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DESIGN AND TECHNOLOGY DEVELOPMENT

NATIONAL MILITARY UNIVERSITY "VASIL LEVSKI"
ESTONIAN UNIVERSITY OF LIFE SCIENCES
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GREEN FUTURE TECHNOLOGIES

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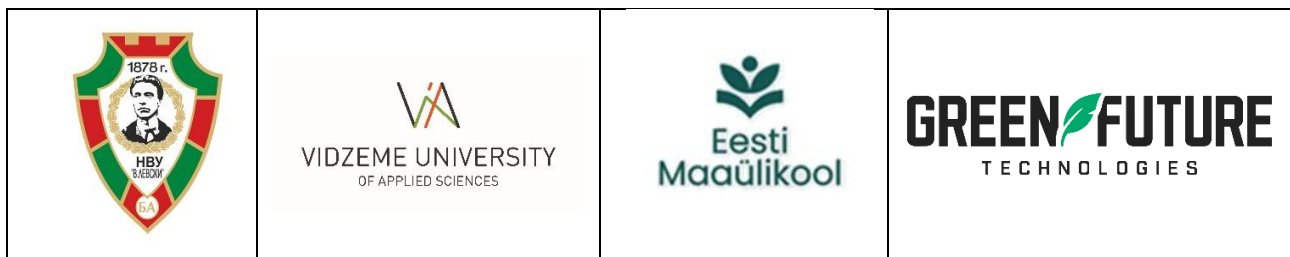
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II

ENGINEERING SCIENCES AND PRODUCTION TECHNOLOGY

Secure Cross-Border Innovation Clusters in Industry 4.0: A Model and Empirical Study of the Burgas–Edirne Region

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Abstract— This study investigates the development of secure cross-border innovation clusters within the context of Industry 4.0, focusing on the Burgas–Edirne region. The main objective is to develop and empirically demonstrate a conceptual and analytical model for evaluating the interrelationship between technological development, cybersecurity, trust, and entrepreneurial activity within innovation ecosystems.

The proposed framework integrates four core dimensions—technology level, security, trust, and entrepreneurship—and enables quantitative assessment through a composite Secure Innovation Cluster (SIC) index. The research methodology combines comparative regional analysis with a simulation-based empirical approach using realistic indicators for Bulgaria and Türkiye.

The findings indicate that although both regions demonstrate comparable innovation potential, significant disparities exist in cybersecurity maturity and trust levels, which directly affect the efficiency of cross-border collaboration. The study highlights cybersecurity as a critical enabler of sustainable technological entrepreneurship and the development of resilient innovation clusters in Industry 4.0 environments.

Keywords— cross-border innovation clusters, cybersecurity, innovation ecosystems, digital transformation, Industry 4.0

I. INTRODUCTION

The intensive processes of globalization and internationalization stimulate both enterprises and individual countries to seek opportunities to promote entrepreneurial activity through various mechanisms [1], [2]. The free movement of people, goods and capital in the EU, on the one hand, provides access to the single

European market, and on the other hand, leads to disparities in the regional development of the countries [3]. The main part of the production is concentrated in large cities, which poses serious challenges to small settlements and especially border regions [4], [5]. One of the mechanisms of the modern economy aimed at reducing regional differences is business cooperation and participation in clusters of enterprises. This enables business organizations to carry out joint activities with enterprises on both sides of the border, to achieve common goals or tasks, to realize economies of scale, access to innovations and markets, as a result of which their competitiveness increases. In this regard, Burgas and Edirne have common economic, cultural and geographical features [6], [7]. Access to the Black Sea and the Mediterranean Sea through the Bosphorus and the Dardanelles provides transport links to the whole world. The presence of sectors with clustering potential on both sides of the border, as well as access to the Instrument for Pre-Accession Assistance (IPA) and Cross-Border Cooperation (Interreg) programmes provide opportunities for the creation and development of innovative cross-border clusters, transformation at the regional level and achieving synergy effects in the long term.

In turn, Industry 4.0 fundamentally transforms the way industrial systems, supply chains and innovation processes function [8], [9], [10], [11]. The widespread application of artificial intelligence, cloud technologies, the introduction of cyber-physical systems create conditions for the development of intelligent, autonomous and highly connected production environments. This transformation leads to the emergence of new business models, increased efficiency and accelerated implementation of innovations, but at the same time it also gives rise to new challenges related to security, trust and data management. As a result, innovation clusters are becoming a key mechanism for

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stimulating technological entrepreneurship and regional development. They are the connecting link between enterprises, research organizations, universities and public institutions within a shared ecosystem aimed at creating and commercializing innovations. Despite their enormous potential, cross-border innovation clusters also face barriers such as differences in the institutional and regulatory framework, the degree of technological development, insufficiently well-developed mechanisms for trust and coordination between participants [13]. In addition, growing cyber threats create uncertainty regarding the security of industrial systems, the protection of sensitive data and the resilience of digital ecosystems [14]. In the context of Industry 4.0 and the transition to Industry 5.0, cybersecurity is now in the first place as a factor that is not only associated with data protection but also with building trust and developing innovative cross-border cooperation [15]. This necessitates the development of integrated models that integrate technological, organizational and entrepreneurial aspects of security within cluster structures.

The main objective of the study is to develop and present an integrated model for assessing the possibility of creating secure innovation clusters in the cross-border region of Burgas, Bulgaria and Edirne region, Turkey.

In addition, the study has specific objectives that support the achievement of the main objective. They are:

- a) assessment of the relative impact of cybersecurity, technological development, trust and entrepreneurship on innovation cross-border clusters;
- b) comparative analysis of the Burgas and Edirne regions in order to identify structural differences and potential opportunities for synergy between the two regions;
- c) analysis of the possibilities for creating a secure cross-border innovation cluster by assessing key factors and the interaction between them;
- d) conclusions and guidelines for improving cooperation, cybersecurity and trust within innovation ecosystems.

II. MATERIALS AND METHODS

This current study is rooted in an interdisciplinary and multi-component research that integrates theoretical and empirical studies for the analysis and evaluation of innovative clusters with security. Qualitative and quantitative approaches have been employed to enhance the reliability and validity of the results. The index model, based on rating scores of technological innovation, cybersecurity, trust, and entrepreneurship, has been used, and the results have been analyzed using statistical and simulation models. The results obtained were analyzed using a comparative approach to assess the influence of individual factors on the development of cross-border innovation clusters. Interviews were conducted with 20 cluster representatives, specialists in the field of IT and cybersecurity, as well as entrepreneurs from both fields.

The experts were selected on the basis of their proven practical and scientific experience in the field of innovation clusters, cybersecurity, entrepreneurship and the concept of Industry 4.0. They meet the following characteristics: minimum 5 years of professional experience in projects or policies related to innovation and digital transformation, as well as the ability to assess complex systems in an interdisciplinary manner. The study covers the period 2022-2025. The choice of the study period is in line with the accelerated digitalization after COVID-19, the increased development of Industry 4.0 and the increasing share of cyber risks in recent years.

Fig. 1 presents the conceptual model of the Secure Innovation Composite Index (SICI), which visualizes the interaction between the four main dimensions of the study – technological development, cybersecurity, trust and entrepreneurship – in the context of the cross-border innovation cluster Burgas-Edirne.

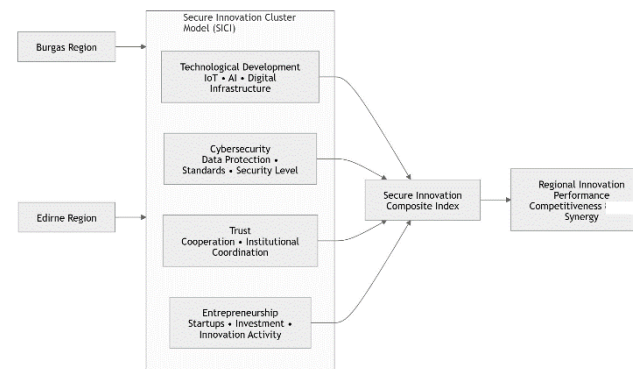


Fig. 1. Conceptual framework of Secure Innovation Clusters

The applied methodology has the following algorithm:

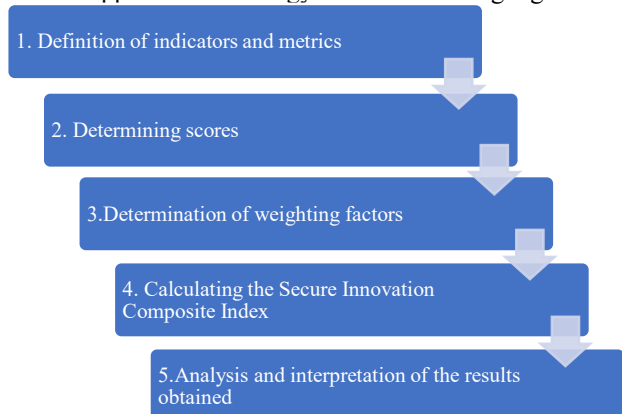


Fig. 2. Algorithm for assessing the possibility of creating a secure innovation cluster between the cross-border region Burgas-Edirne

The first stage of the algorithm is related to determining the indicators that have the greatest impact on the development of innovation ecosystems. They are identified based on a review of the scientific literature and established models in the field of Industry 4.0, innovation clusters, cybersecurity and technological entrepreneurship. A

systematic approach is applied, in which the indicators are summarized in four main groups: technological development, cybersecurity, institutional trust and entrepreneurship. Each group includes specific indicators that reflect the relevant aspect of cluster development. The indicators are determined through an integrated approach based on theoretical models of Industry 4.0, expert assessment and regional adaptation, which guarantees their relevance, measurability and applicability in a cross-border context. The second stage is related to the conversion of the indicators into score scores in the range from 0 to 1. This allows for comparability and aggregation of the obtained results into a complex index. The conversion into bath ratings is done using the formula:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (1)$$

Where:

X – the actual value of the indicator

Xmin – the minimum value in the data set

Xmax – the maximum value

Xnorm – the normalized value

Stage three is linked to the calculation of weights for indicators. These are calculated via expert analysis to ensure balance between theory and practice in relation to the region of Burgas-Edirne border area. The weights reflect the relative importance of each indicator, its impact on cybersecurity and innovation capacity, as well as its role in Industry 4.0 and the transition to Industry 5.0. Table 1 presents the indicators, metrics and weighting factors. Technological development has a weighting factor of 0.25 because, according to experts, it is the main driver of innovation capacity. Cybersecurity has a weight of 0.30, which is determined by the critical role of cybersecurity in industrial and cross-border systems. The trust indicator (Tr) refers to institutional and inter-organizational trust within the cross-border innovation ecosystem, including the degree of cooperation, the reliability of information exchange, and the effectiveness of institutional coordination between stakeholders. Trust has a weighting of 0.20 because, according to experts, it is a supporting but indirect indicator. Entrepreneurship has a weight coefficient of 0.25, as it is directly related to the economic realization of innovations. The different weights of the indicators reflect their relative importance for the individual components in Industry 4.0. Cybersecurity receives the highest weight due to its key role in building reliable and sustainable digital and cross-border systems. The remaining weights are balanced in view of their direct and indirect impact on the innovation capacity and the economic realization of the results.trust

A hierarchical distribution of weight coefficients is applied in the research methodology. Initially, the weights of the main groups of indicators were determined, after which the values were distributed proportionally between

the indicators from each group of indicators. The weight of each individual indicator is determined by the formula:

$$w_{ij} = n_j / W_j \quad (2)$$

where:

w_{ij}- the weight of the i-th indicator in the j-th group

W_j - the weight of the jth indicator group,

n_j - the number of indicators in the group

TABLE 1 INDICATORS, SUB-INDICATORS AND WEIGHTS FOR CALCULATING THE SECURE INNOVATION COMPOSITE INDEX

No	Indicators	Sub- Indicators	Weighting factor
1	Technological development (T)	– Degree of automation – IoT implementation – Digital infrastructure	0.25
2	Security (S)	– Cybersecurity level – Data protection – Availability of standards	0.30
3	Trust (Tr)	– Degree of cooperation – Information exchange – Institutional coordination	0.20
4	Entrepreneurship (E)	– Number of startups – Investments in innovation – Entrepreneurial activity	0.25

The fourth stage involves calculating a summary index, the Secure Innovation Composite Index (SICI).

$$SICI = 0,25T + 0,30S + 0,20Tr + 0,25E \quad (3)$$

The index shows the level of secure innovation development in the cross-border region Burgas-Edirne. Table 2 shows the reference values of the index.

TABLE 2 SECURE INNOVATION COMPOSITE INDEX VALUES

SICI value	Interpretation
0.00 – 0.40	Low level
0.41 – 0.60	Medium level
0.61 – 0.80	High level
0.81 – 1.00	Very high level

III. RESULTS AND DISCUSSION

Table 3 presents the results obtained from the research conducted on the possibility of creating secure cross-border innovation clusters between Burgas and Edirne.

TABLE 3 RESULTS OBTAINED FROM THE ANALYSIS OF THE TWO REGIONS

Indicator	Under indicators	Burgas (Xi)	Edirne (Xi)	W	Burgas (w·Xi)	Edirne (w·Xi)
T	Degree on automation	0,83	0,72	0,083	0,069	0,06
	Implementation on IoT	0,88	0,71	0,083	0,073	0,059
	Digital infrastructure	0,79	0,67	0,083	0,066	0,056
S	Level on cybersecurity	0,95	0,79	0,1	0,095	0,079
	Protection on data	0,97	0,73	0,1	0,087	0,073
	Availability on standards	0,93	0,69	0,1	0,093	0,069
Tr.	Degree on cooperation	0,75	0,63	0,067	0,05	0,042
	Exchange on information	0,63	0,62	0,067	0,042	0,042
	Institutional coordination	0,69	0,61	0,067	0,046	0,041
E	Starting companies	0,79	0,73	0,083	0,066	0,061
	Investments in innovation	0,78	0,75	0,083	0,065	0,062
	Entrepreneurial activity	0,75	0,73	0,083	0,062	0,061

The data in the table shows that for both regions, the cybersecurity indicator has the highest weight. It has the greatest impact on SICI. Unlike Edirne, Burgas has a higher level of cybersecurity, data protection and the presence of security standards. Cybersecurity is a critical indicator for cluster development and for this reason its importance should not be underestimated. In Edirne, the values are stable but indicate structural limitations in the development of the digital and innovation environment. This is mainly associated with the caution of partners and limited data exchange, which is associated with differences in regulations and the lack of common standards. The observed differences between Burgas and Edirne are mainly due to inequalities in the maturity of cybersecurity and technological infrastructure, rather than entrepreneurial capacity, which shows that security and digital readiness act as the main drivers of cluster performance. Technological development is the second most important indicator. Burgas shows higher automation and higher IoT implementation and the presence of a developed digital environment. While Edirne lags behind in terms of technology, it has a huge potential for catching up. In this regard, Burgas is a technological leader and this determines its position in the innovation cross-border cluster. The results confirm an asymmetric development model in the cross-border region, where Burgas acts as a technologically and cybersecurity-oriented center, while Edirne represents a peripheral but entrepreneurially active

and logistics-oriented innovation node. The entrepreneurship indicator is a stabilizing indicator, as it has similar values for both regions. Edirne compensates for the lag in technological development with higher values in the field of investments, trade and the share of start-ups. Trust is the weakest component. The interaction between cybersecurity and trust demonstrates a reinforcing cycle, in which increased levels of security increase institutional trust, which in turn improves data sharing and innovation outcomes. The low values are mainly due to the limited cooperation between the two regions, insufficient information exchange and weak institutional coordination. Given the results obtained, the main constraint for the development of secure innovation clusters between Burgas and Edirne is security. The SICI values indicated in Table 4 show that Burgas, with a score of 0.814, has a much higher readiness for the development of a secure innovation cluster. This is confirmed by the well-developed technological environment, the high level of cybersecurity, the presence of a stable entrepreneurial ecosystem and a relatively good institutional framework. Edirne, in turn, falls into the category of high, but not leading level. This is due to better business activity, developing digitalization and lower security and standardization. The difference between the two indices shows that Burgas is distinguished by a more mature structure, higher sustainability and better readiness for Industry 4.0. Edirne is in the process of catching up and has potential, but key factors for this are missing. The difference in SICI values (0.814 compared to the lower level for Edirne) shows a significant structural difference in the readiness for innovation between the two regions.

TABLE 4 SUMMARIZED WEIGHTED VALUES BY INDICATORS AND SICI FOR BURGAS AND EDIRNE

Indicators	Burgas ($\sum w \cdot Xi$)	Edirne ($\sum w \cdot Xi$)	Deviations
Technological development (T)	0,208	0,175	0,033
Security (S)	0,275	0,221	0,054
Trust (Tr)	0,138	0,125	0,013
Entrepreneurship (E)	0,193	0,184	0,009
SICI	0,814	0,705	0,109

A decomposition analysis of the SICI index shows that cybersecurity contributes the greatest impact on the overall index, followed by technological development, entrepreneurship and trust.

The differences in the profiles and values of the SICI of Burgas and Edirne create opportunities for synergy between the cross-border region indicated in Table 5. This means that their strengths can be combined and create higher added value than their individual development. Burgas is distinguished by a higher level of technological development and cybersecurity level, which defines it as a leading innovation center. In turn, Edirne demonstrates

stable entrepreneurial activity and strategic logistical importance. The combination of these characteristics creates conditions for accelerated digital transformation and market expansion. Synergy in the field of security allows the implementation of common standards and increased trust between partners. This leads to the effective functioning of cross-border supply chains. The technology transfer from Burgas to Edirne contributes to reducing regional disparities and at the same time, the dynamism of entrepreneurship in Edirne creates opportunities for new business models and innovations. An extremely large potential is observed in the area of institutional cooperation and trust. As a result of these processes, a significant improvement in SICI and the competitiveness of the two regions is expected. The synergy between the two regions operates through three mechanisms:

- technology transfer from Burgas to Edirne,
- spreading entrepreneurial potential from Edirne to Burgas
- joint governance structures reducing institutional asymmetry.

TABLE 5 SYNERGIC OPPORTUNITIES AND EFFECTS

District on synergy	Strengths of Burgas	Strengths of Edirne	Mechanism on synergy	Expected results	Effect on SICI
Technological development	High automatio, IoT, digitalization	Developing is industrial base	Technologic al transfer , joint projects	Accelerate d digitalizati o, implement ation of Industry 4.0	↑ T (+15–20%)
Cyber-security	High standards, regulations	Need from development	Introduction on common standards, training	Increased protectio, secure systems	↑ S (+20–25%)
Logistics and industry	Port , industrial capacity	Transport and border hub	Integration on chains for supplies	Optimized logistics, reduced expenses	↑ T / ↑ E
Entrepre- neurship	Developed innovative environment	High business activity	Joint startups, investments	New business models, growth on companies	↑ E (+10–15%)
Trust and coordinat- ion	Institutional capacity	Flexibility and adaptability	Partnerships, clusters structures	Increased cooperatio n	↑ Tr (+25–30%)
Economical development	Stable economy	Dynamic market	Integration on markets	Increased competitiv eness	↑ All

The creation of secure innovation clusters in the Burgas-Edirne cross-border region must meet the following conditions:

- availability of an existing industrial base
- potential for digitalization and AI implementation
- high need for cybersecurity

From a policy perspective, the findings show that the main obstacle is not technological capacity, but the lack of harmonized cybersecurity standards and frameworks for cross-border data management.

These findings emphasize that cybersecurity should be considered not only as a technical requirement, but also as a key factor for the formation of a cross-border innovation ecosystem in the context of Industry 4.0.

The regional analyses conducted show that there are several areas with potential for cross-border synergy within the framework of the Industry 4.0 concept. These sectors act as integration nodes where technological, economic and security dimensions converge. One of the sectors with the highest potential for creating a secure innovation cluster is “Smart Manufacturing and Industrial Automation”. The sector is a leading support point for an industrial synergy effect, where Burgas has an advanced technological infrastructure, and Edirne contributes with its adaptive production capacity.

The introduction of artificial intelligence-driven production systems and digital twins allows for the creation of a unified ecosystem for smart manufacturing.

The second area with high potential is “Logistics and Smart Supply Chains”. The strategic geographical location of the two regions, the presence of the Burgas port and the Edirne transit corridor enable the development of AI, cross-border smart logistics networks with real-time tracking and transparency based on blockchain technologies. Thus, a synergistic effect is achieved in practice for both regions.

Industrial cybersecurity is the third sector that enables the creation of a secure innovation cluster. Its synergistic potential lies in protecting shared digital infrastructure, industrial systems and logistics platforms, thus ensuring trust and operational continuity across borders.

Artificial Intelligence and Data Analytics. Artificial Intelligence serves as the technological backbone of the cluster, enabling predictive analytics, process automation and decision support systems across all sectors. Synergies stem from shared data ecosystems and joint AI platforms.

Green technologies and circular economy. This sector will provide sustainability-based synergies through resource optimization, waste reduction and energy efficiency. AI-based environmental monitoring improves industrial sustainability in both regions.

Energy systems and smart grids. Energy represents an area of infrastructure synergy, where AI-based smart grids and energy management systems enable efficient cross-border energy optimization and industrial sustainability.

Table 6 shows a clear asymmetric effect of the creation of a secure innovation cluster between Burgas and Edirne.

The impact on Edirne is significantly higher in all components of SICI, confirming the presence of a catch-up effect. The strongest growth is in security (+20%), which shows the critical role of cybersecurity in increasing innovation capacity. Technological development also reports a significant increase (+18%), due to technology transfer and implementation of Industry 4.0 solutions.

TABLE 6 SUMMARIZED PERCENTAGE IMPACT ON SICI BY COMPONENTS
BURGAS-EDIRNE

Component of SICI	Burgas – impact (%)	Edirne – impact (%)	Basic contributing sectors	Type effect
T	12%	18%	AI and analytics on data; Intelligent production; Logistics	Convergence
S	10%	20%	Industrial cybersecurity; Energy systems; Logistics	Strongest effect
Tr.	15%	18%	Cybersecurity; AI; collaborative platforms	Systemic effect
E	13%	15%	AI; Intelligent production; Food and beverage industry	Stabilizing effect
General SICI index	+13–14%	+17–19%	All sectors (synergistic)	Convergence + multiplicative effect

In Burgas, the influence is somewhat lower, and it makes sense since the initial position was quite good to begin with; however, there is an increase in the level of trust (+15%), and this helps improve cross-border collaboration. In general, the value of the SICI index rises for both regions, with the gap between them getting smaller, indicating the existence of a convergence effect. It can be concluded that the influence of the cluster has a structurally balanced nature.

IV. CONCLUSIONS

The report presents the developed conceptual and analytical model for secure innovation clusters in the context of Industry 4.0 and the opportunities for cross-border technological entrepreneurship between Burgas and Edirne. The proposed index of secure innovations is based on four main indicators such as technological development, security, trust and entrepreneurship. This allows for a structured quantitative assessment of the effectiveness of innovation ecosystems in relation to the development of cross-border cooperation and entrepreneurship. The empirical studies conducted show disproportionality/disproportions in the development of the two regions. Nevertheless, both Burgas and Edirne have significant innovation potential for creating a secure innovation cluster. Burgas is technologically advanced and has better positions in terms of cybersecurity, while Edirne is a dynamically developing, entrepreneurially active and logistics-oriented region. This disproportion in regional specializations shows that cybersecurity and the level of digital maturity are the main factors related to the

effectiveness of cluster development. This places the creation of secure cross-border clusters outside of traditional entrepreneurial indicators.

One of the key conclusions from the study is that cybersecurity does not exist only as a protective mechanism, but is one of the main factors for building trust between partners for the purpose of data exchange and sustainable cross-border cooperation. On the one hand, the interrelation and interdependence between cybersecurity and institutional trust create the conditions for the sustainability and efficiency of the innovation ecosystem. On the other hand, trust is defined as one of the weakest components, which largely limits the full deployment of the potential and the achievement of a synergistic effect between the two regions.

The sectoral analysis shows that the highest synergistic potential exists in the areas of smart manufacturing, logistics and smart supply chains, industrial cybersecurity, artificial intelligence, energy systems and green technologies. These sectors form the basis of the proposed cluster model.

One of the main obstacles is the lack of harmonization between cybersecurity standards and effective frameworks for cross-border data management. Addressing these institutional barriers will lead to improved cooperation and acceleration of digital transformation in both regions.

The main contribution of the study is the proposed Secure Innovation Index, which brings together technological development, cybersecurity, institutional trust and entrepreneurship in a single framework. The model allows for a comparative assessment of cross-border regions and provides a tool to support decision-making for the design of innovation policy in an Industry 4.0 environment. It also highlights the importance of cybersecurity, which should be considered as a strategic factor for the development of innovation, and not only as a technical requirement and necessity. The presence of secure digital infrastructure and trust mechanisms are the basis for the creation of sustainable, competitive and innovative cross-border clusters.

The report should address several limitations in the interpretation of the results obtained. First, the model is based on a composite index that combines four main indicators, which reduces the complexity in measuring innovation ecosystems. Second, the empirical data are based on expert assessments and simulation approaches, which may lead to some subjectivity in the results obtained. The study is limited to the area of Burgas and Edirne, which reduces the possibility of applying the model to other cross-border areas. The results cover a specific time period and are subject to update, provoked by the development of Industry 4.0 and the continuous changes and innovations in the field of cybersecurity.

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Study of the Influence of Tire Air Pressure on Natural Frequencies of a MacPherson Suspension

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Abstract—The natural frequencies affect ride comfort and stability of vehicle. This paper presents the results of the natural frequencies of a quarter car MacPherson suspension system, obtained with different tire pressures and by using bushings made from different materials. The natural frequencies and mode shapes were obtained from finite element analysis (FEA) and the natural frequencies were also obtained by the using Fast Fourier Transform (FFT). To perform the analyses, an experimental study of the accelerations of various components of the quarter suspension was conducted. The experimental test was conducted of the MacPherson strut suspension system of an Audi A3 passenger car using a rubber bushing and a polyurethane bushing, mounted on the arm. The results were compared and analyzed.

Keywords— FEA, FFT, MacPherson suspension, natural frequency, study, tire air pressure.

I. INTRODUCTION

The suspension is one of the main vehicle systems that determines ride comfort, stability, road behavior and the dynamic loads transmitted to the vehicle body. During vehicle motion, road irregularities generate vibrations that are transferred through the wheel, arms, ball joints and bushings, spring and damper to the sprung mass of the vehicle. Therefore, the correct selection of the suspension parameters and the mechanical properties of its components is essential for ensuring both ride comfort and vehicle safety [1]–[6].

The vibration behaviour of suspension is commonly evaluated by parameters such as displacement, velocity, acceleration, damping, natural frequencies and mode shapes. Natural frequencies are of particular importance

because they indicate the frequency ranges in which resonance phenomena may occur. When excitation frequencies caused by road unevenness or by the operation of a suspension tester are close to the natural frequencies of the system, the vibration amplitudes may increase significantly. This may lead to deterioration of ride comfort, reduced grip and increased dynamic loading of suspension components [1], [2], [7].

In many studies, vehicle dynamics are investigated using simplified quarter-car models, finite element analysis of the 3D models and experimental frequency response analyses [8]–[16]. The quarter-car approach is widely used because it allows the sprung and unsprung masses, suspension stiffness, damping and tire stiffness to be represented in a relatively simple mechanical model. At the same time, 3D suspension models using FEA allow the study of the natural frequencies and mode shapes of both individual suspension components and the entire suspension assembly with more realistic geometry and boundary conditions [8], [15]–[17].

The tire is an important component in the wheel–suspension–body system. Its radial stiffness depends on the tire construction, dimensions, vertical load and value of air pressure. A change air pressure affects the radial stiffness of the tire and, consequently, affects the dynamic response of the suspension system. For this reason, the influence of tire air pressure on the natural frequencies of suspension is important in the evaluation of vehicle vibration behaviour [2], [7], [18].

Another significant factor influencing the dynamic behaviour of the suspension is the elastic characteristics (stiffnesses) of the bushings. Rubber and polyurethane

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bushings are used to connect suspension elements and to reduce the transmission of vibration and noise to the vehicle body. However, different bushing materials have different stiffness [19]–[21] and damping properties. These differences may affect the natural frequencies, mode shapes and vibration amplitudes of the suspension components.

Various researchers have studied the stress and strain state, vibration behaviour and vibration response of vehicle suspension components using numerical and experimental methods [8]–[17]. Other studies have focused on the mechanical behaviour and stiffness characteristics of rubber and polyurethane bushings used in automotive suspensions [19]–[20]. However, the combined influence of tire air pressure and the mechanical properties of the arm bushings on the natural frequencies of a quarter MacPherson suspension requires further investigation.

The aim of this study is to determine the natural frequencies and mode shapes of vibrations of a quarter MacPherson suspension of an Audi A3 passenger car at different tire air pressures, using bushings with different mechanical properties mounted in the arm. The natural frequencies and mode shapes are obtained by finite element analysis (FEA), and the numerical results are compared with natural frequencies determined by processing experimental acceleration data through frequency response function (FRF) analysis. The obtained results are compared and analyzed to evaluate the influence of tire air pressure and bushing material properties on some of the vibration parameters of the suspension.

II. MATERIALS AND METHODS

The natural frequencies of vehicle suspensions can be determined through solved the matrix equation by using various products – Matlab, Ansys, Abaqus and etc., and by processing of experimental data with different analysis.

The modes and natural frequencies of the system are derived from the solution of the equation

$$[K][\Phi] = [M][\Phi][\omega^2] \quad (1)$$

where $[K]$ is $n \times n$ symmetric stiffness matrix; $[M]$ is $n \times n$ symmetric inertia matrix; $[\Phi]$ is transformation matrix and contains the normal modes for $i=1..n$, arranged as $[\Phi] = [\{\phi_1\} \dots \{\phi_n\}]$; $[\omega^2]$ is the diagonal matrix of the natural frequencies squared.

A. Methodology of simulation study

The focus of simulation is a quarter front independent MacPherson suspension. Fig. 1 illustrates simplified 3D model created with the SolidWorks program. An Audi A3 passenger car served as a prototype and the nominal air pressure of the front tire is 0.22 MPa and the value is recommended by the car manufacturer. Each geometric part of the suspension is individually modeled to form the assembly.

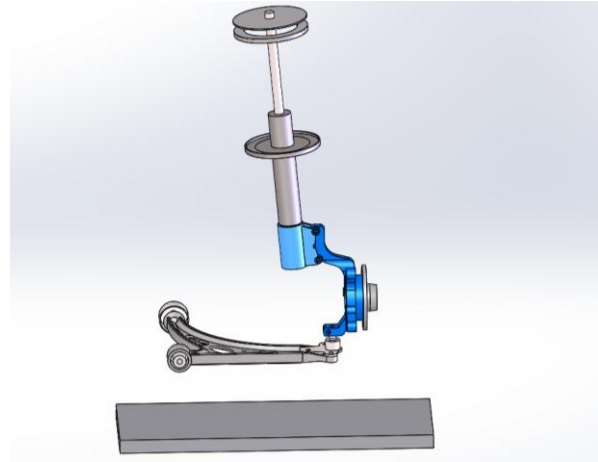


Fig. 1. Simplified 3D model of a quarter car suspension.

The natural frequencies and mode shapes of the quarter suspension was determined through frequency SolidWorks Simulation analysis. The necessary mass properties of the individual suspension elements are determined automatically by the program.

The static mass on one front wheel was measured using a suspension tester BEISSBARTH SA640. Suspension components are connected through local interaction and different types of connectors. Between hub and knuckle was used flexible bearing connector. The static stiffnesses of the bushings, spring and tire were presented by using spring connectors. The values of the polyurethane and rubber bushing stiffnesses were the same as [19]–[20]. The spring stiffness is 24 000N/m. The radial stiffness of the tire with dimension 205/55R16 were obtained experimentally using the laboratory setup of the flat bed tire testing machine [21] at different air pressures – 0.15, 0.20, 0.25, 0.30 MPa and a normal load of 5000 N. Fig.2 presents the experimental results for the radial tire stiffness and the linear approximation at different air pressures.

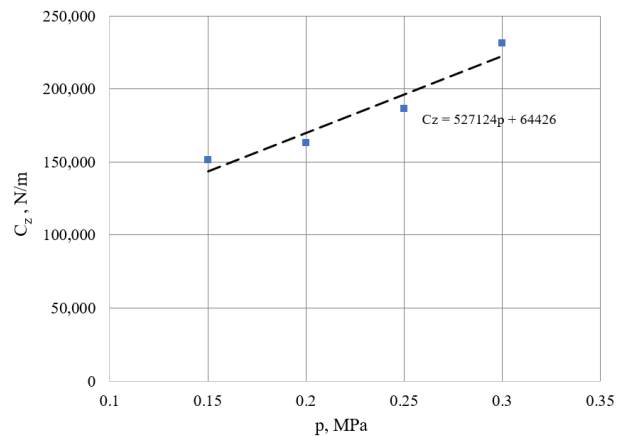


Fig. 2. Experimental results and linear approximation for the static radial stiffness.

Table 1 displays the results of the tire stiffness at air pressures 0.18, 0.20, 0.22, 0.25 MPa, respectively.

TABLE 1 RADIAL TIRE STIFFNESS

Air pressure, MPa	Tire stiffness, N/m
0.18	159,308
0.20	169,851
0.22	180,393
0.25	196,207

To perform the analysis, it is necessary to distribute the masses of the missing components to the sprung and unsprung parts in the 3D model.

Frequency analysis of the suspension was performed, and three-dimensional blended curvature-based mesh was generated. The mesh includes 346,003 nodes and 212, 369 elements.

B. Methodology of experimental study

The natural frequency of the vehicle body was estimated by frequency-domain analysis of the acceleration signal measured by a triaxial accelerometer mounted near the upper shock absorber attachment point to the vehicle body. The acceleration signals were recorded in the time domain and subsequently processed in MATLAB (Fig.3a). Prior to the frequency analysis, the initial inactive part of the record, corresponding to the time before the shock absorber tester started operating, was removed (Fig.3b). The beginning of the excitation was detected automatically based on the moving RMS value of the dynamic acceleration signal.

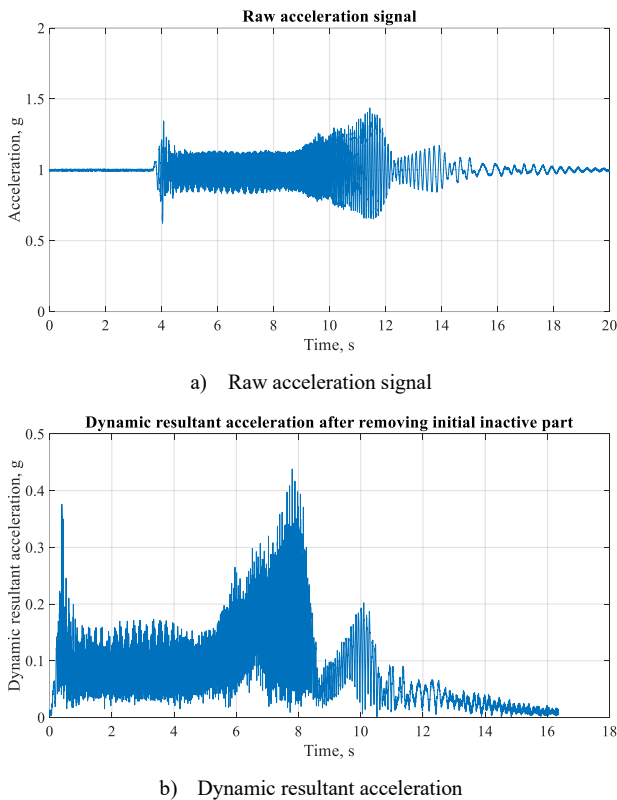


Fig. 3. Acceleration signal at tire air pressure 0.22 MPa.

most representative component for the bounce motion of the sprung mass. The DC component, including the gravitational component, was removed from the signal. A band-pass filter in the frequency range of 0.5–3 Hz was then applied in order to isolate the low-frequency response of the vehicle body from the higher-frequency components associated with the unsprung mass, wheel dynamics, and suspension elements (Fig.4).

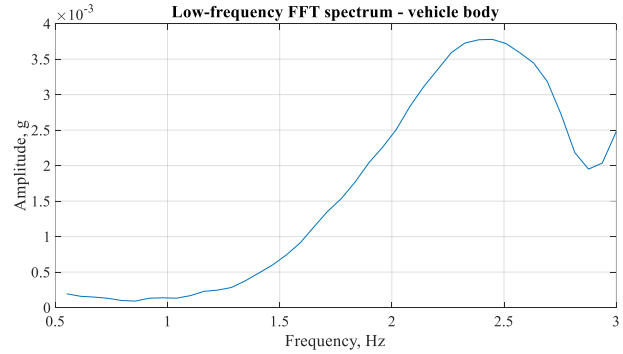


Fig. 4. Low-frequency FFT spectrum at tire air pressure 0.22 MPa.

The frequency spectrum of the filtered signal was obtained using the Fast Fourier Transform. A Hann window was applied to reduce spectral leakage. The natural frequency of the vehicle body was estimated as the frequency corresponding to the dominant peak in the amplitude spectrum within the selected low-frequency range. Therefore, the obtained value should be interpreted as an estimate of the dominant low-frequency dynamic response of the vehicle body at the measurement location.

III. RESULTS AND DISCUSSION

A. FEA frequency results

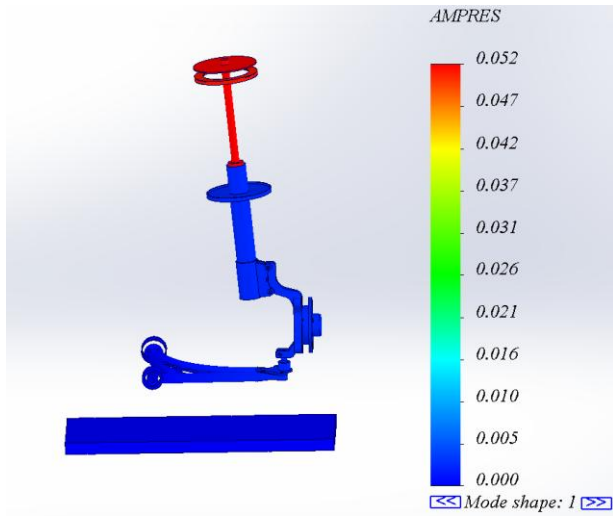
Table 2 presents the obtained results of the first and second natural frequencies of a quarter MacPherson suspension at different air pressures using polyurethane and rubber bushings of the arm.

Fig. 5 presents the obtained results of the first and second mode shapes of a quarter MacPherson suspension at tire air pressure 0.22 MPa.

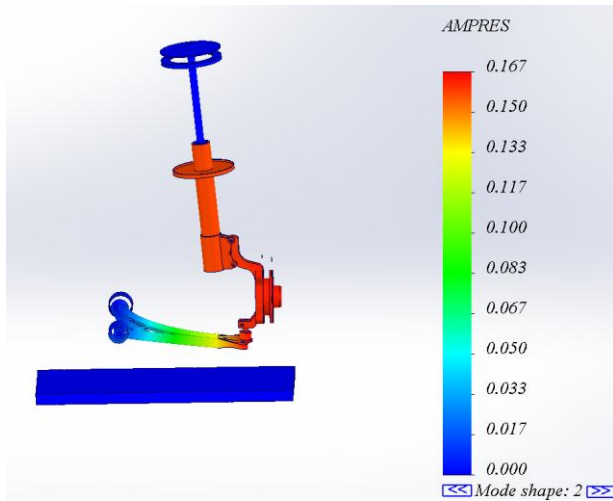
TABLE 2 NATURAL FREQUENCY FROM FEA.

Mode number	Natural Frequency, Hz			
	0.18	0.20	0.22	0.25
First	1.23	1.23	1.24	1.24
Second	14.4	14.6	14.8	15.2

The vertical acceleration component was used for the estimation of the vehicle body frequency, since it is the



a) first mode shape



b) second mode shape

Fig. 5. Mode shapes.

The results of the first and second natural frequencies are realistic, as their frequency range is from 0 to 20 Hz, which is recommended for uneven road surfaces.

B. FFT frequency results

TABLE 3 NATURAL FREQUENCY FROM FFT.

Mode number	Natural Frequency, Hz			
	0.18	0.20	0.22	0.25
First	2.49	2.42	2.38	2.33
Second	11.02	11.12	11.35	11.40

A dominant peak was observed at approximately 2.38 Hz at tire air pressure 0.22 MPa in the low-frequency spectrum. This frequency was considered as an estimate of the vehicle body low-frequency natural response at the upper shock absorber mounting point.

The second natural frequency of 11.35 Hz at tire air pressure 0.22 MPa is more likely related to the dynamics of the unsprung mass, whose vibrations are transmitted to

the vehicle body through the shock absorber attachment point.

The variation of tire air pressure in the investigated range did not lead to a significant shift of the first and second identified natural frequencies. The maximum relative variation of the first natural frequency is 0.066 % and of the second natural frequency is 0.034 %.

The results obtained of natural frequencies by FEA are comparable to those obtained FRF analysis.

IV. CONCLUSIONS

Based on the performed study the following conclusions are made:

To validate the FEA model developed of the quarter front MacPherson suspension, was conducted frequency-domain analysis of the acceleration signal, yielding results close to those obtained through FEA. The obtained results indicate that the lowest natural frequency is in the range of 1.24 to 2.4Hz, and is in the frequency range of road surface irregularities (0 to 20 Hz).

The use of experimental data and obtained elastic characteristics of the tire, spring and bushings of previous studies by the authors allows to obtain more realistic results for the natural frequencies and mode shapes using FEA, which more accurately reflect the actual behavior of the suspension.

The developed 3 D model of quarter suspension, along with the study methodology and results, can be used for various types of analysis.

ACKNOWLEDGMENTS

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Possibilities for Increasing the Accuracy of Active Control in Turning on CNC Machine Tools Through Adaptive Accuracy Control

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Abstract— In clean and fine turning on CNC machine tools, it is advisable to carry out active control by measuring the parts after their processing. With this type of active control, accuracy is highly dependent on dimensional dispersion caused by random factors. A solution for reducing these errors and increasing the accuracy of active control is the use of adaptive control of roughing accuracy.

Keywords— Active control, adaptive control, CNC machine tools intelligent computer control, mechanical engineering.

I. INTRODUCTION

Studies on the accuracy capabilities of Active Post-Processing Control (APPC) [1]-[3] show that the instantaneous dimensional dispersion field, which is caused by random factors, occurring during the machining process, has a significant impact on the total field of dimensional dispersion of the machined parts.

In classical APPC algorithms, after assuming that the magnitude of the sub-adjustment pulse ΔA cannot be smaller than the instantaneous dispersion field ω , the dependencies are obtained for the smallest possible total dispersion field $\omega_{\Sigma \min}$ [4]:

- for APPC, applied according to the individual values of the processed parts:

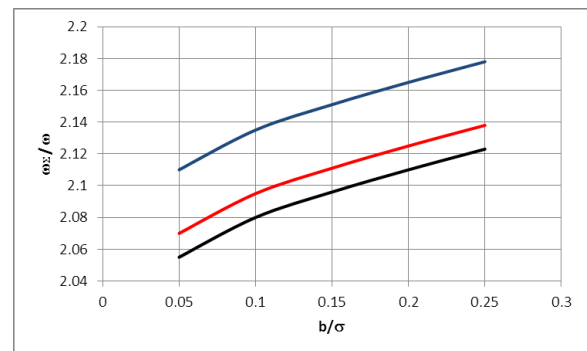
$$\omega_{\Sigma \min} = \omega \sqrt{4 + \left(\frac{\Delta_p}{\omega}\right)^2 + \left(\frac{b}{\sigma}\right)^{0,5}}, \quad (1)$$

- for APPC, based on the group average values of the dimensions of the machined parts:

$$\omega_{\Sigma \min} = \omega \sqrt{4 + \left(\frac{\Delta_p}{\omega}\right)^2 + \left(\frac{b}{\sigma}\right)^{0,5} n^{2\frac{b}{\sigma}-0,5}}, \quad (2)$$

where Δ_p is the positioning error of the sub-adjustment system; σ - mean square deviation, characterizing the instantaneous field of dispersion; b - trend of the average dimensional value; n - number of parts in the current sample (sample volume).

Fig. 1 presents the graphical interpretation of formulas (1) and (2), and shows that $\omega_{\Sigma \min}$ is greater than 2ω for both methods. This proves the significant influence of the random factors on the accuracy of APPC.



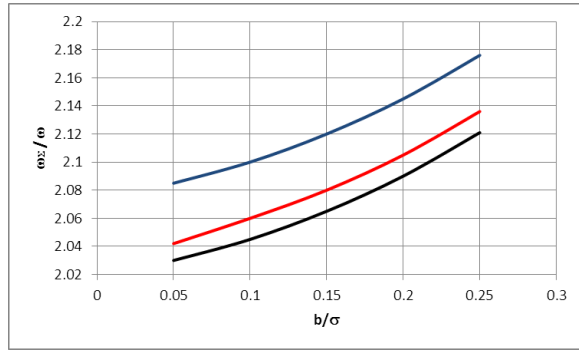
(a) APPC according to individual values

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(b) APPC according to group average values, at $n = 5$

Fig. 1. Graphical dependences for the smallest possible total dispersion field $\omega_{\Sigma\min}$

II. MATERIALS AND METHODS

The possibilities for increasing the accuracy of the APPC need to be analyzed and the search should go in two directions:

- finding an algorithm, in which the magnitude of the sub-adjustment pulse is possible to be smaller than the instantaneous field of dimensional dispersion;
- reduction of the instantaneous field of dimensional dispersion.

A. APPC algorithm with real-time processing of the statistical data about the technological process

The classical APPC algorithm is based on known characteristics of the technological process. It is applied in large-scale and mass production, where the process has been sufficiently studied and both the instantaneous dispersion field and the trend of the average dimension value are known. Control limits are set in this case, and the size of each processed part, or the average size of a periodically taken current sample, is monitored. The magnitude of the pulse for dimensional sub-adjustment is also determined in advance. When the part size (average dimension value) is outside the control limits, a signal for dimensional sub-adjustment is given.

Modern computer technologies make it possible to apply a different algorithm than the described above. It must meet the present-day requirements for production flexibility with frequent changes in the product range and a high degree of process automation with small batch volumes [5], [6]. Under these conditions, the statistical characteristics of the technological process must be established dynamically during its course, and therefore the decisions for dimensional sub-adjustment and the magnitude of the sub-adjustment pulse must be made in real time.

Research in this direction has shown [7] that if the regression equation for the average value is determined after machining each part, by the results from the dimension control over the processed parts, then it is possible to determine with sufficient accuracy both the

moment for dimensional sub-adjustment and the magnitude of the sub-adjustment pulse. The idea is presented graphically in Fig. 2.

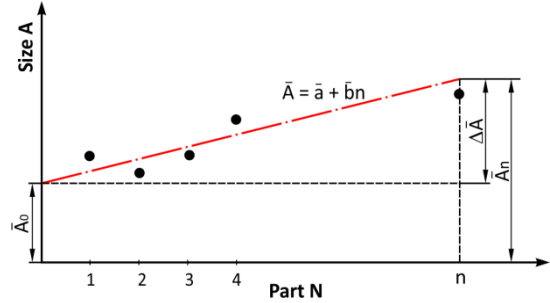


Fig.2. Linear regression of the sizes

After each processed part, from the regression equation for all parts processed so far, the change in the average dimension value from the beginning of work to the present can be determined:

$$\Delta \bar{A} = \bar{A}_n - \bar{A}_0 = \bar{b}n. \quad (3)$$

If the resulting difference $\Delta \bar{A}$ is statistically significant, there is reason to perform a dimensional sub-adjustment with a pulse, equal to $\Delta \bar{A}$.

Due to the small volume of statistical data at the beginning of the process, the regression equation has a wide confidence interval, and a significant fluctuation in its slope is observed. This can be considered as a “precession” of the regression equation. With increasing the number of processed parts, the precession decays and this process can be described by an equation of an exponentially decaying cosine function [8].

The decision to make a dimensional sub-adjustment is made when the following three conditions are simultaneously met:

- adequate regression equation;
- sufficiently damped precession;
- statistical significance of the difference $\Delta \bar{A}$.

With this algorithm, for the smallest value of the total dispersion field it is obtained:

$$\omega_{\Sigma\min} = \omega \sqrt{1 + \frac{1}{n} + \frac{t_{\alpha,k}^2}{6n}}, \quad (4)$$

where $t_{\alpha,k}$ is the critical value of the Student's t-test at a significance level α and degrees of freedom $k = 2(n - 1)$.

Dependence (4) is presented graphically in Fig. 3. It can be seen that, together with the increase in the number of the processed parts, the total dispersion field with this algorithm approaches the instantaneous one. In practice, the value of $\omega_{\Sigma\min}$ is higher, because formula (4) does not

take into account the error with which the sub-adjustment is performed.

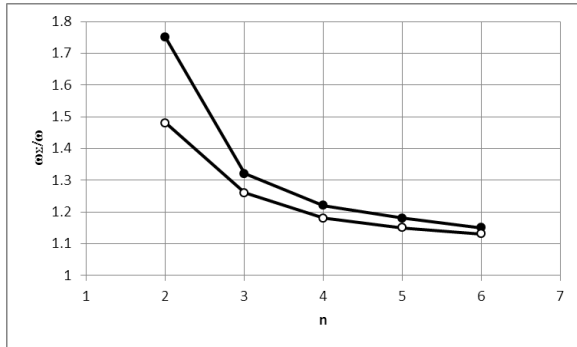


Fig.3. Dependence of the total dispersion field on the instantaneous one at APPC, applied according to the regression equation

The results obtained from the analysis of the accuracy of APPC prove that the main direction for increasing accuracy is to reduce the instantaneous dispersion field.

