{aligned}
 \int_0^l \frac{M_{y_i} M_{1x(y_i)}}{EI_{y_i}} dz &= \int_0^l \left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \varphi - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi \right] \cdot \sin \varphi \\
 &= \int_0^l \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin^2 \varphi - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \sin^2 \varphi d\varphi - \\
 &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos \varphi \sin \varphi \cdot d\varphi
 \end{aligned} \quad (23)$$

After calculating the first integral of expression (21), we obtain:

$$\begin{aligned}
 \int_0^l \frac{M_{x_i} M_{1y(x_i)}}{EI_{x_i}} dz &= \int_0^l \left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\sin \varphi) + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\cos \varphi) \right] \cdot (-\cos \varphi) \\
 &= \int_0^l \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \varphi \sin \varphi + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos^2 \varphi \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{5}{2}} \cdot q_1}{4\sqrt{l} EI_{x_i}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi + \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^{\frac{5}{2}} \cdot q_2}{4\sqrt{l} EI_{x_i}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi = \\
 &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \varphi^{\frac{5}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos \varphi \sin \varphi \cdot \frac{6l}{\pi} d\varphi + \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \varphi^{\frac{5}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos^2 \varphi \cdot \frac{6l}{\pi} d\varphi = \\
 &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos \varphi \sin \varphi d\varphi + \frac{\left(\frac{6l}{\pi}\right)^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{5}{2}} \cdot \cos^2 \varphi d\varphi;
 \end{aligned} \quad (24)$$

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:

$$J_{\text{np}x_i} = \sum_{i=1}^n F_{\text{inp}} \cdot x_i^2 \quad (30)$$

The formula determining the moment of resistance of the wing section relative to the same axis $O_i x_i$ will be:

$$W_{x_i} = \frac{\sum_{i=1}^n F_{\text{inp}} \cdot x_i^2}{y_{\text{max}}} \quad (31)$$

The normal stress from this bending moment is found using the formula [4, 6]:

$$\sigma_{x_i} = \frac{M_{x_i}}{W_{x_i}} = \frac{\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cos \frac{z\pi}{6l} + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \sin \frac{z\pi}{6l}}{\frac{\sum_{i=1}^n F_{\text{inp}} \cdot x_i^2}{y_{\text{max}}}} = \frac{y_{\text{max}} \left(\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cos \frac{z\pi}{6l} + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \sin \frac{z\pi}{6l} \right)}{\sum_{i=1}^n F_{\text{inp}} \cdot x_i^2}; \quad (32)$$

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:

$$J_{\text{np}y_i} = \sum_{i=1}^n F_{\text{inp}} \cdot y_i^2 \quad (34)$$

The formula determining the moment of resistance of the wing section relative to the same axis $O_i y_i$ will be:

$$W_{y_i} = \frac{\sum_{i=1}^n F_{\text{inp}} \cdot y_i^2}{x_{\text{max}}} \quad (35)$$

The normal stress from this bending moment is found using the formula:

$$\sigma_{y_i} = \frac{M_{y_i}}{W_{y_i}} = \frac{M_1 \cdot \sin \frac{z\pi}{6l} - M_2 \cdot \cos \frac{z\pi}{6l}}{\frac{\sum_{i=1}^n F_{\text{inp}} \cdot y_i^2}{x_{\text{max}}}} = \frac{x_{\text{max}} \left(\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \sin \frac{z\pi}{6l} - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cos \frac{z\pi}{6l} \right)}{\sum_{i=1}^n F_{\text{inp}} \cdot y_i^2}; \quad (36)$$

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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Hermodynamic 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 consequentially 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.

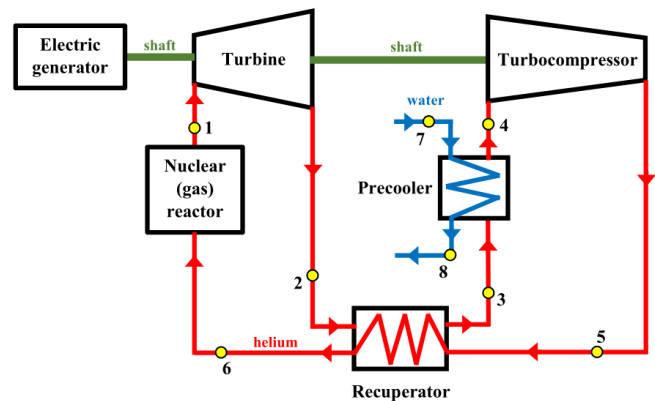


Fig. 1. General scheme of the helium closed-cycle gas turbine plant with operating points required for the thermodynamic analysis

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:

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

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

Turbocompressor

Turbocompressor exergy destruction and exergy efficiency are:

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

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

Precooler

Precooler exergy destruction and exergy efficiency are:

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

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

Recuperator

Recuperator exergy destruction and exergy efficiency are:

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

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

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:

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

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

Whole plant

Whole plant exergy destruction and exergy efficiency are:

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

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

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.

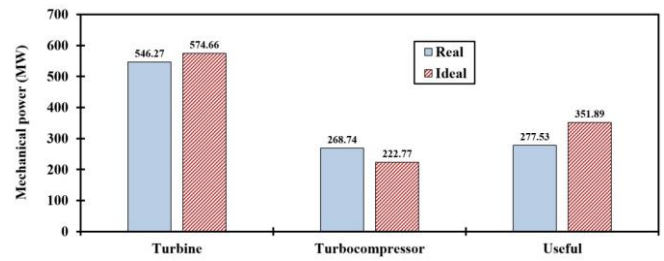


Fig. 2. Produced (turbine), consumed (turbocompressor) and useful mechanical power (in both ideal and real operating conditions)

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].

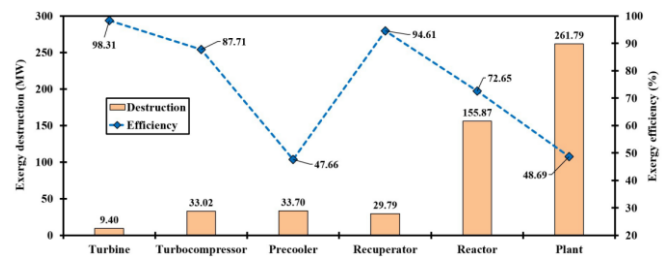


Fig. 3. Exergy destruction and exergy efficiency of all components and whole analyzed plant

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.

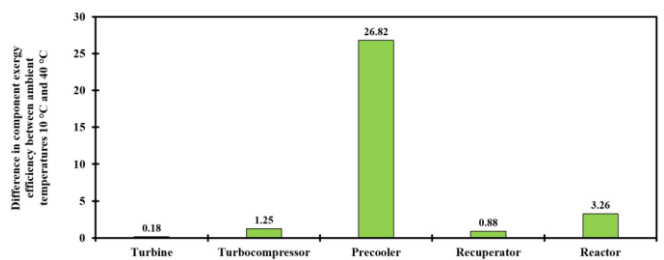


Fig. 4. Helium closed-cycle gas turbine plant components sensitivity to the ambient temperature change

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

This work was supported by the Croatian Science Foundation under the project number HRZZ-IP-2022-10-2821; University of Rijeka scientific grants: Funded by the European Union – NextGenerationEU – ENERGOPT - uniri-iz-25-6; GENE-CLASS - uniri-iz-25-220 and VEDRO - uniri-iz-25-10.

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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

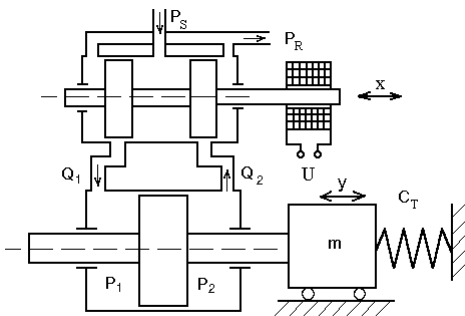


Fig. 1 Physical model of electrohydraulic system.