B. Opportunities for reducing the instantaneous dispersion field with adaptive control

It is known that the force deformations of the technological system are the main factor, which determines dimensional dispersion in machining. Therefore, options to increase the accuracy of the APPC should be sought through the methods for reducing the influence of the force deformations, using adaptive accuracy control (AAC). In this case, accuracy and productivity increase simultaneously [9] – [14].

The idea of reducing the dimensional dispersion caused by random factors through adaptive control was proposed and developed as early as the 1960s and 1970s [15]. In all implementations of this idea, the technological system includes a special device for real-time control of force deformations and an automatic adjustment device. Since these devices are not universal, the application of the method is economically justified in large-scale production.

Other options for obtaining data about force deformations are being sought under the modern conditions. As a result of the development and achievements of the CNC machine tools, of computer equipment and technologies, as well as of information technologies, it has become possible to implement control over the dimensional process and, more specifically, on the deformation behavior of the technological system, based on mathematical models [16].

In general, force deformation at a certain point M of the workspace can be represented as a function of the forces, acting in the technological system, and the coordinates of this point [11]. When brought to point M , the action of the system of forces is represented by the dynamo of the system – a vector of the resultant force $\vec{F}_{tot}$ and the torque $\vec{M}_{tot}$. Thence, the mathematical model for the force

deformations at a certain point in the machine's workspace has the form:

$$y = \varphi[\vec{F}_{tot}, \vec{M}_{tot}, M(x_M, y_M, z_M)]. \quad (5)$$

Under specific operating conditions, if the influence of only the cutting depth a and the feed f on the magnitude of the force deformation is studied, the mathematical model will have the form:

$$y = b_0 + b_1 a + b_2 f + b_{12} a f + b_{11} a^2 + b_{22} f^2. \quad (6)$$

If the coordinate of the cutting area has a significant influence on the magnitude of the force deformation, it is included in the model as a third variable.

The model (6) provides the possibility to implement adaptive control for stabilizing or for compensating the force deformation, using both the working parts of the CNC machine tool and direct computer control [16]-[20].

• Adaptive control for stabilizing the force deformations

In the two-factor model of the force-deformation errors, the influence of the cutting depth a and the feed f is represented by the polynomial (6) [16], [18].

Fig. 4 presents the graphical interpretation of this polynomial. A two-dimensional diagram is used, representing the cutting depth a by a family of curves, which reflect its different values in the range from a_{min} to a_{max} .

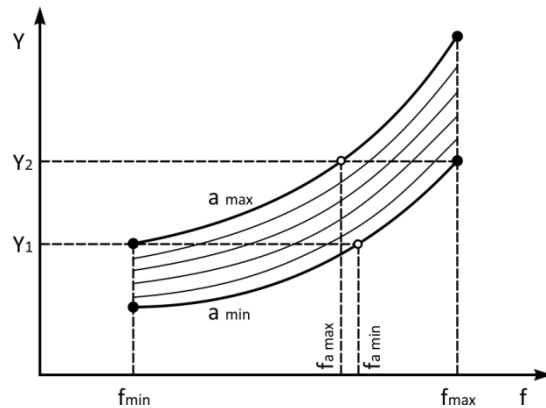


Fig. 4. Graphical interpretation of the force-deformation error model and the characteristic levels of stabilization

The solution to the problem of stabilizing the force deformations at a given level $Y = \text{const}$ at a measured cutting depth a_i by finding the feed rate with which to perform the machining, is the cross-section of the regression surface with a plane $Y = \text{const}$.

Equation (6), expressed to the feed f , has the following form:

$$b_{22}f^2 + (b_2 + b_{12}a)f + (b_0 + b_1a + b_{11}a^2 - Y) = 0. \quad (7)$$

The root of this quadratic equation, satisfying the condition $f_{\min} \leq f_i \leq f_{\max}$, is a solution for the chosen value of Y at a cutting depth a_i .

The described method stabilizes the errors, resulting from force deformations, by selecting a feed rate f depending on the specific depth of cutting.

The choice of a level of stabilization is determined by the machining efficiency indicators – productivity, cost, dimensional accuracy, micro-geometric shape accuracy, etc. It is, therefore, necessary to evaluate the different stabilization levels from the perspective these indicators.

The levels can be compared by the accuracy of the obtained dimensions, based on known data about the dimensional dispersion, resulting from the force deformations. The existence of a correlation between the magnitude of the deformations and the dispersion field of the dimensions ω is well known. Then, as Y increases, ω also increases. For the force-deformation error model, used to implement the control, this increase will be within the dispersion around the regression surface.

An analysis of the process efficiency indicators shows their inconsistency. Thence, when implementing adaptive control by using the algorithm for stabilizing the errors from force deformations, an opportunity should be created to choose the level from the perspective of prioritizing one or another of them.

Based on the model for stabilizing the force deformations, an algorithm for programmatic adaptive control has been developed.

Initially, input data about the machined part, the workpiece, and the mathematical model are introduced. The way of determining the stabilization level depends on the performance and surface quality conditions. High productivity and high surface quality variants are possible, as well as variants in the possible solutions area between Y_1 and Y_2 .

The limit levels of deformation Y_1 and Y_2 are calculated.

The value of the deformation Y_c , at which stabilization will take place, is determined.

The algorithm is completed after calculating the feed for performing the machining.

- *Adaptive control for compensating the force deformations*

The method is described and illustrated by the two-factor model (6) and its graphical interpretation in Fig. 4 [16], [19].

Adaptive control, aiming at compensating for the force deformations, is reduced to determining the value of the deformation Y_i at a cutting depth a_i in the range $a_{\min} - a_{\max}$ at a feed $f = \text{const}$, selected in the range $f_{\min} - f_{\max}$. Under

these conditions, the solution to equation (6) for Y_i gives us the required compensation value.

The determined value of the force deformation error Y_i is used as a correction of the set-up dimension, which defines the tool path for the specific machining operation.

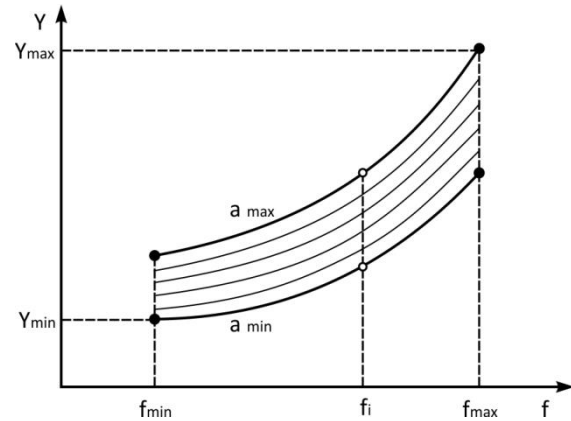


Fig. 5. Graphical interpretation of the model of errors, resulting from of force deformations in case of applying adaptive control for their compensation

The compensation level is determined for each machined surface and depends on the cutting depth a and the selected feed. It can be seen from the diagram in Fig. 5 that at higher feed values the compensation level value will be higher.

The choice of the feed f is determined by the machining efficiency indicators: productivity, cost, dimensional accuracy, micro-geometric shape accuracy, etc.

There are certain limitations to applying the method. When the deformations change within a machined section due to a variable value of the cutting depth or the influence of the coordinates of the cutting area, then dimensional sub-adjustment is required within the boundaries of a machined surface. This will generate a step-shape appearance on the treated surface. Therefore, the method is suitable for cases, in which within the boundaries of the workpiece surface under machining the allowance and system stability are relatively constant.

An algorithm for applying programmatic adaptive control has been developed based on the model, which aims at compensating for the force deformations [19].

Input data about the machined part, the workpiece, and the mathematical model are entered first. The feed rate f is selected depending on the process requirements. The error due to force deformations Y is calculated. The algorithm completes with calculating a correction to the set dimension.

- *Complex adaptive control, aiming at stabilizing and compensating for the force deformations*

The method for complex adaptive accuracy control combines the two methods for force deformations stabilization and compensation for their joint operation.

The combination of the two algorithms is imperative in cases, in which the task of stabilizing the force deformations does not have a solution for the entire range of the cutting depth dispersion. Such a case is presented in Fig. 6 [16], [20].

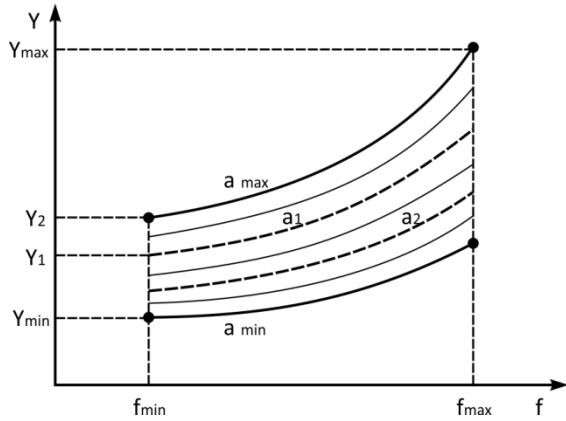


Fig. 6. Graphical interpretation of the force-deformation error model in complex adaptive control

In the general case, presented in Fig. 6, it is not possible to achieve complete stabilization of the force deformations for all values of the cutting depth of the considered model (there is no deformation level Y at which all curves for a intersect in the feed range from $f_{\min}$ to $f_{\max}$). For some of the possible cutting depth values, it is necessary to compensate for the residual deformation after force deformations stabilization. The compensation value is determined by the expression:

$$Y_c = Y_s - Y_{cal}, \quad (8)$$

where: Y_c is the compensation value (residual deformation); Y_s – deformation, at which stabilization is performed; Y_{cal} – deformation, calculated from (6) for the feed value f_i and allowance a_i .

The sign of the obtained Y_c determines the direction of compensation. With a “–” sign, the tool moves towards the workpiece, with a “+” sign, the direction of its motion is away from the workpiece.

The system of adaptive control is adjusted to operate at a selected level of stabilizing the force deformations Y_c . The choice of this level is determined by the machining efficiency indicators: productivity, cost, dimensional accuracy, micro-geometric shape accuracy, etc.

Three characteristic cases can be considered in the case of applying complex adaptive control, depending on the selected level of deformation.

1) *The selected deformation level is in the range from Y_2 to $Y_{\max}$ ($Y_2 < Y_s \leq Y_{\max}$).*

The stabilization of the force deformations is carried out at a feed $f_i > f_{\min}$. The increase in the value of the selected deformation leads to limitation of the range in which the feed changes. As Y_c increases, the minimum value for f increases.

The compensation Y_c , determined by (8) in the considered section, takes positive values. The compensation is performed when working with feed $f = f_{\max}$.

In the borderline case $Y_c = Y_{\max}$, the system will operate as an adaptive control system for compensating the force deformations with a feed $f = f_{\max}$.

In the considered case ($Y_s > Y_2$), and the productivity of the system is higher since it operates with higher feed values.

The accuracy of the obtained dimensions depends on the dispersion of the force deformations ωY , meaning that higher deformation levels will lead to greater dispersion of the dimensions.

2) *The selected deformation level is in the range from Y_1 to Y_2 ($Y_1 \leq Y_s \leq Y_2$).*

In this case, the entire feed range is used to control the force deformations for stabilization purposes.

The compensation value can take both positive and negative values.

In the borderline case $Y_c = Y_1$ at cutting depths $a_i > a_1$, compensation of the force deformations is needed, working with a feed $f_{\min}$ and compensation value Y_c , determined for the corresponding cutting depth a_i .

In the borderline case $Y_c = Y_2$ at cutting depths $a_i < a_2$, compensation of the force deformations is needed, using a feed $f_{\max}$ and compensation value Y_c , determined for the corresponding cutting depth a_i .

When working with deformations in the considered range, the adaptive system operates according to one of the two options considered for the borderline cases. The value of the allowance a_i is decisive.

The productivity of the system in the considered case is lower, compared to its operation at larger deformations. If we assume that the allowance is distributed according to a normal law, it follows from the principle of the system operation, that we will mainly work with average feed values.

The dispersion of the obtained dimensions is expected to be less than it is in case 1, due to working with smaller deformation values.

3) *The selected deformation level is in the range from $Y_{\min}$ to Y_1 ($Y_{\min} \leq Y_s < Y_1$).*

In this case, the stabilization of the force deformations occurs at a feed rate $f_i < f_{\max}$. Decreasing the value of the selected deformation results in limiting the range in which the feed changes. As Y_c decreases, the maximum value of the stabilization feed decreases.

The compensation Y_c , determined by (8) in the considered section, takes negative values. The compensation is performed when working with a feed rate $f = f_{\min}$.

In the borderline case $Y_c = Y_{\min}$, the system works as an adaptive control system, aiming to compensate for the force deformations with a feed $f = f_{\min}$.

The productivity of the system in the considered range of Y_c is lowest due to its operation with feeds close to $f_{\min}$.

The dispersion of the obtained dimensions should be lower than it is in the other two cases due to the low deformation values.

In the first two variants, the limiting value of the cutting depth a_1 or a_2 , respectively, is determined by substituting Y_s and the feed for the considered variant in formula (6). A check is made to see if compensation is necessary. If it is needed, the feed f is determined as $f = f_{\min}$ or $f = f_{\max}$, correspondingly, and then the compensation Y_c is calculated.

Based on the model of applying complex control over the force deformations, an algorithm for programmatic adaptive control has been developed.

After entering the input data, the corresponding levels Y_1 and Y_2 are calculated. A check is performed to see if the model is of a type, requiring stabilization and compensation.

If it is not of this type, stabilization of the force deformations is performed according to the corresponding algorithm. If the model satisfies the condition $Y_1 < Y_2$, then a deformation level Y_s is determined according to the conditions of the introduced input data.

Next, a check follows, for affiliation to one of the three characteristic cases according to the selected deformation level $Y_s (Y_c < Y_2; Y_s < Y_1; Y_1 \leq Y_s < Y_2)$.

III. RESULTS AND DISCUSSION

A. Research on the adaptive control algorithm with stabilization of the force deformation errors during scraping

Conditions of the experimental study: machine tool – CNC lathe LT580; workpieces – cylindrical sleeves mounted on a mandrel; fixture – mandrel mounted in a chuck and rear center; machined material – steel BDS EN 10083-2 C45; diameter of the machined workpieces – $\varnothing 100$ mm; width of the machined workpieces – 25 mm; cutting tool – cutter with mechanically fixed carbide insert with designation PSBNR 25 25 L 12; main tool mounting angle $\chi_r = 75^\circ$; cutting speed $V_c = 80$ m/min.

A total of fifteen trials is performed at five cutting depths. For each cutting depth, using the force-deformation error model, presented in Table 1, the problem of calculating the feed f at cutting depth a and deformation level $Y = 14,7 \mu\text{m}$, is solved.

The regression equations in normalized and natural coordinates, describing the force deformation errors for the studied area of the workspace and at the given technological parameters, are written in Table 1.

The data on the conducted experiments and the obtained results are presented in Table 2 and Fig. 7.

TABLE 1 REGRESSION EQUATIONS FOR ERRORS FROM FORCE DEFORMATIONS DURING SCRAPING

Normalized coordinates
$Y(X_1, X_2) = 16,6 + 4,8X_1 + 12,4X_2 + 0,75X_1X_2 + 3X_1^2 + 3,5X_2^2$
Natural coordinates
$Y = 11,3 - 17,5a_p - 21f + 10a_p f + 12a_p^2 + 156f^2$

TABLE 2 RESULTS FROM STUDYING AN ALGORITHM FOR ADAPTIVE CONTROL WITH FORCE DEFORMATIONS STABILIZATION DURING SCRAPING

a_p, mm	0,6	0,8	0,9	1,2	1,4
$f, \text{mm/ob}$	0,3	0,29	0,28	0,24	0,19
$Y, \mu\text{m}$	20	25	17	15	17
$Y, \mu\text{m}$	15	19	17	17	21
$Y, \mu\text{m}$	17	16	21	16	20

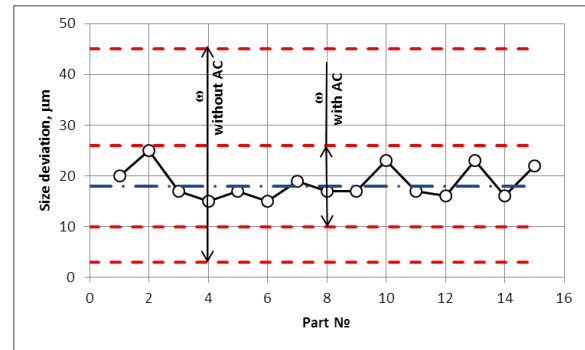


Fig.7. Scatter diagram of adaptive control, aiming to stabilize errors from force deformations during scraping

Figure 7 illustrates the probable dispersion fields, ω , obtained without adaptive control (AC) and with adaptive control applied to stabilize errors caused by force deformations.

The data from the process of machining are subjected to statistical analysis. The following results are obtained:

- arithmetic mean value: $\bar{X} = 18,2 \mu\text{m}$;
- dispersion: $s^2 = 7,6 \mu\text{m}^2$;
- probable dispersion field at $n = 15$; confidence level $\gamma = 0,95$; coverage probability $P = 0,95$; $k = 2,945$; $\omega = 16,23 \mu\text{m}$.

Both the probable dispersion field around the regression surface for the model $\omega_1 = 7,22 \mu\text{m}$ and the total dispersion field for the force-deformation error model $\omega_m = 41,6 \mu\text{m}$ are known. Thence, a reduction of the order of three times in the probable dispersion field of the errors, resulting from force deformations, is achieved.

B. Research on the adaptive control algorithm with compensation of errors from force deformations during scraping

The experimental conditions are the same as in the previous case and the same force-deformation model is used (Table 1).

A total of fifteen trials is performed at five cutting depths. For each cutting depth, using the force-deformation error model, the problem of calculating the force-deformation error level Y is solved. The feed is constant for all trials $f = 0,3$ mm/rev.

The machining is performed by compensating the calculated error from force deformations through the controlled elements of the machine. The resulting error is measured after machining.

The data on conducting the experiments and the obtained results are presented in Table 3 and Fig. 8.

TABLE 3 RESULTS FROM STUDYING AN ADAPTIVE CONTROL ALGORITHM WITH COMPENSATION FOR FORCE DEFORMATIONS DURING SCRAPING

a_p , mm	0,6	0,8	0,9	1,2	1,4
Y , μm	15	15	16	19	22
Y_{res} , μm	6	8	7	7	11
Y_{res} , μm	5	12	7	14	8
Y_{res} , μm	7	5	10	8	7

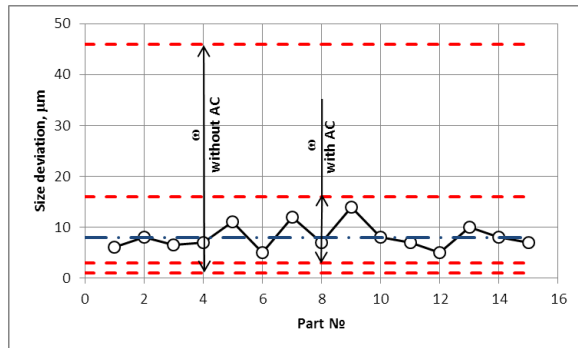


Fig.8. Scatter diagram, illustrating the application of adaptive control to compensate for errors from force deformations during scraping

Figure 8 illustrates the probable dispersion fields, ω , obtained without adaptive control and with adaptive control applied to compensate errors caused by force deformations.

In Table 3, Y denotes the calculated values for the force-deformation error, and Y_{res} denotes the measured error after conducting the experiment.

The following results are obtained from the statistical analysis:

- arithmetic mean value: $\bar{X} = 8,0667$ μm ;
- dispersion: $s^2 = 6,780952$ μm^2 ;
- probable dispersion field at $n = 15$; confidence level $\gamma = 0,95$; coverage probability $P = 0,95$; $k = 2,945$: $\omega = 15,34$ μm .

The probable dispersion field around the regression surface for the model $\omega_1 = 7,22$ μm and the total scattering field for the force-deformation error model $\omega_M = 41,6$ μm are known.

The application of the adaptive control algorithm with compensation of force deformation errors leads to a reduction by about three times in the field of dimensional dispersion during machining.

C. Research on an adaptive control algorithm with stabilization of errors from force deformations during boring

Conditions of the experimental study: machine tool - CNC lathe LT580; machined material - steel BDS EN 10083-2 C35, outer diameter of the sleeves $\varnothing 40$ mm; diameter of the machined hole - $\varnothing 30$ mm; length of the workpiece - $L = 30$ mm; cutting tool - boring bar with mechanically fixed carbide plate; diameter of the cutting tool - 20 mm; length of the cantilever part of the cutting tool - $L_u = 100$ mm; main tool setting angle $\chi_r = 90^\circ$; cutting speed $V_c = 100$ m/min;

Variable factors: depth of cut a_p . The research uses the methodology, presented in [7].

A total of twenty-five trials were conducted at five cutting depths, with five trials for each depth.

For each cutting depth, the feed f at the deformation level $Y = 83\mu\text{m}$ is determined from the force deformation error model, presented in Table 4.

The regression equations in normalized and natural coordinates, describing the force deformation errors for the studied area of the workspace, and at the given technological parameters, are given in Table 4.

TABLE 4 REGRESSION EQUATIONS FOR ERRORS FROM FORCE DEFORMATIONS DURING BORING

Normalized coordinates
$Y(X_1, X_2) = 135 + 57,1X_1 + 67,8X_2 + 46,3X_1X_2 - 7,5X_1^2 - 8,8X_2^2$
Natural coordinates
$Y = 8 + 71,4a_p + 8f + 925a_p f - 120,4a_p^2 - 219f^2$

The preliminary preparation for conducting the study involves machining the hole in the sleeves and a 5mm-long step at one of their ends. The resulting step shape of the workpiece ensures the required cutting depth a_p for the experiment.

The results of the study are presented graphically by means of a scatter diagram in Fig. 9.

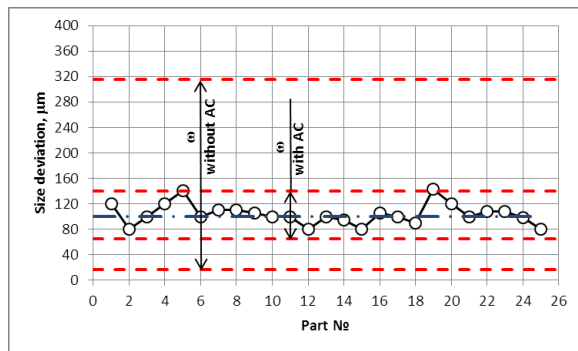


Fig.9. Scatter diagram, illustrating the application of adaptive control, aiming to stabilize errors from force deformations during boring

Figure 9 illustrates the probable dispersion fields, ω , obtained without adaptive control and with adaptive control applied to stabilize errors caused by force deformations.

From the statistical processing of the data, after eliminating a gross error, the following results are obtained:

- arithmetic mean value: $\bar{X} = 101,456 \mu\text{m}$;
- dispersion: $s^2 = 161,9112 \mu\text{m}^2$;
- probable dispersion field at $n = 26$; confidence level $\gamma = 0,95$; coverage probability $P = 0,95$; $k = 2,945$: $\omega = 68,879 \mu\text{m}$

The probable dispersion field around the regression surface for the model $\omega_1 = 51,45 \mu\text{m}$ and the total scattering field for the force-deformation error model $\omega_m = 301 \mu\text{m}$ are known.

The diagram shows the probable dispersion fields both without applying adaptive control and in case of implementing adaptive control. The probable field of dispersion of errors from force deformations when applying the adaptive control algorithm is more than 4 times smaller than the total one, obtained during modeling in the studied area.

IV. CONCLUSIONS

One of the possibilities for increasing the accuracy of APPC is to reduce the instantaneous field of dimensional dispersion. This can be achieved through adaptive control to reduce the influence of force deformation errors.

The control of force deformations can be implemented based on mathematical models for the deformation behavior of the technological system. Adaptive control can compensate for or stabilize the force deformation errors.

The experimental study conducted during CNC machining, has proven the feasibility and possibility of increasing the accuracy of APPC by applying adaptive control to reduce the influence of errors from force deformations.

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Artificial Intelligence in Logistics: Adoption Patterns, Performance Effects, and Market Structure

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Abstract— The aim of the paper is to analyse the impact of AI implementation on logistics performance and to develop an action framework that can be used to measure the improved efficiency achieved with AI in an environment of scarce available data. This paper examines the use of AI in the logistics sector in Bulgaria. The study assesses revenue distribution and market concentration to determine when the introduction of AI can be expected to have significant positive effects. A methodological approach is also proposed for the analysis of AI and operational efficiency, and a basis for future research is provided when better information becomes available. Furthermore, the present study focuses on large logistics companies that have the technological and economic means to build AI-based solutions at different levels in their operations. Performance measures, including delivery time, fuel consumption and forecast reliability, are used to highlight the efficiency improvements that are available through the adoption of AI. This article offers an assessment of the efficiency gains from artificial intelligence in logistics operations and proposes that from a scientific perspective, artificial intelligence should be used to consider efficiency gains in order to analyse the limited empirical data.

Keywords— *AI Adoption, KPI, Logistics Sector, Performance Improvement*

I. INTRODUCTION

Artificial Intelligence (AI) plays a role in logistics and logistics companies. Artificial Intelligence (AI) technology has changed everything - planning methods, procedures and operating systems in logistics have been revolutionised by intelligent systems for supply chains [1]. The proliferation of logistics networks' increasing complexity, combined with increased customer expectations for speed and reliability, together with increased complexity of the business environment, has accelerated demand and led to a

surge in the adoption of AI-driven solutions [2]. Machine learning, predictive analytics, intelligent routeing systems, etc., to optimise transportation, logistics warehousing, demand, and demand forecasting have seen some of the most efficient transportation, warehousing, and demand forecasting and management solutions, and they are also seeing increasing use [3].

As the interest in AI-as-a-service technology proliferates, the level and potential effectiveness of AI adoption across logistics companies differ greatly from the degree of adoption, as well as the level of effectiveness and utility of AI adoption, which is determined mostly by the firm size and level of digital maturity, availability of data and digital readiness and the like [4]. Big logistics and logistics firms are better placed to invest in advanced AI systems compared to the small players because they usually have more money and more access to company or operational data to work with [5], [6].

By contrast, the logistics sector, as a high concentration of market players, plays a crucial role in competitive interactions and innovation diffusion. Hence, understanding the links between AI adoption, the performance impact, and market structure is significant for both academic and managerial research [7]. To date, empirical findings on the quantifiable performance impacts of AI in logistics are scarce, especially the studies with publicly available data. This presents a void in developing methodological perspectives that can gauge AI effects under an information-limited environment [8]. Through this lens, the proposed study seeks to add to the literature analysis by evaluating adoption trends, performance impacts and market structures in the context of the logistics industry [9], [10].

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The logistics sector has entered a period of accelerated digital transformation, driven by globalisation, rapid growth in e-commerce, rising customer expectations, and intensifying competition. In this evolving environment, artificial intelligence (AI) has emerged as a strategic enabler capable of fundamentally reshaping how logistics companies plan, execute, and optimise their operations [11], [12]. AI-based systems contribute to improvements in demand forecasting, route optimisation, warehouse automation, predictive maintenance, risk management, and customer service personalisation. Globally, leading logistics providers are already integrating machine learning models into transportation planning, using computer vision in sorting centers, and deploying autonomous or semi-autonomous vehicles across the supply chain.

In Bulgaria, the logistics sector is critical to the transportation and trade of national and regional products, in view of the fact that Bulgaria is a gateway between Europe, Asia, and the Middle East. AI adoption is much more moderate than, say, Western Europe; however, there's increased activity across the sector, and some companies are beginning to use digital tools, automation, and data analytics [13]. Yet the level of technology breakthroughs differs significantly between companies. Big courier and postal companies tend to adopt high-tech solutions early, as medium-sized transport providers face structural or financial barriers to digital innovation.

II. MATERIALS AND METHODS

The study used publicly available annual reports, press releases, and official disclosures from major logistics companies working in Bulgaria. The empirical dataset encompassed five firms since financial information was publicly available, and ten major players were conceptualised in the market data to characterise the market. The methodology includes calculating market shares within the sample and constructing comparative revenue analyses. Key formula used

Market share. Its formula indicates how much of the total revenue in the market goes to one company. In brief: Market share tells you what proportion a given company controls over the whole market, formula 1:

$$MS_i = \text{Revenue}_i / \Sigma \text{Revenue}_j \quad (1)$$

Where:

MS_i - market share of firm I;

Revenue_i - revenue of firm I;

$\Sigma \text{Revenue}_j$ - total of revenues from all companies covered by sample.

It helps us justify the use of the market share formula ($MS_i = \text{Revenue}_i / \Sigma \text{Revenue}_j$) as it quantifies the relative position of firms against each other in the competitive marketplace. By transforming the size of company revenue into a share of the total market, this metric provides a standardized reference point from which to compare firms of different sizes. It also allows finding key players, competitive balance, and structural features in the industry structure to be determined. In order to study the multi-year

performance dynamics of the examined logistics companies, the study uses the Compound Annual Growth Rate (CAGR) method, the average annual growth rate compared to the market for the period 2019-2023 is provided by using formula 2:

$$CAGR = (\text{Revenue}_{\text{end}} / \text{Revenue}_{\text{start}})^{1/n} - 1 \quad (2)$$

Where:

$\text{Revenue}_{\text{end}}$ - final value;

$\text{Revenue}_{\text{start}}$ - initial value;

n - number of years.

The fact that we use the formula of Compound Annual Growth Rate (CAGR) is perfectly justified, as the long-term growth of all businesses should be captured by the CAGR formula while short-term fluctuations are balanced. CAGR measures the average annual clip of a company's revenue increase (if any), but where the variation is less than half of the CAGR, it makes the strategic progress more closely a reasonable view than an apples-to-apples view of the trend. Cumulatively, market share and CAGR present a full analytical structure that accounts for the present competitive position and evolving revenue trajectory of each entity. Thus, by focusing on both market factors in the short- and medium-term with static and longitudinal market dynamics, this dual approach contributes to the robustness of the research.

Limitations of the Study

The limited data available for Bulgaria-specific international logistics companies limits the scope of this study. Some leading organisations release only consolidated global results, which preclude country-level comparison. Estimated values were needed for firms that did not release recent detailed statements, limiting precision. The sample size is smaller than intended, making the results less generalisable. In addition, internal KPIs (key performance indicators) or interviews were not used to provide insight into internal AI deployment. Lastly, given the acceleration of AI adoption, real-world developments may exceed the analysis's scope.

III. RESULTS

Table 1 shows a comparison with five logistics companies in Bulgaria in relation to annual revenues, estimated market shares, and compound annual growth rate (CAGR). Results show a highly concentrated market with the top three companies that control a disproportionately large proportion of total sector revenue, suggesting that they have strong competitive dominance. The middle-sized players are those for whom annual revenues are average and a stable/low-level position is relatively found in competitors. The rest of the companies hold much smaller shares, suggesting a fragmented lower segment with relatively less market power.

TABLE 1. THE REVENUES OF SELECTED LOGISTICS FIRMS OPERATING IN BULGARIA

Company	Year	Revenue (BGN million)
Gopet Trans	2022	354.01
Speedy	2023	316.0
Bulgarian Posts	2023	252.756
Econt	2020	232.5
Transpress	2020	27.285

Data covers a period of years from 2020 to 2023. This shows:

Analysis is provided from Speedy and Bulgarian Posts (2023) [14], [15]. For Econt and Transpress, data are from 2020, and they probably understate their real market position on a given date. We also must update to the same reference year for dynamic analysis. The market position of big private operators (Gopet, Speedy, and Econt) is stronger thanks to big machines, stable infrastructure, digitalisation, and the investments in these operations [16], [17]. While Bulgarian Post enjoys remarkable penetration, it has lagged private sector rivals in overall digital maturity. Transpress is a small segment and likely targets niche logistics operations [18]. That sort of highly concentrated market makes it far easier to see where future competition is headed and how AI affects it.

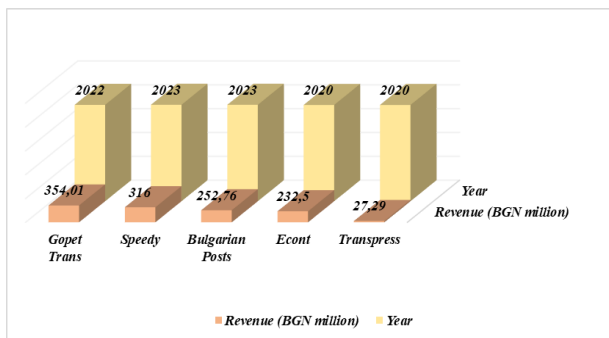


Fig. 1. Revenue distribution.

Figure 2 visualises the market share of the companies based on their revenues. The diagram shows a highly uneven distribution, which is typical of logistics markets with a high degree of concentration.

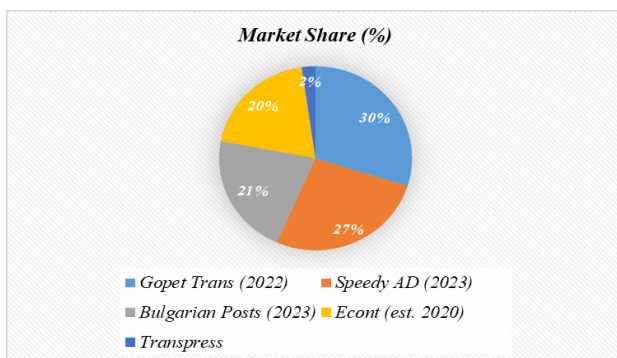


Fig. 2. Market share within the sample.

First of all, the largest companies - Gopet Trans, Speedy and Bulgarian Posts - comprise the backbone of the market, and together they account for more than 75% of total revenues. This result suggests that the market is oligopolistic and there are dominant leaders who control the primary flows of logistics in the country.

Second, Econt also holds a consistent but noticeably smaller share than Gopet and Speedy, indicating a differentiated positioning - more courier and network services instead of heavy transport or international forwarding. Yet it remains a big player with almost 20% share.

Third, Transpress constitutes a minimal relative share in the revenue picture, making the contribution of niche or medium-sized companies to overall revenue look minimal. But not low efficiency, just a specific scale of activity.

Figure 3 illustrates the estimated impact of AI-driven optimisation on selected performance metrics critical to logistics operations. These improvements are based on typical results observed in international AI implementation studies and provide a basis for assessing the potential benefits for Bulgarian companies when detailed operational data becomes available.

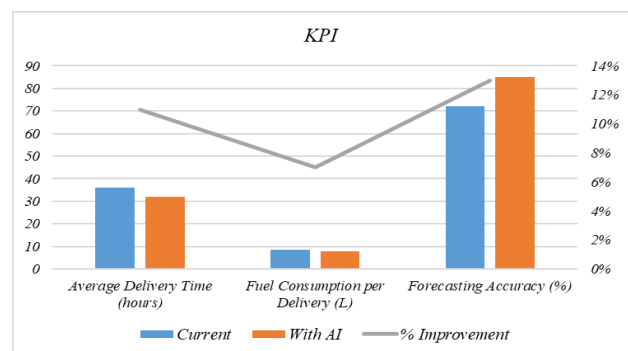


Fig. 3. Estimated impact of AI-driven optimisation on selected performance metrics critical to logistics operations.

The following figure 3 compares the logistics indicators — average delivery time, fuel use and forecast accuracy - in two scenarios: (1) under the present state and (2) under the implementation of AI, as well as the percentage of the improvement. The graph clearly shows that when AI is implemented, there is a real improvement in an organisation's efficiency in logistics.

1. Average Delivery Time (hours)

AI shortens the delivery time, showing a drop in the bars from about 38 to 32 hours. This is about a 12-15% improvement, which is represented by the % Improvement line. Such enhanced routeing, automatic rerouting, load optimisation, and dynamic vehicle allocation generally account for the betterment.

2. Fuel Consumption per Delivery (L)

Fuel consumption reduces by roughly 2 liters per delivery (from ~6 L to ~4 L), which is an important outcome for an operator functioning in a large logistics

environment. That translates to around 10-12% savings. The improvement is attributable to AI-driven solutions in route planning, fleet maintenance, and driver behaviour monitoring.

3. Forecasting Accuracy (%)

The largest improvement in prediction accuracy is greater than anything else, with an improvement from 75% to 85%, which is more than 13-14%. That makes a lot of sense, since, for forecasting models (demand forecasting, and inventory optimisation), AI has the strongest impact through machine learning algorithms and big data analysis.

Table 2 presents a qualitative assessment of the digital maturity of Bulgaria's largest logistics companies.

TABLE 2. DIGITAL MATURITY ASSESSMENT OF LARGE BULGARIAN LOGISTICS COMPANIES (QUALITATIVE ASSESSMENT)

Company	Data digitalisation level	AI readiness	Fleet telematics	Warehouse automation
Speedy	High	Medium-High	High	Medium
Gopet Trans	Medium-High	Medium	High	Low
Econt	High	High	Medium-High	Medium
Bulgarian Posts	Medium	Low-Medium	Low	Low
Transpress	Medium	Low	Medium	Low

The data also identifies large differences in technological development among the members. Companies such as Speedy and Econt have significant digitalisation and good AI readiness, as they have positions in the business in order to deal with complex logistics. Medium enterprises such as Gopet Trans have more significant development of the telematics system and less automation. That means they are investing more in transportation technologies than warehouses and operational systems. The tech maturity of both state and traditional operators such as Bulgarian Posts is low to medium – slowing things down and making their readiness for implementing AI lower. The table shows that the automation rate is the weakest link for almost all companies - and investment in robotic warehouses, autonomous systems and intelligent paths is thus very much required.

IV. DISCUSSION

The results of the empirical evaluation suggest some critical patterns regarding the construction, potential and trends of technology development in the Bulgarian logistics industry. The revenue distribution of the sample first reflects a fairly substantial concentration of firms in the sample (Speedy, Gopet Trans, and Econt are high, for example) with a significant share of the total market. This architecture indicates that large companies have the economic stability and the size of operations to spend money on such new (technological) investments in high-level solutions such as AI-enhanced routing, predictive and automation systems. Compared to larger logistics organisations, smaller and mid-sized companies operate on

thinner margins and may not be willing to adopt expensive digital technologies, which could gradually widen the performance gap.

Second, the study demonstrates that there are significant differences in the technology maturity of firms. Although some vendors have automated core processes with barcode-based technology, automated sorting facilities, or fleet telematics, much remains based on fragmented legacy systems. Such heterogeneity complicates the sector - wide integration of AI because AI-based solutions usually involve single databases, similar workflows and uniform real-time data streams. Without these conditions, well-designed AI models, if not already in place, can produce poor, less than optimal or inaccurate results, compromising the practical utility of investment.

Third, AI integration for logistics needs to be viewed in terms of the impact on strategies, not just operations, that it will bring. Predictive analytics, for example, can provide much higher accuracy to plans and decrease the under- and over-use of the transport capacity. Algorithms that optimise the route - including live traffic, the weather and the priorities of shipments - can provide immense cost savings and reliability in delivery. Warehouse management systems with AI can reveal inefficiencies in picking paths, replenishment cycles, and inventory accuracy. Such improvements can be directly reflected as key indicators of performance, such as delivery time, cost per shipment, fleet fuel efficiency, and customer satisfaction ratings.

There are, however, remaining limitations, despite these benefits. The absence of standardised digital reporting in the logistics industry of Bulgaria results in evidence - driven analysis and benchmarking. Operational data, such as shipment volume, average delivery time, fleet utilisation or routeing performance, are not being disclosed by many firms, as these are variables critical to measuring the ROI of AI-based improvements. Moreover, the inclusion of AI in logistics functions frequently involves organisational reorganisation and employee training, as well as cultural adjustment, all of which may delay technology implementation. The adoption of AI in this context has become even worse with increasing cyber threats and data breach risks associated with digitalising operations, thus, firms are also being forced to invest in a layer-up of new security features.

The discussion must also address the world speed of AI advancement. While global logistics giants (e.g., DHL, Geopost/DPD, and Gebrüder Weiss) are developing their digital capabilities, Bulgarian firms risk being left behind if they do not invest in similar technology. This digital divide has the potential to influence competitiveness and cooperation, especially in cross-boundary logistics and multimodal transportation operations, where real-time synchronisation is essential. Hence, adopting AI is not just a matter of efficiencies: it is becoming more and more essential to maintain market position within an increasingly interconnected European logistics ecosystem.

V. CONCLUSIONS

The results of this study emphasize that AI is emerging as an important determinant for competitiveness,

efficiency, and strategic differentiation in logistics. Bulgaria's logistics industry is still at a relatively early stage of AI adoption compared to Western Europe, but the assessment indicates huge potential of positive transformational influence. The bigger firms, those which lead with revenue and scale today, are also the most ideal participants in harnessing AI in major activities like route optimisation, forecasting, and warehouse automation. The increasing trend indicates that digital capabilities may increasingly shape leaders over the next ten years. For example, the study suggests that the remaining disparities in the maturity of technology across the sector are persistent. Decentralised legacy systems have become entrenched in many firms while only partially digitising processes.

Consequently, they are structurally prevented from using AI to their maximum potential. Filling such gaps will call for focused investments not only in digital infrastructure but also in the skills of our workforces, in data governance, and in the integration of our staff between departments. National-level programmes - digital skills courses, incentives for innovation, and easier access to credit - will also serve to boost the rate at which adoption is happening, especially by medium-sized players. In addition, the research points to a requirement for more transparent and standardised corporate reporting. Access to extensive operational information such as shipment volumes, the fleet use rates, and delivery performance indicators is necessary to assess the actual impacts of the AI in reality. Lacking such data, academic studies and managerial decision-making are hamstrung in many respects.

Achieving this benchmarking across sectors and pushing companies to publish more granular KPIs would also greatly improve the ability to gauge efficiency and quality of service improvement driven by AI. AI tools will become ever more available and at lower prices, making implementation even more realistically feasible for even smaller logistics operators in the future. Pilot projects - such as predictive analytics, dynamic routeing, or automated customer service - can result in substantial performance improvements with modest upfront investment.

Formal innovation, data, and experience will allow firms to move into more sophisticated solutions, including autonomous vehicles, robotic warehouses, and AI-driven supply chain orchestration platforms, as they mature over time. More importantly, we should adopt AI not because of a technology upgrade but because of a change in the company as a whole. There is a greater likelihood of better results for businesses that strategically integrate AI - on the one hand, with the long-term objectives, on the other hand, and in the design of processes, culture through data, or on the data - at scale. Keeping up with global trends in innovation is essential to keep Bulgaria's logistics industry competitive in local and global value chains. This report sets a basis of an analytical framework, and it will be imperative for research which is built on larger datasets to

have an expanded perspective on the full effect of AI on the sector.

Contributions of the study. The report provides a systematic review on the adoption of artificial intelligence in the logistics field of Bulgaria, connecting technological progress to actual economic measures. A process methodology has been developed to evaluate efficiency with the restricted data. The study also uses delivery time, fuel consumption and forecast accuracy, among others, as indicators to measure the effect of AI and provides an empirical analysis of market structure as the main KPIs for the performance measurement. The market structure by computing market shares and CAGR has performed an empirical analysis. The report identifies a prominent concentration of the logistics industry and discusses that that is closely associated with innovative potential for introduction. A relationship between the size of companies and implementation of AI solutions is introduced. We have established dependencies between digital maturity and operational efficiency. As data becomes more available, a framework for future studies is suggested. Some real companies in the Bulgarian market have been analysed, which has helped clarify a focus on the practical aspects. As it includes unique elements for the Bulgarian market, the report helps clarify originality, while further introducing state-of-the-art artificial intelligence technologies for improved predictive accuracy.

Scientific novelty. This study's novelty is the construction of an adapted methodology adopted to evaluate the impact of AI (that is, AI in general) in settings of scarce empirical data. For the first time, the study integrates indicators of market structure into indicators of technological readiness in the Bulgarian logistics industry. An integrated perspective connects economic and operational indicators with digitalisation is introduced. The report highlights a feasible analytical framework that can establish the benefits from AI based on the comparative scenario analysis presented, specifically for decision-making processes and data access at Bulgarian companies. The report represents a new take on using open data to evaluate innovations. A new concept arises from the dependence relationship of concentration in markets with the speed of AI implementation. There's a bonus factor to include: a qualitative evaluation of companies' digital maturity. Through these indicators, the researcher proposes a quantitative measure of the impact of AI. The concept will be the idea of AI being a means to fill its role as a medium for overcoming informational deficits in a certain domain is developed. It's a novelty, too, to concentrate on the Bulgarian setting, which is under-investigated in the literature, in explaining new ways of deploying AI in neglected fields and also on the wider landscape of AI impacts in other locations.

Originality is shown when an analytical framework combines both theoretical and empirical thinking. None of these studies have examined a real data set of Bulgarian logistics companies in a way that can be described as authentic, which is rarely attempted in the literature. The author shares his reading on AI in critical logistics

processes. An initial visualisation of the impact of AI implementation impact on KPI indicators was developed. The analyses utilise both quantitative and qualitative approaches with a unique approach for the analysis. It is present a classification of specific companies by their digital maturity within different types of classifications of companies. The report is unique in its rationale for evaluating efficiency in an indirect manner by the company itself through customer satisfaction, employee engagement metrics, and other indicators that yield a multifaceted picture of organisational performance. Original, due to the inclusion of new relevant factors for the Bulgarian market and the use of novel AI technologies used to improve predictive accuracy. The results are interpreted according to the details of the Bulgarian economic landscape. The research reveals the author's stance as to the strategic importance of AI in logistics. The report demonstrates high significance – for the Bulgarian context and applied analyses; medium significance – for the international scientific community; and usefulness as a basis – for future, deeper empirical research.

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Intelligent Production and Business Processes: Application in the Mechanical Engineering Enterprises of Northeastern Region, Bulgaria

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Abstract - The article presents the application of smart manufacturing and digitalization of business processes in the mechanical engineering enterprises of Northeastern region. The aim is to study the impact of Industry 4.0 technologies on energy efficiency, productivity and return on investment. The applied methodology uses energy indicators such as energy intensity, energy per employee, return on investment, based on industrial data for the country and the region. The results have a huge potential for optimization, as even relatively moderate energy efficiency measures can bring tens of millions of euros in annual savings to the industry, which in recent years has been characterized by dynamic changes in both demand and supply of the service. The report emphasizes the regional strategic importance of digital technologies for the sustainable industrial development of the region, as according to recent data, Bulgarian industrial enterprises are on average 2.7 times more energy inefficient than enterprises from the same industrial sector in the EU.

Keywords - business processes, Industry 4.0, smart manufacturing.

I. INTRODUCTION

Concerning global competition and accelerated technological development, industrial businesses face the challenge of reconciling high productivity, energy efficiency, and sustainable growth. Intelligent manufacturing, through proper management of business processes and achieving energy efficiency in enterprises, is one of the main fields of Industry 4.0.

Smart manufacturing incorporates the use of technology such as the Internet of Things (IoT), artificial intelligence (AI), and digital twins. IoT within manufacturing guarantees timely predictive maintenance and optimizes supply chains. Real-time data analysis provides for the identification of inconsistencies that can be used to streamline the production process and improve the final product. Digital twins are virtual copies whose advantages include increasing efficiency and optimizing

resources, anticipating and preventing problems, emulation of several different scenarios, compatibility with new technologies, etc. AI is one of the technologies that are revolutionizing the world and is a crucial element in optimizing business processes, quality management, and increasing security in the industrial sector [1], [2].

Industry 4.0 brings about a change in industrial business processes along with a search for possible opportunities of enhanced productivity, sustainability, and competitiveness based on energy efficiency. Energy efficiency in mechanical engineering firms is among the most significant parameters for smart production and green development. Mechanical engineering firms' production lines use a lot of energy and resources and hence are highly dependent on regulatory and market requirements [3], [4], [5]. From the perspective of Industry 4.0, energy efficiency is seen as an active management process wherein digital technologies are utilized for the minimization of losses, optimization of production processes, and harmonization with the consumption of renewable energy sources. In this regard, Industry 4.0 and attaining energy efficiency are intimately linked and interdependent processes with the potential to transform not just mechanical engineering enterprises but even other industrial enterprises [6].

In the context of this study, intelligent manufacturing is understood as a production paradigm based on the integration of digital technologies, automation, cyber-physical systems, Internet of Things (IoT), artificial intelligence (AI), and real-time data analytics to optimize production processes, improve flexibility, and enhance energy efficiency [7], [8], [9]. Intelligent manufacturing enables adaptive and self-regulating production systems capable of responding dynamically to operational changes and resource constraints.

Furthermore, digital transformation is defined as the systematic integration of digital technologies into business and industrial processes with the aim of improving

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operational performance, productivity, sustainability, and decision-making [10], [11], [12]. In the industrial sector, digital transformation extends beyond simple automation and includes the redesign of organizational processes, predictive maintenance systems, digital twins, and intelligent resource management.

Business processes are logically sequential, relevant activities that are formulated to produce value and a finished product through transformation, meeting the needs and desires of users. Industry 4.0 initiates the revolutionization of business processes through the Internet of Things (IoT) technologies, artificial intelligence (AI), Big data, digital twins and cyber-physical systems [13], [14].

Bulgarian machine-building enterprises, and enterprises of the Northeastern Region as a whole, represent strategic importance for the national economy. The fact that Northeastern is a transportation and industrial center (port, industrial parks, university potential) guarantees prerequisites for the integration of intelligent technology in production and logistics.

This study aims to assess the opportunities for improving business processes and energy efficiency in the mechanical engineering sector of the Northeastern Region through the implementation of Industry 4.0 technologies, including IoT monitoring, digital twins, predictive maintenance, and ERP systems, as instruments of intelligent manufacturing and digital transformation.

II. MATERIALS AND METHODS

The scope of the research is to assess the energy efficiency of the mechanical engineering businesses in the Northeastern District and provide an estimate of the savings when employing Industry 4.0 technologies.