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**

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

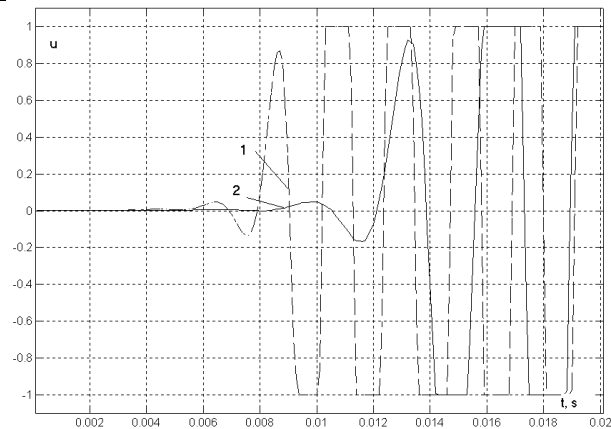


Fig. 2. Input control variable time-response curve.

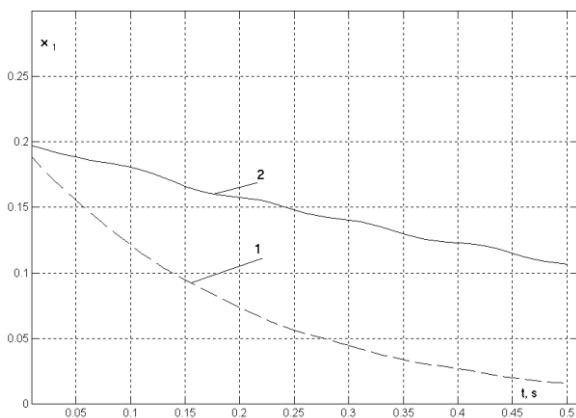


Fig. 3. State variable x_1 responses curves

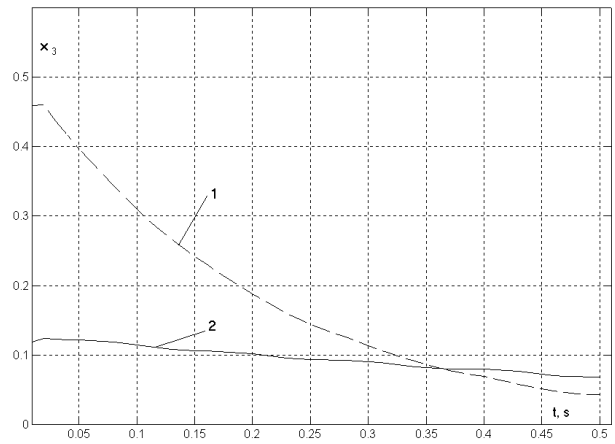


Fig. 4. State variable x_2 responses curves

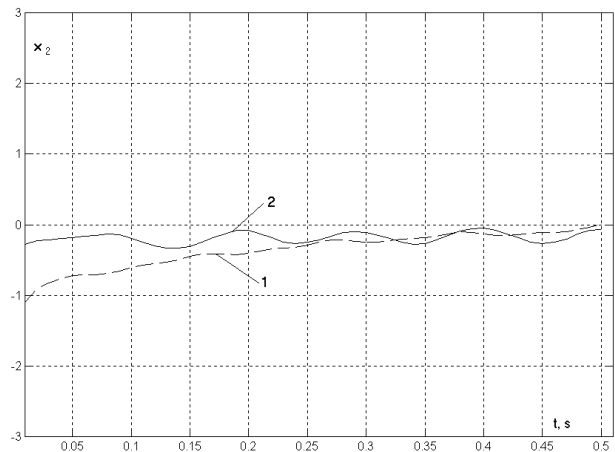


Fig. 5. State variable x_3 responses curves

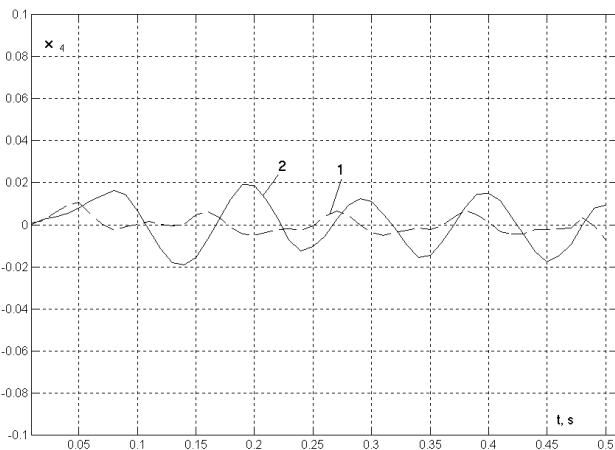


Fig. 6. State variable x_4 responses curves

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

This study has been supported by the Project НИП2026-12 of the Technical University of Gabrovo, Bulgaria.