1. The National Statistical Institute's value of industrial production and employed workers in Northeastern District (2023) was used, as well as national statistics regarding energy consumption in industry.

2. It is assumed that machine-building enterprises have a share of 3%, 6%, and 10% of the regional industrial economy (three variants).

3. Consumption of energy is estimated by proportional division to the value of production.

The present analysis is based on several methodological assumptions that should be explicitly acknowledged. First, due to the lack of disaggregated sectoral statistics for mechanical engineering enterprises in the Northeastern District, energy consumption was estimated proportionally according to the production value of the industrial sector. This assumes a relatively homogeneous relationship between production output and energy use, which may not fully reflect the technological heterogeneity of firms.

Second, three hypothetical scenarios (3%, 6%, and 10% sectoral share) were developed to account for uncertainty regarding the actual contribution of mechanical engineering enterprises to regional industrial production.

These scenarios should be interpreted as indicative rather than exact measurements.

Third, the analysis assumes constant electricity prices and uniform implementation effects of Industry 4.0 technologies across enterprises. In practice, savings may differ significantly depending on production specialization, degree of automation, existing energy management systems, and company size.

Finally, the estimated savings percentages (5–20%) are based on findings from previous studies on Industry 4.0 adoption and industrial energy optimization and therefore represent achievable but context-dependent values rather than guaranteed outcomes.

4. The following formulas were used:

4.1. Energy Intensity (EI):

$$EI = E/Q \quad (1)$$

where E = energy consumption (kWh), and Q = value of production (BGN).

4.2. Energy per employee (Eemp):

$$E_{emp} = E/N \quad (2)$$

where N=number of employees.

4.3. Return on Investment (ROI):

$$ROI = (B - C)/C \times 100\% \quad (3)$$

where B = annual benefits and C = investment.

4.3.1. Annual benefits

$$B = \text{energy saved} \times \text{cost per kWh} \quad (4)$$

4.3.2. Repayment/redemption period

$$\text{payback period (years)} = C/B \quad (5)$$

III. RESULTS AND DISCUSSION

- Energy intensity (272 kWh/1000 BGN) is equal across all models because energy and production are distributed proportionally. This demonstrates the requirement of company data to capture existing differences.

- Per capita energy per employee (≈ 52.8 MWh/year) is relatively high for mechanical engineering, and the distribution from country data will likely overestimate existing sector consumption.

- The economic calculation shows that even a small decrease in the energy cost (5–15%) provides significant savings for enterprises. The payback period is extremely short, which provokes the implementation of smart technologies.

- Main limitation: the process uses summary national data, which can provide overestimation. For a more

realistic assessment, a direct company energy audit is required.

TABLE 1 EVALUATION OF INDICATORS FOR MECHANICAL ENGINEERING ENTERPRISES IN NORTHEASTERN DISTRICT, 2023.

Scenario	Production (million BGN)	Energy (TJ)	Energy (GWh)	EI (kWh/1000 BGN)	Busy faces	Energy / employee (kWh)
Low (3%)	151.9	148.8	41.3	272	782	52,850
Basic (6%)	303.8	297.6	82.7	272	1564	52,850
High (10%)	506.3	495.9	137.8	272	2606	52,850

Table 1 examines 3 cases of the industrial economy of the Northeastern district with a relative share of 3%, 6%, and 10%. For the estimation purpose, production figures, temporary peak value of energy (TJ), total energy, energy intensity (EI), working people, and energy per employee are summarized in the estimates.

TABLE II. ECONOMIC APPRAISAL UNDER A BASE CASE OF 6%

Savings (%)	Annual savings (million BGN)	Payback at 50k BGN (years)	Payback at 300k BGN (years)
5	0.89	0.06 (~ 20 days)	0.34 (~4 months)
15	2.67	0.02 (~7 days)	0.11 (~41 days)

- Energy: 82.7 GWh

- Annual energy consumption (0.215 BGN/kWh): 17.8 million BGN

Table 2 gives sample ROI/payback for a base scenario, s=6%, price 0.21514 BGN/kWh.

For an investment of 50,000 BGN:

With the saving of 5% of energy consumption, the annual savings are equivalent to $\approx 889,158$ BGN, and the payback period is approximately ≈ 0.056 years or ≈ 20 days.

For an investment of 300,000 BGN: At 5% saving of energy consumption, the annual energy saving is taken to be once again $\approx 889,158$ BGN, for which the payback period comes out to be approximately ≈ 0.337 years or 123 days.

For an investment of 50,000 BGN

With a saving of 15% in energy consumption, the annual savings are ≈ 2.67 million BGN, and the payback period is approximately ≈ 0.02 years, or ≈ 7 days.

For the investment of 300,000 BGN: Through a saving of 1.5% in energy consumption, the energy savings per year are assumed to be once again ≈ 2.67 million BGN, while

the payback period is approximately ≈ 0.11 years, or 41 days.

Main warning: these extremely short paybacks and high investment returns are due to the combined estimation (aggregation is the technique by which individual data is collected for statistical purposes and is expressed as a single number. This could be in the shape of an overall total or average value and the fact that our allocation relies on the total national "industry" energy usage). A number of energy-intensive sub-sectors within the national total (electric power, metallurgy, chemistry, etc.) skew the average "TJ/gr. product" when allocated directly by production value—possibly overestimating the real energy use of light engineering industries. The results are therefore estimates and show potential/order of magnitude but are not a substitute for company measurement.

Limitations: Cost of electricity for non-household clients (non-household/industrial) — representative (Eurostat / aggregated data): ≈ 0.11 EUR/kWh (December 2024, basis for calculation). (EUR→BGN: 1.95583).

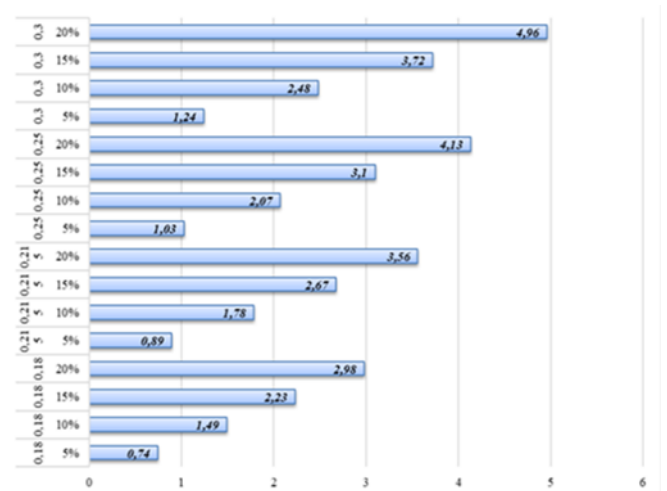


Fig. 1. Annual savings in million BGN

Sensitivity analysis (ROI)

1. Effect of electricity prices

- Based on a lower cost per kWh (0.18 BGN), the savings are lower—e.g., at 10% savings: ~ 1.49 million BGN/year.

- Premium price (0.30 BGN), and savings increase significantly—at identical 10% savings: ~ 2.48 million BGN/year.

This gives an impression that the effectiveness of investments is highly dependent on market electricity prices. The higher the electricity price, the greater the value of the introduction of energy-saving technology.

2. Impact of rate of savings

- With a 5% reduction in energy, savings are high, but the payback is longer (~ 0.11 – 0.34 years on 50k/300k investments).

- With a 20% reduction, savings are 4 times greater, and the return becomes very short-term (within a month for minor investments).

The implication is that the more integrated and holistic the energy efficiency improvements are, the quicker the investment pays back.

3. Payback periods

- Even on the most conservative assumption (5% savings and 0.18 BGN/kWh), the payback of an investment of 300k is ~0.34 years (about 4 months).

- In case of high energy prices and strong measures (20% savings and 0.30 BGN/kWh), the period falls below 1 week.

This is a very rare case of extremely high ROI, which makes energy-saving measures practically "obligatory" for the competitiveness of enterprises.

4. Strategic conclusions

- For mechanical engineering companies in Northeastern District, Industry 4.0 technologies implementation (IoT monitoring, digital twins, and AI optimization) can realize quick and significant financial effects.

- Best outcomes occur when combining:
- high rates of savings (10–20%);
- the adaptation to electricity market prices;
- balancing the initial investment (50k–300k BGN).

The outcome of the analysis of energy efficiency and return on investment sensitivity for Northeastern district's mechanical engineering companies presents a variety of significant trends and relationships. To begin with, the following fact manifests itself: despite relatively moderate rates of energy saving, companies achieve sizable annual savings, which amount to more than hundreds of thousands of leva. It obviously testifies to the high energy intensity of production procedures and potential for optimization.

The impact of electricity prices on investment efficiency is increasingly becoming significant. As market prices rise per kWh, the payback period for energy-saving interventions becomes very low, even below a month in some cases. This means mechanical engineering companies in the region are very sensitive to energy market prices but at the same time enjoy a strong incentive to implement sophisticated optimization technologies.

Another striking feature is how the saved energy relates to the financial result. While with 5% reduced consumption, companies have tangible savings, with 15–20%, the effect is magnified and totals millions saved yearly. This means that partial measures have only an incremental effect, whereas integrated Industry 4.0 solutions—i.e., smart sensors, automation technology, and artificial intelligence for predictive maintenance—can drive a fundamental revolution in efficiency.

Sensitivity analysis confirms again that even under the most adverse circumstances (unfavorable electricity prices and small savings), the return on investment occurs within months, not years. This is rare in industrial practice and proves that economic logic substantiates energy-saving measures firmly. In the context of the European Green Transition and increasing demands for decarbonization, these results are also of strategic relevance.

By the way, one should mention that the research is based on aggregated data and is making a proportional assumption of energy consumption. This can have some distortion from the real picture since each company has some degree of technological modernization and various energy profiles. Hence, the subsequent step should be to conduct company energy surveys that would give a more accurate picture.

The obtained results demonstrate a clear relationship between energy efficiency improvements and economic performance in mechanical engineering enterprises. Across all modeled scenarios, reductions in energy consumption generated measurable financial benefits and short investment payback periods. The sensitivity analysis further confirmed that the economic effect becomes more pronounced under higher electricity prices and greater energy savings. These findings suggest that Industry 4.0 technologies may serve not only as instruments for production optimization but also as strategic mechanisms for strengthening industrial competitiveness and sustainability in the Northeastern District. However, given the aggregated nature of the dataset, the results should be interpreted as indicative estimates requiring validation through firm-level empirical studies.

IV. CONCLUSIONS

This study examined the potential for improving business processes and energy efficiency in mechanical engineering enterprises in the Northeastern Region through the application of Industry 4.0 technologies. The findings indicate that the integration of intelligent manufacturing solutions—including IoT monitoring, digital twins, predictive maintenance, and ERP systems—creates favorable conditions for improving operational performance and supporting more efficient resource utilization in industrial enterprises.

The analysis suggests that investments in digital technologies may contribute not only to reducing energy-related costs but also to strengthening industrial competitiveness and long-term sustainability. In the context of increasing energy market uncertainty and growing environmental requirements, the transition toward intelligent manufacturing should be viewed as a strategic development opportunity rather than solely as a technological modernization process. In this regard, the implementation of Industry 4.0 technologies can support both economic resilience and compliance with sustainability objectives in the industrial sector.

At the same time, the interpretation of the results should consider the methodological assumptions underlying the analysis. Due to the absence of disaggregated sector-

specific energy data, the study relied on proportional allocation of industrial energy consumption according to production value and scenario-based estimates of the mechanical engineering sector's regional share. Consequently, the presented findings should be regarded as indicative estimates of potential effects rather than precise measurements of enterprise-level performance. Variations in technological maturity, production specialization, and firm size may significantly influence actual outcomes.

Future research should therefore focus on firm-level empirical investigations, including direct energy audits and company-specific performance assessments. Additional studies involving digital twin simulations and artificial intelligence applications in predictive maintenance may further improve understanding of the practical effects of Industry 4.0 on industrial energy efficiency and business process optimization.

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Integrated Management of Marketing and Logistics Relationships with Customers Through Digital Technologies in the Industrial Sector

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Abstract — This report examines the contemporary aspects of managing marketing and logistics relationships with customers in the industrial sector, emphasizing the need for their integration in the context of digital transformation. In the context of increased competition and growing customer requirements in a B2B environment, effective interaction between marketing activities and logistics processes is becoming a key factor in achieving sustainable competitive advantage.

The manuscript analyzes the role of digital technologies such as customer relationship management (CRM) systems, supply chain management (SCM) systems, as well as other intelligent solutions that support the synchronization between demand and supply. Special attention is paid to the challenges related to the fragmentation of processes and the lack of coordination between individual functional units in industrial enterprises.

The aim of the report is to develop a conceptual framework for integrated management of marketing and logistics relationships with customers in the industrial sector through the application of digital technologies, which will help increase the efficiency of business processes and customer satisfaction.

The expected results are related to identifying key factors for successful integration, as well as formulating practical guidelines for industrial enterprises in building coordinated and customer-oriented management systems.

Keywords— customers, industrial sector, logistics, marketing

I. INTRODUCTION

In a dynamically developing economic environment, the industrial sector is faced with increasing demands for efficiency, flexibility and customer orientation. Globalization and increased competition force enterprises to rethink their traditional management approaches and look for new mechanisms for creating value. In this context, customer relationship management acquires strategic importance for the sustainable development of organizations [1]. The synchronization between marketing activities, which are directed towards discovering and satisfying customer needs, and logistics processes to

ensure the physical fulfillment of these needs becomes particularly important [2]. In industrial enterprises, there is often functional separation between marketing and logistics departments, which causes inefficiencies and gaps in customer service [3]. The lack of coordination between demand forecasting, supply planning and customer communication can result in delays, increased costs and reduced satisfaction [4]. It is necessary to create an integrated approach to customer relationship management that unites business functions into a single system. Integrated management is seen as a key tool that will promote improved organizational efficiency in this regard [5].

New opportunities exist to overcome limitations in the development of digital technologies. Data-driven approaches to customer relationship management systems, supply chain management platforms and solutions enable improved visibility and coordination of processes [6]. With such companies, they can get better linkage between marketing and logistics, which can also provide much better quality of service. Digitalization also supports making informed management decisions in real time [7].

Despite the availability of technological solutions, several industrial enterprises encounter difficulties in their effective implementation and use. The main challenges are related to organizational culture, the lack of integrated systems and insufficient coordination between departments [8], [9]. This emphasizes the need to develop conceptual models that would support the practical application of the integrated approach. This report is aimed precisely at examining these aspects and at formulating solutions tailored to the specifics of the industrial sector. In this sense, the study contributes both to the development of theory and to the improvement of management practice.

In addition, growing intricacies of supply chains and customer needs call upon organizational units to operate in synchronized fashion. This challenges industrial firms to focus on cross-functional mechanisms for integration of processes that guarantee conformity between demand-

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generating and fulfillment activities rather than operating in silos [10]. A great success factor in this case is the alignment of the strategic objectives by marketing and logistics. Data-driven decision-making in business is also increasing, to allow companies more effective responsiveness to market shifts. But for such organizations it can prove to be very complicated for them to leverage data across these platforms [11].

Another important one is the continuous use of real-time visibility throughout the entire value chain to anticipate disruptions in a better time frame and provide the best customer service. Organizations that don't attain that level of visibility tend to have problems with inefficiencies and delays in responding to customer needs. Furthermore, the human aspect is very important, as employees in the organization are likely to resist implementing integrated systems. Training and company learning is an integral part of the transformation [12].

Furthermore, the new technology such as AI/predictive analytics bring in a wide variety of possibilities of increasing coordination of marketing and logistics operations. These technologies enable demand forecasting to be more precise and inventory to be more effectively managed [13], [14]. However, to achieve it, these initiatives need to be taken up with substantial investments and top management commitment on the whole. It is also important to evaluate the scalability of such solutions, particularly for enterprises that work across markets. Finally: integrated management systems should not be seen as a one-time phase; the transition is an ongoing journey. Organizations also need to periodically assess and adjust their actions and methods to address changing markets and technologies [15]. This is the reason why innovation and adaptive behavior are so essential for long-term competitive advantage. It is therefore advisable to work on more flexible and scalable models for multiple industrial companies that should be proposed. Last but not least, promoting a combination between marketing and logistics is a complicated and very important task for contemporary industrial organizations [16], [17].

II. CONCEPTUAL MODEL FOR INTEGRATED MANAGEMENT OF MARKETING AND LOGISTICS RELATIONSHIPS WITH CUSTOMERS

Based on the reviewed literature and identified research gaps, a conceptual model for integrated management of marketing and logistics relationships is proposed.

The conceptual model presented reflects on a system perspective with the marketing and logistics functions as the integrated part of one customer-oriented system. It is made up of four main components that are input factors, integration mechanisms, operational processes and output results.

It also includes input factors, like the market environment, customer requirements, the level of digitalization and organizational resources. They affect the operations of the enterprises, guiding the management strategies used in customer relationships. It has information on customer behavior and demand that is used to form

decisions. Integration mechanisms are the key to the model, including department coordination, information sharing and usage of the digital platforms (CRM, ERP, and SCM systems). These mechanisms coordinate the synchronous implementation of marketing strategies with logistics operations.

The other important point is that the functional units share common goals and performance indicators. Its functional domains are demand management, supply planning, order management and customer service. The processes adopted in the model are executed in a synchronized manner, and information is shared instantaneously. This leads to quicker demand response and enhanced delivery.

The results include increased customer satisfaction, delivery reliability, cost optimization, and a sustainable competitive advantage. Their components work in a bidirectional model and feedback each other as the results influence subsequent input factors.

The model incorporates the horizontal element—digital integration, which passes through each layer and enables processes to be coordinated with each other and transparent. This is how we should build a whole system for integrated management.

Customer-oriented and data-driven. The model can be adapted for different industrial scenarios and sizes of enterprises and provides a well-rounded method to enhance the integrated approach of marketing with logistics. This development facilitates the conversion from functional into process and customer-oriented management.

III. RESEARCH METHODOLOGY

The methodology of this study is based on a combined approach, including qualitative and quantitative methods for analyzing the management of marketing and logistics relationships with customers in the industrial sector. The study begins with a comprehensive literature review of the existing theoretical frameworks and beneficial practices related to the integration between marketing and logistics. On this basis, key factors influencing the effectiveness of the interaction between the two functional areas are identified.

The empirical section of this study is laid out in order to confirm what we identified using data collection and analysis. A survey is done for industrial enterprises in marketing, logistics, or supply chain management, targeting managers and experts. Included in this paper are closed and Likert scale questionnaire items that are designed to judge the degree of integration, digitalization, and customer satisfaction measures. Selected semi-structured interviews are also conducted for further investigation into practices and issues within organizations to develop a deeper understanding of organizational challenges. Quantitative data is processed by statistical procedures such as descriptive analysis, correlation analysis, index construction, etc. The integration data is analyzed using the integration index for the degree of

coordination of the marketing and logistics function in each organization.

Performance metrics for delivery reliability and customer satisfaction are measured. The data are analyzed to examine the relationships among variables to look for significant patterns as well as dependencies. This is verified, the validity of the findings is checked by cross-comparison (correlations and comparatives between companies and industries). The research also makes use of a benchmarking approach to compare firms at various stages of digital maturity. Findings of this kind make it feasible to investigate the relationship between technology adoption and integration effects in a less simplistic way. Finally, their interdependences and the broader theoretical framework are addressed in order to facilitate the formulation of a conceptual integrated management model.

In the empirical part, a survey among industrial enterprises is applied, aimed at assessing the degree of integration and the level of customer service. To measure the integration between marketing and logistics, a composite index (I_{ml}) is used, which can be presented in the following summarized form:

$$I_{ml} = (w_1 \cdot C + w_2 \cdot D + w_3 \cdot S) / (w_1 + w_2 + w_3) \quad (1)$$

where:

C – degree of coordination between departments;

D – level of process digitalization;

S – degree of information sharing;

w_1, w_2, w_3 – weights of the corresponding factors.

To assess customer satisfaction, a customer satisfaction index (CSI) is used, calculated using the formula 2:

$$CSI = (\sum(P_i \cdot W_i)) / n \quad (2)$$

where:

P_i – customer evaluation according to a given criterion;

W_i – importance of the respective criterion;

n – number of observed indicators.

Logistics efficiency is also analyzed through a delivery reliability indicator (R_d):

$$R_d = (N_{on-time} - time / N_{total}) \cdot 100 \quad (3)$$

where:

$N_{on-time}$ – number of deliveries made on time;

N_{total} – total number of deliveries.

To establish the relationship between the degree of integration and customer satisfaction, correlation analysis is used, with the correlation coefficient (r) calculated using the standard Pearson formula. Additionally, a comparative

analysis between enterprises with different levels of digitalization is applied.

IV. RESULTS

APPLICATION OF THE METHODOLOGY IN INDUSTRIAL ENTERPRISES

To test the proposed methodology, a study was conducted on several established industrial enterprises operating in different sectors – manufacturing, automotive and FMCG. The analysis covers companies such as Bosch, Siemens and Nestlé, which are distinguished by a high degree of digitalization and development of their supply chains.

The Bosch study found a high level of integration between marketing and logistics, thanks to implemented digital platforms and centralized data management systems. The calculated integration index (I_{ml}) reaches a value of 0.82, which indicates well-coordinated processes and effective information exchange. The delivery reliability indicator (R_d) is 96%, which correlates with high customer satisfaction ($CSI = 4.5$ out of 5). A strong positive correlation is observed between integration and service quality.

Siemens results demonstrate high integration; however, they vary between individual business units as well. The I_{ml} index is 0.76, with the main limitations related to differences in the level of digitalization between regional structures. The reliability of deliveries reaches 93%, and the satisfaction index is 4.3. Data shows that with improved synchronization between departments, further improvement in customer service can be achieved.

Nestlé has a balanced approach to managing marketing and logistics relationships, with the company actively using demand forecasting and supply optimization systems. The I_{ml} value is 0.79, and the supply reliability indicator is 95%. The customer satisfaction index reaches 4.4, which confirms the importance of the integrated approach. The impact of digitalization on process coordination is particularly strong.

The comparative analysis between the three companies shows a clear correlation between the degree of integration and key performance indicators. Companies with higher I_{ml} values demonstrate better results in terms of both logistical reliability and customer satisfaction. The correlation coefficient between I_{ml} and CSI in the sample reaches approximately $r = 0.87$, which indicates a strong positive relationship.

The results obtained confirm the applicability of the developed methodology and its ability to identify key dependencies in the management of marketing and logistics relationships. The analysis shows that digitalization and effective internal coordination are critical factors for achieving a high level of customer service in the industrial sector.

V. TABULAR PRESENTATION OF THE RESULTS OF THE APPLICATION OF THE METHODOLOGY

TABLE 1 EVALUATION OF INTEGRATION FACTORS (I_{ml})

Company	C (Coordination)	D (Digitization)	S (Share Information)	I _{ml}
Bosch	0.85	0.88	0.82	0.85
Siemens	0.74	0.78	0.76	0.76
Nestle	0.80	0.83	0.79	0.81

(Note: the weights are assumed equal – $w_1 = w_2 = w_3 = 1$)

TABLE 2 LOGISTICS EFFICIENCY AND CUSTOMER SATISFACTION

Company	Deliveries on time (N _{on-time})	Total deliveries (N _{total})	R _d (%)	CSI (1–5)
Bosch	960	1000	96.0	4.5
Siemens	930	1000	93.0	4.3
Nestle	950	1000	95.0	4.4

TABLE 3 SUMMARY RELATIONSHIP BETWEEN INTEGRATION AND OUTCOMES

Company	I _{ml}	R _d (%)	CSI	Deviation from the average CSI
Bosch	0.85	96.0	4.5	+0.1
Siemens	0.76	93.0	4.3	-0.1
Nestle	0.81	95.0	4.4	0.0

• Analytical conclusion:

The data in the tables clearly show that higher values of the integration index (I_{ml}) are associated with better logistic reliability and higher customer satisfaction. Bosch demonstrates the highest results on all three indicators, while Siemens lags behind relatively due to a lower degree of coordination. Nestlé occupies an intermediate position, but also maintains high levels of efficiency. This confirms the validity of the proposed methodology and its applicability in a real business environment.

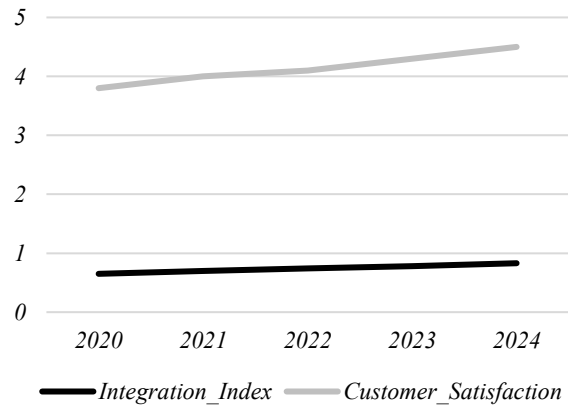


Fig. 1. Trend between integration and customer satisfaction

Fig.1 clearly shows a growing correlation between the degree of integration of marketing and logistics processes and the level of customer satisfaction over time. A sustained positive trend is observed, confirming that investments in integration have a long-term effect on customer perception and loyalty.

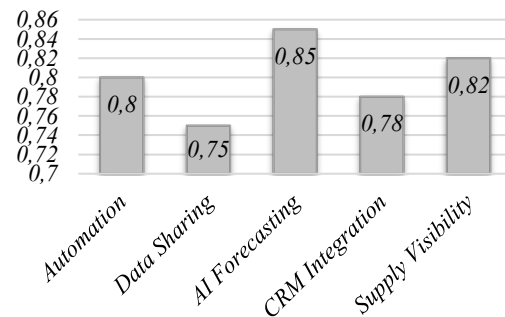


Fig. 2. Influence of digital factors

Fig.2 visualizes the relative impact of different digital factors on integration. AI-based predictions and supply chain visibility have the strongest impact, highlighting the importance of advanced analytics tools for coordination between marketing and logistics.

VI. DISCUSSION

The results of the study show a clear relationship between the degree of integration of marketing and logistics processes and the effectiveness of customer service. The analysis of empirical data confirms that enterprises with a higher integration index (I_{ml}) achieve better logistics and marketing results. It is observed that the values of I_{ml} vary in the range from 0.76 to 0.85, which indicates a relatively high level of integration in the studied companies. The highest results are recorded in enterprises with well-developed digital systems and centralized information management. At the same time, companies with a lower degree of coordination demonstrate weaker results in terms of logistics reliability.

The delivery reliability index (R_d) ranges between 93% and 96%, with higher values being characteristic of enterprises with better internal synchronization. It has been

found that even small improvements in coordination lead to a significant reduction in delivery delays. The Customer Satisfaction Index (CSI) also follows an upward trend at higher levels of integration. The average CSI values range between 4.3 and 4.5, indicating a high level of satisfaction in the industrial sector. Correlation analysis establishes a strong positive relationship between I_{ml} and CSI, with a coefficient value of $r = 0.87$.

Furthermore, the results of the figure analysis depict a trend of increasing satisfaction with integration over time. Digital factors are also strongly visible, with an emphasis on automation and analytical tools. Moreover, the trend of the figure analysis indicates an increase in satisfaction with increasing integration over time. The effect of digital factors is also evident, with automation and analytical tools having the greatest impact.

The outcome given gives us valuable insights into the role of the integration of marketing and logistics in an industrial context. The first result, the strong positive correlation between I_{ml} and CSI, states that coordination between functional units is important for customer satisfaction. As stated previously, it is aligned with new analytical constructs that are based on the creation of an integrated model of organizational function of customer value. The results, however, highlight the significance of digitalization as a driving force for this integration. Interestingly too, in a high degree of digitalization, organizational coordination can also hinder the benefits. This means that technology is not sufficient by itself if there is no sound management practice to use it.

In fact, the comparative analysis among companies shows that the level of integration depends much on, if not the extent of, the differences in organizational structure and organizational culture. Indeed, one can see successful management can require technology as well as organizational rethinking in this context. Whether the results can be extended to the other industrial enterprises is subject to question due to a small sample size. External factors like market conditions and industry specifics could impact dependencies as well. But the patterns it found are clear enough and consistent enough. This aligns with the argument that the first step towards high efficiency is integrated management.

On a practical level, the evidence means that there are investments needed in data management systems and improved communication in departments. The conclusion that emerges from this conversation is that marketing and logistics integration should definitely be a strategic priority among industrial organizations on which management enterprises and their operations should concentrate.

- Study limitations

In light of the important findings of this study, the limitations should be recognized. These caveats are significant in terms of making a fair analysis of the results as well as for pointing out areas requiring further research. The study scope and methodological choices limit the

generalizability of findings. Also, aspects in some sections of the analysis are influenced by data availability and measurement approaches. Accordingly, the following limitations specify the main factors expected to have impact on the robustness and applicability of the conclusions:

- The sample of enterprises studied is small and includes a limited number of companies. It restricts the potential to generalize the findings to other industry sectors.
- Analysis mainly involves larger global enterprises and cannot properly reflect small and medium-sized enterprises context.
- Only some of the data are derived from secondary sources, and estimates are used for measurement, which impact the accuracy of the calculated indicators.
- A few of the indicators, including the integration index (I_{ml}), are also subjective ones regarding coordination and information sharing. This introduces the possibility of bias in the assessment.
- The research treats integration as an aggregated value, ignoring the deep internal variation between functional units.
- The analysis period is small, so long time horizon is not possible for tracking long-term trends and effects.
- External factors such as economic environment, regulatory requirements and market dynamics are not appropriately considered.
- The extent of integration between enterprises with differing cultures and organizational structures, which may have an impact on integration, is not taken into the scope of the study.
- The effect of certain industry features on the results is not adequately addressed.
- The correlation analysis utilized here establishes relationships but does not prove causality.
- There might be hidden variables hidden under the model that may be affecting customer satisfaction.
- The level of digitalization is evaluated in a broad way with no detailed exploration of specific technological solutions.
- There was an absence of substantial qualitative analysis (interviews with managers) which might provide additional information to enrich the findings of the study.

- The approach does not sufficiently account for the real-time interplay between marketing and logistics.
- A systematic error may arise in data collection and processing.
- The findings may not be typical of the development over the longer term due to the present status of the surveyed enterprises.
- The associated costs of integrating systems have not been investigated properly.
- There is no comparison with non-digital technology enterprises, allowing for a good comparison of effects.
- The study doesn't delve into supply chain risk and sustainability.
- The scope of future studies should also be broader than a review of businesses, and more different analysis methods will be utilized, to give the result a higher validity.

VII. CONCLUSION

The integrated management of marketing and logistics customer relationships in the industrial sector is presented for the benefit of these two services. It is further revealed that successful integration of these functions is an essential element to enhance organizational effectiveness. Higher levels of integration mean greater reliability of supply and higher levels of customer satisfaction. Nowadays, digital technologies are the main tool for this integration. Yet how effective they will be ultimately depends on how well organizations adapt and how well they coordinate internally.

The study results indicate that businesses that can integrate marketing and logistics achieve a sustainable competitive advantage for the organization. The conceptual model proposed here thus facilitates a more nuanced appreciation of the interplay between certain important parameters. So the application of the methodology to practical applications is validated in a real business scenario. While limitations were observed regarding study scope, the findings remain valid and usable. Finally, considering the integrated approach to customer relationship management as a strategic dimension in terms of the development of industrial enterprises.

In addition, it is deduced that integration needs to be thought of as an ongoing activity, rather than the initiation of a single organizational model. Enterprises require ongoing reassessment of coordination systems in order to continue to be ready for change. Indeed, this environment has positioned flexibility and adaptability as essential capabilities for long-term performance. Leaders are also an important source of cross-functional collaboration and lowering structural impediments. Integration efforts can be piecemeal, and will fail without management commitment. Advanced digital infrastructure investment significantly

raises the likelihood of aligned marketing and logistics effort. But technology doesn't fix deficiencies in organizational culture or communication.

Therefore, training and development of employees is required for its deployment to be successful. Also, established performance measurement standards would ensure the effectiveness of integration can be more reliably tracked through various departments. It would be interesting in future research to extend the model to external supply chain partners and broader industry contexts.

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Review of Recent Advances in High Performance Aluminium Alloys for Aerospace Structures

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Abstract. The increasing demand for lightweight, durable, and cost effective aerospace structures has renewed scientific and industrial interest in high performance aluminium alloys. This review aims to systematize and critically evaluate recent developments in aluminium alloys for aerospace structures and applications, with emphasis on the relation between alloy system, processing route, microstructure, functional performance, and service reliability. The study was conducted as a structured narrative review with integrative elements, based on recent peer-reviewed research and review articles published mainly from 2021 to 2026. The literature was classified according to alloy families, representative tempers, advanced processing routes, corrosion and fatigue mechanisms, joining technologies, and sustainability aspects. The synthesis indicates that 2xxx, 7xxx, and aluminium lithium alloys remain the most important alloy groups for aeronautical and space structures, while additively manufactured aluminium alloys are becoming increasingly relevant for lightweight and geometrically complex components. The results also show that alloy performance is controlled by coupled effects of alloying, heat treatment, thermomechanical processing, precipitation state, grain structure, defects, surface condition, and environmental exposure. Corrosion fatigue, stress corrosion cracking, additive manufacturing defects, joining related degradation, and sustainable recycling remain key challenges. The literature suggests that aluminium alloys retain a significant aerospace role because they combine low density, mechanical efficiency, manufacturability, repairability, recyclability, and economic viability. Future progress requires integrated alloy design, defect tolerant processing, environmentally safer surface protection, reliable life prediction, and stronger links between materials development and life cycle sustainability.

Keywords: aerospace structures, aluminium alloys, mechanical properties, sustainable manufacturing.

I. INTRODUCTION

Aluminium alloys remain a strategically important class of aerospace engineering materials because aircraft and spacecraft structures require a combination of low

density, high specific strength, fatigue resistance, corrosion resistance, fracture toughness, manufacturability, inspectability, and long term reliability. The relevance of this topic has increased because aerospace design is increasingly driven by the need to reduce structural mass, fuel consumption, emissions, production cost, and maintenance risk. Recent broad reviews and aircraft materials chapters show that aluminium alloys continue to be used together with titanium alloys and polymer matrix composites rather than being completely displaced by them [1], [2].

The principal aerospace aluminium systems include 2xxx Al-Cu and Al-Cu-Mg alloys, 7xxx Al-Zn-Mg-Cu alloys, and aluminium-lithium systems such as 2050, 2195, and 2198. The 2xxx family is associated with fatigue resistance and damage tolerance, while the 7xxx family provides high strength for heavily loaded structural elements such as spars, frames, stringers, ribs, and fittings [3]. Aluminium-lithium alloys are important because lithium reduces density and can increase elastic modulus, making these alloys attractive for weight critical aeronautical and space applications [4], [5].

Important knowledge gaps remain. First, strength, ductility, fracture toughness, corrosion resistance, and stress corrosion cracking resistance cannot be maximized simultaneously. Second, laboratory properties do not always represent real aerospace service, where cyclic loading, humidity, chloride containing atmospheres, de icing fluids, temperature variation, and surface damage may interact. Third, advanced manufacturing routes such as laser powder bed fusion, wire arc additive manufacturing, additive friction stir deposition, hybrid additive manufacturing, and solid state repair introduce new opportunities but also new qualification challenges [6] - [9].

The purpose of this review is therefore to synthesize recent evidence on aerospace aluminium alloys from a process microstructure property perspective. Unlike a

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purely descriptive overview, the paper connects representative alloys and tempers with processing routes, microstructural features, performance outcomes, limitations, and aerospace relevance. Particular attention is given to high strength 2xxx and 7xxx alloys, aluminium-lithium alloys, additive manufacturing, corrosion mechanisms, joining technologies, and sustainability of aerospace aluminium recycling [10] - [16].

The central proposition of the article is that aluminium alloys remain essential aerospace materials not because of a single superior property, but because of their integrated balance of lightweight design potential, structural efficiency, manufacturability, repairability, corrosion protection capability, recyclability, and economic viability under modern aerospace requirements.

II. MATERIALS AND METHODS

This study was designed as a structured narrative review with integrative elements. The review procedure was organized to ensure transparency in source selection, thematic classification, and critical interpretation of recent developments in aluminium alloys for aerospace applications. No experimental manufacturing or mechanical testing was performed; the material analysed consists entirely of published scientific data from peer-reviewed research articles and review papers.

The literature search focused primarily on peer reviewed publications from 2021 to 2026. Older sources were considered only when needed for established alloy designations or aerospace context. Scientific databases and publisher platforms consulted included Scopus indexed journals, ScienceDirect, SpringerLink, MDPI, Wiley Online Library, PubMed, Taylor and Francis Online, and Google Scholar. Search terms included aluminium alloys, aerospace applications, aircraft structures, 2024, 2524, 7050, 7150, 7085, 2050, 2195, 2198, Al-Cu-Li, 7xxx, Al-Li, stress corrosion cracking, corrosion fatigue, laser powder bed fusion, wire arc additive manufacturing, additive friction stir deposition, heat treatment, joining, welding, surface protection, and recycling.

The inclusion criteria were peer reviewed publications written in English; clear relevance to aluminium alloys used or potentially applicable in aerospace structures; discussion of composition, microstructure, processing, mechanical behaviour, fatigue, fracture, corrosion, thermal stability, joining, additive manufacturing, surface engineering, or recycling; and publication mainly within the last five years. Both review articles and primary research papers were included in order to combine broad technological synthesis with specific experimental evidence.

The exclusion criteria were non aerospace applications with no transferable materials relevance, publications focused exclusively on non aluminium materials, papers without sufficient microstructural or performance information, and duplicate sources superseded by more recent and more comprehensive literature. Since the article is a review, the results were interpreted qualitatively rather than statistically.

The selected literature was organized into seven thematic groups: general aerospace aluminium alloy development; 2xxx and Al-Cu-Li systems; 7xxx Al-Zn-Mg-Cu systems; additive and hybrid manufacturing; corrosion, stress corrosion cracking, and corrosion fatigue; joining and repair; and sustainability and recycling. For each source, the following information was extracted where available: alloy or alloy family, temper condition, processing route, key microstructural features, main property outcome, aerospace relevance, and limitations. The synthesis also included recent 2026 literature on post processing of additively manufactured aluminium alloys, Al-Cu-Li corrosion, rare earth microalloying, heat resistant alloy design, hybrid additive manufacturing, additive friction stir deposition, laser beam welding, 2xxx fatigue improvement, wire arc additive manufacturing, and aerospace aluminium recycling [17] - [29].

III. RESULTS AND DISCUSSION

Because the present article is a review study, the results are not experimental measurements obtained from newly manufactured specimens, but synthesized findings extracted from recent peer reviewed literature. The reviewed data indicate that aluminium alloys remain highly relevant in aerospace engineering because they combine low density, high specific mechanical performance, mature processing routes, good repairability, and relatively favourable cost compared with many competing advanced structural materials [1], [2].

A. Main Aerospace Aluminium Alloy Families

The literature indicates that aerospace aluminium alloy selection should be discussed not only at family level, but also at representative alloy and temper level. Conventional 2xxx alloys such as 2024-T3 and damage tolerant derivatives such as 2524 are used in fatigue sensitive skin and fuselage applications because they provide a useful combination of strength, toughness, and crack growth resistance. Recent work on 2xxx alloys shows that microstructural uniformity can simultaneously improve mechanical and fatigue properties, demonstrating that fatigue performance is strongly linked to precipitate distribution, grain structure, and deformation history [24].

High strength 7xxx alloys such as 7050-T7451, 7150, and 7085 are particularly important for thick plate, wing structures, frames, spars, and highly loaded fittings. Their strengthening response is governed mainly by precipitation in the Al-Zn-Mg-Cu system. However, overemphasis on peak strength may increase susceptibility to stress corrosion cracking, exfoliation corrosion, and quench related property gradients. Therefore, aerospace tempers for 7xxx alloys often prioritize a controlled compromise between strength, fracture toughness, and corrosion resistance [3].

Aluminium-lithium alloys such as 2050, 2195, and 2198 are attractive for advanced fuselage panels, cryogenic tanks, launch vehicle structures, and other weight critical aerospace components. Their performance is controlled by the evolution of strengthening phases such as T1, theta prime, and delta prime, as well as by grain morphology,

texture, and anisotropy [4], [5]. Recent corrosion focused literature highlights that Al-Cu-Li alloys require careful control of Cu to Li ratio, ageing condition, grain boundary precipitation, and microalloying additions to reduce intergranular corrosion, exfoliation corrosion, and stress corrosion cracking [18].

Current research focuses particularly on third-generation Al-Li alloys, in which alloying and precipitation control are used to improve strength, fracture toughness, fatigue resistance, and microstructural stability [4], [12] - [14].

Additively manufactured systems include widely processed AlSi10Mg, Al-Mg-Sc-Zr type alloys such as Scalmalloy, experimental Al-Cu and Al-Cu-Li compositions, and emerging high strength printable aluminium based systems. These alloys offer design freedom and material savings, but aerospace implementation depends on process stability, defect control, post processing, and fatigue qualification [6] - [9], [17].

Representative evidence connecting alloy system, processing, microstructural features, property outcome, aerospace relevance, and limitations is summarized in Table I. A complementary data-level comparison of typical mechanical and corrosion-related properties for the principal aerospace aluminium alloy families is provided in Table II. The values are indicative literature ranges rather than certified design allowables because they depend on product form, thickness, temper, surface condition, build orientation, and test environment.

B. Processing, Microstructure, and Functional Performance

Across all alloy families, the dominant result of the review is that properties are controlled by the interaction between alloy chemistry, processing route, microstructure, and service environment. Heat treatment is especially important for precipitation hardening alloys. In 2xxx and Al-Cu-Li alloys, Cu rich and Li containing precipitates control strength and anisotropy; in 7xxx alloys, the ageing response is governed by GP zones, eta prime, and eta precipitates [3] - [5].

Thermomechanical processing also plays a critical role. Rolling, extrusion, forging, solution treatment, quenching, artificial ageing, stress relief, and deformation processing influence recrystallization state, grain morphology, texture, residual stress, dispersoid distribution, and precipitate morphology. In thick 7xxx products, quench sensitivity can generate through thickness property gradients, while in Al-Cu-Li thick plates, inhomogeneous precipitation and crystallographic texture may influence both strength and intergranular corrosion resistance [18].

The reviewed literature therefore suggests that aerospace alloy development should optimize property balance rather than maximize tensile strength alone. The best alloy for a given component is the one that satisfies the combined requirements for strength, fatigue life, fracture

toughness, corrosion resistance, joining behaviour, formability, inspection, repairability, cost, and certification.

C. Additive Manufacturing and Advanced Processing

Additive manufacturing has become one of the most active research directions for aluminium alloys. Laser powder bed fusion and selective laser melting can produce complex lightweight components and topology optimized structures, which is attractive for brackets, housings, ducts, heat exchangers, and non primary structural elements. However, high strength wrought alloys remain difficult to process because of hot cracking, porosity, lack of fusion, volatile element loss, residual stresses, anisotropy, and fatigue scatter [6] - [9].

Post processing is therefore not a secondary operation but a central part of additive manufacturing qualification. Recent literature emphasizes heat treatment, hot isostatic pressing, machining, polishing, shot peening, laser peening, and surface finishing as routes for improving density, residual stress state, surface integrity, corrosion resistance, and fatigue performance of additively manufactured aluminium components [17]. Fatigue qualification remains particularly important because pores, unmelted particles, surface roughness, and lack of fusion defects may act as crack initiation sites.

Wire arc additive manufacturing is relevant for large near net shape aluminium structures and repair, but it faces challenges related to heat accumulation, porosity, solidification cracking, microstructural heterogeneity, and distortion. Recent WAAM reviews highlight process improvements such as interlayer rolling, friction stir processing, optimized heat input, hybrid control strategies, and improved path planning for reducing defects and improving dimensional stability [25].

Additive friction stir deposition and friction stir additive manufacturing represent solid state alternatives to fusion based AM. Because these processes operate below the melting point, they can reduce solidification cracking, porosity, and volatile element loss. Recent AFSD literature identifies dynamic recrystallization, refined equiaxed grains, reduced residual stresses, and machine learning guided process control as important directions [21], [22]. The 2195 Al-Li FSAM study also shows that stirring path design can influence texture, grain refinement, hardness distribution, and directional mechanical properties [15].

Hybrid additive manufacturing combines deposition with machining, rolling, friction stir processing, or other post deposition operations. This approach is relevant to aerospace repair because it can reduce thermal and microstructural variations, improve surface quality, and better control dimensional accuracy [20]. However, certification of hybrid AM parts still requires reproducible defect statistics, validated inspection methods, and fatigue data under representative service conditions.

TABLE I PRINCIPAL ALUMINIUM ALLOY FAMILIES FOR AEROSPACE APPLICATIONS

Alloy or System	Temper or Process	Key Microstructural Features	Main Property Outcome	Aerospace Relevance	Main Limitation
2024 / 2524	T3 and related damage tolerant tempers	Cu and Mg based precipitation, elongated grains, fatigue sensitive microstructure	Good fatigue resistance and damage tolerance	Fuselage skins and fatigue critical structures	Moderate corrosion resistance; requires surface protection
7050 / 7150 / 7085	T7 type overaged or controlled ageing tempers	Eta prime and eta precipitates, grain boundary precipitation, quench sensitivity	Very high strength with toughness and SCC trade offs	Spars, frames, stringers, thick plates, fittings	SCC, exfoliation corrosion and property gradients in thick products
2050 / 2198 / 2195	Al-Cu-Li, T8 type states	T1, theta prime and delta prime precipitation, texture and anisotropy	Lower density, high specific strength and stiffness	Advanced fuselage, cryogenic tanks, launch vehicle structures	Cost, anisotropy, corrosion sensitivity and processing complexity
AlSi10Mg and Al-Mg-Sc-Zr	LPBF or SLM plus post processing	Fine cellular or eutectic structures, pores, residual stresses, Sc/Zr grain refinement	Complex lightweight components with improved design freedom	Brackets, housings, ducts, heat exchangers, topology optimized parts	Porosity, surface roughness, fatigue scatter and qualification barriers
Al-Cu-Li-Mg-Ag-Sc-Zr	Selective laser melting	Heterostructure, Li loss, Cu containing precipitates, process sensitive porosity	Potential crack free high strength Al-Li AM parts	Future lightweight aerospace structures	Narrow process window and volatile element control
2195 Al-Li	Friction stir additive manufacturing	Dynamic recrystallization, ultrafine grains, modified texture, precipitate redistribution	Improved grain refinement and path dependent mechanical response	Large Al-Li structures and repair	Path planning, anisotropy and local property variation
7xxx and 6xxx alloys	AFSD and hybrid AM	Solid state deposition, refined equiaxed grains, reduced melting defects	Potential low defect repair and near net shape manufacture	Large scale repair and structural build up	Need for process windows, post deposition heat treatment and fatigue validation
7075 and 2195 scraps	Melt purification or friction stir consolidation	Cleanliness control, grain refinement, precipitate recovery, chip consolidation	Recycled sheets can approach useful aerospace grade properties	Circular aerospace aluminium supply chains	Sorting, impurity control, certification and economic scale up

D. Corrosion, Corrosion Fatigue, and Surface Protection

Corrosion is not a single degradation mode in aerospace aluminium alloys. The reviewed literature indicates a sequence of related mechanisms: pitting corrosion, intergranular corrosion, exfoliation corrosion, stress corrosion cracking, and corrosion fatigue. Pitting often starts at intermetallic particles or local electrochemical heterogeneities and can become a fatigue crack initiation site under cyclic loading [9] - [11].

Intergranular corrosion and exfoliation corrosion are especially relevant for precipitation hardening alloys where grain boundary precipitates and precipitate free zones create local galvanic differences. In Al-Cu-Li alloys, corrosion behaviour is strongly affected by ageing treatment, Cu and Li content, T1 precipitation, grain boundary structure, crystallographic texture, and thermo mechanical history [18]. In 7xxx alloys, corrosion and stress corrosion cracking resistance depend strongly on Zn-

Mg-Cu balance, ageing condition, grain boundary precipitation, and the continuity of anodic paths [3].

Stress corrosion cracking is critical for highly stressed 7xxx components and for susceptible Al-Cu-Li states. It couples tensile stress, corrosive environment, and microstructural pathways for crack initiation and propagation. Chloride containing atmospheres, marine exposure, humidity, and residual stresses can all increase susceptibility. This is why aircraft alloy tempers are often selected for durability rather than peak strength alone [3], [18].

Corrosion fatigue is particularly important because aerospace structures operate under cyclic loading in variable environments. The literature shows that crack tip chemistry, loading frequency, humidity, chloride concentration, pit morphology, and pre corrosion history may substantially affect crack growth [10], [11]. Prediction models based on data driven approaches can support life assessment, but their reliability depends on high quality experimental datasets and representative environmental conditions [12].

Table II. Comparative Mechanical and Corrosion Property Ranges for Principal Aerospace Aluminium Alloy Families

Alloy Family / Examples	Representative Condition	Density (g cm ⁻³)	YS / UTS (MPa)	Ductility, Fatigue and Toughness	Corrosion and SCC Behaviour	Typical Aerospace Interpretation
2xxx Al-Cu-Mg: 2024, 2524	T3, T351 and damage-tolerant variants	2.77-2.78	320-390 / 430-480	El. 10-20%; good fatigue and crack-growth resistance; 2524 improves damage tolerance.	Moderate corrosion resistance; susceptible to pitting, intergranular attack and exfoliation; cladding, anodizing or coating normally required.	Best suited to fatigue-sensitive fuselage skins and damage-tolerant panels [1], [10], [11], [24].
7xxx Al-Zn-Mg-Cu: 7050, 7150, 7085	T7451, T7651, T7751 and related overaged tempers	2.80-2.85	430-540 / 480-590	El. 6-13%; very high static strength; toughness and fatigue performance depend strongly on temper and section thickness.	SCC and exfoliation are key limitations in peak-strength states; T7-type tempers improve SCC resistance with a strength trade-off.	Preferred for spars, frames, fittings, ribs, thick plates and heavily loaded metallic structures [1], [3].
Al-Cu-Li: 2050, 2195, 2198	T8, T84, T851 and related thermomechanical states	2.55-2.71	350-520 / 430-560	El. 6-14%; high specific strength and stiffness; anisotropy and texture are important design factors.	Intergranular corrosion, exfoliation and SCC depend on ageing condition, T1 precipitation, Cu/Li ratio and grain-boundary chemistry.	Attractive for advanced fuselage panels, cryogenic tanks and launch vehicle structures where mass saving is critical [4], [5], [18].
AM Al-Si-Mg: AlSi10Mg	LPBF/SLM plus stress relief, HIP, machining or T6-type treatment	2.65-2.68	200-330 / 320-460	El. 2-12%; fatigue scatter is controlled by porosity, lack-of-fusion defects and surface roughness.	Generally moderate-to-good corrosion resistance, but pitting and corrosion fatigue are strongly affected by AM defects and surface finish.	Useful for topology-optimized brackets, housings, ducts and heat exchangers when post-processing and inspection are controlled [6], [7], [17].
AM Al-Mg-Sc-Zr: Scalmalloy-type systems	LPBF/SLM plus ageing or tailored post-processing	2.65-2.70	350-520 / 450-560	El. 5-15%; high specific strength and improved printability; fatigue still depends on defect population and surface integrity.	Usually better intrinsic corrosion response than high-Cu and many 7xxx alloys, but AM porosity, roughness and galvanic contacts remain critical.	Promising for lightweight AM structural and secondary aerospace parts, especially where high strength and design freedom are required [6], [7], [19].

Note: YS - yield strength; UTS - ultimate tensile strength; El. - elongation; SCC - stress corrosion cracking; AM - additive manufacturing; LPBF - laser powder bed fusion; SLM - selective laser melting; HIP - hot isostatic pressing. The values summarize typical published ranges and should not be used as certified aerospace design allowables.

Surface engineering remains essential. Anodizing, conversion coatings, sol gel coatings, organic primers, plasma electrolytic oxidation, rare earth based systems, and hybrid organic inorganic coatings are used or investigated to improve corrosion resistance and service life [10]. At the same time, environmental and regulatory pressures require reduction of hazardous chromate systems and development of safer alternatives. Rare earth microalloying also offers a complementary route for improving thermal stability, precipitate control, and corrosion related performance in selected aluminium systems [19].

E. Joining and Structural Integration

Aerospace structures are assemblies rather than isolated materials; therefore joining technologies strongly influence structural reliability. Conventional joining includes riveting, mechanical fastening, adhesive bonding, fusion welding, and brazing, while advanced approaches include

friction stir welding, laser beam welding, hybrid joining, and solid state repair [16].

Friction stir welding is attractive for aluminium alloys because it avoids melting and can reduce solidification cracking and porosity. Nevertheless, it still produces heat affected and thermomechanically affected zones, local softening, texture changes, residual stresses, and possible fatigue hot spots. The fatigue performance of welded joints therefore depends on tool design, heat input, post weld treatment, joint geometry, surface finish, and inspection quality.

Laser beam welding is relevant where high productivity and narrow heat affected zones are required. A 2026 systematic review of laser beam welding of aluminium alloys emphasizes defect mitigation and process optimization, including control of porosity, hot cracking, keyhole instability, shielding, filler strategy, and parameter selection [23]. For Al-Li alloys, joining is especially

challenging because lithium volatility, hot cracking tendency, and precipitate modification can degrade joint performance. Thus, welding and repair should be considered together with alloy selection, heat treatment, and fatigue qualification.

F. Interpretation of the Reviewed Results

The sustainability value of aluminium alloys must be supported by recycling and life cycle evidence rather than by general statements alone. Aluminium is recyclable, but aerospace grade recycling is difficult because high strength alloys have narrow compositional limits and require strict melt cleanliness. Recent research on recycled aerospace grade 7075 sheets shows that with aerospace grade melt purification and quality control, recycled products can approach the microstructure and properties of primary sheet material and may offer economic benefits [26].

Aerospace aluminium scrap recycling also depends on energy flow, impurity control, sorting, alloy compatibility, and high end upcycling technologies. Reviews of aerospace aluminium scrap cycles highlight the need to avoid downgrading and to integrate refining, purification, and certification oriented quality control [27]. For Al-Li alloys, direct solid state recycling of machining chips into sheets by double sided friction stir consolidation has been reported as a promising route for recovering high value lightweight alloy material while producing sheets with useful strength and ductility [28].

Life cycle sustainability assessment is becoming increasingly important for aerospace manufacturing. Recent aerospace decarbonization literature links additive, subtractive, and hybrid manufacturing routes to energy consumption, waste, emissions, and circularity [29]. This supports the conclusion that material selection should include not only density and strength, but also resource efficiency, scrap generation, recycling route, process energy, and maintainability.

G. Limitations of the Review

The reviewed evidence suggests that the technological value of aluminium alloys in aerospace engineering is based on property balance rather than superiority in one isolated category. Titanium alloys provide excellent temperature capability and corrosion resistance, and polymer matrix composites offer substantial weight reduction in large integrated structures. Aluminium alloys remain competitive because they offer a mature and certifiable combination of strength, toughness, fatigue resistance, corrosion protection strategies, manufacturability, inspection capability, repairability, recyclability, and cost effectiveness [1], [2].

The strongest practical interpretation is that alloy selection is application dependent. For fatigue sensitive fuselage structures, 2xxx and selected Al-Li alloys remain attractive because of damage tolerance. For highly loaded structural elements, 7xxx alloys are suitable when corrosion and stress corrosion cracking are controlled. For cryogenic tanks and advanced lightweight structures, Al-Li alloys offer density and stiffness advantages. For brackets, ducts, housings, heat exchangers, and complex secondary

components, additively manufactured aluminium alloys are increasingly relevant, but only when defects and fatigue performance are controlled.

A second interpretation is that aerospace aluminium alloy research is moving from composition based improvement toward integrated control of composition, processing, microstructure, defects, surface condition, joining, and life cycle performance. This process microstructure reliability coupling gives the present review its practical value for engineering materials selection.

H. Practical and Theoretical Significance

A strategic comparison with polymer matrix composites and titanium alloys shows that aluminium alloys are most competitive in subsystems where balanced cost, manufacturability, inspectability, field repair, fatigue tolerance, and recycling are as important as minimum mass. In fuselage skins, lower wing skins, frames, ribs, stringers, floor beams, bulkheads, tanks, and many secondary structures, 2xxx, 7xxx, and Al-Li alloys provide a well-understood design allowables base and predictable forming, fastening, and repair behaviour. Carbon fibre composites can reduce weight in large integrated fuselage shells, wing boxes, control surfaces, and fairings, but they introduce different design drivers, including impact damage sensitivity, delamination, moisture and thermal effects, lightning strike protection, more demanding nondestructive inspection, and more complex end-of-life recycling [1], [2], [29].

Titanium alloys occupy a different strategic niche. They are preferred in high-temperature or chemically aggressive zones and at composite-metal interfaces, including engine-adjacent structures, pylons, firewalls, landing gear components, highly loaded fittings, fasteners, and areas where galvanic compatibility with carbon fibre composites is advantageous. Their higher density and cost, more demanding machining, and lower general formability limit their use in large-area airframe skins where aluminium or composites are more mass- and cost-efficient [1], [2], [16].

The resulting material strategy is therefore not a simple replacement sequence but a subsystem-level hybrid architecture. Aluminium alloys remain attractive for damage-tolerant pressurized fuselage structure, cryogenic and launch vehicle tanks, metallic wing and internal load-bearing elements, repairable secondary structures, and additively manufactured brackets or ducts. Composites are strongest where large-area integral stiffness and mass reduction dominate, while titanium is strongest where temperature capability, corrosion resistance, high bearing strength, or composite compatibility dominates. This comparison reinforces the main conclusion that aluminium alloys retain aerospace relevance because they occupy a broad, certifiable, economical, and repairable design space rather than because they outperform every competing material in every subsystem.

I. Limitations of the Review

The main limitation of this review is that it is based on published literature rather than new experimental testing. The reviewed studies differ in alloy designation, temper

condition, specimen geometry, process route, testing environment, loading regime, and evaluation method. This makes direct quantitative comparison difficult, especially for fatigue life, corrosion fatigue crack growth, fracture toughness, stress corrosion cracking resistance, and additive manufacturing performance.

A second limitation is that some aerospace alloy data, certified processing routes, and design allowables are proprietary or not fully described in open literature. Therefore, the review can identify trends and mechanisms but cannot replace certified design data or material qualification procedures.

A third limitation concerns the rapid development of additive manufacturing, hybrid manufacturing, environmentally safer coatings, and recycling routes. Some promising 2026 results remain at laboratory or early industrial validation level. They should be interpreted as emerging research directions rather than fully established aerospace standards.

J. Practical and Theoretical Significance

From a practical perspective, the results support a material selection approach based on structural function and service environment. High strength 7xxx alloys are appropriate for highly loaded structural elements; 2xxx and Al-Li alloys are appropriate where damage tolerance and weight reduction are important; and AM capable alloys are promising for complex lightweight secondary parts and repair provided that porosity, cracking, anisotropy, post processing, inspection, and fatigue qualification are addressed.

The findings are also relevant to maintenance and life extension. Since corrosion fatigue and surface degradation are major durability concerns, aerospace maintenance programs should combine inspection, protective coatings, corrosion monitoring, structural health monitoring, and predictive models. Data driven crack growth prediction may assist durability assessment, but must be trained and validated on representative alloy, temper, environment, and loading data [12].

From a theoretical perspective, the review highlights the need for models that link precipitation, grain structure, residual stress, defects, surface condition, environmental chemistry, and fatigue crack growth. This integrated approach is essential for next generation aluminium alloys, AM components, solid state repair technologies, and recycled aerospace grade materials.

IV. CONCLUSIONS

The literature synthesis indicates, rather than experimentally proves, that aluminium alloys remain essential aerospace engineering materials because they combine low density, high specific mechanical performance, mature processing routes, repairability, corrosion protection capability, recyclability, and economic efficiency. Their importance is not based on a single superior property but on a balanced set of engineering advantages.

The reviewed evidence suggests that the most important aerospace aluminium alloy systems are still 2xxx, 7xxx, and aluminium-lithium alloys. The 2xxx family is relevant for fatigue critical and damage tolerant structures; the 7xxx family is important for highly loaded components requiring high strength; and Al-Li alloys offer additional weight saving and stiffness benefits. However, their performance depends strongly on temper, precipitation state, grain structure, residual stress, surface condition, joining history, and environment.

The practical significance of the review is that aerospace material selection should be based on integrated criteria including strength, fatigue life, fracture toughness, corrosion resistance, stress corrosion cracking susceptibility, thermal stability, formability, joining behaviour, inspection, repairability, cost, and life cycle sustainability. This is especially important because reducing structural mass must not compromise safety, service life, or certification reliability.

At subsystem level, this means that aluminium alloys should be viewed as complementary to composites and titanium rather than as obsolete substitutes: composites dominate where large integrated stiffness and minimum mass are decisive, titanium dominates where temperature, corrosion resistance, and composite-interface compatibility are decisive, and aluminium remains strategically valuable where certified damage tolerance, manufacturability, repairability, and cost efficiency must be combined.

The review also identifies several directions for future research: better strength toughness corrosion balance in 2xxx, 7xxx, and Al-Li alloys; improved corrosion fatigue testing under realistic service environments; qualification of additively manufactured and hybrid manufactured aluminium components; defect mitigation in welding and solid state joining; chromium free surface protection; high value recycling of aerospace scrap; and predictive models for long term structural reliability.

Overall, the literature suggests that aluminium alloys will remain indispensable in aerospace engineering, but their future role will depend on the ability to integrate alloy design, microstructural control, advanced processing, surface protection, joining, recycling, and life cycle assessment into a unified materials engineering approach.

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Surface Modification of Steel 1.2343 (EN ISO 4957) by Ion Nitriding

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Abstract— The present study investigates the surface modification of tool steel 1.2343 (EN ISO 4957) by ion nitriding. Prior to the chemical–thermal treatment, the specimens were subjected to heat treatment consisting of vacuum quenching followed by triple tempering, ensuring structural stabilization before the diffusion process. Ion nitriding was carried out under two temperature–time regimes, namely 490°C for 16 h and 500°C for 11 h, in order to evaluate their influence on microstructure, hardness distribution, and tribological behaviour. Microstructural analysis revealed the absence of a compound (white) layer composed of ϵ and γ' phases, while a diffusion layer with a relatively uniform thickness of up to $\sim 250\ \mu\text{m}$ was observed. The effect of the nitriding parameters on surface hardness and hardness depth profiles—from the surface to the core—was systematically analyzed. In addition, tribological tests were performed to determine the coefficient of friction and wear characteristics of the treated surfaces. The results indicate that the applied nitriding regimes significantly influence the development of the diffusion layer and the surface properties, with the regime at 500°C providing a more favorable balance between hardness and tribological performance.

Keywords— coefficient of friction; ion nitriding; microstructure; vacuum quenching and tempering

I. INTRODUCTION

Hot-work tool steels are widely used under conditions of elevated temperatures and significant mechanical loads, typical for processes such as die casting, hot forging, and extrusion. Among them, steel 1.2343 (EN ISO 4957), belonging to the Cr–Mo–V class of tool steels, is characterized by a favorable combination of high strength, toughness, thermal fatigue resistance, and stability at elevated temperatures. These properties make it widely applied in the manufacturing of tools operating under severe service conditions [1–3].

The service performance of this steel largely depends on the applied heat treatment. Vacuum quenching combined with multiple tempering represents an established technological approach for obtaining a stable tempered structure with finely dispersed alloy carbides [4–6]. Stepwise heating to the austenitic region ensures a more uniform temperature distribution throughout the component, reduces thermal stresses, and promotes partial dissolution of carbides [7]. Gas cooling in vacuum furnaces, most commonly using nitrogen, allows minimization of distortion and achievement of high dimensional accuracy [8].

After quenching and tempering in the temperature range of 500–600 °C, a secondary hardening effect is observed, associated with the precipitation of fine alloy

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carbides. This process leads to increased resistance to hardness reduction and structural stability during operation at elevated temperatures [9–11]. The influence of alloying elements is essential for the formation of these properties. Chromium increases hardenability and participates in the formation of carbides and nitrides, molybdenum improves heat resistance and reduces tempering brittleness, while vanadium forms stable fine carbides and nitrides that limit grain growth and structural changes at elevated temperatures, thereby enhancing wear resistance and microstructural stability [12–14]. Silicon also plays a significant role in tempering resistance and diffusion processes, as it delays martensite decomposition and contributes to maintaining higher hardness during service.

Despite the favorable bulk properties, the surface of hot-work tool steels remains susceptible to wear, adhesion, and thermal fatigue. To improve surface performance, thermochemical treatments such as ion (plasma) nitriding are widely applied [15–17]. The process is carried out at relatively low temperatures (450–550 °C) under glow discharge conditions, where ionized nitrogen interacts with and diffuses into the surface, forming a hardened layer [18]. Compared to conventional gas nitriding, plasma nitriding offers better control of process parameters, higher efficiency, and reduced environmental impact [19].

As a result of ion nitriding, a multilayer surface structure is typically formed, consisting of a compound (white) layer and a diffusion zone. The compound layer mainly contains iron nitrides, while the diffusion zone is characterized by the formation of fine alloy nitrides of elements such as Cr, Mo, and V, which significantly contribute to increased hardness and wear resistance [20–22]. The thickness of the diffusion layer and the hardness distribution in depth strongly depend on the process parameters, particularly nitriding temperature and time [23].

An increase in nitriding temperature leads to accelerated diffusion processes and higher surface hardness but may result in a steeper hardness gradient and a reduced effective depth of the hardened layer. Conversely, lower temperatures favor the formation of a more uniform diffusion zone with a smoother hardness profile [24,25]. Therefore, the selection of optimal ion nitriding parameters requires a balance between surface hardness and diffusion layer depth.

In this context, the present study is focused on analyzing the influence of different ion nitriding regimes on the microhardness distribution and diffusion layer characteristics of steel 1.2343 (EN ISO 4957), previously subjected to vacuum quenching and multiple tempering. The main objective is to establish the relationship between process parameters and the formation of the nitrided layer, as well as to determine an optimal regime providing the best combination of high surface hardness and sufficient diffusion layer depth.

The scientific novelty of the present study consists in establishing the relationship between ion nitriding parameters, diffusion layer development, hardness distribution, and tribological behavior of vacuum-

quenched and tempered 1.2343 hot-work tool steel under different plasma nitriding regimes.

II. MATERIALS AND METHODS

The present study focuses on tool steel 1.2343 (EN ISO 4957), specified according to the standard BDS EN ISO 4957:2018 [26], with its chemical composition given in Table 1. This steel is primarily used for manufacturing tooling for hot plastic deformation processes. Its chemical composition complies with the standard requirements for Cr–Mo–V hot-work tool steels.

TABLE 1 CHEMICAL COMPOSITION OF STEEL 1.2343

[WT %]

Element	C	Si	Mn	Cr	Mo	V	Fe
wt. %	0.36 – 0.42	0.80 – 1.20	0.30 – 0.50	4.80 – 5.50	1.20 – 1.50	0.85 – 1.15	Rest

Cylindrical specimens with a diameter of $\phi 30$ mm and a thickness of 3 mm were machined from the as-received material. The specimens were prepared for microstructural analysis and microhardness measurements. Prior to heat treatment, the specimen surfaces were mechanically finished and cleaned in order to remove contaminants and ensure good repeatability of the results.

Tool steel 1.2343 (EN ISO 4957), belonging to the Cr–Mo–V class of hot-work tool steels, is characterized by a favorable combination of high strength, toughness, thermal fatigue resistance, and stability at elevated temperatures. Its performance strongly depends on the applied heat treatment, which provides the required balance between hardness and toughness, as well as an appropriate microstructure for subsequent surface modification.

The specimens were subjected to heat treatment consisting of vacuum quenching followed by triple tempering. Heating prior to quenching was carried out in a stepwise manner up to the austenitic region in order to ensure uniform temperature distribution throughout the material, reduce thermal stresses, and promote the dissolution of alloy carbides. The following temperature–time stages were applied: 650°C with a holding time of 30 min, 850°C for 20 min, and 1040°C for 20 min. The heating was performed under vacuum conditions, which prevented oxidation and decarburization and ensured a high surface quality.

After reaching the austenitic temperature and homogenization of the austenite, cooling was carried out in a nitrogen atmosphere at a pressure of 2.3 bar. This ensured a sufficiently high cooling rate for the formation of a martensitic structure with minimal distortion. As a result of quenching, a structure consisting of martensite and retained austenite was obtained, which required subsequent tempering for stabilization. After quenching, the specimens were subjected to triple tempering at temperatures of 500 °C, 520 °C, and 540 °C. During tempering, precipitation of fine alloy carbides occurs, leading to increased resistance to hardness reduction and improved stability of properties

at elevated temperatures. The applied heat treatment resulted in the formation of a stable tempered martensitic structure with a uniform distribution of carbides, providing a suitable substrate for subsequent ion nitriding.

Ion (plasma) nitriding was carried out in a specialized installation under two different temperature–time regimes: 490°C for 16 h and 500°C for 11 h. The process was performed in a gaseous atmosphere consisting of nitrogen and hydrogen under glow discharge conditions. The working gas pressure (ammonia) was maintained in the range of 0.8–0.9 bar. These conditions ensured effective surface activation and enhanced diffusion processes. After nitriding, the specimens were cooled in a controlled environment within the working chamber in order to minimize oxidation and preserve the formed surface layer. The selected regimes allowed investigation of the influence of temperature–time parameters on the formation of the diffusion layer and the hardness distribution in depth.

The thickness of the individual zones of the nitrided layer was determined by optical microscopy using an inverted optical microscope (Kern OLM 171, Kern GmbH, Germany), equipped with a color digital camera (ODC 832) and image analysis software. Prior to metallographic examination, the specimens were prepared by standard procedures including wet grinding and polishing with diamond paste and lubricant, followed by chemical etching using a 4% alcoholic HCl solution for 14 s.

Microhardness measurements were performed using a HVS-1000 hardness tester (Jinan Hengxu Test Technology Co., Ltd., Jinan, China) after heat and thermochemical treatment, including measurements along the depth of the nitrided layer. The tests were carried out using the Vickers method with a load of 0.1 kg ($HV_{0.1}$), in accordance with BDS EN ISO 6507-1:2024 [27].

Tribological tests were conducted to determine the coefficient of friction and to evaluate the influence of ion nitriding on the tribological behavior of 1.2343 steel. The experiments were performed under dry sliding conditions at room temperature. A normal load of 10 N was applied, the sliding speed was 100 rpm, and the test duration was 3 min (sliding distance of 24 m). A ball-on-disc configuration was used with three balls of 6.37 mm diameter, positioned at 120° relative to each other. The balls were located on a diameter of 25 mm relative to the rotational axis and were made of 100Cr6 steel with a hardness of 830 $HV_{0.1}$.

III. RESULTS AND DISCUSSION

The optical metallographic analysis of specimens subjected to ion nitriding at 490°C/16 h and 500°C/11 h reveals the formation of a clearly defined diffusion layer without the presence of a compound (white) layer (Figures 1 and 2). In both regimes, a gradual transition between the nitrided layer and the substrate is observed, indicating a uniform progression of diffusion processes.

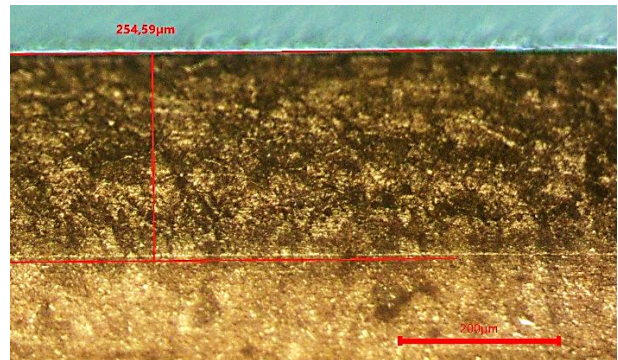


Fig. 1. Microstructure of the nitrided layer of steel 1.2343 after ion nitriding at 490°C for 16h

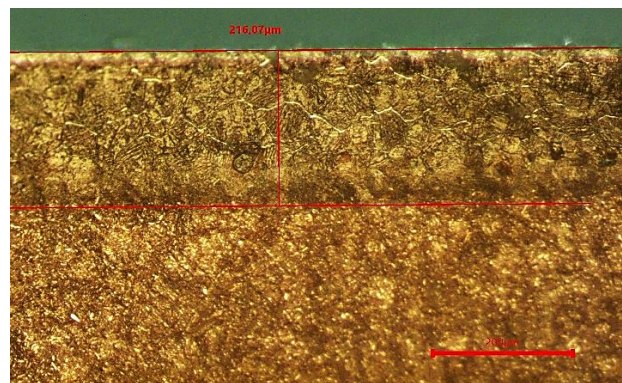


Fig. 2. Microstructure of the nitrided layer of steel 1.2343 after ion nitriding at 500°C for 11h

For the regime 490°C/16 h, a diffusion layer with a thickness of approximately 250 μm is formed, characterized by a relatively uniform microstructure and a gradual transition toward the substrate. The microhardness profile shows high values near the surface ($\sim 627 HV_{0.1}$), which remain relatively constant up to a depth of about 120 μm . With increasing depth, a gradual decrease in hardness is observed, reaching approximately 535 $HV_{0.1}$ at a depth of 300 μm . This smooth decrease in hardness is consistent with the uniform nature of the diffusion layer. In contrast, for the regime 500°C/11 h, a thinner diffusion layer ($\sim 216 \mu\text{m}$) is formed, characterized by a more pronounced transition to the substrate. However, the surface hardness is significantly higher, reaching values of approximately 698 $HV_{0.1}$. With increasing depth, a more pronounced decrease in hardness is observed, reaching about 553 $HV_{0.1}$ at the diffusion layer boundary and approximately 528 $HV_{0.1}$ at a depth of 300 μm . The observed steeper hardness profile is consistent with the reduced layer thickness and more intensive surface hardening. A comparison of the microstructural features and hardness profiles indicates that at lower temperature and longer nitriding time (490°C/16h), a deeper and more uniform diffusion layer is formed, with a gradual variation of properties in depth. In contrast, at higher temperature and shorter time (500°C/11h), higher surface hardness is achieved at the

expense of reduced layer thickness and a steeper property gradient.

Ion nitriding is a diffusion-controlled process in which nitrogen penetrates the surface layer under glow discharge conditions, with temperature, time, and chemical composition playing a key role [7,12]. For steel 1.2343, containing alloying elements such as Cr, Mo, and V, the nitriding process leads to the formation of a complex microstructure consisting of nitrogen in solid solution in ferrite and dispersed nitride phases [10,15]. Under the investigated conditions, no compound (white) layer consisting of ϵ -Fe₂₋₃N and γ' -Fe₄N phases is observed, indicating that the process proceeds predominantly in the diffusion regime [9,12]. In this case, nitrogen diffuses into the material and interacts with alloying elements, leading to the formation of stable alloy nitrides such as CrN, VN, and Mo₂N [10,18]. Chromium, as the primary alloying element, shows a strong tendency to form CrN nitrides, which contribute to increased hardness and wear resistance [10,15]. Vanadium forms highly stable and finely dispersed VN nitrides, which enhance strengthening through a dispersion mechanism and hinder dislocation motion [18]. Molybdenum forms nitrides of the Mo₂N type, improving heat resistance and microstructural stability at elevated temperatures [6,10].

The formation of these nitride phases leads to a significant increase in surface hardness and improved resistance to plastic deformation. Furthermore, the fine and uniform distribution of nitrides contributes to a more homogeneous stress distribution under loading and reduces the tendency for localized wear [15,18]. The absence of a compound (white) layer is beneficial for service performance, as this layer, despite its high hardness, is characterized by increased brittleness and a tendency for crack initiation and propagation [17,21]. Therefore, the obtained structure, consisting primarily of a diffusion layer with dispersed nitrides, provides better adhesion to the substrate and improved wear resistance [18,22]. The comparison between the two regimes shows that at lower temperature and longer duration (490°C/16h), diffusion processes penetrate deeper into the material, resulting in a thicker diffusion layer [15,16]. At higher temperature (500°C/11h), phase formation kinetics are enhanced, leading to stronger surface hardening and, consequently, improved tribological performance [10,18].

Tribological tests conducted under dry sliding conditions demonstrate a significant effect of ion nitriding parameters on the coefficient of friction and wear behavior of the investigated steel (Figure 3).

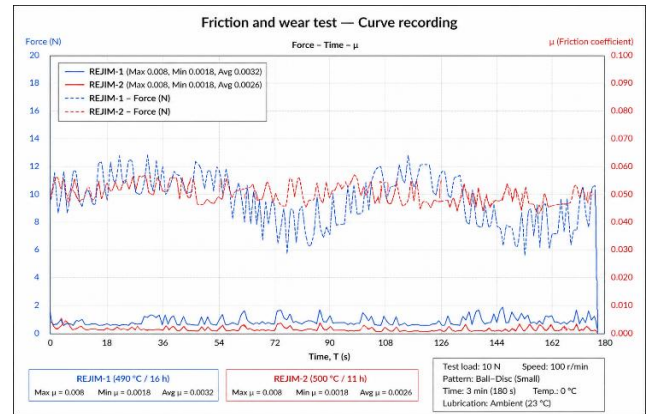


Fig. 3. Variation of the coefficient of friction (μ) as a function of time under dry sliding conditions for ion-nitrided 1.2343 tool steel: comparison between the regimes 490°C/16 h and 500°C/11 h.

As shown in the presented curves, the coefficient of friction exhibits relatively stable behavior over time for both regimes, while lower values and reduced fluctuation amplitude are observed for the 500°C/11h regime, indicating a more stable tribological contact. The average values of the coefficient of friction are $\mu \approx 0.0032$ for the 490°C/16h regime and $\mu \approx 0.0026$ for the 500°C/11h regime, with the lower value for the latter indicating more favorable tribological performance. The low values of the coefficient of friction are directly related to the enhanced wear resistance achieved through the formation of a diffusion layer enriched with fine nitrides of alloying elements (Cr, Mo, and V). These nitrides significantly contribute to increased hardness and resistance to plastic deformation in the contact zone, thereby limiting the development of adhesive and abrasive wear mechanisms [18,21,22]. For the 490°C/16h regime, a deeper diffusion layer is formed, providing a more uniform distribution of mechanical properties in depth. This results in improved load-bearing capacity and more stable behavior under prolonged loading, as stresses are distributed over a larger material volume. Such a structure is characterized by higher resistance to friction fatigue and a lower tendency toward localized wear [18,23]. In contrast, the 500°C/11h regime results in higher surface hardness, leading to a lower coefficient of friction and reduced intensity of adhesive wear. The increased hardness reduces the real contact area and, consequently, the adhesion forces between the contacting surfaces, which is consistent with literature data [21,22]. For both regimes, the absence of a compound (white) layer plays a significant role in wear behavior. Although this layer may exhibit high hardness, it is typically characterized by increased brittleness and a tendency for crack initiation and propagation, leading to localized material removal under loading. Its absence promotes better adhesion between the surface layer and the substrate, resulting in more stable wear behavior without abrupt surface degradation [17,21]. During tribological testing, the formation of a thin transfer layer is also possible, acting as a solid lubricating film and contributing to the reduction of friction and wear, which is typical for

nitrided steels [22]. The comparison of the results (Figure 3) shows that wear behavior is governed by different factors for the two regimes: at 490°C, the dominant factor is the deeper and more uniform diffusion layer, while at 500°C, the higher surface hardness plays the leading role. As a result, the 500°C/11h regime provides the best combination of low friction coefficient and high wear resistance, whereas the 490°C/16h regime ensures greater diffusion layer depth and a more gradual variation of properties in depth.

IV. CONCLUSIONS

Based on the conducted experimental investigations on ion nitriding of tool steel 1.2343, it can be concluded that for both applied regimes (490°C/16h and 500°C/11h), a clearly defined diffusion layer is formed without the presence of a compound (white) layer.

For the 490°C/16h regime, a deeper and more uniform diffusion layer with a thickness of approximately 250 µm is formed, characterized by a gradual hardness variation in depth and good load-bearing capacity. In contrast, the 500°C/11h regime leads to higher surface hardness, reaching values of up to approximately 698 HV_{0.1}, accompanied by a more pronounced decrease in hardness with increasing depth, indicating more intensive surface hardening.

The tribological investigations reveal very low values of the coefficient of friction for both regimes, with the lowest average value ($\mu \approx 0.0026$) obtained for the 500°C/11h regime. This behavior is associated with the formation of a diffusion layer enriched with alloy nitrides, which increase hardness, limit plastic deformation, and suppress adhesive and abrasive wear mechanisms.

A comparison of the results indicates that the 500°C/11h regime provides the best combination of high surface hardness and low coefficient of friction, whereas the 490°C/16h regime is characterized by a deeper and more uniform diffusion layer with improved load-bearing capacity. The obtained results demonstrate that optimization of ion nitriding parameters enables significant improvement of the surface properties of hot-work tool steels and represents an effective approach for enhancing their service performance.

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Investigation the Influence of Multi-Walled Carbon Nanotubes and Amorphous Carbon on the Mechanical Properties of Thermosetting Polymers

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Abstract—Composites based on thermosetting polymers (epoxy, polyester and vinylester resins) with integrated carbon particles have been developed. MWNTs and amorphous carbon, a waste product from the production of "green" hydrogen, have been used. The influence of different concentrations (0.02 wt %, 0.06 wt % and 0.1 wt %) of the two types of particles used on the mechanical properties of the developed composites has been studied, a comparative analysis has been conducted. The results of the studies show that the two types of carbon particles used reduce the tensile strength, but increase the hardness and impact toughness of the resulting composite compared to pure epoxy resin. The composite based on polyester resin with integrated MWNTs has reduced impact toughness, but with significantly higher hardness values compared to the resin used. A relative elongation of the newly obtained material was also registered, and at a concentration of 0.02 wt% MWNTs an increase in tensile strength was registered. The addition of amorphous carbon to the polyester resin has a positive effect on the mechanical properties of the resulting composite. Relative elongation, increased hardness, impact toughness, and higher values of tensile strength were registered. The amorphous carbon and MWNTs used are the basis for obtaining a composite with a vinyl ester resin matrix with

improved mechanical properties. The different concentrations of the two types of carbon particles contribute to obtaining composites with improved mechanical properties compared to pure resin. In this case, multi-walled carbon nanotubes have a greater influence on the studied characteristics compared to amorphous carbon.

Keywords— *amorphous carbon, composites, mechanical properties, MWNTs, thermosetting polymers*

I. INTRODUCTION

The development of modern nanocomposites is closely related to the optimization of polymer matrices by incorporating carbon nanomaterials. Epoxy, polyester and vinylester resins occupy a central place in the industry due to their excellent technological properties, but their high brittleness and low electrical conductivity often limit their application in critical structures.

Carbon nanotubes (CNTs) are an allotropic form of carbon with a one-dimensional (1D) structure. Depending on the number of concentric graphene layers they are made of, they are classified as single-walled (SWCNTs) and

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multi-walled (MWCNTs). Despite their enormous potential, the integration of CNTs in industrial applications is associated with various challenges related to purity control, dispersion in different matrices and precise surface functionalization.

Amorphous carbon (a-C) is an allotropic form of carbon characterized by the lack of long-range order in its atomic structure. In contrast to the well-defined crystal lattices of diamond (sp^3 hybridization) and graphite (sp^2 hybridization), amorphous carbon is a metastable phase consisting of a mixture of these two states. In recent years, interest in amorphous carbon materials has grown significantly due to their exceptional adaptability. The integration of carbon nanotubes (CNTs) and amorphous carbon as stand-alone modifiers offers radically different approaches to overcome these shortcomings.

While multi-walled carbon nanotubes (MWCNTs) are considered as highly effective structural reinforcing agents capable of significantly improving mechanical strength and elastic modulus at minimal concentrations, amorphous carbon remains the preferred choice for modifying the physicochemical and protective properties of polymers. The effectiveness of these fillers depends not only on their morphology but also on the specific interactions with the thermosetting matrix—from high adhesion in epoxy systems to shrinkage and thermal stability in vinylester and polyester resins.

This paper investigates and compares the individual effects of MWCNTs and amorphous carbon on the mechanical properties of epoxy, polyester, and vinylester resins.

II. MATERIALS AND METHODS

In this study, composites based on a polymer matrix and with carbon particles integrated into them were developed. The following thermosetting polymers were used as matrices of the composites: epoxy resin - "LETOXIT" PR 227, polyester resin - "DISTITRON" 429 BSX25Q and vinyl ester resin - "DISTITRON" VE 100). For the polymerization of the indicated polymers, the following hardeners were used - "LETOXIT" EM 315 for the epoxy resin, "MEKR 50" for the polyester resin, "MEKR 50" and accelerator "MEKR" for the vinyl ester resin, and for the preparation of the resin systems, the ratios prescribed by the manufacturer were observed [1].

In recent years, a number of researchers have integrated carbon nanotubes (CNTs) into polymer matrix composites due to their good mechanical, electrical and thermal properties [2]-[17]. Amorphous carbon is a waste product in the production of pure hydrogen using catalytic methane decomposition, and due to its exceptional adaptability, there is considerable interest in it [18]-[30]. Two types of carbon particles were used for the studies. One is multi-walled carbon nanotubes (MWCNTs) with a length $\geq 2 \mu m$, a diameter of 10 - 40 nm, a number of walls of 10 - 20 and a specific surface area of 55 m^2/g . The second type of carbon particles is amorphous carbon with a composition: carbon (C) content of 99.1 at % and oxygen (O_2) content of

0.9 at %. The two types of carbon particles were used in three concentrations: 0.02 wt %, 0.06 wt % and 0.1 wt %.

The developed composites were obtained by mechanical dispersion of the used carbon particles in the liquid resin systems. In order to ensure maximum breaking of the larger agglomerates, intensive mechanical stirring was carried out. The preparation, casting and curing of the composites was at room temperature (25° C according to the manufacturers' prescription), with the epoxy resin-based test bodies undergoing secondary polymerization at the manufacturer's prescribed temperature (55° C) and process duration (12 h) [1].

The uniaxial tensile test was conducted using a Zwick Roell Z050 testing machine, the hardness of the developed composites was measured using the Shore method (D - HSD scale) using an EQUOTIP hardness tester, and impact toughness was examined using the Izod Impact Test.

III. RESULTS AND DISCUSSION

The results of the mechanical tests conducted on the developed composites with epoxy resin matrix "LETOXIT" PR 227 and both types of carbon particles used are presented in Table 1 and Table 2.

TABLE 1 RESULTS OF MECHANICAL TESTS OF EPOXY RESIN AND MWCNTs COMPOSITE

MWNTs [wt. %]	σ_m [MPa]	ε [%]	HSD	KCV _{1/10,2} [J/cm ²]
0 wt. %	49	0.8	76.7	0.180
0.02 wt. %	31.5	0.3	83.2	0.250
0.06 wt. %	26.9	0.7	84.5	0.729
0.1 wt. %	19.8	0.5	84.1	0.313

TABLE 2 RESULTS OF MECHANICAL TESTS OF EPOXY RESIN AND A-CARBON COMPOSITE

a-Carbon [wt. %]	σ_m [MPa]	ε [%]	HSD	KCV _{1/10,2} [J/cm ²]
0 wt. %	49	0.8	76.7	0.180
0.02 wt. %	45	1.2	82.2	0.225
0.06 wt. %	36.9	0.7	83.4	0.604
0.1 wt. %	23.5	0.2	80.8	0.238

The integration of multi-walled carbon nanotubes into the epoxy matrix has a positive effect only on the hardness and impact toughness of the resulting composites. A significant decrease in the tensile strength and a slight decrease in the relative elongation of the newly obtained materials were recorded. When using other carbon particles (a-Carbon), the results are similar. It is noteworthy that when using a concentration of 0.06 wt % of the carbon materials used, the developed composites have the highest values of impact toughness and hardness. The results obtained when using the lowest concentration (0.02 wt %) of amorphous carbon are of interest. At this concentration of carbon particles, a slight decrease in the tensile strength

of the composite was recorded, but an increase in hardness, impact toughness and the highest value of relative elongation were measured. The composite prepared in this way based on an epoxy matrix has an optimal set of mechanical properties. Based on the results obtained, we can say that when developing a composite with an epoxy resin as the base, the use of amorphous carbon is preferred over MWCNTs.

Table 3 and Table 4 show the results of the tests conducted on composites based on polyester resin "DISTITRON" 429 BSX25Q and the two types of carbon particles used.

TABLE 3 RESULTS OF MECHANICAL TESTS OF POLYESTER RESIN AND MWCNTs COMPOSITE

MWNTs [wt. %]	σ_m [MPa]	ε [%]	HSD	KCV _{1/10,2} [J/cm ²]
0 wt. %	34.8	0	79.8	0.03
0.02 wt. %	37.3	1.1	88.7	0
0.06 wt. %	31.6	0.9	91.4	0
0.1 wt. %	31.6	0.6	90.4	0.0625

TABLE 4 RESULTS OF MECHANICAL TESTS OF POLYESTER RESIN AND A-CARBON COMPOSITE

a-Carbon [wt. %]	σ_m [MPa]	ε [%]	HSD	KCV _{1/10,2} [J/cm ²]
0 wt. %	34.8	0	79.8	0.03
0.02 wt. %	37.7	0.5	91.0	0
0.06 wt. %	38.7	0.3	91.8	0.125
0.1 wt. %	34.9	0.4	89.4	0.0875

The MWNTs used in the developed composites based on polyester resin "DISTITRON" 429 BSX25Q have a positive effect on their mechanical properties. At a concentration of 0.02 wt. %, an increase in the tensile strength, relative elongation and hardness of the newly obtained material compared to the base polymer was recorded, but the impact toughness was reduced. The tendency to increase the hardness and relative elongation is also preserved when using 0.06 wt. % MWNTs, but a slight decrease in the strength of the composite compared to the polyester resin was recorded. Increasing the amount of these carbon particles to 0.1 wt. % is the basis for obtaining a composite with the best balance of mechanical properties. After integrating amorphous carbon particles into the polyester matrix, composites with increased properties were obtained. Only at a concentration of 0.02 wt. % was no positive effect on the impact toughness of the composite compared to the starting resin. The highest mechanical properties are possessed by the composite with 0.06 wt. % amorphous carbon integrated into it. As with epoxy and polyester resins, waste amorphous carbon has a better effect on the mechanical properties of the developed composites.

Unlike the cases considered so far, in which amorphous carbon had a more favorable effect on the mechanical

properties of composites based on epoxy and polyester resin, in the case of the vinylester resin "DISTITRON" VE 100, the MWCNTs used had a more favorable effect. It was found that at all three concentrations of carbon nanotubes used, the mechanical properties of the composites are higher than the initial values of the base polymer, with the exception of the impact toughness of the composite with 0.02 wt. % MWCNTs (Table 5). The obtained values for the tensile strength are also higher than the values of the same indicator of the composites in the composition of which the same amounts of amorphous carbon are integrated, and the values of the other studied characteristics are comparable (Table 6).

TABLE 5 RESULTS OF MECHANICAL TESTS OF VINYLESTER RESIN AND MWCNTs COMPOSITE

MWNTs [wt. %]	σ_m [MPa]	ε [%]	HSD	KCV _{1/10,2} [J/cm ²]
0 wt. %	20.5	0	75.7	0.039
0.02 wt. %	45.2	0.8	86.3	0
0.06 wt. %	38.3	1.1	85.6	0.475
0.1 wt. %	31.5	0.7	84.9	0.588

TABLE 6 RESULTS OF MECHANICAL TESTS OF VINYLESTER RESIN AND A-CARBON COMPOSITE

a-Carbon [wt. %]	σ_m [MPa]	ε [%]	HSD	KCV _{1/10,2} [J/cm ²]
0 wt. %	20.5	0	75.7	0.039
0.02 wt. %	18.5	0.7	85.8	0.375
0.06 wt. %	26.9	0.9	84.2	0.350
0.1 wt. %	26.7	0.5	85.7	0.475

Table 6 presents the results of mechanical tests of composites made of vinylester resin "DISTITRON" VE 100 with amorphous carbon particles integrated into it. The minimum amount used of 0.02 wt. % leads to an increase in hardness, impact toughness and relative elongation at a comparable value of the tensile strength of the composite with that of the base resin. With increasing concentrations of the particles used, no significant changes are observed in the hardness of the composites, but the tensile strength increases. The highest value of relative elongation is registered at a quantity of 0.06 wt. % a-Carbon, and the highest value of impact toughness at 0.1 wt. % a-Carbon.

The development of innovative composite materials with a polymer matrix and carbon particles embedded in it, which should have increased mechanical and operational characteristics, including those intended for the construction of systems and devices for detecting and countering low-flying unmanned aerial vehicles, is a current engineering topic. This study examines the possibility of expanding the spectrum of composite materials with a polymer matrix by using thermosetting polymers and carbon particles. At present, waste amorphous carbon has found application mainly in the processing and vulcanization of rubber mixtures, due to its

morphology and the average diameter of its particles. The results of the mechanical tests conducted show that in certain cases, composites with reinforcing waste amorphous carbon particles have properties competing with composites with MWCNTs integrated into them. Obtaining a machine-building material using a waste product, in addition to engineering, has an ecological and economic aspect. By implementing the waste obtained from an innovative technology for producing green hydrogen into a construction material, this technology becomes completely waste-free, i.e. it does not have a negative impact on the environment.

IV. CONCLUSIONS

The integration of 0.02 wt % amorphous carbon in an epoxy matrix leads to the production of a composite with an optimal set of mechanical properties.

The use of MWNTs in an amount of 0.1 wt. % is the reason for the production of a composite based on a polyester resin with the best balance of mechanical properties.

It has been established that waste amorphous carbon has a better effect on the mechanical properties of the developed composites with epoxy and polyester resin bases.

The used MWCNTs have a more favorable effect on the mechanical properties of the vinyl ester resin compared to amorphous carbon. It has been established that at all three used concentrations of carbon nanotubes, composites with increased mechanical properties were obtained.

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Investigation of Differences in Light Transmission in Translucent Materials Used in Additive Manufacturing

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Abstract— The present study investigates the impact of filament colour and specimen thickness on overall light transmittance in fused deposition modelling printed transparent PETG. Flat specimens were prepared in six transparent colour variants (transparent, blue, neon green, orange, red, and yellow) and in thicknesses ranging from 1.0 to 3.5 mm. The measurements were conducted within a custom-built enclosed laboratory stand, thereby ensuring the elimination of ambient light interference. In order to verify the result stability, the transmitted light was measured at four nominal source power levels (200, 2600, 6600, and 10600 lx) and evaluated as normalized transmittance. For all of the materials that were analysed, there was a decrease in transmittance as specimen thickness increased. Transparent PETG demonstrated the highest transmittance from 1.0 to 2.5 mm, while yellow PETG exhibited the highest values at 3.0 and 3.5 mm. In the present study, the lowest transmittance was exhibited by blue PETG at all thickness levels, with the approach of complete attenuation being observed in thicker specimens. Neon green exhibited an intermediate level of transmission, while orange and red demonstrated comparatively reduced transmission following a notable decline between 1.0 and 1.5 mm. The normalized values were found to be consistent across the higher source power settings, thereby supporting the reliability of the measured attenuation trends. The findings of this study demonstrate that transparent tinted PETG filaments cannot be regarded as optically equivalent, and that specimen thickness is a significant factor in determining attenuation in printed components.

Keywords— *additive manufacturing, attenuation, fused deposition modeling, PETG, light transmittance, translucent materials*

I. INTRODUCTION

Additive manufacturing is increasingly utilised for the fabrication of polymer components that are expected to transmit visible light, including lamp covers, optical housings, façade elements, and microfluidic devices [1, 2, 3, 4]. In such instances, the optical performance is not solely governed by the polymer type. The quantity of light that traverses a printed element is contingent on the material itself, the optical path length through the component, and the internal structure that is formed by filament deposition and layer stacking [1, 2, 5, 6]. In the context of translucent FDM materials, it is imperative to acknowledge that both specimen thickness and filament colour can exert a substantial influence on the ultimate attenuation.

In the realm of FDM materials, PETG stands out as a particularly noteworthy contender. This is due to its unique amalgamation of printability, impact resistance, and a notable degree of transparency, as evidenced by numerous studies [1, 3, 7]. This renders it particularly appealing for applications where light transmission is of paramount importance. Recent research in the field of PETG has provided evidence that specimens produced by the FDM method can exhibit high levels of transparency, provided

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that the manufacturing conditions are suitably optimised [1, 3, 5, 7]. However, it is evident that the printed state deviates from the bulk material. The phenomenon of light transmission is influenced by the geometry of deposited roads, layer interfaces, and internal scattering that is introduced during the FDM process [1, 2, 5]. Consequently, it is imperative that transmittance and attenuation are evaluated on printed specimens, as opposed to being assumed from nominal filament properties alone.

The extant PETG literature is characterised by a lack of uniformity in scope. The majority of extant studies concentrate on the manner in which printing conditions can be optimised to maximise transparency or image visibility [1, 3, 5, 7]. The significance of this work lies in its demonstration of the profound impact of processing on optical performance. However, it provides less direct evidence for a related inquiry: namely, how the transmission of light is influenced by variations in specimen thickness and filament colour when these factors are manipulated as the primary variables. In the context of PETG, there is a notable absence of controlled comparisons of transparent coloured filaments tested across a thickness series. Instead, greater emphasis is placed on process optimisation, post-treatment, and application-specific transparency, with the result that the subject is much better documented [1, 5, 7].

Research consistently indicates that thickness is the most supported optical factor across the relevant literature. The findings of PETG-specific studies suggest that an increase in the optical path results in a decrease in transparency. This is due to the fact that high transmission is only maintained under print conditions that are meticulously controlled and under relatively favourable specimen formation [1, 3, 5]. Broader FDM literature elucidates this effect. Hamp et al. conducted a study in which they measured the transmittance of printed samples of varying thicknesses. Their findings indicated that the level of transmission was predominantly influenced by the thickness and colour of the samples [6]. As demonstrated by related studies on translucent PLA, an increase in thickness has been shown to result in a reduction in transmitted light [8, 9]. These results provide substantial support for the hypothesis that, in PETG, the attenuation of specimens will be greater the thicker they are.

The impact of colour is less thoroughly documented in the context of PETG, though it is improbable that its effect is negligible. The most robust PETG papers are those which focus on transparent materials, and they do not make a comparison between several transparent tinted PETG filaments within a single measurement protocol [1, 3, 5, 7]. Evidence pertaining to the broader field of FDM indicates that this is not merely a minor omission, but rather a significant gap. As demonstrated by Hamp et al., colour was identified as a primary factor contributing to disparities in transmittance observed in printed materials [6]. Research conducted on translucent FDM filaments has demonstrated that pigments and additives have the capacity to modify the absorption, scattering, and the spectral character of transmitted light. This effect has been observed to intensify

in proportion to the optical path length [8, 10, 11]. It is important to note that even when the polymer family remains constant, the transparent blue, red, yellow, orange, and neon green materials should not be assumed to attenuate light in the same manner.

As indicated by the extant literature, the attenuation of FDM-printed polymers is not always adequately described by a simple homogeneous slab model. As Hamp et al. reported, the application of a simple exponential relation between thickness and transmission was limited by multiple scattering [6]. The hypothesis that light loss in FDM parts is attributable to both absorption and structure-dependent scattering is corroborated by related research on printed translucent materials and appearance modelling [2, 10]. This is a salient consideration in experimental design, as it underscores the significance of practical measurements of overall transmittance, even in circumstances where the underlying optical behaviour exhibits greater complexity than that of pure bulk absorption.