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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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.

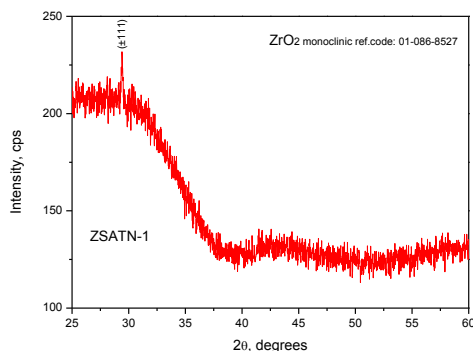


Figure 1. XRD analyses of the surface of the coating on glass /ZSATN-1/

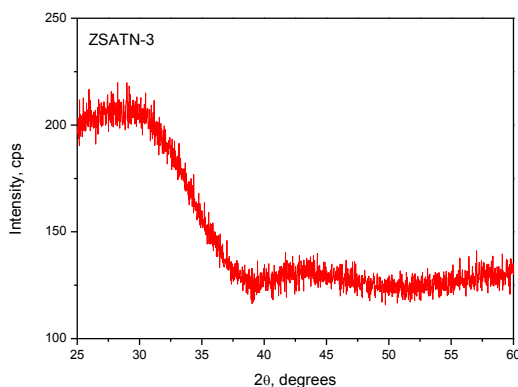


Figure 2. XRD analyses of the surface of the coating on glass /ZSATN-3/

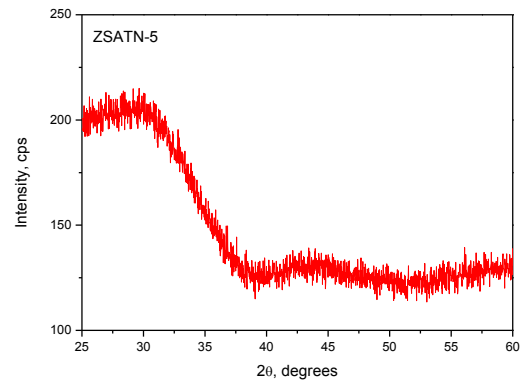


Figure 1. XRD analyses of the surface of the coating on glass /ZSATN-5/

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.

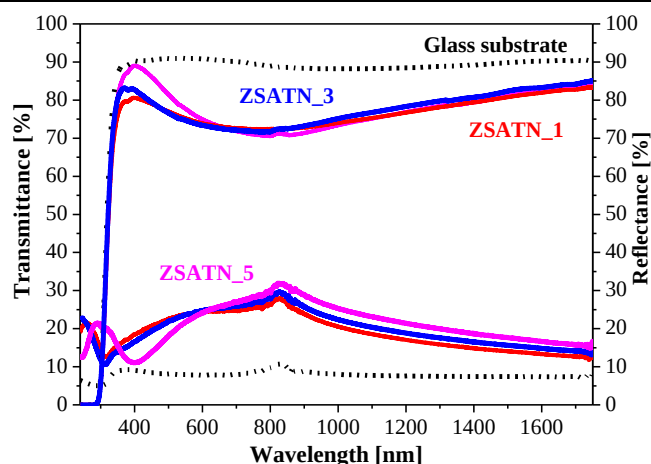


Figure 4. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 400 - 1800 nm / ZSATN-1, ZSATN-3 and ZSATN-5 /

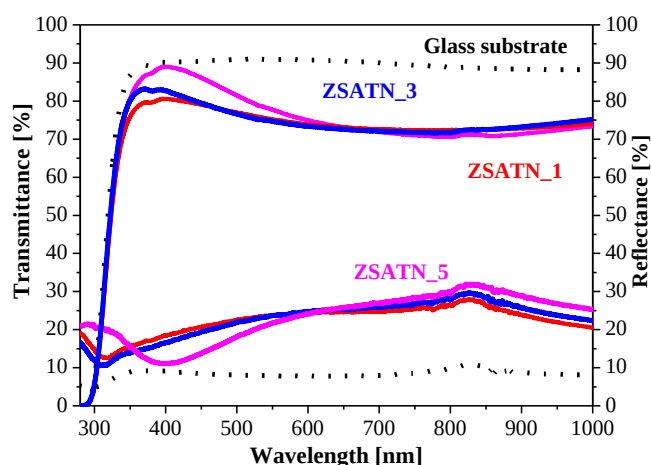


Figure 5. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 300 - 900 nm / ZSATN-1, ZSATN-3 and ZSATN-5 //

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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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.

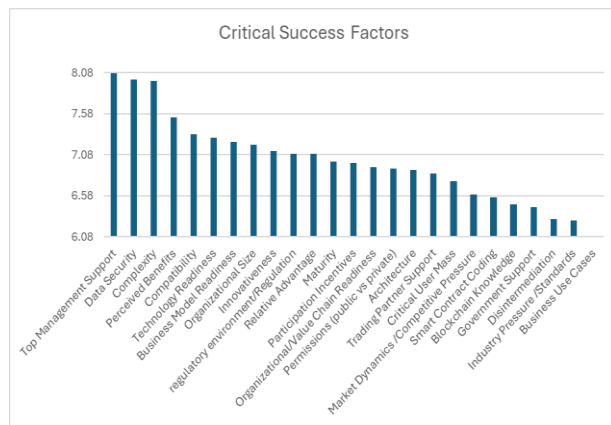
H₀3: There is no significant difference on the critical success factors between manufacturing and service industry for implementing blockchain in the supply chain.

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

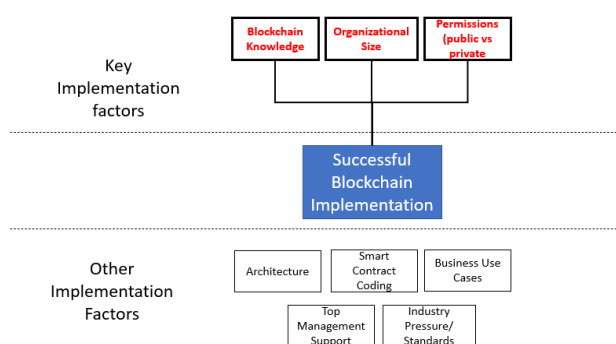
To answer research question 1, the 25 critical success factors had to first be divided into implementation factors and decision factors. The implementation factors are what were considered in developing the model for implementation. The findings for research question 1 indicate that of the eight implementation 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;	[16]
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_{01} (€): <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: $C_{01} = C_{01-1} + C_{01-2} + C_{01-3} + C_{01-4} + C_{01-5} + C_{01-6}$	Direct operation costs – risk related, C_{02} (€) – 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: $C_{02} = C_{02-1} + C_{02-2}$ 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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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.

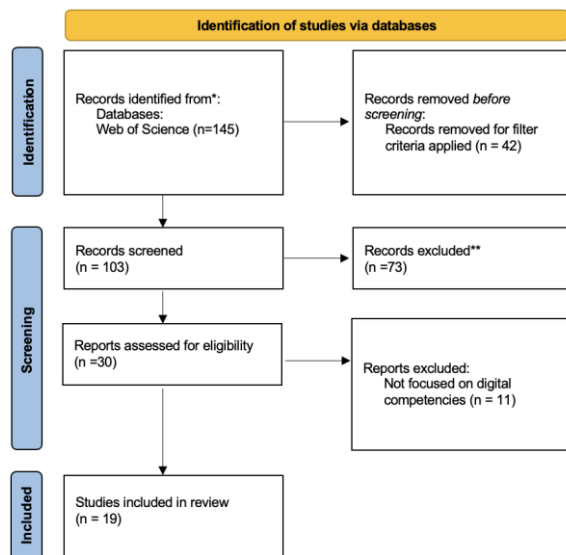
Table 1 Selection criteria

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].