The extant literature on measurement supports the use of controlled specimen series and shielded test arrangements. It is evident that a number of the most prominent publications employ flat samples of defined thickness, stable illumination, and a controlled light path to facilitate a comparison of the transmitted light between specimens [1, 6, 9, 12]. Despite the variation in instrumentation across studies, the fundamental logic remains constant. The reliability of direct comparison is enhanced when the environment is fixed and only one variable is modified at a time [1, 6, 12]. This is particularly pertinent in the context of brief experimental studies, where methodological consistency can serve as a compensatory mechanism for the absence of comprehensive optical characterisation.

A comprehensive review of the extant literature indicates that PETG is a promising transmissive FDM material. However, the current evidence base remains limited in terms of systematic comparisons focused on colour and specimen thickness. A review of extant PETG studies reveals a predominant focus on enhancing transparency through process optimisation. Conversely, a survey of broader FDM studies suggests that both thickness and color can significantly affect the transmission of light [1, 5, 6, 8]. It is evident that there is a clear necessity for comparative data acquired on printed PETG specimens of varying colours and thicknesses under a single stable measurement method. The analysis of such data can facilitate a more comprehensive understanding of the attenuation behaviour exhibited by transparent PETG filaments. Furthermore, it has the potential to broaden the existing literature by expanding its scope beyond the current emphasis on either clear specimens or processing parameters alone.

In this context, the present study investigates overall light transmittance in FDM-printed transparent PETG specimens as a function of colour and thickness. The samples were prepared in six transparent colour variants — transparent, blue, orange, neon green, yellow, and red —

and in thicknesses of 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 mm. The objective of the study is twofold: firstly, to generate directly comparable attenuation data by testing all specimens on the same closed laboratory stand; and secondly, to address the lack of systematic evidence for transparent coloured PETG in the current FDM optics literature.

II. MATERIALS AND METHODS

A. Materials

The study is carried out using transparent PETG filament materials intended for FDM printing. Six transparent colour variants are selected: transparent, blue, orange, neon green, yellow and red. Using one polymer family with several transparent colour variants makes it possible to examine the effect of colour while limiting the influence of large differences in base chemistry. This approach is consistent with previous work on FDM optics showing that colour can significantly impact transmitted light, even when the underlying printing process remains the same [1, 3, 5]. The main factors and used levels are showed in table 1. All used filaments are with a diameter of 1.75 mm, kept in zip-tie bag with silica gel to avoid additional moisture. The materials utilised in the production process are sourced from a variety of manufacturers, primarily due to the fact that not all manufacturers offer the complete range of semi-transparent colours.

TABLE 1 FACTORS AND LEVELS

№	Influencing factors and levels used	
	Factors	Levels used
1	Material	PETG
2	Printing technology	FDM
3	Colours	Transparent, blue, orange, neon green, yellow, red
4	Nominal thickness	1.0, 1.5, 2.0, 2.5, 3.0, 3.5 mm
5	Nominal source power levels	200, 2600, 6600, 10600 lx.

Flat specimens with constant nominal thickness were prepared for optical testing. A thickness series is commonly used in transmission studies of printed polymers because it allows direct comparison of attenuation as the optical path increases [1, 2, 3]. Each specimen group differed only in colour and nominal thickness, while the remaining design features were kept constant. Table 2 shows the main parameters and factors and variables used in specimen design and fabrication. Figure 1 shows the geometry of the tested specimens.

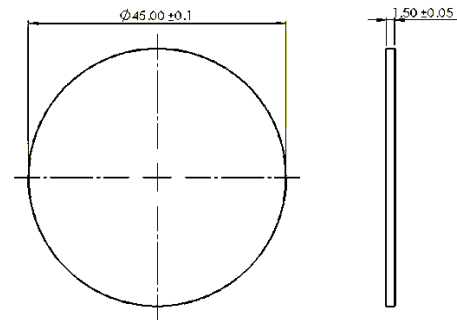


Fig 1. Test specimen Ø45 mm; thickness – 1.5 mm.

TABLE 2 PARAMETERS AND DRAFT DESCRIPTION

№	Specimen parameters and draft description	
	Factors	Levels used
1	Specimen geometry	Flat plate specimens
2	Thickness	1.0 to 3.5 mm in 0.5mm steps
3	Variable factors	Colour and thickness
4	Verification factor	Nominal source power
5	Fixed factors	All remaining print settings held constants for all samples

Specimens were manufactured by FDM printing on a Prusa Mk4S using a 0.4 mm nozzle. Printing is performed with fixed settings for nozzle temperature, bed temperature, layer height, print speed, cooling, extrusion multiplier, infill strategy, and print orientation. These parameters should be reported explicitly because PETG transparency is known to depend on print formation conditions [3, 5, 6]. For the present study, however, such parameters were held constant so that the primary comparison remained centered on color and specimen thickness. Printing conditions are shown in table 3.

TABLE I. PRINTING PARAMETERS

№	Specimen parameters and draft description	
	Parameters	Levels used
1	Printer	Prusa Mk4S
2	Slicer	Prusa SlicerR 2.9.4
3	Nozzle temperature	245 °C
4	Bed temperature	85 °C
5	Layer height	0.15 mm
6	Print speed	Up to 200 mm/s
7	Infill	15 %
8	Infill pattern	Grid
9	Cooling setting	Basic

Overall light transmittance is measured using a laboratory stand designed and manufactured before the present study. The stand is largely 3D printed and fully

enclosed, so that environmental light does not affect the measurement. A closed optical path is appropriate for comparative transmittance testing because it improves repeatability and reduces uncontrolled variation from ambient light [1, 2]. Figure 2 shows the used stand. The test samples are then placed in the holders (8), which have been specially designed for this purpose. The holders are then placed in the test stand (3). The lid (4) is then closed, and the measurement process begins. Sensors (6) are employed to monitor both the ambient temperature and the temperature of the light source. The measuring sensor is located in cover 2; 1 is the test stand; 5 is the cooling element; and 7 is a fan that activates when additional cooling is required.

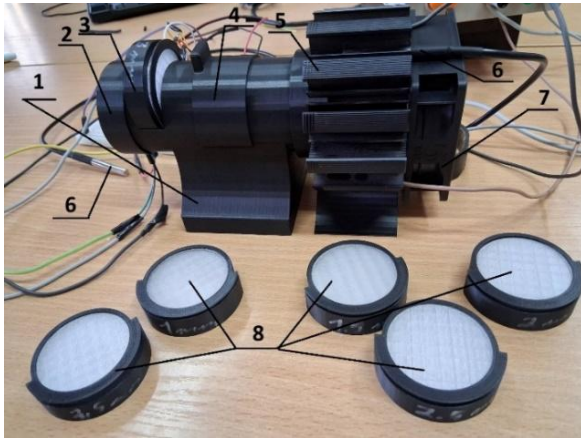


Fig 2. Laboratory stand.

Before specimen testing, the stand should be allowed to reach stable operating conditions. For each measurement series, the nominal light source power was first set to one of four levels: 200, 2600, 6600, or 10600 lx. A reference measurement without a specimen in the optical path was then recorded for that source setting. Each printed sample was placed in the same position inside the stand and measured under identical geometric conditions.

This procedure was repeated for all specimens at all four nominal source-power levels. The source-power series was not treated as a primary experimental factor, but as a consistency check to verify whether attenuation trends remained stable under different illumination intensities.

A practical procedure is given below.

1. Stabilize the light source for a fixed warm-up time.
2. Set the nominal source power to 200, 2600, 6600, or 10600 lx.
3. Record the reference signal with no specimen in the optical path.
4. Insert the specimen into the holder in a repeatable orientation.
5. Record the transmitted-light signal.
6. Repeat the measurement for all source-power levels and all specimen groups.

B. Methods

Calculation of transmittance and attenuation

Because the raw transmitted-light values scaled with source intensity, the comparative optical results should be reported as normalized transmittance. For each specimen and source-power level, transmittance is expressed as the ratio of transmitted intensity to the corresponding reference intensity:

$$T = \frac{I}{I_0} \quad (1)$$

Where I is the measured transmitted-light intensity for the specimen and I_0 is the reference intensity at the same nominal source-power setting. If reported as a percentage:

$$T_{\%} = 100 \cdot \frac{I}{I_0} \quad (2)$$

Attenuation may be expressed as:

$$A = 1 - \frac{I}{I_0} \quad (3)$$

or, in percentage form:

$$A_{\%} = 100 - T_{\%} \quad (4)$$

Because FDM printed translucent materials often show scattering in addition to absorption, the measured attenuation should be interpreted as an effective result of the printed material and structure rather than as pure bulk absorption alone [1, 7].

The method is designed to isolate the two variables of main interest: filament color and specimen thickness. This choice reflects a clear gap in the current literature. PETG studies mainly emphasize how process parameters affect transparency [3, 5, 6], whereas broader FDM studies show that thickness and color are strong optical drivers in their own right [1, 7]. By holding print settings constant and using one enclosed measurement stand for all specimens, the experiment is positioned to deliver directly comparable overall transmittance data for transparent colored PETG samples.

III. RESULTS AND DISCUSSION

The dataset covered six PETG colour variants and six specimen thicknesses, with measurements performed at four nominal light source power levels of 200, 2600, 6600, and 10600 lx. Because the transmitted-light readings scaled with source intensity, the comparative results are reported below as normalized transmittance percentages, obtained from the ratio of transmitted light to the nominal source level. For each colour-thickness combination, the table values represent the mean normalized transmittance across

the four source settings. The main trend was clear. Overall light transmittance decreased with increasing specimen thickness, and the magnitude of transmission depended strongly on filament colour. The mean normalized transmittance is shown in table 4.

TABLE II. MEAN NORMALIZED TRANSMITTANCE

Colour	Mean transmittance, %					
	1.0 mm	1.5 mm	2.0 mm	2.5 mm	3.0 mm	3.5 mm
Transparent	44.22	41.00	30.18	28.03	25.47	24.19
Blue	1.53	0.71	0.24	0.21	0.19	0.18
Neon green	37.08	35.46	23.21	22.20	20.35	19.90
Orange	24.82	13.14	9.71	9.73	9.21	8.40
Red	25.80	15.17	9.31	10.29	9.06	8.40
Yellow	39.91	38.83	26.29	26.45	26.23	25.45

Transparent PETG showed the highest mean transmittance at 1.0 to 2.5 mm, while yellow PETG is highest at 3.0 and 3.5 mm. Blue PETG showed by far the lowest transmittance at all thickness levels. At 1.0 mm, the difference between the highest and lowest transmitting materials is 42.69 percentage points, while at 3.5 mm the difference is 25.27 percentage points. Mean attenuation is presented in table 5.

TABLE III. MEAN ATTENUATION

Colour	Mean attenuation, %					
	1.0 mm	1.5 mm	2.0 mm	2.5 mm	3.0 mm	3.5 mm
Transparent	55.78	59.00	69.82	71.97	74.53	75.81
Blue	98.47	99.29	99.76	99.79	99.81	99.82
Neon green	62.92	64.54	76.79	77.80	79.65	80.10
Orange	75.18	86.86	90.29	90.27	90.79	91.98
Red	74.20	84.83	90.69	89.71	90.94	91.60
Yellow	60.09	61.17	73.71	73.55	73.77	74.55

Transparent PETG showed the highest mean transmittance at 1.0 to 2.5 mm, while yellow PETG is highest at 3.0 and 3.5 mm. Blue PETG showed by far the lowest transmittance at all thickness levels. At 1.0 mm, the difference between the highest and lowest transmitting materials is 42.69 percentage points, while at 3.5 mm the difference is 25.27 percentage points.

The attenuation data follow the inverse pattern of transmittance. For all tested materials, attenuation is high and generally increased with thickness. The strongest attenuation is observed for blue PETG across the full thickness range, whereas transparent and yellow PETG retained the highest transmitted-light fraction.

Thickness effect

For every tested colour, normalized transmittance was lower at greater specimen thickness. The most pronounced

decrease is observed between 1.5 and 2.0 mm for transparent, neon green, and yellow specimens. Transparent PETG decreased from 44.22% at 1.0 mm to 24.19% at 3.5 mm, corresponding to a reduction of 20.03 percentage points. Neon green PETG decreased from 37.08% to 19.90%, and yellow PETG from 39.91% to 25.45%. For orange and red specimens, the dominant drop occurred between 1.0 and 1.5 mm, after which the transmittance values remained in a relatively narrow low range near 8% to 15%. Blue PETG showed extremely low transmittance already at 1.0 mm and approached zero transmission at higher thicknesses. Table 6 shows the effect of the colour at fixed thicknesses.

TABLE IV. COLOUR EFFECT AT FIXED THICKNESS

Thickness	Colour effect at fixed thickness	
	Highest transmittance	Lowest Transmittance
1.0 mm	Transparent	Blue
1.5 mm	Transparent	Blue
2.0 mm	Transparent	Blue
2.5 mm	Transparent	Blue
3.0 mm	Yellow	Blue
3.5 mm	Yellow	Blue

When thickness held constant, the optical effect of colour remained clear. Transparent and yellow PETG consistently transmitted the most light, with neon green forming an intermediate group. Orange and red transmitted substantially less light, while blue is distinctly lower than all other colours at every thickness. This shows that transparent tinted PETG filaments cannot be treated as optically equivalent within one material family.

The four source settings were used as a robustness check rather than as a primary experimental factor. For moderate and high-transmittance specimens, the normalized transmittance values were generally consistent across 2600, 6600, and 10600 lx, which supports the stability of the attenuation trend. The 200 lx condition showed larger deviations for very low-transmittance specimens, especially blue samples at 2.0 mm and above, where the transmitted signal approached the lower resolution limit of the setup.

This pattern suggests that the main conclusions about colour and thickness are stable, while the lowest source-power condition is less informative for heavily attenuating samples.

According to the data shown above a summary of the main findings is presented:

- Overall light transmittance decreased with increasing specimen thickness.
- Colour had a strong effect on transmitted light even within one PETG family.

- Transparent and yellow specimens showed the highest transmittance.
- Blue specimens showed the highest attenuation at all thickness levels.
- Neon green formed an intermediate transmission group.
- Orange and red showed low transmission after a marked drop at small thickness.
- The normalized results were broadly consistent across the higher source-power settings.

IV. CONCLUSIONS

The study examined the influence of filament colour and specimen thickness on overall light transmittance in FDM printed transparent PETG. Based on the obtained results, the following conclusions can be drawn.

- Both specimen thickness and filament color significantly affected transmitted light.
- For all tested PETG variants, transmittance decreased as thickness increased and attenuation increased accordingly.
- Transparent and yellow PETG showed the highest transmittance in the tested set, while blue PETG showed the strongest attenuation at all thickness levels.
- Neon green formed an intermediate optical group, whereas orange and red exhibited lower transmission after a pronounced drop at small thickness.
- The normalized results were broadly consistent across the higher nominal source-power levels, which supports the robustness of the observed attenuation trends.
- Transparent tinted PETG filaments cannot be considered optically equivalent within one material family.

Overall, the work fills a gap in the current literature by providing comparative transmittance data for several transparent coloured PETG specimens tested across a defined thickness range using one enclosed measurement setup. The results can support material selection and design decisions for FDM printed parts in which visible-light transmission is functionally important.

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Methodology for Testing Bearings by the Damping Oscillation Method

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Abstract— Rolling bearings are machine components widely used in mechanical engineering. They are used under various operating and load conditions. Their widespread use makes it necessary to test them under certain conditions to study their behavior. This paper presents a methodology for testing bearings using the damped oscillation method. A specially designed test rig is used in accordance with the method described. The bearing is fixed to the stand by the inner strap and an axle with a movable weight, of the physical pendulum type, is fixed to its outer strap. Decay oscillations are read on an angular scale from 30° to -30° . Experiments have been performed and results obtained with different starting points (10° , 20° , and 30°) and different positions of the weight along the axis. The results obtained are processed using statistical software and presented in the form of graphs and tables. The methodology described can be used both in practice and for training students in laboratory conditions.

Keywords— Bearings, Bearings testing, Damping oscillation, Methodology, Rolling bearing.

I. INTRODUCTION

The damping oscillation method is a widely utilized technique in laboratory-oriented ball bearing testing, allowing the assessment of dynamic parameters such as stiffness, damping coefficients, and the influence of tribological effects. This method is particularly critical in applications ranging from failure diagnostics to predictive maintenance of rolling-element bearings. Despite its importance, explicit research on the development of standardized training methodologies and technical frameworks for the damping oscillation method remains sparse, demanding a deeper investigation into existing experimental setups, modeling techniques, and standardization efforts.

The reviewed literature provides a foundation for understanding the state of experimental methodologies and modeling approaches in ball bearing testing under dynamic conditions. Early studies, such as Kraus et al. [1], introduced an in situ modal analysis method as a pioneering framework for identifying damping and stiffness in fully operational rotor-bearing systems. This was later expanded upon by works such as Dietl et al. [2], Wensing et al. [3], and Lambert et al. [4], which developed experimental setups and theoretical models that accounted for critical damping contributions, including elastohydrodynamic lubrication, bearing preload, and time-dependent system stiffness. A major focus of these studies has been controlling damping variability during testing, with experimental designs such as monolithic bearing assemblies [5, 6] and frequency-domain transfer function analyses [7] addressing the influence of boundary conditions and assembly errors.

In recent years, modeling efforts have emphasized nonlinear and transient damping effects. Peng et al. [8] proposed a multigrid method to incorporate lubrication and load effects into comprehensive damping calculations, while Kong et al. [9] linked lubricant viscosity and grease effects to damping variations in defective bearings. These theoretical and experimental advancements present opportunities to expand the utility of the damping oscillation method for failure mode recognition and diagnostic purposes. Despite these developments, efforts to unify such methodologies under standardized frameworks are limited. Notably, Ratcliffe et al. [10] proposed general vibration testing standardization strategies, but these lack specific application to ball bearing damping oscillation testing.

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The critical gap remains the absence of explicit efforts to translate these methodologies into consistent training programs for laboratory technicians and researchers. The integration of dynamic modeling insights with hands-on experimental setups could improve skill reproducibility and foster standardization in this largely decentralized field. This gap underlines the need for future research that bridges experimental setups, advanced modeling techniques, and technician-oriented training frameworks.

II. MATERIALS AND METHODS

A. Materials

The testing methodology for bearings using the damped vibration method was developed for the test rig shown in Fig. 1. The design and construction of the test rig used are described in detail in "DESIGN, PRODUCTION, AND APPLICATION OF A STAND FOR TESTING FRICTION OF THE BEARINGS" by Katsarova P. et al [11].

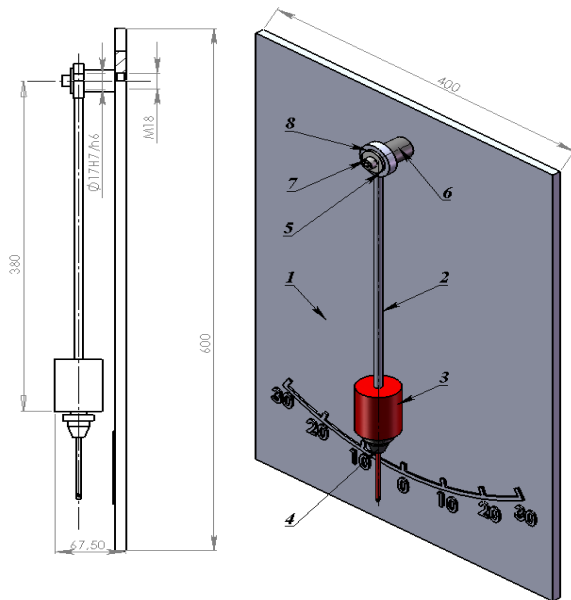


Fig. 1 Bearing testing stand [11]

The stand is composed of the following elements, as illustrated in Figure 1:

- A base (1) constructed from laminated fabric, capable of fixed installation on a wall.
- A pendulum comprising an axis (2), a weight (3), and a control nut (4), all manufactured from steel. The position of the weight relative to the axis of rotation can be adjusted by the control nut up to 100 mm. The tested bearing bush (5) is fastened in the upper part of the pendulum by a threaded joint (M8). The shaft (6) with the bearing bush is mounted to the base by a threaded joint (M18). The bearing bush is mounted on the bearing journal with clearance fit H7/h6. The bolt and the nut (48, 49) are used for axial fixation of the bearing. The parameters of the stand area are as follows:

- Overall dimensions- 67,5/400/600 [mm]
- Mass of the pendulum (3, fig.1) - 0,5÷1 [kg].
- Length of the pendulum l - 0,38 [m];

- Diameter of the tested friction surfaces D - 10÷30 [mm] fig. 2.

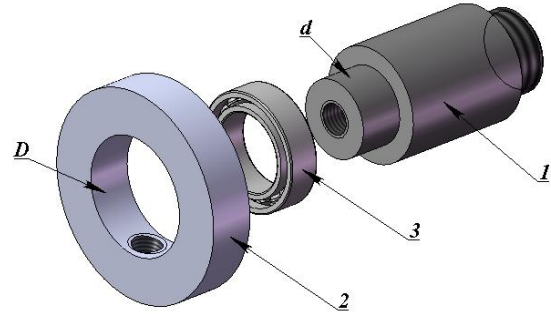


Fig. 2 Friction rig assembly [11]

B. Materials

The testing methodology for bearings entails the use of damping oscillations to assess their performance. This approach is founded on the principle of measuring the change in potential energy of a pendulum during its oscillatory motion.

The stand employed in this methodology is designed to ascertain the friction moment in different bearing supports by means of the damping oscillation method. The pendulum axis is suspended from the bearing support under test and permitted to oscillate freely. Friction in the bearing results in damping oscillations. The damping oscillations are characterized by a gradual decrease in amplitude with decreasing pendulum deflection angle (see Fig. 3) [12,13].

The potential energy of the pendulum is associated with the amplitude changes that occur during its motion.

$$\Delta U = Gh = Gh(\cos \alpha_n - \cos \alpha_0) \quad (1)$$

where:

U - the potential energy of the pendulum;
 G - weight of the pendulum;
 h - length of the pendulum.

When the deviation angles are small ($\alpha < 8-10^\circ$), $\cos$

α can be replaced by $1 - \frac{\alpha^2}{2}$ and the dependence (1)

acquire the following form:

$$\Delta U = Gl \frac{(\alpha_0 - \alpha_n)(\alpha_0 + \alpha_n)}{2} = Gl(\alpha_0 - \alpha_n) \alpha_{cp} \quad (2)$$

The work of the friction forces during the specified time interval of the pendulum from α_0 to α_n can be calculated by multiplying the friction torque M_{tp} by the sum of the pendulum angles of oscillation:

$$A_{tp} = M_{tp}(\alpha_0 + 2\alpha_1 + 2\alpha_2 + 2\alpha_3 + \dots + 2\alpha_{n-1} + \alpha_n) \quad (3)$$

Taking into consideration that:

$$\begin{aligned} \alpha_0 + \alpha_n &= 2\alpha_{mean} \quad \text{and} \\ \alpha_1 + \alpha_2 + \alpha_3 + \dots + \alpha_{n-1} &= (n-1)\alpha_{mean} \end{aligned} \quad (4)$$

The work of friction is received by us:

$$A_{TP} = M_{TP} 2 n \alpha_{\text{mean}} \quad (5)$$

The pendulum potential energy change is equivalent to the work of the friction forces because the friction in the bearing is the sole energy consumer. Subsequent to the equalization of ΔU from (2) to A_{TP} from (3), the ensuing dependence is obtained:

$$M_{TP} = Gl \frac{\alpha_0 - \alpha_n}{2n} \quad (6)$$

or

$$M_{TP} = Gl \frac{\alpha_0 - \alpha_n}{4N} \quad (7)$$

where:

M_{TP} – friction torque [N m];
 G – weight of the pendulum [N];
 l – length of the pendulum [m];
 h – difference of the pendulum height at initial and final position. [m];
 $\alpha_0 \div \alpha_n$ – angles of oscillation of the pendulum [rad];
 n – number of the semi-periods;
 N – number of the oscillation periods of the pendulum -

$$N = \frac{n}{2};$$

The connection between the friction torque and the value of the reduced friction coefficient is:

$$M_{TP} = F \cdot f \cdot r \quad (8)$$

where:

F – loading force [N];
 f – friction coefficient;
 r – bearing's radius [m].

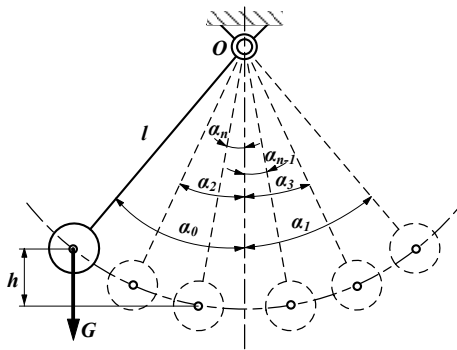


Fig. 3 Theoretical setup

III. FIGURES, TABLES AND EQUATIONS

In order to ensure the accuracy and adequate interpretation of experimental results, it is essential that the operator possesses a comprehensive understanding of the theoretical framework and the methodology employed. The bench methodology is delineated in eight points.

1. The following text presents a theoretical exposition of the method of damping oscillations. It includes a comprehensive introduction to the operator within the theoretical framework of the method of damping oscillations, as outlined in the section entitled "Methods."

2. The operator is required to become acquainted with the stand's design. This involves an examination of the stand's characteristics, features, and capabilities. Refer to Figure 1 for a visual representation of the stand.

3. A consideration of the bearing types is warranted, given that the types of bearing pairs that suit the design features of the rig are of paramount importance.

4. The following steps are taken in order to prepare the stand for operation. At this point, the bearing to be tested is mounted to the stand (see Fig. 2). Once the bearing is fitted and the stand is assembled, the position of the weight is adjusted. The weight can be placed at different heights along the axis of the pendulum, which allows for a multitude of experiments to be conducted. For the present experiment, the NMB SSR-4HH bearing was selected. Once prepared, the characteristics of the rig are as follows:

- Radius of the tested bearing $r = 8,5$ mm;
- Weight of the pendulum $G = 10$ N;
- Length of the pendulum $l = 380$ mm;

5. The experiment is meticulously planned, with a detailed plan of the experimental part being formulated. The heights of the weights and the initial angles are selected with precision α_0 . In this example, two weight positions are selected: 1) weight in the lowest position, and 2) weight in the top position. For each pendulum weight position, three experiments were conducted with starting angles $\alpha_0 = 10^\circ$; 20° ; 30° .

6. The collection of experimental data is to be carried out by conducting the requisite number of experiments, as outlined in Section 5. The resulting data shall be presented in tabular form, and the results of the experiments are to be displayed in Figures 4, 5, 6, and 7.

Weight in top position																											
Semiperiod n																											
Angle,°	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
30	30	-30	28	-26	26	-24	24	-22	20	-20	18	-18	16	-16	14	-14	12	-12	10	-10	8	-8	6	-6	4	-4	2
20	20	-20	18	-18	16	-18	16	-16	14	-14	12	-12	10	-10	10	-10	8	-8	6	-6	4	-4	4	-4	4	-4	2
10	10	-10	10	-10	8	-8	8	-8	6	-6	6	-6	6	-4	4	-4	2	-2	2	-2	2	-2	2	-2	0	0	0

Fig. 4 – Weight in top position – part 1

Weight in top position																										
Semiperiod n																										
Angle,°	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	
30	8	-6	6	-6	6	-6	4	-4	4	-4	2	-2	2	-2	2	-2	0	0	0	0	0	0	0	0	0	
20	2	-2	2	-2	2	-2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Fig. 5 – Weight in top position – part 2

Weight in lowest point																										
Semiperiod n																										
Angle,°	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
30	30	-30	28	-26	26	-24	24	-22	22	-20	20	-18	18	-18	18	-16	16	-16	16	-14	14	-12	12	-12	10	-10
20	20	-20	18	-18	18	-16	16	-16	14	-14	12	-12	12	-10	10	-10	8	-8	8	-6	6	-6	6	-4	4	-4
10	10	-10	10	-10	10	-8	8	-8	6	-6	6	-6	6	-4	4	-4	4	-4	2	-2	2	-2	2	-2	2	-2

Fig. 6 – Weight in lowest position – part 1

		Weight at lowest point																									
		Semiperiod n																									
Angle,°		26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	
30	10	-8	8	-8	8	-6	6	-6	6	-4	4	-4	4	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	0	0
20	4	-4	4	-2	2	-2	2	-2	2	-2	2	-2	2	-2	2	0	0	0	0	0	0	0	0	0	0	0	0
10	2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 7 – Weight in lowest position – part 2

7. Data Processing

Following the execution of the experimental phase, the collected data must undergo processing. This processing involves the construction of graphs depicting damping oscillations, alongside the calculation of the MTP coefficient values utilizing Formula 7. The calculation of the friction moment is performed by employing the relationship between $\alpha_0 - \alpha_n = \alpha_{mean}$. The graphical representation of the results is illustrated in Figures 8 and 9. The values of the friction moment are enumerated in Table 1.

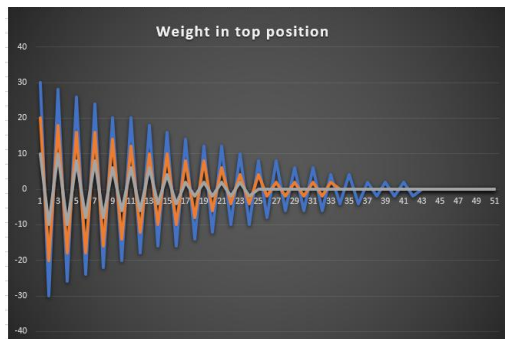


Fig. 8 Weight in top position chart

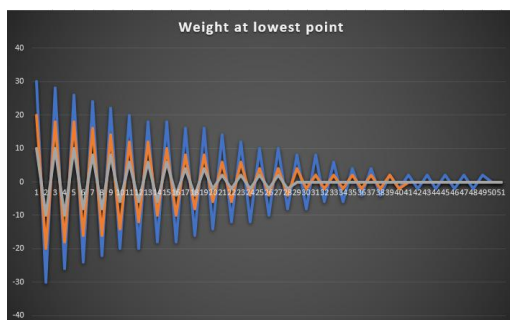


Fig. 9 Weight in lowest position chart

Table 1 Friction torque M_{TP}

Friction pair – Steel/Steel		
	$\alpha_b, ^\circ$	$M_{TP}, N;$
Top position	30	0.012
	20	0.006
	10	0.003
Lowest position	30	0.014
	20	0.009
	10	0.010

8. Analysis

The data obtained from the experiments and calculations are subjected to rigorous analysis.

IV. CONCLUSIONS

1. The methodology presented herein can be utilized in both teaching and practice settings.
2. The obtained results demonstrate the reliability of the methodology and the efficacy of the rig.
3. The methodology presented herein can be applied to the study of friction in different pairs of bearings.

ACKNOWLEDGEMENTS

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Methodology for Performing a Measurement System Analysis with Four Operators

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Abstract— A variety of factors have been shown to influence each measurement process, including environmental elements, the characteristics of the measured object, and the capabilities of the measuring instrument. These factors can be categorised into several overarching groups: external factors, the measurement object, the measuring instrument, and the operator. The present paper sets out a methodology for the evaluation of part quality in the domain of optical manufacturing. The methodology under discussion employs a measurement system analysis (MSA) method. Typically, MSA is applied to two or three operators; however, in this study, it is performed for four operators. In the course of the experiments, ten optical workpieces, lenses, are measured, with each lens undergoing three measurements. Each of the four operators measured the same set of lenses, employing the same measuring instrument. The measurement of identical parts and apparatus serves to eliminate the influence of the measuring instrument on the measuring system and to evaluate the influence of the operator. The objective of this work is to demonstrate the feasibility of employing MSA as a method for assessing the quality of more than three operators. To this end, four distinct analyses are implemented to assess the influence of each operator in relation to the others.

Keywords— *Adapted MSA, Lens, Measurement system analysis (MSA), Optical production, Quality control, Quality assessment.*

I. INTRODUCTION

Measurement Systems Analysis (MSA) and Gauge Repeatability and Reproducibility (R&R) studies are recognised as essential tools for the assessment of the precision and consistency of measurement systems [1]. The prevailing focus of such studies is on the evaluation of both repeatability (i.e. within-appraiser variability) and reproducibility (i.e. between-appraiser variability), with the utilisation of multiple appraisers often being limited to two or three [1]. However, scenarios involving additional appraisers, such as situations where subsets (e.g., 3-of-4 appraiser combinations) are analysed, introduce complexities that remain underexplored in the literature. It

is imperative to comprehend the impact of subset configurations on reproducibility, particularly in high-stakes measurement contexts, such as those involving optical systems. These contexts present distinctive challenges, including sensitivity to environmental factors, nonlinear variability, and calibration dependencies [2,3]. The present paper aims to build on existing knowledge by identifying and analysing relevant methodologies for studying the effect of four appraiser subsets on optical system measurement R&R.

There is a paucity of studies that explicitly address subset-based analyses. A notable exception is Mikulová and Plura [4], who explore appraiser-specific contributions to measurement variability using Gaussian curve visualisations. Their work underscores the variability introduced when analysing 2-of-3 appraiser subsets, thereby establishing a foundation for comprehending appraiser-specific effects that could be expanded to encompass larger groups. In a similar vein, Hamada et al. [5] utilise Bayesian methods and a Balanced Incomplete Block Design (BIBD) to address destructive testing scenarios, where not all appraisers evaluate all objects. These approaches provide methodological insights that are pertinent to the analysis of incomplete appraiser combinations. Furthermore, Jarošová [6] employs D-optimal experimental design to optimise measurement allocations in R&R studies, with the potential to reduce the replication burden and address the common occurrence of unbalanced designs in subset configurations.

Optical systems are known to present additional complications in the context of MSA, a phenomenon attributable to their sensitivity to environmental conditions and calibration inconsistencies. In their study, Groš et al. [2] examined the issue of reproducibility in three-dimensional optical measurement systems. The researchers demonstrated that calibration choices, including filter selection, have a substantial impact on variability. As Fedoryszyn and Brzeziński [3] further emphasise, it is imperative to distinguish between system-induced variability and environmental or process influences in high-

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precision contexts such as casting. These sector-specific studies reveal challenges in analysing optical systems and underscore the need for tailored approaches when applying R&R methodologies.

Notwithstanding the foregoing advancements, extant literature does not directly address the analysis of four appraiser subsets in R&R studies for optical systems. As demonstrated in [4, 5, 6], methodologies for subset analyses provide foundational tools. However, the integration of these methodologies with optical system-specific challenges [2, 3] remains unstudied. This discrepancy underscores the necessity for the development of bespoke experimental designs and statistical models, such as Bayesian frameworks [5] or mixed-effects models [7], which can accommodate subset configurations and the distinct variability sources observed in optical measurements. The objective of this study is to leverage the extant methodologies and insights to adapt MSA and R&R studies for the analysis of four appraiser subsets in optical systems.

II. MATERIALS AND METHODS

A. Materials

The data utilised for the measurement system analysis are obtained through lens measurements (Fig. 1). In view of the stringent precision demands for the optical components, it is imperative that all measurements are conducted within the laboratory environment on the factory premises. The execution of measurements is undertaken by personnel who have undergone specialised training. It is evident that, during the MSA, the diameter of $\varnothing 24$ e8 is designated as the controlled dimension. As demonstrated in Figure 1, two diameters, designated as $\varnothing 24$ e8 and $\varnothing 24$ h8, are apparent. The former, designated as $\varnothing 24$ e8, corresponds to a state prior to varnishing, while the latter, designated as $\varnothing 24$ h8, corresponds to a state subsequent to varnishing. It is imperative that all measurements are conducted with a high-precision micrometer, as illustrated in Figure 2.

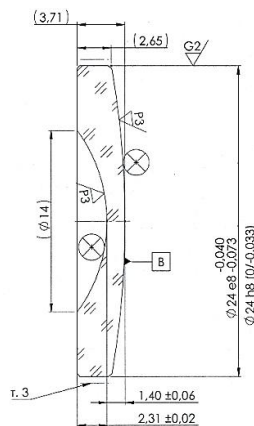


Fig 1. Measured optical detail



Fig 2. Measuring tool [8]

A. Methods

The evaluation of the results is conducted through the utilisation of measurement system analysis (MSA), a method that employs measurement data to assess the performance of a manufacturing process. For instance, the decision to adjust a manufacturing process is commonly based on measurement data. The data, or some of the statistics calculated from it, are then compared with the statistical control limits corresponding to the process. In the event that the comparison indicates that the process is out of statistical control, an adjustment is made. Conversely, if the comparison reveals that the process remains within statistical control, no adjustments are made [9].

The accuracy of measurement devices is defined as their capacity to generate output signals that approximate true values. The concept of accuracy measurement encompasses a multifaceted and substantial issue, namely the impact of repeatability of measurements and the contributions of individual operators. The influence of these elements on measurement methods is delineated through the R&R framework (Repeatability and Reproducibility). Conducting an R&R analysis necessitates the consideration of total variability, encompassing aspects such as repeatability, reproducibility, variability of components, and, most notably, variability of a single component or that arising from the permissible tolerance range [11].

Ishikawa's diagram shown in fig 3. illustrates the Measurement System Variability Cause and Effect Diagram.

In contrast to the prevailing approach to MSA, in which Workpiece, Instrument (Gage), and Person (Appraiser) are considered through their variations, namely Part Variation (PV), Equipment Variation (EV) (which is essentially Repeatability), and Appraiser Variation (AP) (which is essentially Reproducibility), GRR is described as the variance of the internal and external disturbances for the system, represented by the combined variance of repeatability and reproducibility [10].

In light of the aforementioned data, the MSA is executed employing the GRR method as delineated in the

4th Edition Reference Manual [9]. The ensuing values are thus derived:

Repeatability is equal to Equipment Variation:

$$EV = \bar{R} * K_1 \quad (1)$$

In accordance with the principles outlined in the “Measurement Systems Analysis Reference Manual”, the coefficient K_1 is selected from the provided table. K_1 depends on the number of trials in the used gage study [9].

Equipment Variation (EV) can be presented as $\%EV = 100(EV / \text{Tolerance})$, where Tolerance is defined as the difference between the Upper Tolerance Limit (UTL) and the Lower Tolerance Limit (LTL).

Reproducibility is equivalent to Appraiser Variation (AV) [9]:

$$AV = \sqrt{(\bar{X}_{DIFF} * K_2) - \frac{EV^2}{nr}} \quad (2)$$

In accordance with the principles outlined in the “Measurement Systems Analysis Reference Manual”, the coefficient K_2 is selected from the provided table. K_2 depends upon the number of appraisers in the study [9].

The Appraiser Variation could be presented as follows: $\%AV = 100(AV / \text{Tol})$. The influence of the operator can be

disregarded because it has an insignificant impact on the outcome if he performs his duties conscientiously.

$$GRR = \sqrt{EV^2 + AV^2} \quad (3)$$

and

$$\%GRR = 100(GRR / \text{Tol}) \quad (4)$$

Part Variation:

$$PV = R_p * K_3 \quad (5)$$

In accordance with the principles outlined in the “Measurement Systems Analysis Reference Manual”, the coefficient K_3 are selected from the provided table. K_3 depends on the number of parts in the study [9].

Result could be presented as [9]:

$$\%PV = 100(PV / \text{Tol}) \quad (6)$$

It is imperative to note that all abbreviations utilized in the present document are in alignment with the Reference Manual, 4th Edition [9].

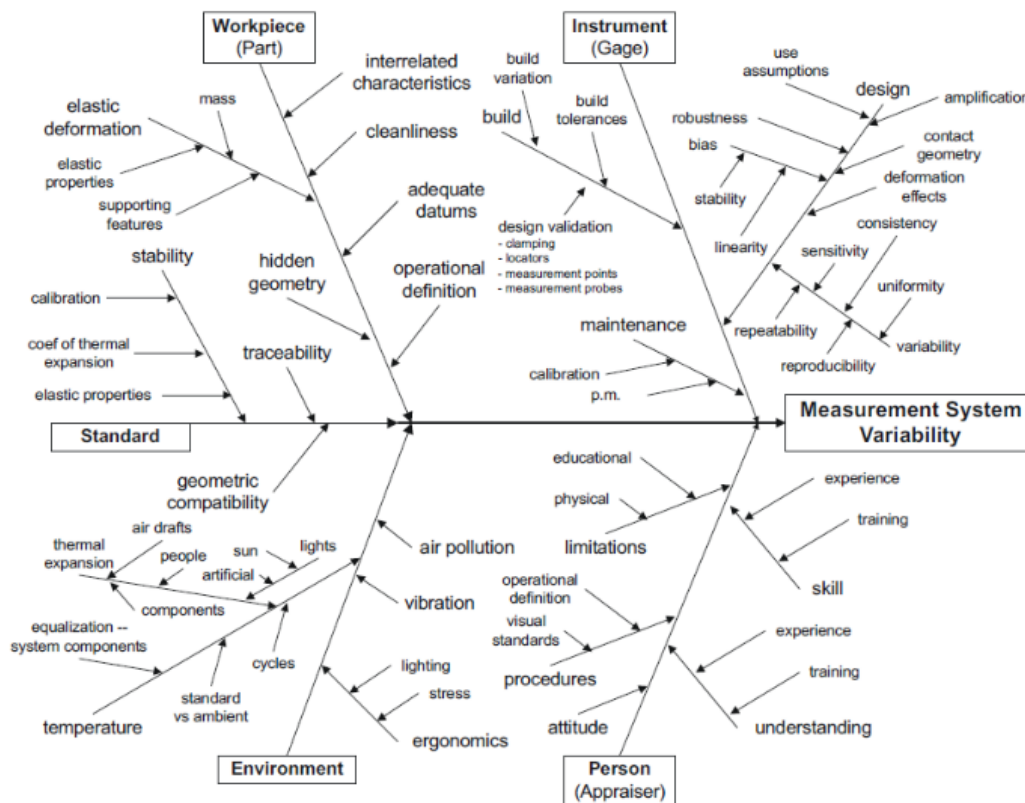


Fig. 3 MSA Cause and Effect Basic Diagram [11]

The MSA is a reliable statistical instrument for the evaluation of measurement systems; however, its application is currently limited to two or three operators. This paper proposes an extension of the MSA to a measurement system comprising four operators. The traditional method's restriction to three operators necessitates an adaptation. To apply the MSA to four operators, it is necessary to apply the known methodology for this analysis several times to cover all possible combinations of operators and to evaluate the impact of the operators on the measurement system. To limit the influence of the measuring instrument and the workpiece, the same ten lenses are measured three times each and the same measuring instrument is used.

III. RESULTS AND DISCUSSION

The experiments were conducted by measuring 10 lenses each three times from all four operators. The measured diameter is Ø24 e8, with upper tolerance limit – 23.960, and lower tolerance limit – 23.927. The results of the measurements were recorded and used to conduct analyses. In order to evaluate the influence of the four operators on the measurement system, four standard MSAs were conducted so that all combinations were covered. The operators are denoted as A, B, C, and D, and the four sets of analyses performed are as follows: Series 1 - A, B, C; Series 2 - B, C, D; Series 3 - C, D, A; Series 4 - D, A, B. The results obtained are presented in the tables below.

TABLE 1. SERIES 1 DATA

APPRAISER/ TRIAL #	1	2	3	4	5	6	7	8	9	10	AVERAGE
1. A	1	23.945	23.938	23.945	23.942	23.946	23.947	23.95	23.928	23.95	23.943
2.	2	23.943	23.936	23.942	23.943	23.946	23.949	23.928	23.95	23.94	23.942
3.	3	23.943	23.938	23.942	23.943	23.947	23.946	23.952	23.929	23.95	23.943
4.	AVE	23.944	23.937	23.943	23.943	23.946	23.946	23.950	23.928	23.950	X _̄ = 23.943
5.	R	0.002	0.002	0.003	0.001	0.001	0.001	0.003	0.001	0.004	I _R = 0.002
6. B	1	23.946	23.938	23.946	23.943	23.948	23.949	23.951	23.929	23.95	23.944
7.	2	23.945	23.936	23.944	23.942	23.947	23.946	23.952	23.927	23.952	23.943
8.	3	23.942	23.938	23.942	23.942	23.946	23.947	23.95	23.949	23.942	23.943
9.	AVE	23.944	23.937	23.944	23.942	23.947	23.947	23.951	23.929	23.950	X _̄ = 23.943
10.	R	0.004	0.002	0.004	0.001	0.002	0.003	0.002	0.003	0.002	I _R = 0.003
11. C	1	23.946	23.936	23.944	23.944	23.947	23.948	23.948	23.93	23.951	23.937
12.	2	23.944	23.937	23.943	23.941	23.944	23.949	23.951	23.928	23.95	23.943
13.	3	23.945	23.938	23.941	23.945	23.948	23.948	23.95	23.928	23.949	23.943
14.	AVE	23.945	23.937	23.943	23.943	23.946	23.948	23.950	23.929	23.950	X _̄ = 23.943
15.	R	0.002	0.002	0.003	0.004	0.004	0.001	0.003	0.002	0.003	I _R = 0.003
16. PART	AVERAGE	23.94	23.94	23.94	23.94	23.95	23.95	23.95	23.93	23.95	X _̄ = 23.943
17.	(I _R + I _B + I _C) / (# OF APPRAISERS) =										R _̄ = 0.002
18.	X _{DIFF} = (Max X - Min X) =										X _{DIFF} = 0.001
19.	* UCL _R = R x D ₄ =										UCL _R = 0.006

TABLE 2. SERIES 1 MSA RESULTS

Total Variation (TV)	Value
Repeatability - Equipment Variation (EV), %	19,71
Reproducibility - Appraiser Variation (AV), %	4,14
Repeatability & Reproducibility (GRR), %	20,14

The analysis of series 1 is shown at table 1 and table 2 demonstrates the variation of results in terms of instrument EV =19.71% (equipment variation) and operator AV (appraiser variation), with a value of 4.14%. The value of EV indicates the influence of equipment on the results, while the value of AV indicates a slight influence of the operator relative to the results obtained. According to the MSA standard is the GRR is less than 10%, so the measurement system is considered as acceptable. If the coefficient GRR is between 10% and 30% the system can be considered acceptable and consideration of risks, application and costs should be made. When GRR is more than 30% the measurement system is considered as unacceptable. The GRR (Gage Repeatability & Reproducibility) value of series 1 is 20.14%, so it indicates that the measurement system's results can be accepted as the GRR value is less than 30%.

Series 2 data and results are presented on table 3 and table 4.

TABLE 3. SERIES 2 DATA

APPRAISER/ TRIAL #	1	2	3	4	5	6	7	8	9	10	AVERAGE
1. B	1	23.946	23.938	23.946	23.943	23.948	23.949	23.951	23.929	23.95	23.944
2.	2	23.945	23.936	23.944	23.942	23.947	23.946	23.952	23.927	23.952	23.943
3.	3	23.942	23.938	23.942	23.942	23.946	23.947	23.95	23.93	23.949	23.942
4.	AVE	23.944	23.937	23.944	23.942	23.947	23.947	23.951	23.929	23.950	X _̄ = 23.943
5.	R	0.004	0.002	0.004	0.001	0.002	0.003	0.002	0.003	0.003	I _R = 0.003
6. C	1	23.946	23.936	23.944	23.944	23.947	23.948	23.948	23.93	23.951	23.937
7.	2	23.944	23.937	23.943	23.941	23.944	23.949	23.951	23.928	23.95	23.939
8.	3	23.945	23.938	23.941	23.945	23.948	23.948	23.95	23.928	23.949	23.936
9.	AVE	23.945	23.937	23.943	23.943	23.946	23.948	23.950	23.929	23.950	X _̄ = 23.943
10.	R	0.002	0.002	0.003	0.004	0.004	0.001	0.003	0.002	0.002	I _R = 0.003
11. D	1	23.944	23.939	23.947	23.945	23.948	23.95	23.949	23.931	23.952	23.942
12.	2	23.946	23.938	23.945	23.944	23.946	23.947	23.95	23.929	23.949	23.943
13.	3	23.943	23.938	23.943	23.944	23.947	23.949	23.951	23.932	23.953	23.938
14.	AVE	23.944	23.938	23.945	23.944	23.947	23.949	23.950	23.931	23.951	X _̄ = 23.944
15.	R	0.003	0.001	0.004	0.001	0.002	0.003	0.002	0.003	0.004	I _R = 0.003
16. PART	AVERAGE	23.94	23.94	23.94	23.94	23.95	23.95	23.95	23.93	23.95	X _̄ = 23.943
17.	(I _R + I _B + I _C) / (# OF APPRAISERS) =										R _̄ = 0.003
18.	X _{DIFF} = (Max X - Min X) =										X _{DIFF} = 0.001
19.	* UCL _R = R x D ₄ =										UCL _R = 0.007

TABLE 4. SERIES 2 MSA RESULTS

Total Variation (TV)	Value
Repeatability - Equipment Variation (EV), %	22,89
Reproducibility - Appraiser Variation (AV), %	8,39
Repeatability & Reproducibility (GRR), %	24,37

EV = 22.89% and AV = 8.39%. The values of EV and AV are higher than the results from series 1. There is no big difference between the values of Equipment variation, they are very close. There is a significant difference between Appraiser variation from series 1 and series 2, the value in the series 2 is two times bigger than the EV from series 1. The GRR (Gage Repeatability & Reproducibility) value is 24.37% it is bigger than GRR in series 1, but it is still under 30%, so the measurement system is acceptable.

The results from series 3 are shown in table 5 and table 6.