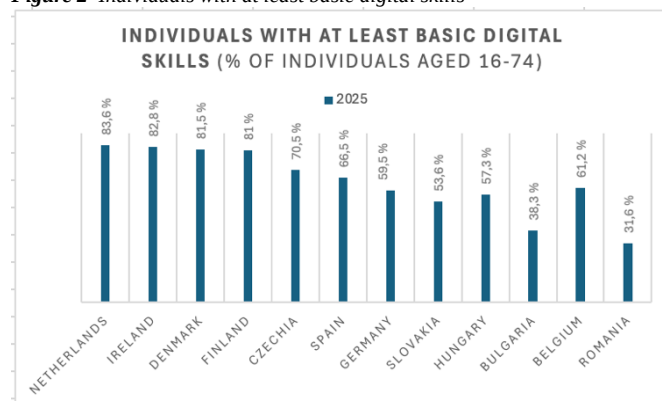
Table 4 Factors contributing to low levels of digital literacy

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].

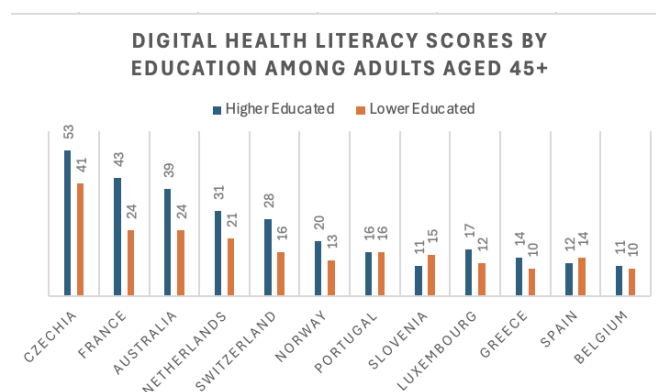
Figure 2 Individuals with at least basic digital skills



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.

6. Acknowledgement

This work was supported by VEGA 1/0276/27: Implementation of Healthcare 5.0 in Healthcare Facilities: Management, Organizational, and Personnel Determinants of Success and by a grant from the Slovak Ministry of Education, Science, Research and Sport, VEGA 1/0188/24: Hybrid work regimes as a result of companies learning from the crisis and the implications of their implementation for the people management.

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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 pafti from a private ethnographic collection

Figure 2 illustrates traditional Bulgarian pafti of Gabrovo style distinguished by detailed metallic ornamentation and sculptural decorative forms [4]. As representative elements of women's traditional costume, pafti 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 (pafti) 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.

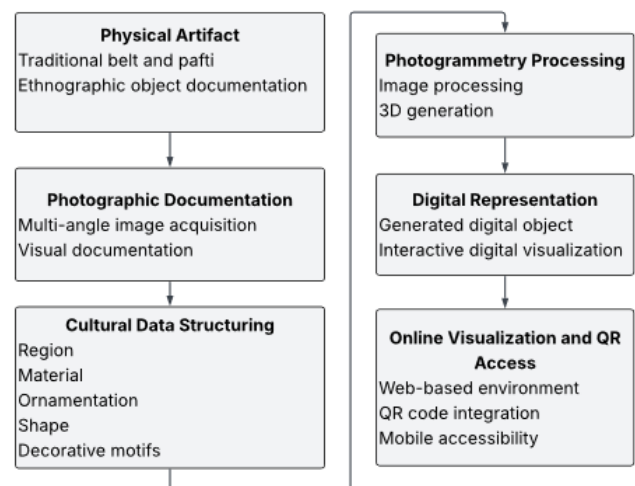


Fig. 3 Methodological framework for the digital profiling and online representation of traditional Bulgarian pafti

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 pafti 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 pafli 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.

7. References

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