TABLE 5. SERIES 3 DATA

APPRAISER/ TRIAL #	1	2	3	4	5	6	7	8	9	10	AVERAGE
1. C 1	23.946	23.936	23.944	23.944	23.947	23.948	23.93	23.951	23.937		23.943
2. 2	23.944	23.937	23.943	23.941	23.944	23.949	23.951	23.928	23.95	23.939	23.943
3. 3	23.945	23.938	23.941	23.945	23.948	23.948	23.95	23.928	23.949	23.936	23.943
4. AVE	23.945	23.937	23.943	23.943	23.946	23.948	23.950	23.929	23.950	23.937	$X_b = 23.943$
5. R	0.002	0.002	0.003	0.004	0.004	0.001	0.003	0.002	0.002	0.003	$r_b = 0.003$
6. D 1	23.944	23.939	23.947	23.945	23.948	23.95	23.949	23.931	23.952	23.942	23.945
7. 2	23.946	23.938	23.945	23.944	23.946	23.947	23.95	23.929	23.949	23.943	23.944
8. 3	23.943	23.938	23.943	23.944	23.947	23.949	23.951	23.932	23.953	23.938	23.944
9. AVE	23.944	23.938	23.945	23.944	23.947	23.949	23.950	23.931	23.951	23.941	$X_b = 23.944$
10. R	0.003	0.001	0.004	0.001	0.002	0.003	0.002	0.003	0.004	0.005	$r_b = 0.003$
11. A 1	23.945	23.938	23.945	23.942	23.946	23.947	23.95	23.928	23.95	23.938	23.943
12. 2	23.943	23.936	23.942	23.943	23.946	23.949	23.928	23.95	23.94		23.942
13. 3	23.943	23.938	23.942	23.943	23.947	23.946	23.952	23.929	23.95	23.936	23.943
14. AVE	23.944	23.937	23.943	23.943	23.946	23.946	23.950	23.928	23.950	23.938	$X_b = 23.943$
15. R	0.002	0.002	0.003	0.001	0.001	0.001	0.003	0.001	0.000	0.004	$r_b = 0.002$
16. PART AVERAGE	23.94	23.94	23.94	23.94	23.95	23.95	23.95	23.93	23.95	23.94	$X = 23.943$ $R_b = 0.021$
17. $(r_b + r_b + r_b) / (\# \text{ OF APPRAISERS}) =$											$R = 0.002$
18. $X_{DIFF} = (\text{Max } X - \text{Min } X) =$											$X_{DIFF} = 0.001$
19. $* UCL_R = R \times D_4 =$											$UCL_R = 0.006$

TABLE 6. SERIES 3 MSA RESULTS

Total Variation (TV)	Value
Repeatability - Equipment Variation (EV), %	20,66
Reproducibility - Appraiser Variation (AV), %	10,52
Repeatability & Reproducibility (GRR), %	23,18

In the 3rd series of the analysis the results shows EV = 20.66%, AV = 10,52 and GRR = 23.18%. A decline in the value of EV is observed, yet the coefficient AV exhibited an increase in comparison to the preceding two analyses. Gage Repeatability & Reproducibility is almost the same as GRR in series 2, the measurement system is still acceptable.

Data and results from the last series are shown on table 7 and table 8.

TABLE 7. SERIES 4 DATA

APPRAISER/ TRIAL #	1	2	3	4	5	6	7	8	9	10	AVERAGE
1. D 1	23.944	23.939	23.947	23.945	23.948	23.95	23.949	23.931	23.952	23.942	23.945
2. 2	23.946	23.938	23.945	23.944	23.946	23.95	23.95	23.929	23.949	23.943	23.944
3. 3	23.943	23.938	23.943	23.944	23.947	23.95	23.951	23.932	23.953	23.938	23.944
4. AVE	23.944	23.938	23.945	23.944	23.947	23.949	23.950	23.931	23.951	23.941	$X_b = 23.944$
5. R	0.003	0.001	0.004	0.001	0.002	0.003	0.002	0.003	0.004	0.005	$r_b = 0.003$
6. A 1	23.945	23.938	23.945	23.942	23.946	23.95	23.95	23.928	23.95	23.938	23.943
7. 2	23.943	23.936	23.942	23.943	23.946	23.95	23.949	23.928	23.95	23.94	23.942
8. 3	23.943	23.938	23.942	23.943	23.947	23.95	23.952	23.929	23.95	23.936	23.943
9. AVE	23.944	23.937	23.943	23.943	23.946	23.946	23.950	23.928	23.950	23.938	$X_b = 23.943$
10. R	0.002	0.002	0.003	0.001	0.001	0.001	0.003	0.001	0.000	0.004	$r_b = 0.002$
11. B 1	23.946	23.938	23.946	23.943	23.948	23.95	23.951	23.929	23.95	23.94	23.944
12. 2	23.945	23.936	23.944	23.942	23.947	23.95	23.952	23.927	23.952	23.941	23.943
13. 3	23.942	23.938	23.942	23.942	23.946	23.95	23.95	23.93	23.949	23.942	23.943
14. AVE	23.944	23.937	23.944	23.942	23.947	23.947	23.951	23.929	23.950	23.941	$X_b = 23.943$
15. R	0.004	0.002	0.004	0.001	0.002	0.003	0.002	0.003	0.003	0.002	$r_b = 0.003$
16. PART AVERAGE	23.94	23.94	23.94	23.94	23.95	23.95	23.95	23.93	23.95	23.94	$X = 23.943$ $R_b = 0.021$
17. $(r_b + r_b + r_b) / (\# \text{ OF APPRAISERS}) =$											$R = 0.002$
18. $X_{DIFF} = (\text{Max } X - \text{Min } X) =$											$X_{DIFF} = 0.001$
19. $* UCL_R = R \times D_4 =$											$UCL_R = 0.006$

TABLE 8. SERIES 4 MSA RESULTS

Total Variation (TV)	Value
Repeatability - Equipment Variation (EV), %	20,56
Reproducibility - Appraiser Variation (AV), %	10,47
Repeatability & Reproducibility (GRR), %	23,07

Again, the coefficient EV = 20.56%, which is the same as the other three MSA analysis. The value of AV is 10,47%, and it is the same as the value of AV in the third series. GRR is 23,07%, again it is under 30%, so the system is acceptable.

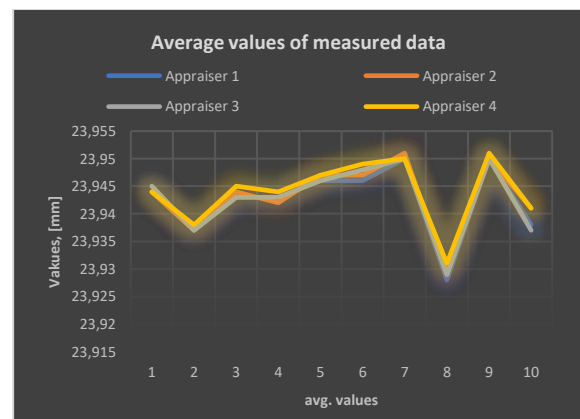


Fig. 4 avg values of measured data

Figure 4 shows a comparison between the average values of the four operators. The graphical representation of the results shows equivalent results for each operator, with no significant differences in their performance. In summary the results from the first series show the best results overall. There are no significant

changes in the EV values, they are all grouped in about 4%. Every measurement system is acceptable because the values of all GRRs are under 30%. The most notable change is observed when operator A is substituted by operator D, resulting in a doubling of the value of AV.

IV. CONCLUSIONS

The paper presents the flexibility of MSA, and how it can be adapted to different situations. Measurement system analysis is suitable for evaluating measurement systems with more than three appraisers. The equipment's influence on the measurement system is presumed to be constant, as evidenced by the similarity in the resulting EV values. The values of the Gage Repeatability & Reproducibility indicators for all four analyses are found to be less than 30%, indicating that the measurement system is acceptable. Due to the values of GRR between 10% and 30% a consideration should be given of risk, appliance and cost. The analyses indicate that operator A's measurements are the most consistent, and the analyses with his participation demonstrate a reduced operator influence on the measurement system. Through MSA, the influence of a specific operator on the measurement system can be determined.

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From Conventional Camouflage Textiles to Metamaterial-Based Combat Protection: Review

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Abstract—This paper presents a conceptual review of the evolution of military camouflage systems from conventional textile-based concealment to advanced metamaterial-enabled multispectral protection. The study analyzes the current limitations of traditional camouflage materials in the face of modern detection technologies, including infrared imaging, radar systems, LIDAR platforms, and AI-assisted sensor fusion and automated target-recognition systems. Particular attention is given to metamaterial structures based on split-ring resonators (SRRs), transformation optics, coding metasurfaces, and adaptive electromagnetic shielding concepts. The paper discusses integrating conductive and resonant elements into textile architectures through embroidery, nanoprinting, and composite fabrication. Recent developments in self-healing polymers, omniphobic coatings, and adaptive thermal camouflage are also reviewed as emerging technologies for future combat equipment. The advantages, operational limitations, and engineering challenges of wearable metamaterial systems are critically evaluated. The study concludes that metamaterial-assisted combat gear is a promising direction for next-generation multispectral military protection, although significant challenges remain regarding durability, scalability, and battlefield implementation.

Keywords— *camouflage textiles, coding metasurfaces, electromagnetic shielding, metamaterials, multispectral protection.*

I. INTRODUCTION

Modern military operations require integrated protection systems capable of simultaneously addressing ballistic, thermal, chemical, and electromagnetic threats. Research on protective equipment encompasses various aspects of military clothing, including the development of functional textile structures, the optimization of garment components, and the improvement of camouflage coloration. Particular attention is given to protection against electromagnetic radiation by integrating conductive elements into textile structures, enabling shielding effects without significantly compromising flexibility and functionality [1].

Alongside the development of advanced textile structures for specialized applications, considerable research focuses on enhancing the protective and operational performance of military clothing. These approaches include incorporating nanomaterials to improve fabric properties, designing multifunctional composite systems [2], and developing advanced camouflage fabrics to enhance the effectiveness and functionality of combat uniforms in field conditions [3].

The evolution of military camouflage has closely followed advances in textile technologies and dye chemistry. The transition from brightly colored historical uniforms to modern digital camouflage is driven by a common objective: minimizing visual detection by adapting to the surrounding environment. Today, the digital transformation of defense technologies marks a new stage in protective equipment development, shifting from conventional passive camouflage to advanced, adaptive, and multifunctional systems. However, the emergence of multispectral sensing technologies has fundamentally changed the requirements imposed on camouflage systems.

This transformation responds to the rapid advancement of surveillance and detection technologies. In the contemporary operational environment, military personnel face threats beyond conventional visual observation. Modern detection systems include thermographic sensors, laser-guided targeting technologies, multispectral aerial surveillance platforms, and high-resolution radar systems. Consequently, a major challenge in developing military protective equipment is achieving effective concealment and survivability across multiple detection spectra, not just the visible spectrum. This paper is based on a structured literature review of recent advances in metamaterials, electromagnetic shielding textiles, and multispectral camouflage systems. The analyzed sources include experimental studies, theoretical models, and defense technology reports focused on split-ring resonators,

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transformation optics, coding metasurfaces, and wearable electromagnetic shielding structures.

This paper analyzes the technological transition from conventional camouflage textiles to metamaterial-based multispectral protection systems by critically reviewing current scientific developments and emerging defense applications.

II. THE TECHNOLOGICAL LIMIT OF TRADITIONAL SYSTEMS

In modern combat environments, rapid detection is often followed by immediate engagement. Conventional camouflage textiles have reached their functional limits because they mainly provide passive visual concealment. Their material properties limit effective modulation of thermal emissions and radio-frequency reflections, exposing the technological limits of traditional camouflage compared to new multispectral intelligence methods. Regardless of camouflage quality, thermal radiation from the body or radar reflections from conventional metal-textile models remain unchanged, as these models are primarily designed for visual concealment. In high-tech warfare, such methods are inadequate against drones and autonomous sensor systems [4], [5]. The main disadvantages of commercial fabrics are high thermal emissivity and lack of infrared (IR) thermal control. Additionally, the human body is a significant heat source, and traditional protective fabrics absorb and re-emit heat, creating a strong thermal contrast easily detected by modern thermal imaging cameras [6]. Recent developments highlight the growing importance of multispectral detection and counter-detection technologies. The widespread use of unmanned aerial systems, infrared sensors, and AI-assisted surveillance has significantly reduced the effectiveness of conventional visual camouflage. Modern detection systems in military scenarios integrate radar, thermal imaging, and multispectral analysis to enable high-precision target identification and tracking. As a result, traditional textile-based camouflage materials, which primarily provide passive visual concealment, are insufficient against integrated multisensor detection systems. These systems can reconstruct object geometry using radar- and LIDAR-based 3D sensing, even when visual concealment measures are effective in the visible spectrum. Metamaterial-based coatings and structured electromagnetic surfaces are therefore being investigated as potential solutions to reduce detectability across multiple spectral domains, including the microwave and infrared ranges. Unlike conventional materials, which lack engineered subwavelength resonant structures, metamaterial systems can be designed to actively manipulate reflection, scattering, and absorption characteristics of incident electromagnetic waves.

III. METAMATERIALS AND TRANSFORMATION OPTICS

Metamaterials represent engineered structures whose electromagnetic properties are primarily determined by subwavelength geometry rather than chemical composition. While conventional textiles exhibit limited optical and electromagnetic responses governed primarily by reflection and absorption, metastructured shielding systems can manipulate electromagnetic wave propagation through engineered effective permittivity and permeability distributions. This figure explains the two fundamental mechanisms by which metamaterials manipulate the electromagnetic spectrum.

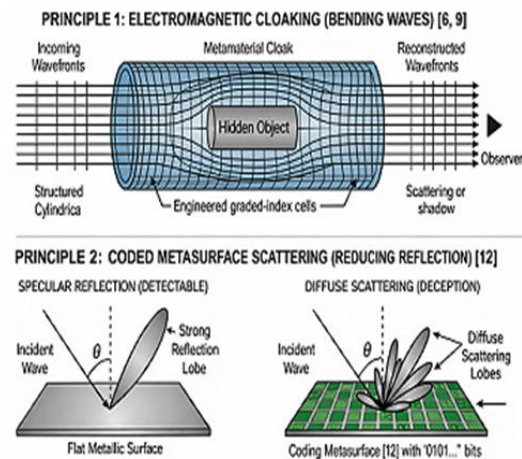


Fig. 1. Fundamental mechanisms of electromagnetic control in metamaterial systems: (a) wavefront bending principle for cloaking applications [7], [8]; (b) comparison between conventional specular reflection and programmable diffuse scattering in coding metasurfaces [9].

Figure 1 illustrates two complementary physical mechanisms used in metamaterial-based electromagnetic manipulation. The first mechanism relies on transformation optics to redirect incident wavefronts around an object, while the second employs programmable phase distributions to engineer controlled scattering patterns and reduce detectability.

Early studies identified several classes of engineered resonant materials capable of supporting negative-index electromagnetic behavior suitable for multispectral cloaking applications [7]. These developments demonstrated that electromagnetic wave propagation could be artificially redirected around protected objects, thereby establishing the engineering foundation for practical cloaking technologies. In the initial experimental technology transfer system [8], the metastructures were implemented on printed circuit boards. This first-of-its-kind laboratory success is fundamental to the current integration of resonators into textile frames using industrial embroidery and nano-printing. In short, the transition from rigid laboratory prototypes (constructed on printed circuit boards) to individualized real-world protection is facilitated by injecting meta-elements directly into the textile matrix. For example, through

computerized embroidery with metalized threads and direct nano-printing, complex geometries of ring resonators are embedded in the underlying fabrics, preserving ergonomics and tactical comfort. The transition from rigid laboratory-scale metastructures fabricated on printed circuit boards toward textile-integrated systems has enabled the development of flexible wearable electromagnetic shielding architectures. Contemporary fabrication approaches include conductive embroidery, nano-printing, and the direct integration of split-ring resonators (SRRs) into textile matrices, all while preserving flexibility and ergonomic performance.

Foundational studies by David R. Smith and co-workers [10], [11] demonstrated experimentally and theoretically that artificially engineered structures can exhibit negative refractive index behavior. Due to this physical property, metastructures not only interact with incident radiation but also can be engineered to manipulate the phase and amplitude distribution of incident electromagnetic waves. To describe the far-field scattering response of a coding metasurface, the following generalized expression can be used:

$$f(\theta, \varphi) = f_e(\theta, \varphi) \sum_{m=1}^N \sum_{n=1}^N e^{-i[\Phi(m,n) + kD \sin \theta ((m - \frac{N+1}{2}) \cos \varphi + (n - \frac{N+1}{2}) \sin \varphi)]} \quad (1)$$

where:

- $f(\theta, \varphi)$ - the far-field scattering function;
- $f_e(\theta, \varphi)$ - the element radiation pattern;
- $\Phi(m, n)$ - represents the programmable phase response of the (m, n) metasurface element;
- k - the electromagnetic wave number;
- D - the periodic spacing between adjacent metasurface elements;
- θ - 12 the observation angles in spherical coordinates.

The equation indicates that the far-field scattering response of the coding metasurface is governed by the spatial phase distribution $\Phi(m, n)$ imposed across the metasurface elements. Through engineered phase modulation of the metasurface elements, electromagnetic waves can interfere destructively in selected directions, resulting in the suppression of specular reflection and a significant reduction in radar cross-section (RCS) [9].

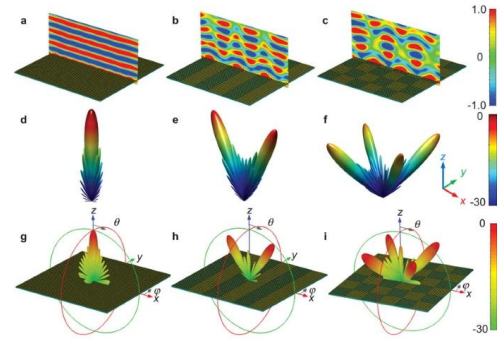


Fig. 2. Numerical simulation of electromagnetic wave scattering in coding metasurfaces [9]: (a–c) electric field distribution; (d–f) far-field radiation patterns; (g–i) three-dimensional scattering redistribution.

Numerical simulation results of electromagnetic wave scattering from coding metasurfaces [9]: (a–c) electric field distributions; (d–f) 3D far-field radiation patterns demonstrating controlled scattering redistribution; (g–i) full 3D visualization of diffuse electromagnetic scattering for passive radar deception and radar cross-section (RCS) suppression.

IV. TECHNOLOGICAL INTEGRATION AND APPLICATIONS

The use of geometries such as hexagonal or decagonal resonators helps precisely manipulate the electromagnetic response of equipment to microwave radiation [12], leading to significantly improved shielding effectiveness, ranging from 6 dB to 15 dB [13]. Modern advances enable the integration of meta-elements into textile structures using conductive threads (stainless steel or silver) applied via industrial embroidery. This addresses the key tension between functionality and ergonomics, allowing the material to retain porosity and mechanical adaptability while the embedded periodic array of resonators actively controls the object's radar signature. Such hybrid systems turn the uniform into an active element of contribute to passive electromagnetic signature management. Similarly, technologies such as „Lenticular metasurfaces for passive deception“ [9] offer a practical approach for adapting to this new environment. Using lenticular optical lenses, these systems refract visual space, distorting or reducing visual signature perception under selected observation conditions. The current stage of military technology marks the transformation of a single combat unit from a simple concealment system into an active interface for multispectral protection. This transition reflects the evolution of camouflage systems from passive visual concealment toward adaptive multispectral signature-management technologies [14].

Applying the principles of transformation optics, the energy flow is channeled and contoured around the protected object, thereby shielding it from detection by multispectral sensors. The physical realization of this process, in which resonant elements are embedded in the textile matrix, is illustrated in Fig. 3.

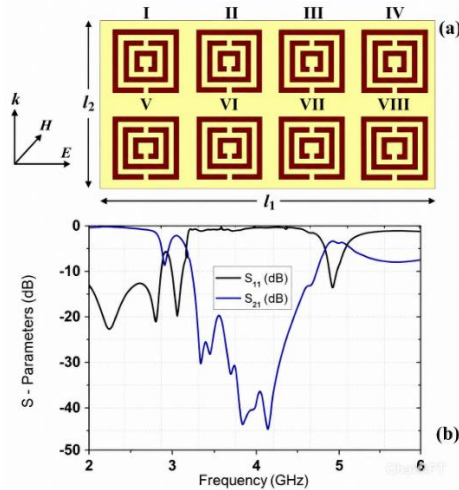


Fig. 3. Textile-integrated SRR-based metamaterial composite structure with conductive embroidery and periodic resonant elements [13].

Figure 3 demonstrates the practical implementation of split-ring resonators embedded into textile-compatible substrates. The conductive network enables controlled interaction with incident electromagnetic waves, supporting radar cross-section reduction while preserving mechanical flexibility.

The integration of metamaterial-based armor systems with ballistic protection technologies represents a fundamental shift in the concept of military survivability. Future protective systems are expected not only to provide conventional camouflage but also to significantly reduce the optical, infrared, and electromagnetic signatures of personnel and military platforms, thereby limiting detectability by advanced sensor systems. Recent studies have demonstrated the feasibility of flexible metamaterial layers for integration into personal protective systems and armored vehicles. These adaptive structures enable dynamic manipulation of electromagnetic wave propagation in both the visible and microwave spectral regions, allowing objects to partially match their surrounding environment and reduce detectability under multispectral surveillance conditions [15].

In parallel, nanostructured surfaces for adaptive thermal camouflage have been developed to emit controlled infrared radiation that simulates the thermal characteristics of the surrounding environment. Such systems reduce infrared contrast and thermal detectability, contributing to the development of low-observable military platforms capable of operating under continuous electronic, optical, infrared, and radar surveillance.

V. CHALLENGES TO OPERATION

Despite significant advances in metamaterial engineering, the practical implementation of wearable metamaterial systems in extreme battlefield conditions remains a major challenge. The electromagnetic behavior of metamaterials depends on subwavelength precision and geometric periodicity of their resonant structures, called “meta-atoms.” Repeated bending, abrasion, mechanical

deformation, and long-term wear may significantly affect their electromagnetic performance and structural stability. In real battlefield environments, contamination by dust, mud, moisture, oils, or other particles may alter the local dielectric properties of the metasurface. These changes can cause unwanted thermal anomalies may alter local electromagnetic boundary conditions and generate detectable thermal or electromagnetic inconsistencies. Maintaining the functional stability of metamaterial-based camouflage under operational conditions is therefore a major engineering challenge for the development of next-generation combat equipment.

Another important limitation concerns maintenance and durability. Conventional chemical cleaning and thermal treatments may irreversibly damage delicate nanostructured layers and reduce shielding efficiency. Current research focuses on omniphobic and self-cleaning protective coatings that preserve electromagnetic functionality during repeated washing and prolonged exposure to the field [16].

Additional progress has been achieved through the development of hybrid textile composites in which metastructures are encapsulated within elastomeric protective matrices or directly integrated into textile fibers. Such encapsulation strategies improve mechanical durability, environmental resistance, and long-term operational stability while preserving multispectral shielding capabilities and ballistic protection performance [17].

VI. MULTIFUNCTIONAL METAMATERIAL ARCHITECTURES FOR ADAPTIVE ELECTROMAGNETIC CAMOUFLAGE AND SIGNATURE MANAGEMENT

The implementation of metamaterial structures with negative refractive index properties ($n < 0$) marks a significant transition from conventional passive camouflage toward active electromagnetic signature management. Through the precise design of resonant meta-atoms integrated into protective systems, modern combat equipment can enable engineered manipulation of the propagation, reflection, and scattering of electromagnetic waves across multiple spectral ranges.

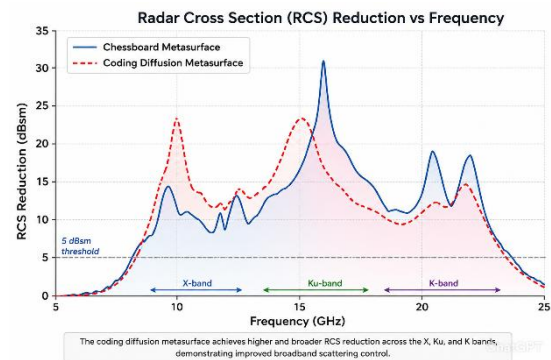


Fig.4 Comparison of electromagnetic wave scattering from a traditional metal surface (left) and a digital sequence encoding metasurface (right).

Figure 4 illustrates the difference between electromagnetic wave scattering from a conventional metallic surface and from a coding metasurface with programmable phase distribution. Unlike traditional reflective surfaces, the metasurface redistributes electromagnetic energy diffusely, thereby reducing radar cross-section (RCS) and enhancing passive sensor deception capabilities [9].

This technological approach enables the development of multispectral protection systems that reduce detectability across the infrared, visible, and microwave spectral regions. The integration of electromagnetic functionality with advanced ballistic protection represents one of the central engineering challenges in modern defense materials research. In particular, the combination of wave-manipulation capability with high mechanical durability requires the development of hierarchical composite architectures and multifunctional nanostructured materials.

Recent advances in hierarchical nanocomposites, adaptive polymers, and self-healing materials have enhanced the structural stability and operational durability of metamaterial-based protective systems under mechanical and ballistic stresses. Such technologies may enable future combat equipment to maintain both mechanical integrity and electromagnetic performance during prolonged operational deployment.

The reviewed studies demonstrate that metamaterial-assisted protection systems have the potential to significantly improve multispectral concealment and reduce vulnerability to advanced surveillance technologies, including radar, infrared imaging, and AI-assisted sensor platforms [5]. As a result, modern camouflage concepts are evolving from passive visual concealment to adaptive, multifunctional protection systems capable of dynamically controlling electromagnetic signatures.

VII. CONCLUSION

The reviewed literature shows that military camouflage is evolving from conventional passive concealment to adaptive multispectral protection systems that control electromagnetic signatures across multiple spectral domains. Traditional camouflage textiles remain effective for visual blending, but have limited ability to regulate infrared emission, radar reflection, and electromagnetic scattering. This significantly reduces their effectiveness against modern multisensor surveillance technologies such as radar, thermal imaging, LIDAR, and AI-assisted detection systems.

Metamaterial-based architectures offer an effective alternative by integrating engineered resonant structures that manipulate the propagation, absorption, reflection, and scattering of electromagnetic waves. Technologies based on split-ring resonators (SRRs), coding metasurfaces, and transformation optics show

considerable capability to reduce radar cross-section (RCS) and infrared detectability while maintaining the flexibility and wearability required for combat equipment.

Integrating conductive as well as resonant meta-elements into textile structures through embroidery, nanoprinting and hybrid composite fabrication is an important step towards wearable electromagnetic shielding systems. Recent advances in hierarchical nanocomposites, adaptive polymers, self-healing materials, and omniphobic protective coatings have also improved the durability, environmental resistance, and functional stability of metamaterial-enabled combat textiles under realistic combat conditions.

In spite of these advances, several major challenges persist, including large-scale manufacturability, long-term mechanical reliability, preservation of electromagnetic performance under deformation and environmental contamination, and integration of multispectral protection with ballistic and ergonomic requirements. Additional interdisciplinary research combining materials science, textile engineering, nanotechnology, and electromagnetic design is needed before widespread battlefield implementation becomes feasible.

Overall, metamaterial-assisted protection systems constitute a major technological direction for advanced military equipment. Their future development may enable lightweight, adaptive, and multifunctional combat platforms capable of dynamically managing electromagnetic signatures while simultaneously providing mechanical protection and operational survival in complex multispectral combat settings.

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Hydrodynamic Jet Reaction Analysis for Marine Propulsion Control Units

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Abstract— Modern requirements in shipbuilding and marine engineering necessitate continuous improvement of propulsion systems, with particular emphasis on waterjet propulsors due to their high manoeuvrability and efficiency at elevated speeds. This study presents an analysis of hydrodynamic reaction forces generated during the interaction of a high-speed water jet with deflector surfaces of varying geometries. The results demonstrate that the jet deflection angle strongly influences efficiency, with the semi-circular surface achieving the highest energy utilization.

The experimental investigation was conducted using a specialized laboratory test stand (HM 150.08), enabling precise measurement and quantitative assessment of momentum change. Four deflector geometries were examined: flat (90° deflection), semi-circular (180°), oblique (45°), and conical (135°). Experimental results were compared with theoretical predictions based on the conservation of momentum.

The results confirm that the jet deflection angle plays a critical role in system efficiency, with the semi-circular surface achieving the highest energy utilization and the oblique surface the lowest.

Keywords—conservation of momentum, deflector surfaces hydrodynamic jet reaction, marine waterjet propulsion, mechatronic control system.

I. INTRODUCTION

In fluid dynamics, changes in momentum during the acceleration, deceleration, or deflection of a flowing fluid lead to the generation of significant mechanical forces. These fundamental principles, theoretically described by Bernoulli's equation and the law of momentum conservation, form the basis for the design of both classical Pelton turbines and modern high-tech marine waterjet propulsion systems [1], [2].

Detailed control volume analysis is a critical element for accurately calculating reaction forces arising from fluid interaction with surfaces of varying geometry [1]. The methodology for visualization and quantitative measurement of jet momentum, enabling a precise transition from theoretical models to practical engineering calculations, is described in [2].

In the context of marine engineering and shipbuilding, understanding jet hydrodynamics is essential for optimizing thrust and propulsion system efficiency. The characteristics of waterjet systems are closely related to the profile of blades and guide vanes, where each degree of deflection affects the overall efficiency coefficient [3]. In the design of high-speed vessels, where reaction force is the primary principle for achieving design speed, precise analysis of the interaction between the jet and deflector systems is essential for improving hydrodynamic stability and energy efficiency [4].

Modern requirements for marine machinery, however, go beyond purely mechanical design, necessitating the integration of complex mechatronic control solutions. Reaction force data are no longer merely of static laboratory interest; they serve as input parameters for automated control systems. These hydrodynamic forces can be successfully modelled and transformed into algorithms for dynamic positioning and motion control [5]. The transition from physical force measurement to electronic control is further described in [6], where precise regulation of reactive flows through feedback systems is essential for achieving high manoeuvrability under complex marine conditions.

II. MATERIALS AND METHODS

The experimental investigation was conducted using the HM 150.08 module, which includes a transparent tank, a nozzle with a diameter of 10 mm, and a lever mechanism with calibrated weights.

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The experimental setup and procedure are summarized as follows:

1. Deflectors: Four interchangeable aluminium deflectors were used: flat surface (90°), semi-circular surface (180°), inclined surface (45°), and conical surface (135°).

2. Measurement: The jet force was measured using a lever mechanism with calibrated weights to the lever mechanism (ranging from 0.2 N to 5 N).

3. Flow rate: The volumetric flow rate ($\dot{V}$) was determined by measuring the time (t) required to fill 10 liters of water in the measuring tank of the base HM 150 module.

4. Calculations: The jet velocity (v) was determined from the volumetric flow rate and nozzle cross-sectional area, while the theoretical force (F) was derived from the momentum conservation principle.

III. RESULTS AND DISCUSSION

A. Results

The experimental data (Tables 1-4) reveal a direct relationship between the flow rate and the generated force for all investigated surfaces at a volume of 10 liters .

TABLE 1 DEVIATION 90° AT FLAT SURFACE

Specification	Measured	Calculated
Force, F [N]	Measurement time t for 10 L [s]	Flow rate, $\dot{V}$ [L/s]
0.5	46	0.21
1	32	0.31
2	22	0.45
3	17	0.59
4.5	13	0.77

TABLE 2 DEVIATION 180° AT SEMI-CIRCULAR SURFACE

Specification	Measured	Calculated
Force, F [N]	Measurement time t for 10 L [s]	Flow rate, $\dot{V}$ [L/s]
0.5	59	0.17
1	40	0.25
2	30	0.33
3	24	0.42
4.5	19	0.53

TABLE 3 DEVIATION 45° AND 135° AT INCLINED SURFACE

Specification	Measured	Calculated
Force, F [N]	Measurement time t for 10 L [s]	Flow rate, $\dot{V}$ [L/s]
0.2	52	0.19
0.5	40	0.25
0.8	25	0.40
1.0	21	0.48
1.5	17	0.59

TABLE 4 DEVIATION 135° AT CONICAL SURFACE

Specification	Measured	Calculated
Force, F [N]	Measurement time t for 10 L [s]	Flow rate, $\dot{V}$ [L/s]
0.5	49	0.20
1	35	0.29
2	27	0.37
3	22	0.45
4.5	16	0.63

Table 5-8 presents the values of the calculated force F_{th} and measured force F_{meas} for the different types of deflectors.

TABLE 5 FLAT SURFACE

Flow rate, $\dot{V}$ [L/s]	Flow, $\dot{V}$ [m ³ /s]	Velocity, w_1 [m/s]	Calculated force, F_{th} [N]	Measured force, F_{meas} [N]
0.21	0.00021	2.67	0.56	0.5
0.31	0.00031	3.94	1.22	1.0
0.45	0.00045	5.72	2.58	2.0
0.59	0.00059	7.49	4.42	3.0
0.77	0.00077	9.78	7.56	4.5

TABLE 6 SEMI-CIRCULAR SURFACE

Flow rate, $\dot{V}$ [L/s]	Flow, $\dot{V}$ [m ³ /s]	Velocity, w_1 [m/s]	Calculated force, F_{th} [N]	Measured force, F_{meas} [N]
0.17	0.00017	2.16	0.73	0.5
0.25	0.00025	3.18	1.59	1.0
0.33	0.00033	4.20	2.77	2.0
0.42	0.00042	5.35	4.51	3.0
0.53	0.00053	6.75	7.19	4.5

TABLE 7 INCLINED SURFACE

Flow rate, $\dot{V}$ [L/s]	Flow, $\dot{V}$ [m ³ /s]	Velocity, w_1 [m/s]	Calculated force, F_{th} [N]	Measured force, F_{meas} [N]
0.19	0.00019	2.41	0.22	1.19
0.25	0.00025	3.18	0.30	1.57
0.38	0.00038	4.84	0.46	2.39
0.48	0.00048	6.11	0.58	3.02
0.59	0.00059	7.52	0.71	3.72

TABLE 8 CONICAL SURFACE

Flow rate, $\dot{V}$ [L/s]	Flow, $\dot{V}$ [m ³ /s]	Velocity, w_1 [m/s]	Calculated force, F_{th} [N]	Measured force, F_{meas} [N]
0.20	0.00020	2.54	1.26	0.5
0.29	0.00029	3.68	2.03	1.0
0.37	0.00037	4.69	2.59	2.0
0.45	0.00045	5.72	3.16	3.0
0.63	0.00063	8.01	4.42	4.5

B. Results Analysis

Table 9 presents the difference between the calculated theoretical force (F_{th}) and the experimentally measured force (F_{meas}) for four surface types. The conical surface yields the highest theoretical value (2.03 N), while the inclined surface shows the lowest (0.30 N), compared to a constant measured force of 1 N.

TABLE 9 COMPARATIVE DATA BETWEEN THEORETICAL AND MEASURED FORCE UNDER A WEIGHT OF 1 N

Surface	Calculated Force, F_{th} [N]	Measured Force, F_{meas} [N]
Flat surface	1.22	1.0
Semi-circular surface	1.59	1.0
Inclined surface	0.30	1.0
Conical surface	2.03	1.0

- The semi-circular surface (180°) demonstrates the closest agreement between theoretical and measured values, indicating higher efficiency and lower energy losses.
- The inclined surface shows a significant deviation between theoretical and measured force, indicating increased losses due to geometry-related factors.
- The conical surface, despite producing the highest theoretical force, also exhibits a notable discrepancy from the measured value, which may indicate limitations of the theoretical model under these conditions.

Figure 1 and Figure 2 illustrate the variation of the flow rate $\dot{V}$ for the four deflectors relative to the theoretical force F_{th} and the measured force F_{meas} , respectively.

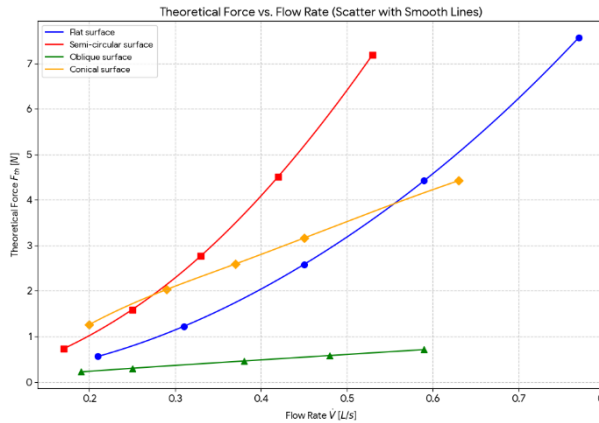


Fig. 1. Flow rate variation versus theoretical force.

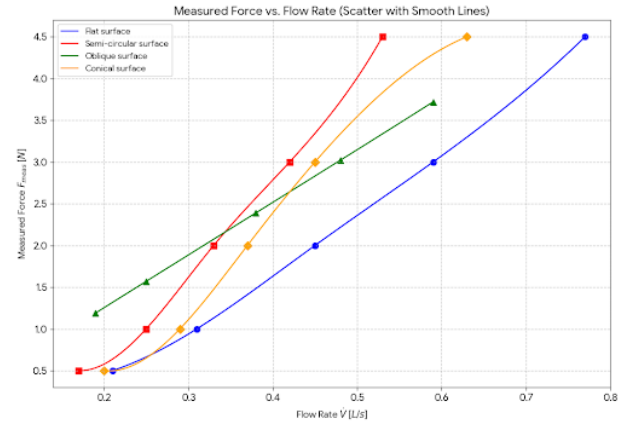


Fig. 2. Flow rate variation versus measured force

The graphical results suggest that, for the same force level, the lowest flow rate is required for the semi-circular surface.

This plot, shown in Fig. 2, illustrates the actual experimental results. The data presented correspond to the measured force (F_{meas}) and the associated flow rate ($\dot{V}$) for the four types of bodies.

- Flat surface: data from Table 1;
- Semi-circular surface: data from Table 2;
- Inclined surface: data from Table 3;
- Conical surface: data from Table 4.

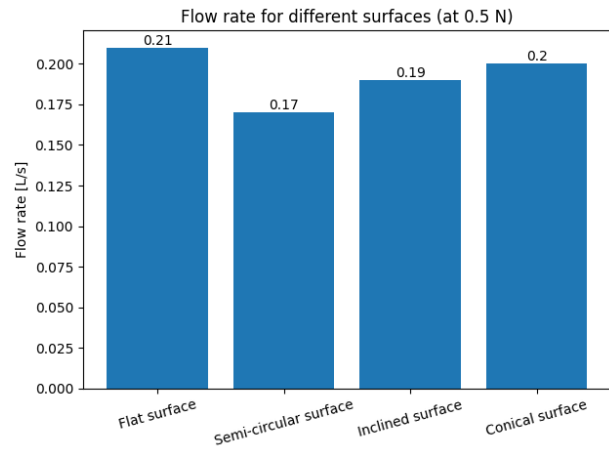


Fig. 3. Flow rate ratio for the four types of deflectors under a weight of 0.5 N

The graph clearly shows that, for generating the same force, the semi-circular surface requires the lowest flow rate, confirming its highest efficiency.

The conical surface exhibits the highest theoretical potential, but its actual efficiency depends strongly on the accuracy of jet deflection.

Table 10 illustrates the required volumetric flow rate ($\dot{V}$) in L/s to maintain a force of 0.5 N. The highest flow rate is observed for the flat surface (0.21 L/s), while the lowest is associated with the semi-circular surface (0.17 L/s).

TABLE 10 COMPARATIVE DATA FOR FLOW RATE UNDER A WEIGHT OF 0.5 N.

Surface	Force, 0.5 [N]	Flow rate, [L/s]
Flat surface	0.5	0.21
Semi-circular surface	0.5	0.17
Inclined surface	0.5	0.19
Conical surface	0.5	0.20

C. Discussion

The analysis of the results indicates that the semi-circular surface utilizes the energy of the water jet most efficiently, as it deflects the fluid by 180° , thereby maximizing the change in momentum. In contrast, the inclined surface demonstrates the lowest level of energy utilization, requiring a significantly higher flow rate to achieve the same reaction force.

These differences in hydrodynamic performance are relevant for the design of Marine Propulsion Control Units. Reaction force data are transformed into control algorithms that regulate pump speed and nozzle angle in waterjet propulsion systems [5]. Accurate modelling of these forces enables automation systems to compensate for nonlinearities and improve vessel manoeuvrability. The use of high-efficiency deflectors (such as semi-circular geometries in Pelton turbine buckets) can be applied in the design of more efficient reversing devices in shipbuilding.

IV. CONCLUSIONS

The conducted study successfully demonstrates the principle of momentum and its practical application in marine engineering. The results indicate that surface geometry is a determining factor in hydrodynamic reaction efficiency. The semi-circular geometry proves to be the

most efficient, while the inclined surface offers the least resistance and consequently generates the smallest force.

The obtained data can be used as a basis for calibration of sensors and control systems in waterjet propulsion applications.

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Numerical Modeling of Conjugate Heat Transfer Between a Fluid and a Solid Using ANSYS Fluent

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Abstract—The present study develops a numerical model of conjugate heat transfer between a fluid and a solid, which is essential for the optimization of engineering systems such as heat exchangers, electronic cooling systems, and industrial reactors. The simulation is performed using ANSYS Fluent, where heat transfer in both domains and at their shared interface is analysed.

The modelling procedure includes mesh generation, definition of physical models and material properties, as well as specification of boundary conditions for temperature and fluid velocity. The governing equations of mass, momentum, and energy conservation are solved, with automatic coupling of temperature and heat flux at the fluid–solid interface. The obtained results provide temperature and heat flux distributions, enabling quantitative evaluation of heat transfer efficiency and identification of critical thermal regions.

Keywords—ANSYS Fluent, CFD, conjugate heat transfer, fluid, heat transfer, solid.

I. INTRODUCTION

Conjugate heat transfer (CHT), defined as the simultaneous solution of heat conduction in solids and convective heat transfer in fluids, is a fundamental phenomenon in many engineering applications such as heat exchangers, electronic cooling systems, and thermal devices [1], [2].

Accurate numerical modelling of CHT enables prediction of global thermal performance as well as identification of localized regions with high temperature gradients, which may lead to system inefficiencies or failure [3], [4].

The literature demonstrates extensive application of CHT modelling in different engineering configurations. For example, nanofluid flow simulations in enclosed geometries show strong dependence of heat transfer on

geometric parameters and material properties [1]. In thermal management of data centres, CHT models are used to analyse interactions between solid components and cooling fluids, enabling optimization of thermal design [2], [5].

Furthermore, studies on enhanced heat exchangers indicate that modified geometries and induced vertical structures significantly increase heat transfer performance [6], [7]. In modern CFD practice, solid domains are treated as active computational regions rather than simplified thermal boundaries, which leads to more accurate prediction of temperature fields and interface heat flux distribution [3], [4].

The present work develops a conjugate heat transfer model implemented in ANSYS Fluent for a simplified but representative configuration consisting of a solid block subjected to external fluid flow. The objective is to analyse temperature distribution and heat transfer characteristics and to identify thermally critical regions within the system.

II. MATERIALS AND METHODS

Geometry

The investigated configuration consists of a solid rectangular block with dimensions, $L=0.1\text{ m}$, $W=0.05\text{ m}$, $H=0.02\text{ m}$, surrounded by a fluid domain (air) with dimensions $L_f=0.5\text{ m}$, $W_f=0.25\text{ m}$, $H_f=0.1\text{ m}$ (Figure 1).

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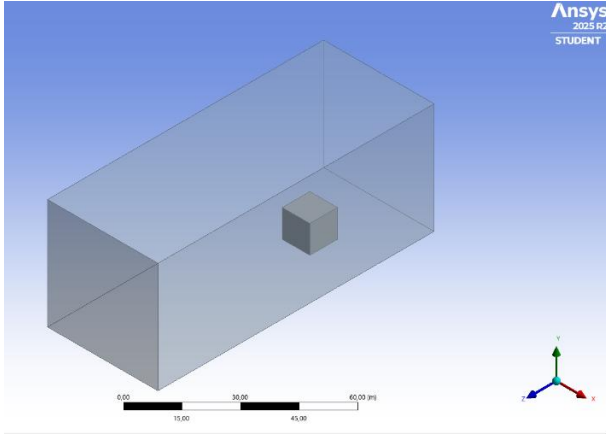


Fig. 1. Computational domain geometry

The air flows around the block from the inlet with velocity $U_{in}=1 \text{ m/s}$ and exits through the outlet and the lateral boundaries. The CAD model is used for visualization purposes, while the numerical simulation is performed using the actual physical dimensions of the computational domain.

Boundary Conditions

The following boundary conditions are applied:

- Inlet: uniform velocity $U=1 \text{ m/s}$, temperature $T=300 \text{ K}$. This condition defines both the incoming momentum and thermal energy of the fluid and governs the development of convective heat transfer along the solid surface;
- Outlet: gauge pressure – $p=0 \text{ Pa}$. This condition allows fully developed flow to exit the computational domain without artificial reflections and ensures numerical stability of the solution;
- Walls: All external solid boundaries are treated using a no-slip condition ($u=0$) which represents viscous adherence of the fluid to the wall. The outer surfaces of the computational domain are assumed adiabatic ($q=0$) meaning that no heat exchange occurs between the system and the surrounding environment. Thus, heat transfer is restricted only to interaction between the fluid and the solid body;
- Fluid-Solid Interface (Physical Description): The interaction between the fluid and solid domains is modelled using a conjugate heat transfer approach, ensuring thermal coupling at the interface. The interface treatment in ANSYS Fluent guarantees energy exchange between the two domains without thermal discontinuities [8].

Mathematical Model

The physical basis of conjugate heat transfer includes solving the following governing equations for the fluid and the solid domains:

- Continuity equation (mass conservation) [9], [10].

$$\nabla \cdot u = 0, \quad (1)$$

where:

$u \text{ [m/s]}$ – velocity vector.

- Navier-Stokes equations for incompressible Newtonian fluid (momentum) [9], [10].

$$\rho(u \cdot \nabla)u = -\nabla p + \mu \nabla^2 u, \quad (2)$$

where:

$p \text{ [Pa]}$ – pressure,

$\mu \text{ [Pa}\cdot\text{s]}$ – dynamic viscosity,

Body forces are neglected ($F=0$), assuming no buoyancy effects.

- Energy equation (fluid) [11], [12].

$$\rho c_p (u \cdot \nabla T) = \nabla \cdot (k_f \nabla T), \quad (3)$$

where:

$\rho \text{ [kg/m}^3\text{]}$ – fluid density;

$c_p \text{ [J/(kg}\cdot\text{K)]}$ – specific heat at constant pressure;

$T \text{ [K]}$ – absolute temperature;

$k_f \text{ [W/(m}\cdot\text{K)]}$ – thermal conductivity of the fluid.

- Heat conduction (solid) [13].

$$\nabla \cdot (k_s \nabla T) = 0, \quad (4)$$

where:

$k_s \text{ [W/(m}\cdot\text{K)]}$ – thermal conductivity of the solid.

Mesh Generation

The computational mesh for the conjugate heat transfer analysis was generated using ANSYS Meshing, employing a hybrid discretisation approach based on the MultiZone method for sweepable body regions, in accordance with the recommendations of the official software documentation [14].

The global element size was set to $2.87 \times 10^{-3} \text{ m}$, with a maximum allowable size of $3 \times 10^{-3} \text{ m}$, while the defeature size was defined as $1.435 \times 10^{-2} \text{ m}$. Curvature-based refinement was applied with a minimum curvature size of $2.87 \times 10^{-2} \text{ m}$ and a curvature normal angle of 18° , ensuring accurate geometric resolution in regions with changing surface curvature.

The computational domain bounding-box diagonal was 114.89 m , with an average surface area of 1188.2 m^2 . The minimum edge length was controlled to ensure sufficient geometric fidelity for thermal interface resolution.

Mesh quality was controlled by imposing a target skewness of 0.9 , while the transition ratio was limited to 0.272 to ensure smooth variation in element size and numerical stability during solution convergence.

Near the solid boundaries, an inflation mesh was applied consisting of up to five layers, with a growth rate of 1.2 , providing enhanced resolution of the thermal

boundary layer and improved prediction of conjugate heat transfer across the fluid-solid interface.

Figure 2 presents the generated computational mesh, showing local refinement near the fluid-solid interaction zone, where steep temperature gradients are expected.

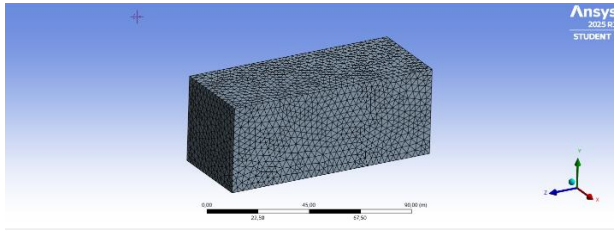


Fig. 2. Computational mesh structure

The final computational mesh contains 10298 nodes and 53335 elements, providing an appropriate balance between computational efficiency and numerical accuracy for conjugate heat transfer simulation.

The selected discretisation strategy ensured sufficient spatial resolution of temperature gradients in the interface region while maintaining computational efficiency for steady-state numerical analysis.

Numerical Procedure and Convergence Criteria

The numerical solution of the governing equations is performed in ANSYS Fluent using a steady-state solver, based on the finite volume method (FVM). Second-order discretization schemes are used, providing higher accuracy in the computation of temperature and velocity gradients. Pressure-velocity coupling is achieved using the SIMPLE algorithm.

Convergence of the solution is assessed by monitoring the scaled residuals, with the convergence criterion defined as a reduction below 10^{-6} for the energy equation and below 10^{-3} for the continuity and momentum equations. Additionally, the stabilization of temperature at characteristic points in the computational domain is monitored. The flow regime is assumed to be laminar, which is consistent with the characteristic Reynolds number of the configuration.

III. RESULTS AND DISCUSSION

Temperature Distribution

After achieving numerical convergence, the temperature distribution in the fluid and solid domains was analyzed. Figure 3 presents the temperature field in the form of contour plots in a representative cross-section, illustrating the thermal interaction at the fluid-solid interface.

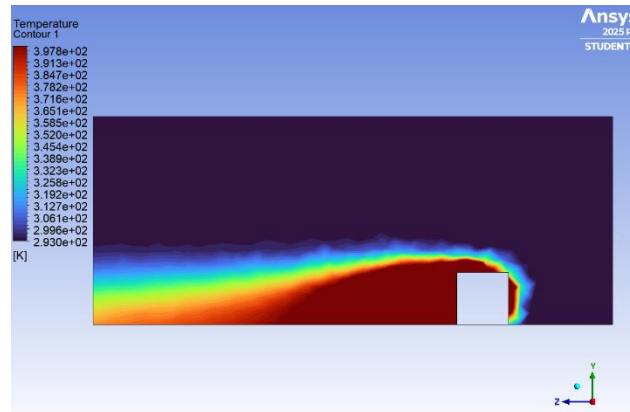


Fig. 3. Temperature contours in the fluid and solid domains in a characteristic cross-section

For a more illustrative representation of the three-dimensional nature of heat transfer, Figure 4 shows a volumetric rendering of the temperature field, providing a comprehensive view of the heat distribution within the computational domain.

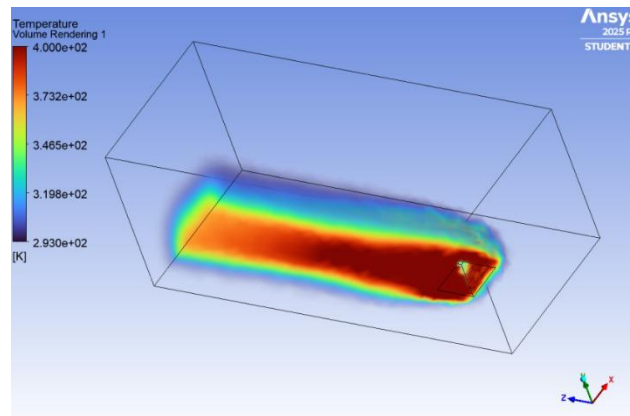


Fig. 4. Three-dimensional volumetric visualization of the temperature field in the computational domain

The three-dimensional temperature field confirms a temperature range between 293.0 K and 397.8 K. The highest temperature values are concentrated within the solid body and the immediate fluid-solid interaction region, while the surrounding fluid remains close to ambient temperature, indicating effective thermal dissipation through forced convection.

The maximum temperature values are observed in the central region of the solid block, reaching approximately 397.8 K, while the minimum temperature in the surrounding fluid remained close to 293.0 K. This thermal difference of approximately 104.8 K results from limited conductive heat removal inside the solid and convective interaction with the external airflow.

In the fluid domain, the temperature gradually decreases from approximately 397.8 K near the heated solid interface to 293.0 K in the free-stream region, reflecting efficient convective heat transport. This behaviour is characteristic of conjugate heat transfer and

reflects the balance between conduction in the solid and convective transport in the fluid.

The observed temperature field is consistent with the expected physical behaviour for external forced convection over a heated solid body and confirms the adequacy of the applied numerical model and boundary conditions.

Heat Transfer Intensity (Qualitative Analysis)

The intensity of heat transfer between the fluid and the solid is analyzed based on the obtained temperature field and local temperature gradients at the fluid-solid interface.

The highest heat transfer intensity is observed in the inlet region, where the temperature difference between the fluid and the solid surface is maximal and the thermal boundary layer is weakly developed. Along the length of the solid block, a gradual decrease in heat transfer intensity is observed as a result of thermal boundary layer development and the corresponding reduction in local temperature gradients at the interface.

This behavior confirms the physical consistency and numerical adequacy of the applied conjugate heat transfer model.

Engineering Analysis and Interpretation

The obtained results demonstrate that the conjugate modelling approach provides a more realistic representation of the thermal behaviour of the system compared to models in which the solid is treated as an isothermal or prescribed-temperature boundary.

The predicted thermal field spans approximately 104.8 K, confirming strong thermal coupling between conductive heat transfer inside the solid and convective heat transport in the surrounding fluid.

The numerical results indicate stable thermal interaction at the fluid-solid interface, with clearly resolved temperature gradients across the contact region. The highest thermal gradients are concentrated in the upstream region, where the incoming fluid interacts with the heated solid surface and convective heat transfer is most intensive.

A gradual reduction in thermal intensity is observed downstream due to thermal boundary layer development, which reduces the local temperature gradient and consequently decreases the heat transfer rate along the solid surface.

The resolved temperature field clearly identifies thermally critical regions concentrated near the fluid-solid interaction zone, providing useful information for targeted optimisation of material properties, operating conditions, and system geometry.

These results demonstrate the applicability of conjugate heat transfer analysis as an effective tool for engineering thermal optimisation and design improvement.

Mesh Independence Study

A mesh independence study was performed to evaluate the sensitivity of the numerical solution to grid refinement, with particular focus on the fluid-solid interaction region where the steepest thermal gradients occur.

The variation of key output parameters, including average temperature and local thermal characteristics, remained below 2% between successive refinement levels. This confirms grid-independent behaviour and demonstrates the numerical stability and reliability of the adopted discretisation strategy.

Validation of Results

The obtained results were qualitatively validated against classical heat transfer theory and existing literature on convective and conjugate heat transfer phenomena. The observed temperature distribution and heat transfer trends are consistent with established correlations for external forced convection, where higher heat transfer rates occur near the inlet region due to the development of a thin thermal boundary layer.

Furthermore, the results show good qualitative agreement with established numerical trends for conjugate heat transfer in comparable engineering configurations. This confirms the physical reliability of the numerical model and the correctness of the applied boundary conditions.

IV. CONCLUSION

The present study presents a numerical analysis of conjugate heat transfer between a fluid and a solid, implemented using ANSYS Fluent. The developed model successfully describes the interaction between convective heat transfer in the fluid domain and conductive heat transfer in the solid, ensuring continuity of temperature and heat flux at the fluid-solid interface.

The obtained results show clearly pronounced temperature gradients near the contact surface, as well as a characteristic development of the thermal boundary layer along the flow direction. It is observed that the maximum temperatures are concentrated inside the solid body, while in the fluid domain a gradual cooling occurs due to convective heat transfer.

The analysis of heat transfer intensity shows that the most effective heat transfer occurs in the inlet region of the fluid, while along the length of the body the efficiency decreases due to boundary layer development. These results are consistent with theoretical formulations and confirm the validity of the numerical model.

The developed approach demonstrates the applicability of conjugate heat transfer as a reliable tool for analysis and optimization of engineering systems. Future work may focus on turbulent flow regimes, different working fluids, and geometry optimization aimed at improving heat transfer performance.

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Engineering Aspects of Innovation Management Systems

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Abstract—Innovation management systems enhance the quality and foster the continual improvement of industrial processes and products. Product innovations are often associated with inventions and breakthrough discoveries. When the output of innovation initiatives and actions results in a product that is significantly different from its competitors and adds value to interested parties, then usually engineers and inventors choose to protect their intellectual property by a patent or a utility model. This paper presents a methodology for applying the guidance, tools and methods for intellectual property management of ISO 56005 in industrial organizations in Bulgaria.

Keywords— innovation management systems, intellectual property, ISO 56001, ISO 56005.

I. INTRODUCTION

Innovation management deservedly attracts the attention of professionals and company owners around the world. Innovation is an original way to improve existing products, services, systems and networks, and adds value to a plethora of interested parties.

Traditionally, improvement was considered a domain reserved primarily for experts in the quality field. Probably every self-respecting quality manager would argue that the continuous improvement cycle, known as Deming's cycle or the PDCA (Plan-Do-Check-Act) cycle, in the ISO 9000 series of standards, is the foundation of most modern ISO-based management systems. And not surprisingly, this is a fact, as PDCA is the methodology for improvement in standards for quality management systems, environmental management systems (ISO 14000 series), occupational health and safety management systems (ISO 45000 series), artificial intelligence management systems (ISO/IEC 42000), etc.

All the core standards in the abovementioned series are based on the high-level structure known as Annex SL. As such, they all require that processes related to the improvement of the management system (MS) are in place. These requirements are specified in Clause 10 "Improvement" and its two sub-clauses:

- 10.1 "Continual improvement", and
- 10.2 "Nonconformity and corrective action".

What is typical for innovation management is that it thrives in volatile, uncertain, complex, and ambiguous (VUCA) environments. It recognizes and captures value from an opportunity, an idea, or a concept, where other types of MS predominantly perceive threats. This is in contrast with other standards for MS that rely mainly on establishing stable processes and aim for results that are relatively easy to forecast and control.

The purpose of this paper is to present a methodology for applying the guidance, tools and methods for intellectual property management of ISO 56005 in industrial organizations, with a specific focus on Bulgaria.

II. MATERIALS AND METHODS

The paper uses materials published by the International Organization for Standardization (ISO), the World Intellectual Property Organization (WIPO), the European Union Intellectual Property Office (EUIPO), the European Patent Office (EPO), and the Patent Office of the Republic of Bulgaria (BPO).

The methods applied in preparing this paper are: analysis of published standards with requirements and guidance, analysis of statistical data, critical review of intellectual property rights (more specifically patents and

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utility models), and comparison of trends on global, regional and national levels.

III. STANDARDS FOR INNOVATION MANAGEMENT

A. The ISO 56000 Series of Standards

The ISO 56000 series of standards came into focus when ISO 56002, with guidance for innovation MS, was first published in 2019 [1]. Since then, this series has grown significantly to include 11 standards. 3 additional standards for innovation management are under development as of 2026-04-26 [2].

The core standard in the ISO 56000 series – ISO 56001– was published as late as 2024 [3]. It follows the PDCA cycle and the high-level structure and clauses of Annex SL. This structure is expanded with elements that are specific to an innovation MS:

- Innovation intent (Clause 4.3.1);
- Innovation strategy (Clause 5.3);
- Innovation culture (Clause 5.4);
- Innovation portfolio (Clause 6.4);
- Organizational structures (6.5);
- Collaboration (Clause 6.6);
- Additional resources (Clause 7.1) that are key for innovation MS: time (7.1.3), finance (7.1.4), and intellectual property (7.1.7). The latter is discussed in more detail in the following sections of this paper;
- Innovation initiatives (Clause 8.2);
- Innovation processes (Clause 8.3).

ISO 56001 requires that the intellectual property (IP) management approach takes into consideration the following activities:

- Monitoring published IP rights (IPR);
- Analysing IPR to establish existing gaps to be exploited and/or to avoid potential IPR infringements;
- Identifying intellectual assets of the organization and/or its personnel that need to be protected by appropriate forms of IPR;
- Clarifying the ownership of IP;
- Maintaining an inventory, or an innovation portfolio, of innovation assets, IP and IPR;
- Periodically reviewing IPR (own IPR to establish whether it still maintains its value, and other organizations' IPR to decide whether it can obtain their IPR by purchasing, licensing, or creating partnerships).

ISO 56002 provides additional guidance for IP management in its Clause 7.8. A draft version of the upcoming second edition of this standard has been

developed and is being reviewed by the ISO Technical Committee ISO/TC 279 “Innovation Management” [4].

The guidance of this standard can help innovation managers by integrating some additional aspects of IP management into ISO 56001 MS requirements. These are:

- Justifying the need for creating, updating, and utilizing IP;
- Justifying the decision not to protect IP (associated costs, risks, confidentiality, etc.);
- Raising awareness and providing training related to IPR for all personnel to promote an environment that stimulates creativity and value creation;
- Ensuring or restricting access to IPR based on actual needs and potential impact;
- Monitoring IPR trends by country and type of innovation, as well as scanning for competitors (both in research and in industry).

IP and IPR are also discussed in other standards of the ISO 56000 series. The concrete examples are as follows:

- ISO 56003 clauses: 5 “Entering an innovation partnership”, 6.2 “Generating a long-list of potential partners”, 6.3 “Generating a short-list of potential partners”, 8 “Interactions between the partners”, and more specifically – 8.2 “Key factors of interaction”. In two of the Annexes to ISO 56003, there is also a mention of “Intellectual assets” (D.1.5) and IP (Annex E “Performance evaluation criteria” / E.1 “Monitoring, measurement, analysis, and evaluation”) [5];
- ISO/TR 56004 clauses: 8.3.2 “Data interpretation and gap identification”, 9.2.1 “Examples of the data analysis results organized by topic/theme”, 9.3 “Communication of the Innovation Management Assessment results” [6];
- ISO 56006 clauses: 4.2 “Strategic intelligence needs”, 4.5 “Expected strategic intelligence outcomes”, 4.6 “Strategic intelligence essentials”, 5.1 Operational planning and control”, 5.4.3 “Outcome of data gathering – Data and information (analysed data)”; 5.5.2 “Outcome of interpretation – Knowledge (interpreted information)” [7].
- ISO 56007 clauses: 5.4.2 “Culture, motivation and recognition”, 5.4.3 “Idea ownership and intellectual property (IP) management” [8];
- ISO 56009 clauses: 7.2.2 “Measurements for the preparation of the innovation initiative” and 7.2.4 “Measurements for developing the solution” [9], also invoking ISO 56008 [10];
- ISO/TS 56010 clause 4.8 “Distinguishing innovation from other related concepts” [11];

- ISO 56000 specifies the terms and definitions, as well as the innovation management principles. Clause 3.6 presents 13 “Terms related to intellectual property”. Furthermore, Annex A.3 “Definitions of intellectual property, bridging with the TRIPS/WIPO convention” clarifies IP and IPR as defined in the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) and the World Intellectual Property Organisation (WIPO) Convention [12].

Three additional standards are planned by ISO/TC 279 “Innovation management” to join the ISO 56000 series:

- ISO/DIS 56011 “Competency framework for innovation management — Guidance” [13];
- ISO/AWI 56012 “Innovation management — Innovation Ecosystem Management — Guidance” [14];
- ISO/AWI 56013 “Innovation management — Innovation Portfolio Management — Guidance” [15].

Another standard that is not officially part of the ISO 56000 series, but upon publication will provide competence requirements for auditing and certification of IM systems, is ISO/IEC CD TS 17021-16 [16].

B. Intellectual Property Management using ISO 56005

The standard ISO 56005 presents 8 principles that are the basis for IP management and are derived from the IM principles of ISO 56000 [17]. The content of this standard is structured in 6 clauses (1. Scope; 2. Normative references; 3. Terms and definitions; 4. IP management framework; 5. IP Strategy; 6. IP management in the innovation process) and 6 informative annexes with various IP tools and methods:

- Annex A “Tools and methods for invention record and disclosure”;
- Annex B “Tools and methods for IP generation, acquisition and maintenance”;
- Annex C “Tools and methods for IP search”;
- Annex D “Tools and methods for IPR evaluation”;
- Annex E “Tools and methods for IP risk management”;
- Annex F “Tools and methods for IP exploitation”.

The proposed methodology for IP management in the innovation process is based on Clause 6 of ISO 56005. Each process step is presented in the standard with the following elements: why, input, how, and output. All the steps of IM are linked to the PDCA cycle (see Fig. 1).

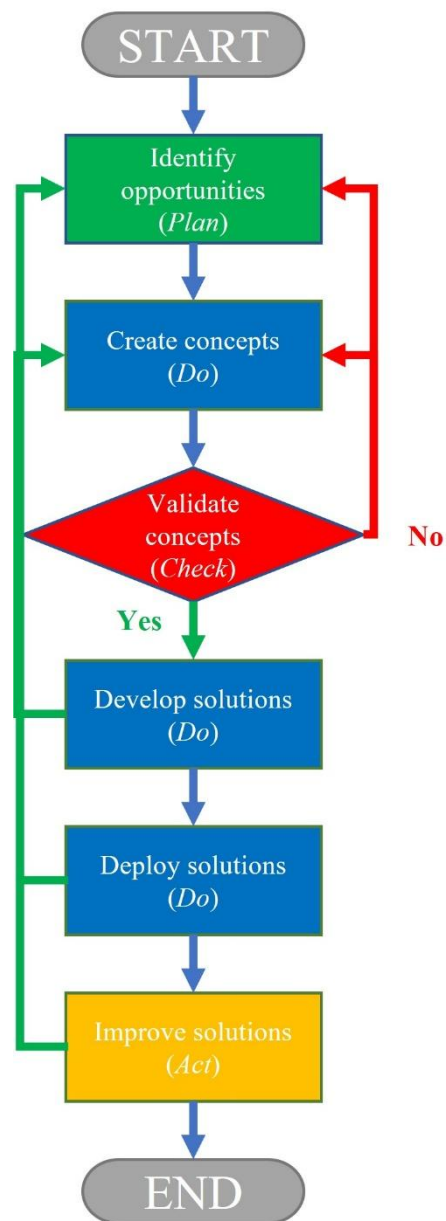


Fig. 1. IP management and the PDCA cycle.

The IP management process is iterative and non-linear. Only in some rare cases do innovations go “according to plan” from start to end. This is due to the high uncertainty and the many “unknowns” when developing a truly innovative solution.

At the “Plan” stage of the PDCA cycle, opportunities are identified. Initially, this can be done through IP landscaping and reviewing existing solutions that form the state-of-the-art in a specific industrial sector. Feedback collected throughout the entire IP management cycle can be used as input for the “Identify opportunities” step.

Several steps from ISO 56005 are considered as “Do” stages of the PDCA cycle:

- Creating concepts, which includes generating concepts based on the identified innovation opportunities and selecting concepts that possess the necessary potential to be converted into viable solutions;
- Developing solutions based on the opportunities, ideas and concepts, and executing the IP plan;
- Deploying and implementing solutions that have the highest perceived value for the interested parties. This would justify the protection and the commercialisation of IPR.

The “Check” stage of the PDCA cycle is represented by the step “validate concepts”. Validation is based on analysis of IP risks and opportunities, interaction with interested parties, IPR protection, tangible effects from technology transfer, etc.

The “Act” stage of the PDCA cycle is not officially mentioned in ISO 56005. It is proposed by the authors based on their experience that shows that to maintain the competitiveness of any industrial organization, any manager should continuously strive for improvement of the company’s offerings.

IV. INTELLECTUAL PROPERTY RIGHTS AND KEY ENGINEERING DOMAINS

A. Global Trends

The World Intellectual Property Organisation (WIPO) maintains data regarding patents and utility models, industrial designs, trademarks, and geographical indications. The IP data is presented with appropriate insights and analyses. The 18th edition of the Global Innovation Index (GII) was published in September 2025 [18]. Four out of the top 5 innovation clusters are based in Asia: Shenzhen–Hong Kong–Guangzhou (China), Tokyo–Yokohama (Japan), San Jose–San Francisco (USA), Beijing (China), and Seoul (South Korea). In the top 100 innovation clusters for 2025, China has 24, the USA – 22, Germany – 7, the United Kingdom and India – 4, and Japan, the Republic of Korea, and Canada – 3.

The stable growth in international patent filings is mainly due to China, which has 1795715 or 49,1 % of the 3725000 world patent applications. It is followed by the USA (501831), Japan (419132), the Republic of Korea (295722), and Germany (133485) [19].

China has a vast dominance in utility models with 3183030 applications out of nearly 3,3 million worldwide. It is followed by the Russian Federation (13594), Germany (6169), Indonesia (4842), and Thailand (4227).

The technology fields that prevail in the top 5 countries of origin for patent applications are: computer technology; digital communication; electrical machinery, apparatus, energy; measurement; medical technology; and transport. The technological sectors that show advances are supercomputing, electric vehicles and batteries, solar power, genomics, etc.

B. European Trends

Two organizations are key to understanding IP trends in Europe: the European Patent Office (EPO) and the European Union Intellectual Property Office (EUIPO).

The EPO maintains services that enable searching for patents in the European Patent Register by using the Espacenet search, as well as online filing of patent applications. The EPO also uses various channels to raise awareness about IP: the World IP Day (26 April), the European Inventor Award, the Young Inventors Prize, the “Talk innovation” podcast, etc.

201974 patent applications were filed in 2025 according to EPO data published as the EPO Technology Dashboard 2025 (formerly Patent Index) [20]. 47008 of these patent applications are filed from the USA, 24476 from Germany, 22031 from China, 21304 from Japan, and 14355 from the Republic of Korea. The top 10 is completed by France (10932), Switzerland (9914), the Netherlands (7006), the United Kingdom (5875), and Italy (4767). 67 % of the patent applications are filed by large enterprises, 26 % by SMEs and individual inventors, and 7 % by universities and public research organizations.

The technical fields with the highest number of EPO patent applications are: Computer technology, Digital communication, Electrical machinery, apparatus, energy, Medical technology, Transport, Measurement, Biotechnology, Pharmaceuticals, Other special machines, and Organic fine chemistry.

The EUIPO provides searches in their databases for trademarks (TMview), registered designs (DesignView), and geographical indications (GIview). Online application services are available for all these forms of IP. EUIPO also has a platform for dealing with the enforcement of IP rights (the IP Enforcement Portal, IPEP).

In January 2026, EPO and EUIPO jointly published “IP and innovation in European sectors” [21]. The study focuses on 361 IPR-intensive industries that apply various forms of IPR: patents, trademarks (TM), designs, copyright, geographical indications (GI), including protected designation of origin (PDO) and protected geographical indication (PGI), and plant variety rights (PVR). According to this study, “IPR-intensive industries generated 30.6% of all jobs in the EU during the 2021–2023 period” and “47.9% of total economic activity (GDP) in the EU, worth €7.7 trillion”.

C. Trends in Bulgaria

Bulgaria ranks 37th in the GI 2025 [18]. This is mainly due to strengths such as: “Industrial designs by origin/GDP”, “Creative goods and services”, “Knowledge and technology outputs”, “Venture capital investment/GDP”, “Domestic industry diversification”, ISO 9001 and ISO 14001 certification, etc.

The legal protection of industrial property in Bulgaria is overseen by the Patent Office of the Republic of Bulgaria (BPO). The Annual report for 2025 summarizes information regarding patents, utility models, industrial designs, trademarks, and geographical indications [22].

The patent applications for 2025 are 194 and show a growth of 4,3 % against the previous year. The 284 utility model applications have decreased by 15,7 % compared to 2024. The explanation provided in [22] about these figures is “the small number of programmes for improving the competitiveness of small- and medium-sized enterprises (SMEs) that state the registration of a utility model as a positive criterion”.

The technical domains for the patent applications in Bulgaria are: electrotechnics and electronics (41 %), manufacturing and construction (36 %), and chemistry and biotechnologies (23 %). The same technical domains have different shares in the applications for utility models filed in 2025: manufacturing and construction (44 %), electrotechnics and electronics (32 %), and chemistry and biotechnologies (24 %).

CONCLUSIONS

The paper has presented a comprehensive overview of the ISO 56000 series of standards for innovation management systems. The specific focus is on ISO 56005 and its guidance on tools and methods for intellectual property management.

The trends and dynamics of applications and registrations of patents and utility models are demonstrated by data from official sources and reputable organizations like the WIPO, EPO, EUIPO, and BPO.

The analyses in this paper can help innovation managers and inventors in their efforts to improve innovation management performance and create value from their intellectual property assets.

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Determination of Optimal Underwater Cutting Parameters for Ship Hull Steel of Scientific Research Vessel RSV 421 "St. St. Cyril and Methodius"

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Abstract: This article presents an in-depth study of underwater exothermic cutting technology with exothermic electrodes, applied to the hull steel of the Bulgarian research vessel RSV 421 "St. St. Cyril and Methodius". Having identified the steel type in previous studies as low-carbon Grade A, the focus here shifts to the optimization of underwater repair procedures. The thermodynamic fundamentals of the exothermic reaction, the impact of hydrostatic pressure on cutting parameters, and the strict safety protocols required for operations in extreme marine conditions are examined. The energy characteristics, the specifications of EP-1 and EP-3 type electrodes, and the metallurgical transformations in the cutting zone are analysed.

Keywords: cutting parameters, exothermic electrodes, safety protocols, underwater cutting, underwater repair procedures.

I. INTRODUCTION

The operation of research vessels in polar conditions, such as the RSV 421 "St. St. Cyril and Methodius", involves a constant risk of structural damage due to ice collisions, dynamic loads, and aggressive electrochemical corrosion.

Ensuring the structural integrity of the hull during these missions often necessitates urgent underwater repair activities. The ability to quickly and precisely cut damaged metal elements is critical both for the success of the expeditions and for the safe operation of the ship as a whole. Underwater cutting is a complex engineering process in which the aquatic environment directly affects arc stability, temperature distribution, and the safety of the diver-operator. The present work defines the technological

standard for these interventions on the specific material of RSV 421 [1], [2], [3], [4], [5].

II. CHARACTERISTICS OF THE BASE HULL STEEL OF THE RESEARCH VESSEL RSV 421 "ST. ST. CYRIL AND METHODIUS"

Based on previous comprehensive analyses (optical microscopy, XRD, and mechanical testing), the hull of RSV 421 is defined as being made of hypoeutectoid low-carbon unalloyed structural steel, corresponding to marine Grade A, shown on figure 1 [6], [2], [7].

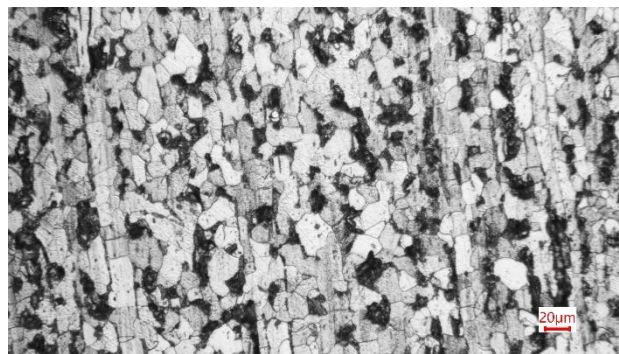


Fig. 1. Optical micrograph of RSV 421 hull steel, showing a dominant ferritic matrix (light phase) and dispersed pearlite colonies (dark phase).

The main material parameters that determine its technological applicability for underwater cutting are summarized in the following points:

- Chemical composition: An approximate carbon content of 0.16%, which provides a low carbon equivalent.

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- Microstructure: A dominant ferrite matrix (80–85%) with fine pearlite colonies, guaranteeing high plasticity and resistance to brittle fracture at low temperatures (Fig. 1) [1], [6], [8], [7].
- Mechanical properties: Average microhardness of 132.8 HV0.2/10 with pronounced homogeneity of the metal matrix (Fig. 2).
- Weldability and hardenability: The low carbon equivalent suppresses the steel's tendency to form hard martensitic structures under extreme underwater cooling rates. This minimizes the risk of cold cracking in the heat-affected zone (HAZ) during the cutting process.

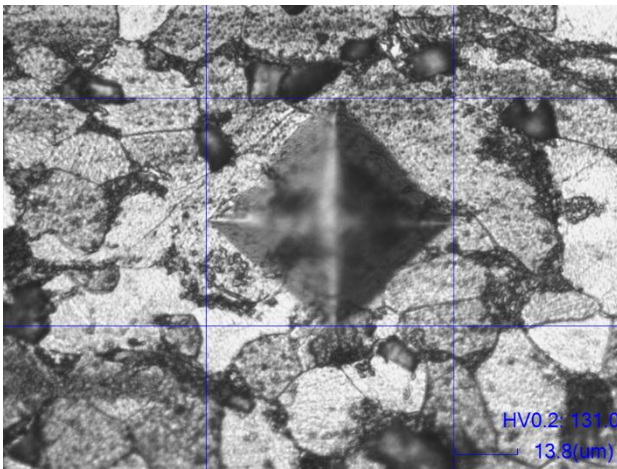


Fig. 2. Optical micrographs showing Vickers (HV0.2/10) microhardness indentation on the RSV 421 ship hull steel sample

These characteristics make the steel of RSV 421 an excellent base for the application of thermal processing methods, as it tolerates temperature deviations that are unavoidable in a marine environment.

III. THEORETICAL FUNDAMENTALS OF UNDERWATER EXOTHERMIC CUTTING

The exothermic cutting process with exothermic electrodes is based on combining the heat of an electric arc and the energy from the chemical oxidation of iron in a stream of pure oxygen. Unlike standard oxy-fuel cutting, the primary heat source here is the exothermic metal oxidation reaction.

A. Thermodynamics of the Exothermic Reaction.

The foundation of the process is the oxidation reaction of the steel; when the metal is heated to its kindling temperature by an electric arc and pressurized oxygen is supplied, a reaction begins that releases a large amount of heat. The temperature at the centre of the arc can reach over 10,000°F (approximately 5500°C), which is sufficient to melt any metallic and non-metallic formations on the hull [8], [9].

B. Dynamics of the Vapour-Gas Cavity.

Underwater, the electric arc burns in a pulsating gas bubble (vapour-gas cavity) [10]. The stability of this bubble is crucial for the quality of the cut. The oxygen pressure must be high enough to keep the cavity open against the hydrostatic pressure of the water while simultaneously blowing molten metal out of the cutting zone.

IV. SYSTEM CONFIGURATION AND TECHNICAL EQUIPMENT

The underwater cutting setup intended for use on RSV 421 is designed to be mobile and adaptable to ship conditions. The diagram on Fig. 3 shows an example setup for underwater exothermic cutting, including its mandatory components:

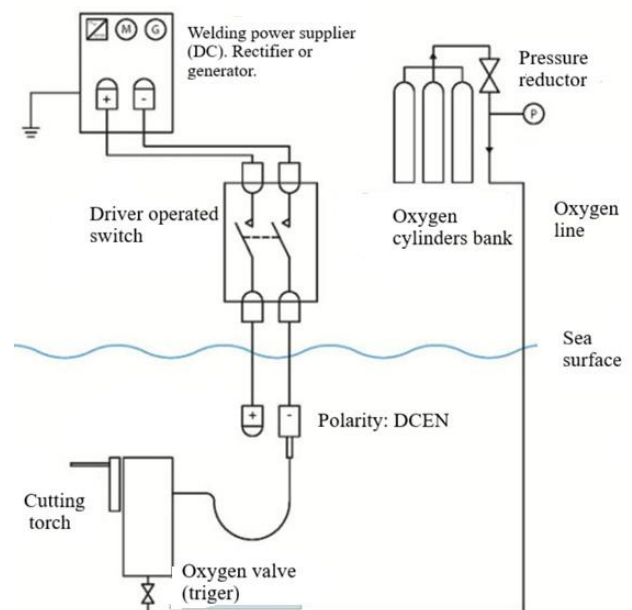


Fig. 3. Diagram of example setup for underwater exothermic cutting, including its mandatory components.

The main components of the setup for underwater exothermic cutting include:

- Power source: Standard welding power sources, rectifiers, or direct current (DC) generators providing at least 300A are used. It is important for the power source to have a suitable volt-ampere characteristic to maintain a stable arc under pressure;
- Oxy-gas line: Includes a bank of oxygen cylinders, a high-flow pressure regulator, and flexible hoses resistant to seawater. The oxygen must have a purity of no less than 99.5%, as even 1% impurities reduce cutting efficiency by 25% [11];
- Torch (Holder): A specialized tool with an ergonomic design, providing complete waterproofing and an airtight connection for the electrode. It features a lever mechanism (trigger) allowing the diver to control the oxygen flow;

- Command-communication system: Mandatory telephone connection between the diver and the surface station, as well as a double-pole circuit breaker (knife switch) on the surface for emergency shutdown;

- Auxiliaries: A submersible platform to stabilize the diver, underwater lighting, and specialized light filters for the helmet, matched to water visibility (filters No. 4 for murky water and No. 8 for clear water are recommended, ISO 4850 [12]).

V. OPTIMIZATION OF TECHNOLOGICAL PARAMETERS OF UNDERWATER EXOTHERMIC CUTTING FOR THE HULL STEEL OF RSV 421

Efficient cutting of Grade A steel up to 10-12 mm thick (typical for the vessel's shell plating) requires precise balancing of electrical and gas parameters.

A. Energy regimes:

- Operating current: A current in the range of 300–400 A is recommended. High current is necessary to compensate for the intense heat dissipation into the surrounding water;

- Voltage: The open-circuit voltage of the power source should not exceed 65 V to ensure the diver's safety in the event of an insulation breach [2];

- Polarity: Direct current electrode negative (DCEN) straight polarity is strictly used—the torch (holder) is connected to the negative pole of the power source. This prevents accelerated electrolysis and the destruction of the torch's brass components [13];

- The power cables should be kept to a minimum length whenever the cutting depth allows. Cables with a cross-section of 75 mm² are used for lengths up to 2x25 m. For greater lengths, a larger cable cross-section is required. If there is excess cable while operating at maximum power settings, it is advisable to submerge the extra length in the sea to ensure better cooling. It is recommended that the welding circuit be connected to the hull ahead of or behind the cutting line.

B. Adjustment of oxygen pressure relative to depth and hose length:

The oxygen pressure on the surface must be set so that an effective pressure of at least 0.6 MPa above ambient pressure is achieved at the working depth. Line losses directly depend on the hose length. The following table presents the corrected values for the surface pressure gauge relative to the working depth and oxygen hose length [9], [11].

Table 1 presents specific data regarding oxygen pressure as a function of depth and oxygen hose length.

TABLE 1. RESULTS FROM MICROHARDNESS TESTING OF RSV 421 HULL

Depth, m	Pressure at 15 m. hose, MPa	Pressure at 30 m. hose, MPa	Depth, m	Pressure at 45 m. hose, MPa	Pressure at 60 m. hose, MPa
0	0.65	0.65	0	0.72	0.75

3	0.68	0.68	6	0.78	0.82
6	0.71	0.71	12	0.84	0.88
9	0.74	0.75	18	0.91	0.94
12	0.77	0.77	24	0.97	1.00
15	0.80	0.81	30	1.03	1.06
18	-	0.84	36	1.08	1.12
21	-	0.87	45	1.18	1.22
24	-	0.90	54	-	1.31
27	-	0.93	60	-	1.37
30	-	0.96			

Insufficient pressure leads to inadequate clearing of oxides from the cut, while excessive pressure causes unnecessary spatter and arc instability.

VI. SPECIFICATION AND APPLICATIONS OF EXOTHERMIC ELECTRODES

When underwater exothermic cutting of the hull plates of RSV 421 is required, two main types of electrodes are used, covering the entire spectrum of necessary thicknesses.

A. Type EP-1 electrodes (diameter - 8 mm).

These electrodes are optimal for precise repair work and cutting thinner plates (up to 7 mm.). They provide a narrow kerf and maximum oxygen economy.

- Efficiency: A single electrode can achieve a cut length of 500–600 mm on a 7 mm thick material;

- Application: Ideal for cutting out corroded sections on superstructures or the upper shell plating layers near the waterline.

B. Type EP-3 electrodes (diameter - 10 mm).

These are preferred for greater thicknesses (up to 25 mm) and in poor visibility conditions, as they generate a more powerful cavity and a brighter arc.

- Efficiency: With a steel thickness of 12 mm, one electrode provides a 300–500 mm cut;

- Application: Primary tools in emergency situations requiring rapid separation of massive structural elements or cutting in the lower part of the hull.

Both electrode types, EP-1 and EP-3, feature the construction shown on Fig. 4, which ensures stable burning of the electrode without extinguishing throughout the entire process.

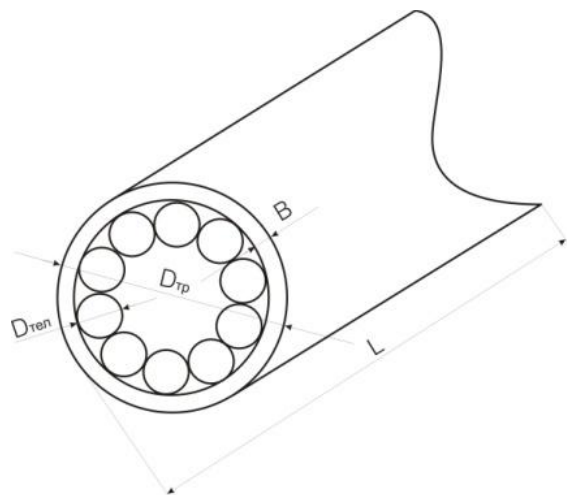


Fig. 4. Construction of electrode types, EP-1 and EP-3, where: D – outer diameter of the electrode, B – electrode wall thickness, and D_{tel} – wire diameter. These electrodes contain 10 wires.

Table 2 presents data, regarding the two most applicable types of electrodes for this specific case.

TABLE 2. SPECIFIC PARAMETERS OF ELECTRODES TYPE EP-1 AND EP-2

Electrode type	Metal thickness, mm	Cutting length, mm
EP-1	7	500-600
	12	250-350
EP-3	12	300-500
	25	200-350

VII. METALLURGICAL ANALYSIS OF THE HEAT-AFFECTED ZONE (HAZ)

Although Grade A steel is resistant to hardening, thermal underwater cutting creates an extremely severe processing regime. A steep temperature gradient is observed at the boundary of the cut—from the melting temperature to the ambient seawater temperature within a few millimetres [4], [14]. This causes certain microstructural changes.

Martensitic-bainitic type microstructures can be observed in the outermost layer of the HAZ (width up to 0.1-0.2 mm). Due to the low carbon content (0.16%), these structures are not brittle enough to cause spontaneous cracking. However, when preparing for subsequent welding, it is mandatory to mechanically remove this layer by grinding to ensure a defect-free weld seam [15].

Another potential issue during underwater welding/cutting operations is hydrogen induction.

The aquatic environment is a source of atomic hydrogen, which easily diffuses into the heated metal. Rapid cooling, traps the atomic hydrogen in the metal, creating a risk of subsequent defects (micro cracks - flakes) [16]. When working with the hull steel of RSV 421, this risk can be managed by maintaining a high cutting speed

(over 300 mm/min), which limits the time available for hydrogen to diffuse deep into the material [14] [17].

VIII. SAFETY MEASURES FOR APPLYING OXY-FUEL CUTTING IN SPECIFIC SITUATIONS

The specifics of the operations on RSV 421 mandate the application of the highest safety standards, as medical assistance is limited in polar conditions.

A. Prevention of gas explosions.

The underwater cutting process generates hydrogen and free oxygen [3], [16]. Their accumulation in enclosed spaces (pontoons, double bottoms) creates an explosive mixture.

- Ventilation: Before starting work, it is mandatory to drill ventilation holes at the highest points of the compartment;

- Cutting direction: Work must always be performed from top to bottom. This allows gas bubbles to float freely through the already made cut instead of accumulating beneath the uncut surface.

B. Electrical safety of the operator.

Electric shock is a major hazard when working in saltwater.

- Insulation: The diver must wear heavy-duty rubber gloves over neoprene ones. Any tear in the suit is a signal to immediately halt work [18];

- Grounding: The ground clamp must be placed as close to the cutting site as possible, on a surface cleaned to a metallic shine [19]. The diver must never stand between the ground and the electrode.

IX. CONCLUSIONS

Based on the investigations conducted in this paper, the following main conclusions can be drawn:

- A. The study confirms that underwater exothermic cutting technology with exothermic electrodes is fully compatible with the Grade A hull steel of RV 421. Optimal technological regimes include an operating current of 300–400 A and oxygen pressure compensated relative to hydrostatic pressure and supply line length.

- B. The use of EP-1 and EP-3 type electrodes provides the necessary flexibility for both precise and heavy-duty destructive underwater operations.

- C. Strict adherence to ventilation and electrical protocols remains a mandatory condition for safety.

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Opportunity to Increase the Competitiveness of the Industrial Enterprise and Transition to Industry 4.0 Through the Implementation of Business Projects from the European Structural and Investment Funds

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Abstract — This paper examines the opportunities for enhancing the competitiveness of industrial enterprises through the transition to the Industry 4.0 concept, by means of the effective utilization of business projects financed by the European Structural and Investment Funds. In the context of intensified global competition and accelerated digitalization, enterprises are faced with the need to implement innovative technologies and intelligent manufacturing systems. The paper analyzes the role of digital transformation as a key factor for the sustainable development and growth of industrial organizations. Special attention is given to the integration of cyber-physical systems, the Internet of Things, and artificial intelligence in production processes. The main sources of funding within the framework of the European Structural and Investment Funds and their significance for the modernization of the industrial sector are examined. The degree of absorption of these funds and their impact on improving enterprise efficiency and innovation capacity are also analyzed. The paper identifies the main challenges faced by businesses in the application for and implementation of projects related to digital transformation. Good practices and successful examples of Industry 4.0 implementation through European funding are discussed. The importance of strategic planning and project management for achieving sustainable results is emphasized. The effects on productivity, quality, and production flexibility are also considered. Particular attention is paid to the role of human capital and the need for the development of digital competencies. The paper highlights the synergy between public policies and business initiatives in the process of industrial transformation. The impact of digitalization on supply chains and logistics processes is also examined. The aim of the paper is to analyze the potential of the European Structural and Investment Funds as a tool for accelerating the transition to Industry 4.0

and enhancing the competitiveness of industrial enterprises. In conclusion, recommendations are formulated for improving access to funding and the effectiveness of implemented projects.

Keywords— business projects, competitiveness, European funds, Industry 4.0, innovation.

I. INTRODUCTION

In the context of the modern global economy, industrial enterprises are facing increasing pressure aimed at enhancing competitiveness. The dynamic development of technologies and digitalization is fundamentally transforming the way production systems operate. The concept of “Industry 4.0” is established as a leading paradigm for the modernization of the industrial sector. It integrates the use of intelligent technologies, automation, and the integration of information systems in manufacturing. In this context, enterprises must adapt their business models to new technological realities. This requires significant investments in innovation, digital infrastructure, and human capital. For many enterprises, especially small and medium-sized ones, access to financial resources remains a serious challenge. In this regard, the European Structural and Investment Funds serve as a key instrument for supporting industrial transformation. They provide opportunities for financing projects aimed at technological renewal and efficiency improvement [1]. Through them, the implementation of modern solutions related to digitalization and automation is stimulated. Despite the availability of these opportunities,

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the absorption of funds is often accompanied by a number of administrative and organizational difficulties. This requires good planning and effective project management on the part of enterprises. The introduction of innovation is not only a technological process but also a managerial one. It also requires the development of new competencies and skills among the workforce [2]. The transition to Industry 4.0 also implies changes in organizational culture and strategic thinking. An important role is played by the interaction between business, state institutions, and the scientific community. This cooperation creates prerequisites for sustainable development and an innovation ecosystem. A significant place in modern project management is also occupied by the use of artificial intelligence, which actively supports decision-making through the analysis of large volumes of data and information sets. In the context of European projects supporting the transition to Industry 4.0, AI technologies directly assist in planning, budgeting, risk forecasting, and resource optimization during project implementation. The automation of processes increases efficiency and reduces the likelihood of human error in project management, relying on a database of successfully implemented and problematic projects financed by the European Structural and Investment Funds [3]. In addition, intelligent systems enable better coordination between project partners and stakeholders and facilitate adaptive management in a rapidly changing economic environment. In this way, artificial intelligence becomes an important tool for the successful management and implementation of European projects supporting digital transformation and the adoption of Industry 4.0 principles [4]. The introduction section of this paper aims to outline the significance of digital transformation for industrial enterprises. It emphasizes the role of European funding as a catalyst for this process. In conclusion, the necessity of an integrated approach for the successful implementation of the transition to Industry 4.0 is highlighted.

II. MATERIALS AND METHODS

The methodology of the present study is aimed at analyzing the opportunities for enhancing the competitiveness of industrial enterprises through the implementation of projects financed by the European Structural and Investment Funds in the context of the transition to Industry 4.0. The study is based on a combined approach including both qualitative and quantitative methods of analysis. In the first stage, a theoretical review of the scientific literature related to digital transformation, industrial competitiveness, and European funding is conducted [5]. In the second stage, an empirical analysis is applied to enterprises that have implemented projects under operational programs. For the assessment of competitiveness, an integral index (CI) is used, which combines several key indicators:

$$CI = w_1P + w_2Q + w_3I + w_4E \quad (1)$$

where P represents productivity, Q represents product quality, I represents innovation activity, and E represents

resource efficiency, while w_i are weighting coefficients. To measure the effect of Industry 4.0 project implementation, a productivity growth coefficient is used:

$$G_P = (P_t - P_0) / P_0 \quad (2)$$

where P_0 represents the initial level of productivity, and P_t represents the level after project implementation. Additionally, the degree of digitalization is assessed through a Digital Maturity Index (DM):

$$DM = (D_1 + D_2 + D_3 + D_4) / 4$$

where D_i are individual components such as automation, system integration, data utilization, and digital skills.

The collected data are processed through comparative analysis before and after project implementation. Correlation analysis methods are also used to determine the relationship between the degree of digitalization and competitiveness. For greater reliability of the results, graphical analysis and trend interpretation are also applied. The methodology allows for the assessment of both the direct and indirect impact of European funding on enterprise development. In conclusion, the selected approach ensures systematicity and objectivity in the study of the investigated problem.

III. RESULTS AND DISCUSSION

In the result of the conducted empirical study on 25 industrial enterprises in Bulgaria that implemented projects under the European Structural and Investment Funds in the period 2021–2025, clearly expressed positive trends are identified regarding productivity, digital maturity, and competitiveness [6].

Randomly, five industrial enterprises from the conducted study are selected, whose results are presented in detail. The average productivity of the enterprises, measured through an index (base year 2021 = 100), increases from 100 in 2021 to 150 in 2025, representing a 50% increase. This confirms the significant effect of the implementation of automated production systems, ERP platforms, and IoT solutions.

The Digital Maturity Index increases from 0.45 to 0.75, indicating accelerated integration of digital technologies and an increase in the level of technological readiness of the enterprises. The strongest growth is observed in the components “system integration” and “data utilization”.

Competitiveness, measured through the integral index, increases from 0.50 to 0.80, representing a 60% growth. This is due both to improved efficiency and to enhanced product quality and reduced production cycles. The figure below visualizes the trend in productivity growth:

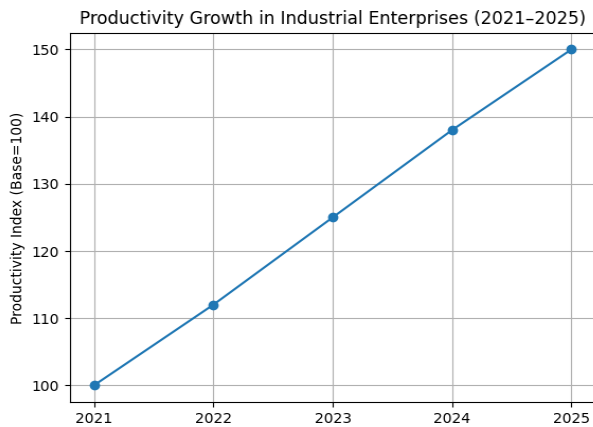


Fig. 1. Trend in productivity growth

Interpretation of Trends

The analysis of Fig. 1 shows a stable upward trend without sharp fluctuations, which is an indicator of gradual and effective implementation of innovations. The most significant growth is observed in the period 2022–2024, when enterprises actively absorb European funding and implement digitalization projects. A strong positive relationship is observed between digital maturity and productivity—enterprises with a higher digitalization index achieve on average 20–25% higher productivity. This confirms the hypothesis of a direct link between Industry 4.0 and competitiveness.

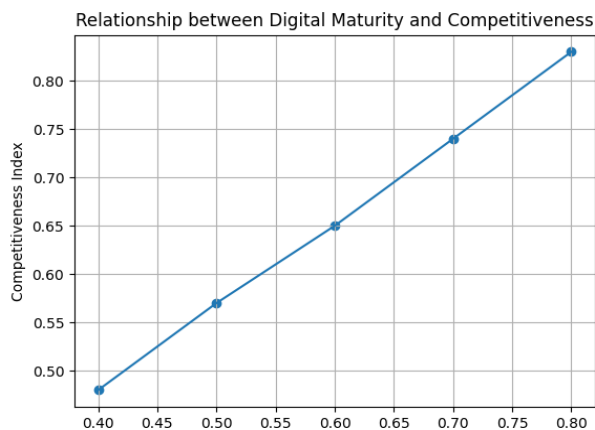


Fig. 2. Relationship between the digital maturity index and the competitiveness of industrial enterprises

Figure 2 shows a clearly expressed positive linear relationship, indicating that as the level of digitalization increases, competitiveness also increases. The trend shows that enterprises with a higher degree of implementation of Industry 4.0 technologies (such as automation, IoT, and data analytics) achieve significantly better market positions. The absence of deviations in the graph suggests stability of the relationship and predictability of the effect of digital investments. This result complements the main conclusions of the paper, confirming that digital transformation is not only a technological process but also a strategic tool for sustainable growth. In practical terms, this means that enterprises should deliberately increase their digital maturity if they aim to improve their

competitive position. Additionally, it is found that enterprises investing in staff training demonstrate more sustainable growth compared to those focusing solely on technological upgrading.

TABLE 1 INVESTMENTS AND RETURN ON INVESTMENT FROM INDUSTRY 4.0 PROJECTS

Enterprise	Investment (thousand EUR)	EU funding (%)	Implementation period (months)	ROI (%)
Enterprise A	850	70	18	28
Enterprise B	1200	65	24	34
Enterprise C	640	75	12	22
Enterprise D	980	60	20	30
Enterprise E	1500	68	30	37

TABLE 2 INVESTMENTS AND RETURN ON INVESTMENT FROM INDUSTRY 4.0 PROJECTS

Enterprise	Cost reduction (%)	Reduced production time (%)	Defect reduction (%)	Capacity increase (%)
Enterprise A	15	18	22	20
Enterprise B	18	25	28	24
Enterprise C	12	15	19	17
Enterprise D	20	22	30	26
Enterprise E	23	28	35	32

Brief interpretation of the two tables

The data from the first table show that a higher share of European funding leads to a shorter payback period and higher return on investment. The second table clearly demonstrates significant improvements in operational efficiency, with the most pronounced effects observed in defect reduction and production capacity increase.

In Table 3, the linear correlation coefficients (r) are calculated:

TABLE 3 CORRELATION ANALYSIS – INVESTMENT AND RETURN ON INVESTMENT

Indicators	Correlation (r)
Investment – ROI	0.91
EU funding (%) – ROI	0.76
Implementation period – ROI	0.68
Investment – Implementation period	0.83

Interpretation of Table 3

There is a very strong positive correlation ($r = 0.91$) between the level of investment and return on investment (ROI), indicating that larger projects generally generate higher economic efficiency. The share of European funding also has a strong positive influence ($r = 0.76$) on ROI, confirming the importance of grant-based support. The moderate relationship between the implementation period and ROI suggests that longer projects are often more complex and lead to higher results, but with slower realization.

TABLE 4 CORRELATION ANALYSIS – OPERATIONAL EFFICIENCY

Indicators	Correlation (r)
Cost reduction – Capacity increase	0.88
Defect reduction – Reduced production time	0.92
Cost reduction – Defect reduction	0.85
Reduced production time – Capacity increase	0.90

Interpretation of Table 4:

The results show **very strong positive relationships between all operational indicators**. The strongest correlation is between defect reduction and reduced production time ($r = 0.92$), indicating that improved quality leads to faster processes. The high correlation between reduced production time and capacity increase ($r = 0.90$) confirms that production efficiency is a key factor for growth.

Summary of Trends Analysis

The correlation analysis clearly shows that:

- Investments in Industry 4.0 **have a direct and strong effect on economic outcomes**;
- European funding acts as an **accelerator of return on investment**;
- Operational improvements are **interconnected and mutually reinforcing (a synergistic effect)**;
- The greatest effect is observed when technologies are implemented in combination with process optimization within the enterprise.

These relationships confirm that digital transformation does not affect individual indicators in isolation, but instead creates an overall improvement in **industrial efficiency and competitiveness**.

Discussion

The discussion of the obtained results confirms the significant role of digital transformation in enhancing the competitiveness of industrial enterprises. The analysis shows that enterprises that actively implement Industry 4.0 technologies achieve substantial improvements in productivity and efficiency. The identified positive trends are consistent with theoretical assumptions regarding the impact of digitalization on economic performance. It is particularly important that the effects are not limited solely to technological modernization, but also extend to organizational processes.

A clear relationship is observed between the level of digitalization and improvements in product quality. This leads to a reduction in production defects and optimization of resources. On the other hand, the results show that the implementation of new technologies requires significant initial investments. In this context, the European Structural and Investment Funds play a key role in reducing the financial burden on enterprises. The data indicate that enterprises with a higher share of external funding implement their projects more quickly. However, the process of absorbing funds is often accompanied by administrative difficulties. This highlights the need to

improve the institutional framework and application procedures.

It is also established that the human factor is of essential importance for the successful implementation of innovations. The lack of sufficiently qualified personnel can limit the effectiveness of technological investments. In this regard, training and the development of digital competencies should be a priority for enterprises. Additionally, the results show that synergy between different elements of Industry 4.0 leads to stronger effects compared to isolated investments. This emphasizes the importance of an integrated approach to digital transformation.

The observed improvements in operational efficiency have a positive impact on the market position of enterprises. Despite the positive results, there are also risks associated with technological dependency and cybersecurity. This necessitates the implementation of balanced risk management strategies. In conclusion, the discussion confirms that a successful transition to Industry 4.0 requires a comprehensive approach, including technology, financing, and human resources.

IV. CONCLUSIONS

Based on the conducted research, the following main conclusions and recommendations can be formulated. First, the implementation of Industry 4.0 technologies leads to a significant increase in the competitiveness of industrial enterprises. Digital transformation has a direct positive impact on productivity and the efficiency of production processes.

It is established that enterprises investing in automation and digitalization achieve better economic results. European Structural and Investment Funds are confirmed as a key factor for the realization of innovation projects. They reduce financial constraints and stimulate the adoption of modern technologies. It is observed that a higher share of European funding is associated with better results and faster return on investment. At the same time, the effective absorption of funds requires good project management and administrative capacity.

A significant interrelationship between digital maturity and operational efficiency is identified. Improvements in product quality lead to cost reductions and increased production capacity. Human capital is a critical factor for the successful implementation of digital transformation. A lack of qualified personnel may limit the potential benefits of implemented technologies.

An integrated approach to the implementation of Industry 4.0 generates more sustainable and long-term results. Despite the positive effects, challenges remain related to administrative procedures and technological risks. In conclusion, the transition to Industry 4.0 through European funding represents an effective tool for modernization and sustainable development of industrial enterprises.

The synergy between public policies and business initiatives is a key factor for successful industrial transformation. Government strategies and programs

create a favorable environment through financial incentives, regulatory support, and innovation promotion. At the same time, businesses play an active role by implementing new technologies and optimizing production processes. Effective interaction between the public and private sectors leads to faster adoption of innovations and increased competitiveness. This interdependence creates a sustainable foundation for long-term economic development and the transition to Industry 4.0.

To improve access to funding, it is necessary to simplify administrative procedures for applications under European programs. The time required for evaluation and approval of project proposals should be reduced. It is important to increase the transparency of project selection and evaluation criteria. The creation of specialized consulting centers to support small and medium-sized enterprises is necessary. It is recommended to expand opportunities for pre-financing and advance payments. To improve project effectiveness, modern project management methods should be applied. Investment in training for personnel involved in project implementation is essential. Monitoring and control over project execution should be strengthened. Cooperation between business, scientific organizations, and the public sector should be encouraged. In conclusion, an integrated approach to financing and project management will lead to higher efficiency and sustainable results.

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Analysis of Accuracy in Different Positioning Schemes Using Statistical Methods

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Abstract— The choice of fixtures, the type of clamping, and the clamping force are key criteria for minimizing adverse effects that lead to deterioration in the geometric characteristics of the machined surfaces. This article examines the accuracy of cylindrical and conical surfaces under different clamping schemes—in a chuck (three-jaw self-centering) and between a chuck and a center. The accuracy of the machined surfaces has been analyzed and evaluated using statistical methods, with a comparative analysis performed between the mathematical expected value and the variance for the two clamping schemes.

Keywords— accuracy, cylindrical surfaces, conical surfaces, geometric characteristics, machined surfaces.

I. INTRODUCTION

With the advance in the technological development, mechanical and device engineering are facing a number of tasks, one of which is to maintain a balance between quality and high productivity.

The implementation of computer numerically controlled (CNC) machine tools satisfies the requirement for productivity. By refinement of the modes of cutting, conditions are created to increase productivity while sufficing the durability of the tools, taking part in the cutting process. Geometric accuracy is a fundamental parameter, required for the proper operational characteristic of a given part. In the process of machining through chip removal, conditions are created for violating

the tolerances, one of the factors for this being the way the product is positioned during cutting.

The generated geometric errors in the process of machining exert a significant influence on the accuracy of the machined surfaces. The accuracy depends on various factors, including shape-forming errors, deformations caused by the cutting force, thermal errors, part positioning errors, etc. In turn, geometric accuracy includes dimensional errors, shape errors, and positioning errors [1], [2], [3].

A number of authors [1], [4], [5], [6] have considered the topical problem, related to measuring the deviations from a proper geometric shape in the process of turning, by modeling the influence of the geometric errors of the machines and the tool wear on the accuracy of the machined surfaces.

Paper [7] defines the technological tasks and the modern approaches to achieving the specified accuracy when processing parts on CNC machine tools. The need for automation of the functions, performed by an operator, including the control on his/her side, in order to increase the efficiency of the technological processes has been argumentized. Approaches for automation, as well as for selecting appropriate schemes of tool setting have also been proposed in [8], [9], [10]. In [11], a new approach is discussed for predicting and compensating for the deviations of the surfaces, machined by turning, taking into account the stages of planning before machining. A model

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is proposed for determining the allowable value of deviations from dimensions and geometric shape, which is used to set appropriate operating conditions.

Yousefi et al. [12] have studied the dependence between dimensional accuracy, on the one hand, and vibration, cutting forces and tool wear, on the other. They establish that feed is the main factor, influencing the roughness of the machined surfaces. However, the depth of cut and cutting speed have the greatest influence on dimensional accuracy, while the radius at the tool tip does not have a significant effect.

There are studies, focused on the possibility for error compensation, aiming at improving machining accuracy. By compensating for transportation errors, Gao et al. [13] achieve reduction of the deviation from flatness from 0.27 μm to 0.12 μm . Kong et al. [14] have studied the influence of X and Z axis straightness when carrying out facing, tapering and spherical turning. They have proposed a method to compensate for a software error, and the method is applied by changing the tool trajectory while taking into account changes in the kinematics of the process.

Studies, related to machined surface accuracy have been conducted by Peterka et al [15]. The authors analyze the shape errors and the roughness of parts, made of heat-treated steel DIN EN 1.2842 (ISO 90MnCrV8) with a hardness of 58 HRC. Dimensional deviations, as well as errors in cylindricity and parallelism of hole generatrices in transmission parts serial production have been studied by Kundrák et al. [3].

The existing research, related to ensuring accuracy of dimensions and shape of machined surfaces concerns specific operating conditions. It has been established that the choice of fixtures, type of clamping and clamping force are key criteria for reducing the adverse effects, leading to deterioration in the geometric characteristics of the machined surfaces. In this regard, the present paper studies and analyzes, by applying statistical methods, the accuracy of cylindrical and conical surfaces when clamping under different schemes – in a chuck (three-jaw self-centering) and between a chuck and a center.

II. MATERIAL AND METHODS

Two series of 10 parts with shape, dimensions and accuracy presented in Fig. 1, were machined for the analysis of the geometric parameters. The material under machining was steel 45 (1.0503) with chemical composition and mechanical properties, complying with the standard EN 10277-2-2008 (Table 1).

The selected steel is medium-carbon structural steel, occupying a significant share among structural carbon steels (approximately 22%), used in machine building, and its main uses being for manufacturing shafts, axles, gears, fasteners and others.

The studied parts were machined on a RAIS T200 computer-controlled lathe, the working space of which is shown in Fig. 2. Two schemes of clamping were used – in a three-jaw self-centering chuck and between a chuck and a rotating center.

The processing of the parts was carried out under the following cutting mode: cutting speed $V_c = 100$ m/min; depth of cut $a_p = 0.83$ mm; feed $f = 0.1$ mm/rev. A lathe turning tool DDJNR2525JM15 was used as a cutter (designation according to ISO 5608:2012) with a P25 cermet insert with a wear resistant titanium nitride (TiN) coating and a designation according to ISO 1832:2017 DNMG 150604.

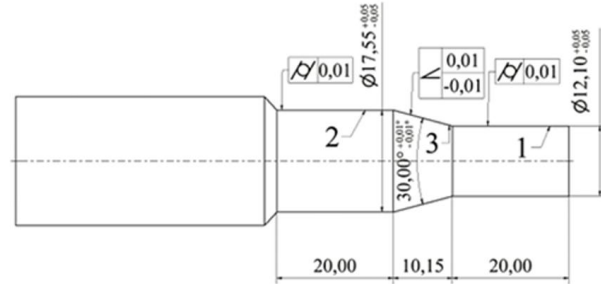


Fig.1 Shape, dimensions and accuracy parameters of the machined part .

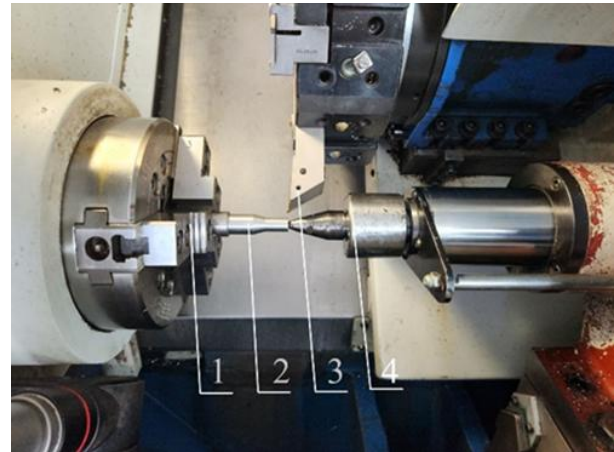


Fig.2 Workspace of a computer-controlled lathe. 1-self-centering chuck, 2- workpiece, 3- cutting tool, 4- rotating center.

The geometry of the cutting tool was: tool back race angle $\gamma_p = -6^\circ$; tool major cutting edge angle $\kappa_r = 93^\circ$; tool minor cutting edge angle $\kappa_r' = 32^\circ$; rake angle of the main cutting edge $\lambda_s = -7^\circ$; tool tip radius $r_e = 0.4$ mm.

In order to compare the accuracy of the machined parts in the two schemes, the following parameters were measured: the diameters of the cylindrical surfaces 1 and 2 - $d_i = 12.10$ mm and $D_i = 17.55$ mm; the deviation from cylindricity of surfaces 1 and 2 - $\Delta_{i,d}$ and $\Delta_{i,D}$; the angle of the cone of surface 3 - δ_i ($i = 1, 2$, respectively, when clamping in a chuck and in a chuck and center).

A DEA Global Performance coordinate measuring machine was used to measure the specified parameters (Fig. 3).

The measurement of the diametric dimensions of cylindrical surfaces 1 and 2 was carried out at 5 points across 72° .

The cone angle of surface 3 was measured in three cross-sections spaced 3 mm apart, with measurements taken at 5 points across 72° in each cross-section.

TABLE I. CHEMICAL COMPOSITION AND PHYSICO-MECHANICAL PROPERTIES OF THE STUDIED MATERIALS

Machined material	Hardness HB	Tensile strength MPa	Yield strength Rp _{0.2} , N/mm ²	Relative elongation A, %	Chemical composition, %
C45	170-210	600-800	300-450	16-20	C-0.48; P-0.022; Mn-0.6; S-0.1; Si-2.1

The deviation from cylindricity of surfaces 1 and 2, was estimated by using the transverse cross-section method. The measurements were performed in four cross-sections, spaced 6.2 mm apart, with measurements taken at 5 points in each of the cross-sections.



Fig. 3 DEA Global Performance coordinate measuring machine

The deviation from cylindricity of surfaces 1 and 2, was estimated by using the transverse cross-section method. The measurements were performed in four cross-sections, spaced 6.2 mm apart, with measurements taken at 5 points in each of the cross-sections.

Statistical analysis, comprised of testing two statistical hypotheses – for equality of two mathematical expectations; and for equality of two variances – was conducted in order to compare the results, concerning the accuracy of the surfaces, machined when fixed in a chuck or between a chuck and a center. Statistical hypothesis testing is a method by which a number of comparison and evaluation tasks are solved in engineering practice. At the heart of the method is a statistical criterion, determining the rules by which the formulated null hypothesis is accepted or rejected.

The verification of the statistical hypotheses was carried out in accordance with the methodology, presented below in the following sequence [16]:

1. Determining the arithmetic mean values of the studied parameters: diameter d_i (mm); diameter D_i (mm);

deviation from cylindricity of a surface with a diameter $d_i - \Delta_{i,d}$ (mm); deviation from cylindricity of a surface with a diameter $D_i - \Delta_{i,D}$ (mm); cone angle δ_i (grad):

$$\bar{X}_i = \frac{\sum_{u=1}^n X_{iu}}{n}, \quad (1)$$

where $X_i = d_i; D_i; \Delta_{i,d}; \Delta_{i,D}; \delta_i$; $n = 10$ – number of observations in each experiment.

2. Determining the estimates of the variances of the studied parameters X_i :

$$S_{X_i}^2 = \frac{\sum_{u=1}^n (X_{iu} - \bar{X}_i)^2}{n-1}. \quad (2)$$

3. Testing the hypothesis for equality of variances of the studied parameters when fixing in a chuck and a center, using the Fisher criterion, the empirical values of which are determined by the dependence:

$$\widehat{F}_X = \frac{s_{X_1}^2}{s_{X_2}^2}. \quad (3)$$

If $\widehat{F}_X \leq F_{\alpha, k_{X_1}, k_{X_2}}$ ($F_{\alpha, k_{X_1}, k_{X_2}}$ - Fisher's quantile, $\alpha=0.05$ – significance level; $k_{X_1} = k_{X_2} = n - 1$), then it is assumed that the compared parameters have equal variances. Otherwise, this hypothesis is rejected, i.e., the variance of the studied parameter X_1 is greater than that of the parameter X_2 .

4. Testing the hypothesis for equality of the mathematical expectations of the studied parameters in the case of clamping in a chuck and a center, using the Student's criterion, the empirical values of which are determined by the dependence:

$$\hat{t}_X = \frac{|\bar{X}_1 - \bar{X}_2|}{\sqrt{\frac{s_{X_1}^2 + s_{X_2}^2}{2}}} \sqrt{n}. \quad (4)$$

If $\hat{t}_X \geq t_{\alpha/2, k}$ ($t_{\alpha/2, k}$ – Student's quantile, $k = n + n - 2$), the mean value of the studied quantity X_1 is greater than that of the studied quantity X_2 . Otherwise, the mean values of the two quantities do not differ.

III. RESULTS AND DISCUSSION

The results from the measurements of the studied parameters – diameter d_i ; diameter D_i ; deviation from cylindricity $\Delta_{i,d}$ of the surface with a diameter d_i ; deviation from cylindricity $\Delta_{i,D}$ of a surface with a diameter D_i ; cone angle δ_i – are presented in Tables 2 - 6. Part of the protocol of the performed measurements is shown in Fig. 4.

In accordance with the methodology presented in Section II and with the help of the QstatLab [17] software product, a statistical analysis of the experimental data was

conducted (Tables 2 – 6), the results of which are presented in Table 7

⌀	MM	DEVIATION FROM THE DIAMETER					
AX		NOMINAL	+TOL	-TOL	MEAS	DEV	OUTTOL
D		12.100	0.050	-0.050	12.148	0.048	0.000

Fig. 4. Protocol of measurement of the machined parts

TABLE II. DIAMETERS OF SURFACE 1

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	d_1 (mm)	d_1 (min)	d_1 (max)	Measured deviation	d_2 (mm)	d_2 (min)	d_2 (max)	Measured deviation
1	12.148	12.142	12.156	0.048	12.092	12.087	12.097	-0.008
2	12.146	12.141	12.153	0.046	12.089	12.080	12.095	-0.011
3	12.148	12.143	12.158	0.048	12.088	12.075	12.096	-0.012
4	12.149	12.143	12.157	0.049	12.084	12.077	12.092	-0.016
5	12.147	12.141	12.154	0.047	12.086	12.079	12.094	-0.014
6	12.144	12.141	12.150	0.044	12.089	12.082	12.096	-0.011
7	12.147	12.142	12.153	0.047	12.091	12.084	12.102	-0.009
8	12.147	12.142	12.153	0.047	12.084	12.074	12.091	-0.016
9	12.147	12.142	12.153	0.047	12.094	12.081	12.112	-0.006
10	12.145	12.141	12.152	0.045	12.090	12.082	12.097	-0.010

TABLE III. DIAMETERS OF SURFACE 2

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	D_1 (mm)	D_1 (min)	D_1 (max)	Measured deviation	D_2 (mm)	D_2 (min)	D_2 (max)	Measured deviation
1	17.578	17.576	17.58	0.028	17.543	17.54	17.547	-0.007
2	17.577	17.574	17.58	0.027	17.54	17.537	17.545	-0.01
3	17.577	17.573	17.587	0.027	17.54	17.536	17.545	-0.01
4	17.577	17.575	17.579	0.027	17.536	17.531	17.545	-0.014
5	17.577	17.575	17.582	0.027	17.539	17.535	17.543	-0.011
6	17.573	17.571	17.578	0.023	17.541	17.538	17.545	-0.009
7	17.577	17.575	17.581	0.027	17.54	17.535	17.55	-0.01

8	17.576	17.574	17.578	0.026	17.537	17.532	17.544	-0.013
9	17.576	17.574	17.579	0.026	17.545	17.532	17.562	-0.005
10	17.574	17.572	17.577	0.024	17.542	17.536	17.547	-0.008

TABLE IV. DEVIATIONS FROM CYLINDRICITY OF SURFACE 1

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	$\Delta_{1,d} (mm)$	$\Delta_{1,d} (min)$	$\Delta_{1,d} (max)$	<i>Measured deviation</i>	$\Delta_{2,d} (mm)$	$\Delta_{2,d} (min)$	$\Delta_{2,d} (max)$	<i>Measured deviation</i>
1	0.007	-0.003	0.004	0.007	0.005	-0.003	0.002	0.005
2	0.006	-0.002	0.004	0.006	0.008	-0.004	0.003	0.008
3	0.008	-0.003	0.005	0.008	0.011	-0.006	0.004	0.011
4	0.007	-0.003	0.004	0.007	0.007	-0.003	0.004	0.007
5	0.007	-0.003	0.004	0.007	0.008	-0.004	0.004	0.008
6	0.005	-0.002	0.003	0.005	0.007	-0.003	0.004	0.007
7	0.005	-0.002	0.003	0.005	0.009	-0.004	0.006	0.009
8	0.006	-0.002	0.003	0.006	0.008	-0.005	0.004	0.008
9	0.006	-0.003	0.003	0.006	0.016	-0.006	0.009	0.016
10	0.005	-0.002	0.003	0.005	0.008	-0.004	0.004	0.008

TABLE V. DEVIATIONS FROM CYLINDRICITY OF SURFACE 2

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	$\Delta_{1,D} (mm)$	$\Delta_{1,D} (min)$	$\Delta_{1,D} (max)$	<i>Measured deviation</i>	$\Delta_{2,D} (mm)$	$\Delta_{2,D} (min)$	$\Delta_{2,D} (max)$	<i>Measured deviation</i>
1	0.002	-0.001	0.001	0.002	0.004	-0.002	0.002	0.004
2	0.003	-0.002	0.001	0.003	0.004	-0.002	0.002	0.004
3	0.007	-0.002	0.005	0.007	0.004	-0.002	0.003	0.004
4	0.002	-0.001	0.001	0.002	0.007	-0.002	0.004	0.007
5	0.003	-0.001	0.002	0.003	0.004	-0.002	0.002	0.004
6	0.004	-0.001	0.002	0.004	0.003	-0.001	0.002	0.003
7	0.003	-0.001	0.002	0.003	0.008	-0.003	0.005	0.008
8	0.002	-0.001	0.001	0.002	0.006	-0.003	0.003	0.006
9	0.003	-0.001	0.002	0.003	0.015	-0.006	0.008	0.015
10	0.002	-0.001	0.001	0.002	0.005	-0.003	0.003	0.005

TABLE VI. CONE ANGLE OF SURFACE 3

№	Setting in a 3-Jaw self-centering chuck				Setting in a 3-Jaw self-centering chuck and a center			
	$\delta_1 (grad)$	$\delta_1 (min)$	$\delta_1 (max)$	<i>Measured deviation</i>	$\delta_2 (grad)$	$\delta_2 (min)$	$\delta_2 (max)$	<i>Measured deviation</i>

1	29.999	29.999	29.999	-0.001	30.013	30.013	30.013	0.013
2	30.006	30.006	30.006	0.006	30.059	30.059	30.059	0.059
3	30.009	30.009	30.009	0.009	30.074	30.074	30.074	0.074
4	30.014	30.014	30.014	0.014	30.052	30.052	30.052	0.052
5	30.001	30.001	30.001	0.001	30.058	30.058	30.058	0.058
6	30.016	30.016	30.016	0.016	30.06	30.06	30.06	0.06
7	30.021	30.021	30.021	0.021	30.043	30.043	30.043	0.043
8	30.024	30.024	30.024	0.024	30.05	30.05	30.05	0.05
9	30.003	30.003	30.003	0.003	30.055	30.055	30.055	0.055
10	30.025	30.025	30.025	0.025	30.053	30.053	30.053	0.053

TABLE VII. STATISTICAL ANALYSIS OF THE STUDIED PARAMETERS

Studied parameter	Arithmetic mean values		Variances		Fisher criteria		Student's criteria	
	$\bar{X}_1$	$\bar{X}_2$	$S_{X_1}^2$	$S_{X_2}^2$	$\widehat{F}_X$	$F_{\alpha, k_{X_1}, k_{X_2}}$	$\widehat{t}_X$	$t_{\frac{\alpha}{2}, k}$
d_i (mm)	12.1468	12.0887	$2.25 \cdot 10^{-6}$	$10.89 \cdot 10^{-6}$	4.84	3.18	50.68	2.101
D_i (mm)	17.5762	17.5403	$2.25 \cdot 10^{-6}$	$7.29 \cdot 10^{-6}$	3.24		36.76	
$A_{i,d}$ (mm)	0.0062	0.0087	$1 \cdot 10^{-6}$	$2.25 \cdot 10^{-6}$	2.25		4.23	
$A_{i,D}$ (mm)	0.0031	0.006	$9 \cdot 10^{-6}$	$12.25 \cdot 10^{-6}$	1.36		1.99	
δ_i (grad)	30.0118	30.0517	$92.16 \cdot 10^{-6}$	$249.6 \cdot 10^{-6}$	2.70		6.83	

The conducted statistical analysis shows that the scheme of basing exerts different influence on the studied accuracy parameters of the machined surface.

The comparison of the arithmetic mean values of the diametric dimensions of cylindrical surfaces 1 and 2 shows a systematic displacement of the mathematical expectation for the second scheme (a chuck and a center), where the dimensions are smaller but the variance is significantly larger. The estimates of the mathematical expectation for the diameters d_i and D_i ($\widehat{t}_d = 50.68 > t_{\frac{\alpha}{2}, k} = 2.101$; $\widehat{t}_D = 36.76 > t_{\frac{\alpha}{2}, k} = 2.101$) confirm the presence of a systematic difference between the two groups of dimensions. The Fisher criterion confirms the inhomogeneity of the variances ($\widehat{F}_d = 4.84 > F_{\alpha, k_{X_1}, k_{X_2}} = 3.18$; $\widehat{F}_D = 3.24 > F_{\alpha, k_{X_1}, k_{X_2}} = 3.18$), with the accuracy for the cantilever type of setting being on average 70% higher.

The test of the hypothesis of equality of variances of the deviation from cylindricity and the conc angle for both setting schemes shows commensurability of the variances of the studied parameters ($\widehat{F}_{A_d} = 2.25 < F_{\alpha, k_{X_1}, k_{X_2}} = 3.18$; $\widehat{F}_{A_D} = 1.36 < F_{\alpha, k_{X_1}, k_{X_2}} = 3.18$; $\widehat{F}_\delta = 2.7 < 3.18$). The mathematical expectations of the deviations from cylindricity of surface 2 when basing in a chuck and

in a chuck and a center, are also commensurable ($\widehat{t}_{\Delta_D} = 1.99 < t_{\frac{\alpha}{2}, k} = 2.101$).

The introduction of a second support (a center) deteriorates both the diametric accuracy and the correctness of the geometric shape of surface 1 and surface 3 ($\widehat{t}_{\Delta_d} = 4.23 > t_{\frac{\alpha}{2}, k} = 2.101$; $\widehat{t}_\delta = 6.83 > t_{\frac{\alpha}{2}, k} = 2.101$).

This is probably due to accumulated errors from lack of coaxiality in the technological system or from part deformation under the action of the pressing force of the center.

IV. CONCLUSIONS

The accuracy of the cylindrical and conical surfaces of parts, made of C45, has been studied after turning, depending on the setting scheme. It has been established that the choice of fixture and type of clamping is a fundamental criterion, influencing the geometric characteristics of the machined surfaces.

The accuracy of the machined surfaces has been analyzed and assessed by applying statistical testing of parametric hypotheses, while making a comparative analysis between the mathematical expectation and the variance of the diametric dimensions, the deviation from cylindricity and the cone angle for the two setting schemes

(in a three-jaw self-centering chuck and between a chuck and a center).

It has been found that the setting scheme has the greatest impact on the accuracy of the diametric dimensions, as well as on their variance.

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Competency-Focused Aviation English for Aircraft Maintenance

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Abstract — This paper presents a mixed-methods needs analysis of Aviation English requirements for aircraft maintenance technicians operating in international and multilingual environments. The study addresses the role of precise and context-appropriate communication in maintenance, repair, and overhaul settings, where language use directly influences operational safety and reliability.

The research adopts an exploratory sequential design combining qualitative and quantitative methods. In the first phase, data were collected through an international focus group using the DACUM method to identify key communicative competences. In the second phase, a context-specific survey was administered to practicing aircraft maintenance professionals and trainee cadets in Bulgaria, Ukraine, and Algeria to validate and extend the qualitative findings. The results identify a multidimensional competence framework comprising linguistic, interactional, intercultural, and professional competences required for effective communication in maintenance contexts. Statistical analysis reveals strong correlations between linguistic competence and both interactional and professional competences, highlighting the integration of language performance with operational capability. The findings also identify priority thematic areas for Aviation English instruction and confirm the predominance of receptive skills, particularly reading and listening, in maintenance-related tasks. The study provides empirically grounded insights into the communicative demands of aircraft maintenance personnel and supports the adoption of a competency-focused approach to Aviation English training. This approach emphasizes the ability to apply language in operational contexts and aligns language instruction with the needs of engineering education and industry practice.

Impact Statement

This study provides empirical evidence on Aviation English requirements in aircraft maintenance, supporting the development of competency-focused language training aligned with engineering practice. The findings contribute to improving communication effectiveness, human factors performance, and operational safety in international aviation contexts.

Keywords— *aircraft maintenance, aviation English, competence*

I. INTRODUCTION

Since the early days of aviation, the focus has often been placed on pilots as the visible actors of flight; however, the safety and reliability of aviation operations depend equally on the often less visible, yet indispensable, work of aircraft maintenance personnel. In contemporary aviation environments, effective communication constitutes a core component of professional competence. A high level of proficiency in Aviation English is therefore essential not only for pilots and air traffic controllers, but also for aircraft maintenance technicians (AMTs), cabin crew, ground personnel, and other aviation professionals operating in both civil and military contexts [1]–[3]. This necessity arises from the inherently international nature of aviation, where communication frequently occurs among individuals from diverse lingua-cultural backgrounds.

One of the primary functions of English for Specific Purposes (ESP) in higher education is to prepare graduates for successful professional performance. It is an approach that is driven by an analysis of what learners need to do in the language; it focuses primarily on the linguistic knowledge and skills required to undertake professional tasks and deals with topics and issues within a specific academic, professional or vocational field [4]–[6]. However, the requirements for fulfilling this function evolve in response to ongoing technological, economic, and social changes. In current aviation contexts, particularly in maintenance, repair, and overhaul (MRO) environments, communication is embedded in technical procedures, safety-critical documentation, and multidisciplinary coordination. As a result, AMTs require not only knowledge of specialized terminology but also the ability to perform communicative tasks accurately and efficiently under operational constraints. In such environments, communication is directly linked to the reliability of maintenance processes and, consequently, to aviation safety. The importance of communication in

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aviation maintenance has also been emphasized in human factors research, particularly in relation to outsourced and distributed maintenance contexts, where communication breakdowns may directly affect safety outcomes [3]. Aviation English instruction must therefore address these domain-specific communicative demands to ensure safe and effective professional practice.

Pedagogical approaches such as task-based and content-based instruction have contributed to aligning language learning with professional practice, particularly in contexts where subject-matter instruction is delivered in English. Nevertheless, their applicability is more limited in contexts such as Bulgaria, Ukraine, and Algeria, where technical training is conducted in the local language and English functions as an auxiliary professional medium. In such settings, the challenge is not the integration of content and language per se, but the development of communicative performance that can be effectively transferred to operational environments. This requires a stronger emphasis on the ability to use language under real-world conditions, where time pressure, procedural constraints, and safety considerations shape communication.

In response to these challenges, the present study adopts a competency-focused approach to Technical Aviation English instruction. This approach differs from established competency-based models by emphasizing the operational use of language in context rather than reliance on formalized competency frameworks alone. It integrates elements of credit-based and competency-based education while prioritizing the ability to apply linguistic resources effectively in authentic professional situations. In doing so, it shifts the focus from the acquisition of specialized vocabulary to the functional use of language, from grammatical knowledge to pragmatic competence, and from language as a system to language as professional practice embedded in safety-critical workflows.

Within this framework, communicative competence is understood as the integrated application of knowledge, skills, and attitudes required for effective performance in specific professional contexts. In this study, communicative competence refers to overall communicative ability, while competences denote its constituent domains; the term competency-focused approach is used to emphasize the application of these competences in operational contexts. In line with training principles reflected in aviation standards (e.g., International Civil Aviation Organization), Aviation English for AMTs should support the development of observable and measurable communicative abilities. These include the accurate interpretation of technical documentation, precise use of domain-specific terminology, effective incident and fault reporting, and interaction within multicultural and multidisciplinary teams. The focus is placed on clarity, intelligibility, and appropriateness in safety-critical communication.

Despite these requirements, existing Aviation English research and training frameworks remain largely oriented toward pilots and air traffic controllers, with insufficient empirical attention to the domain-specific communicative

requirements of aircraft maintenance technicians (AMTs). In addition, current pedagogical models—primarily task-based and content-based—do not adequately capture the complexity of communication in maintenance, repair, and overhaul (MRO) contexts, nor do they provide a sufficiently flexible framework for linking language performance to operational competence and safety outcomes. Previous research suggests that the task-based approach and the content-based approach are logically related [7]. To address the above mentioned gap, the present study proposes a competency-focused approach to Aviation English for AMTs, supported by empirical data from a mixed-method needs analysis. This approach aims to align language training more closely with the communicative realities of maintenance practice and to contribute to the enhancement of safety through improved communication performance. Recent studies have begun to address the needs of aircraft maintenance personnel [1], [2], yet a comprehensive competency-focused framework grounded in empirical data remains underdeveloped.

II. MATERIALS AND METHODS

This study employed a mixed-methods exploratory sequential design following the model proposed by John Creswell and Vicki Plano Clark [8]. The research was conducted in two consecutive phases: an initial qualitative exploration followed by quantitative validation. The qualitative phase aimed to identify key variables and underlying constructs related to Aviation English use among aircraft maintenance technicians (AMTs), while the quantitative phase examined the extent to which these findings could be generalized across a broader sample. The results from both phases were subsequently integrated to provide a comprehensive understanding of domain-specific communicative requirements in maintenance contexts. In this study, the term AMTs is used to refer to both practicing aircraft maintenance professionals and trainee cadets specializing in aircraft maintenance.

Data for the qualitative phase were collected through an international focus group using the DACUM (Developing a Curriculum) method. The focus group consisted of 11 participants from Bulgaria, Greece, Poland, Romania, and Ukraine. Participants were selected based on their expertise in aviation education and practice and included subject-matter instructors, English language teachers, and aircraft maintenance professionals. All participants had a minimum of five years of professional experience in the aviation field. The group comprised 5 female and 6 male participants, aged between 28 and 56 years.

The findings from the qualitative phase informed the development of a context-specific survey instrument designed to assess the relevance and distribution of the identified competence domains. The survey was administered to a sample of 95 AMTs, including civilian and military maintenance engineers ($n = 58$) and military cadets specializing in aircraft maintenance ($n = 37$), from Algeria, Bulgaria, and Ukraine. The inclusion of both experienced professionals and trainee cadets provides a comprehensive perspective on current and emerging communicative requirements in aircraft maintenance.

The participant group comprised individuals with direct or developing experience in target language use (TLU) contexts. Regarding age distribution, 44.2% of respondents were between 20 and 30 years old, while the remaining participants were aged between 30 and 50 years. In terms of professional experience, 56.8% of the total sample (n = 95) reported more than ten years of experience in the aviation field. Overall, the sample reflects a balanced representation of early-career trainees and highly experienced practitioners engaged in aircraft maintenance operations.

Quantitative data were analyzed using descriptive statistics and correlation analysis. Pearson correlation coefficients were calculated to examine relationships between the identified competence domains.

III. RESULTS

The focus group participants identified English language proficiency as essential across three key domains: academic training, practical traineeship, and professional practice. They emphasized its role in supporting teamwork and maintaining safety in operational environments. Participants also highlighted the use of technical Aviation English in a range of routine activities during a typical working day, as well as in international training exercises. One participant stated, “the importance of English language for effective and well-organized job performance cannot be overstated.”

The analysis further indicated that communication in aviation maintenance contexts is highly context-dependent and technically referential. Core communicative activities include reading technical documentation, interpreting instructions, and engaging in task-oriented professional interaction. These activities require not only linguistic knowledge but also domain-specific background knowledge related to aircraft systems, avionics, and maintenance procedures.

The competence framework derived from the focus group is presented in Table 1, which summarizes the core competence domains: linguistic, interactional, intercultural, and professional. Each domain includes a set of subcomponents such as vocabulary, pronunciation, accuracy, fluency, teamwork, collaborative communication, background technical knowledge, and regulatory awareness.

TABLE 1. TECHNICAL AVIATION ENGLISH COMMUNICATIVE COMPETENCES

linguistic competence	interactional competence
know and use correctly technical aviation vocabulary	communicate successfully in everyday situations
know and use clear, concise and unambiguous technical language in aviation context	communicate successfully in unpredictable situations
use intelligible pronunciation and intonation	cope adequately with apparent misunderstanding by checking, paraphrasing, confirming, clarifying information and repairing breakdowns
be able to accommodate to various native speaker and non-native speaker accents	demonstrate fluency in speaking

know and use accurate grammar	demonstrate accuracy in speaking
intercultural competence	professional competence
be aware that there are different cultures with different values, beliefs and behaviors	possess initial background professional knowledge
demonstrate openness and flexibility to different cultures e.g. accept their communication style or work strategy	comply with the rules and procedures for communication
be aware of the effects of gender on communication	demonstrate a professional attitude and tone
be aware of the effects of losing face on communication	demonstrate tolerance and collaborative efforts for successful communication
be aware of the effects of hierarchy and authority on communication	be able to offer and accept teamwork

These findings indicate that effective communication in maintenance contexts extends beyond linguistic competence alone and requires an integrated set of communicative abilities.

The quantitative results confirm the importance of Aviation English in the professional domain of AMTs. A total of 96.2% of respondents indicated that English is an integral part of their professional activities. The analysis of Likert-scale responses showed that all identified competence domains were rated as important or very important for a technical Aviation English course.

Correlation analysis (Table 2) revealed statistically significant relationships between the competence domains. Linguistic competence showed a strong positive correlation with interactional competence ($r = 0.810$) and professional competence ($r = 0.793$), and a moderate correlation with intercultural competence ($r = 0.490$). These results indicate that language proficiency is closely associated with effective professional performance and interaction in maintenance environments.

TABLE 2. CORRELATIONS BETWEEN THE COMPETENCES

		Interactional competence
Linguistic competence	Pearson Correlation	0.810**
	Sig. (2-tailed)	0.000
	N	95
		Intercultural competence
Linguistic competence	Pearson Correlation	0.490**
	Sig. (2-tailed)	0.000
	N	95
		Professional competence
Linguistic competence	Pearson Correlation	0.793**
	Sig. (2-tailed)	0.000
	N	95

Descriptive statistics revealed differences in perceived importance of language skills between aircraft maintenance technicians (AMTs) and cadets. Among AMTs (n = 58), reading comprehension was rated as the most important skill (M = 4.89, Mo = 5), followed closely by listening and speaking. Writing received the lowest mean score within this group, although it was still generally considered

moderately important for occupational tasks such as reporting and documentation.

A similar ranking pattern was observed among cadets ($n = 37$), with reading comprehension ($M = 4.62$, $Mo = 5$) and listening ($M = 4.82$, $Mo = 5$) rated as highly important, followed by speaking. However, writing was rated substantially lower than all other skills ($M = 3.00$, $Mo = 2$), indicating a clear tendency among cadets to perceive writing as only marginally important for aircraft maintenance communication contexts.

TABLE 3. MEAN AND MODE OF LANGUAGE SKILLS

variable	N of AMTs	mean	mode	N cadets	mean	mode
Reading	58	4.89	5	37	4.62	5
Listening	58	4.52	5	37	4.82	5
Speaking	58	4.25	4	37	4.05	4
Writing	58	3.85	4	37	3.00	2

Overall, while both groups identified receptive skills as most critical for occupational performance, cadets assigned substantially lower importance to writing compared to all other skills, in contrast to the more balanced evaluation provided by experienced AMTs. The prominence of reading skills identified in the present study is consistent with previous findings, where “the most important skill to be mastered in this field was reading since most tasks require strong reading ability” [1, p. 38].

Survey responses also identified key thematic areas relevant to Technical Aviation English instruction, which informed the organization of topic-based modules for training.

IV. DISCUSSION

Taken together, these findings indicate that communication functions as an integrated component of professional competence in aircraft maintenance rather than as an independent skill. The observed relationships among linguistic, interactional, and professional competences suggest that language use is embedded within operational practice. This supports a competency-focused approach to Aviation English that emphasizes context-dependent communicative performance.

The identification of intercultural competence as a relevant dimension further underscores the multidimensional nature of communication in international aviation environments. Although its statistical association with linguistic competence is moderate, qualitative evidence indicates that culturally influenced communication behaviors may affect teamwork, perceptions of hierarchy, and decision-making processes. Reported examples include variation in communication styles, differences in power distance, and divergent perceptions of authority, as well as challenges related to respect, stereotyping, and organizational culture. These results indicate that aviation communication is shaped by socio-cultural factors and is not linguistically neutral.

The results also carry clear implications for instructional design. The identified competence domains

and their interrelationships support the implementation of a competency-focused pedagogical approach that emphasizes observable performance and practical applicability. In this regard, Aviation English instruction should move beyond isolated linguistic elements and prioritize integrated communicative abilities aligned with operational tasks. The findings are consistent with competency-oriented training perspectives in aviation, which emphasize measurable performance outcomes and operational capability over purely content-based instruction [7].

Content selection emerges as a critical factor in aligning instruction with target language use (TLU) requirements. The findings suggest that instructional topics should reflect authentic maintenance contexts while remaining appropriately calibrated to learners’ technical and linguistic proficiency. For trainee AMTs, this necessitates a careful balance between accessibility and operational relevance. Learning materials should therefore be meaningful, task-oriented, and capable of simultaneously supporting language development and professional awareness. The survey data further enabled the identification of priority thematic areas for a technical Aviation English course. A non-exhaustive set of topics was organized into six modules covering core domains of aircraft maintenance, including aircraft structure, tools and instruments, systems (hydraulic, pneumatic, propulsion), avionics and communication, maintenance procedures, and specialized areas such as armament and electronic warfare. Each module comprises multiple subtopics reflecting typical maintenance tasks and operational contexts. The results indicate that topic selection and sequencing play a critical role in supporting learning, as concepts must follow the internal logic of the discipline and should be introduced progressively. Respondents showed a clear preference for professionally relevant and practically oriented topics, particularly those reflecting real-life scenarios and workplace communication. In line with previous research [9], these findings support the use of scenario-based and context-driven materials that replicate operational conditions and facilitate the integration of language, content, and communicative competences. Within a competency-focused framework, such topics function as a mediating structure through which learners develop both domain-specific language and the ability to apply it in context, rather than as isolated units of content.

Differences in skill perception between AMTs and cadets can be interpreted in relation to varying levels of experience in TLU contexts and exposure to workplace communication demands. While both groups consistently prioritized receptive skills, particularly reading and listening, AMTs demonstrated a more balanced appraisal of productive skills, with writing still regarded as moderately important for documentation and reporting tasks. This likely reflects their direct engagement with operational procedures in which written communication forms an integral part of safety documentation, technical reporting, and regulatory compliance. In contrast, cadets attributed considerably lower importance to writing, suggesting that their perceptions are shaped by limited exposure to authentic workplace communication and a

stronger emphasis on immediate, orally mediated instructional activities. The low valuation of writing among cadets may therefore reflect a developmental stage in which awareness of the procedural and operational functions of written communication has not yet fully matured. Overall, these findings highlight a clear distinction between experienced practitioners and trainees, underscoring the role of professional experience in shaping perceptions of communicative demands in aircraft maintenance settings.

Furthermore, the results indicate that instructional effectiveness depends less on the selection of specific teaching methods and more on the formulation of clearly defined learning outcomes. A competency-focused approach supports learner autonomy and encourages students to take responsibility for their own development through tools such as portfolios and individualized learning plans. This approach facilitates the integration of language, content, and professional competences, enabling learners to construct knowledge through engagement with authentic tasks and contexts. The words of Friginal, Mathews and Roberts can be shared, "Much work remains to be done in all sectors of language in aviation, from research to developing academically well-informed aviation English teaching materials, to developing aviation operational awareness within the English language teaching and testing communities, to helping the aviation industry better understand the need for linguistic awareness" [9, p. X].

Overall, the research study demonstrates that Aviation English training for AMTs should be grounded in empirically identified communicative requirements and structured around integrated competence development. Such an approach enhances both the relevance of instruction and the operational readiness of future maintenance personnel.

V. CONCLUSIONS

This research study demonstrates that effective communication is a fundamental component of operational performance in aircraft maintenance environments. The findings confirm that Aviation English for aircraft maintenance technicians (AMTs) extends beyond the acquisition of specialized vocabulary and grammatical knowledge, requiring instead an integrated set of communicative competences that support safe, accurate, and efficient task execution. The proposed competence framework, supported by both qualitative and quantitative data, highlights the interdependence of linguistic, interactional, intercultural, and professional domains in real-world maintenance contexts.

The results further indicate that language performance is closely linked to operational capability, as evidenced by the strong correlations between linguistic, interactional, and professional competences. These findings underscore the need for instructional approaches that reflect the complexity of communication in maintenance, repair, and overhaul (MRO) environments and that are grounded in authentic target language use (TLU) situations.

In response to these requirements, the study advocates a competency-focused approach to Aviation English instruction. This approach provides a flexible and operationally relevant framework by emphasizing measurable outcomes and the ability to apply language effectively in professional contexts, rather than focusing solely on content coverage or task completion. The training aims to ensure mastery of linguistic, intercultural, strategic, and interactional competences, enabling learners to perform successfully in both routine and non-routine situations.

The findings have direct implications for curriculum development, instructional design, and training practices in both civilian and military aviation education. As noted by Erik Friginal et al. [9], continued efforts are required to bridge the gap between linguistic research, pedagogical practice, and operational aviation needs. By aligning language instruction with empirically identified communicative requirements, the proposed approach supports the development of operational readiness and contributes to the enhancement of safety in aviation maintenance.

Behind every safe flight lies a complex network of technical expertise, where precise communication among aircraft maintenance technicians is as critical as the engineering work itself. Strengthening this communication through competency-focused Aviation English training is therefore not only an educational objective, but a safety measure.

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Multifactorial Study of the Influence of an Anamegator on Oil on the Change in the Tribotechnical Parameters of the Friction Pair

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Abstract— The addition of an anamegator to the oil directly affects the change in the tribotechnical parameters of the friction pair by changing its operating environment. The article presents a multivariate study of the influence of the addition of an anamegator to the lubricating medium on the change in the tribotechnical parameters of a friction pair. The main objective is to evaluate the effect of the additive on friction and wear processes under different operating conditions, expressed by the change in roughness. Some of the main factors affecting the operation of friction surfaces are considered, such as load, sliding speed, temperature and concentration of the anamegator in the oil. The experimental methodology is described, including laboratory tests using a specific tribological bench and measuring the mass of the samples. The article analyses the results obtained by statistical methods for multivariate analysis, and it is found that the addition of an anamegator has a significant impact on improving lubrication performance and reducing wear under certain operating modes. The optimal values of the studied factors and the possibilities for practical application of the results are discussed.

Keywords— tribology, anamegator, multivariate analysis, experiment planning.

I. INTRODUCTION

Tribological processes related to friction, wear and lubrication of contact surfaces play a key role in the reliability, efficiency and durability of machines and mechanisms [1]. In the conditions of modern engineering, there is a growing interest in the development and

application of various additives to lubricants aimed at improving their performance characteristics [2]. Among these additives, special attention is paid to the so-called. anamegators, which affect the structure and properties of the lubricating film and the interaction between friction surfaces [3]-[4].

Additives to lubricating oils can significantly alter the mechanism of friction and wear by forming protective layers, reducing adhesion interactions, and improving heat dissipation [5]-[6]. In this context, the study of the effect of different concentrations of additives under a variety of operating conditions is an important scientific and practical task. It is particularly important to analyse the influence of parameters such as load, sliding speed and temperature, which determine the friction mode and, accordingly, the degree of wear.

Modern approaches in tribology include the use of experimental methods combined with statistical tools to analyse the results. Multivariate analysis and experiment planning allow for the simultaneous study of the influence of several variables and their interaction on baseline indicators [7]. This allows for more accurate modelling of real working conditions and determining optimal parameters to minimize wear.

One of the important indicators for assessing the condition of friction surfaces is roughness, which reflects changes in microgeometry as a result of tribological processes. A decrease in roughness is usually associated with an improvement in lubrication mode and lower

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friction coefficient values [8]. Therefore, the analysis of this parameter provides valuable information about the effectiveness of the additives used.

This article aims to investigate the effect of adding an anamegator to lubricating oil on the tribotechnical performance of a friction pair by applying a multifactorial experimental approach. The main factors determining the operating mode are considered and their interaction on the change in the mass of samples is evaluated. The results of the study are aimed at determining optimal working conditions and expanding the possibilities for practical application of additives in industrial systems.

II. METHOD OF WORK

For this article, laboratory accelerated tests of reciprocating motion have been carried out. Samples and counterbodies of the most commonly used materials in transport equipment were used. The experiments were carried out with a certain duration, not taking into account the pairs' operation. The prototypes are X9CrMov10 steel, GG25 cast iron and CuSu7 bronze. The friction pairs are of the steel-steel, steel-cast iron and steel-bronze type. The counterbodies are made of the steel mentioned above. The experimental setup of this article uses a standard bench for testing friction pairs in an oily medium operating on a reciprocating motion (Fig. 1).

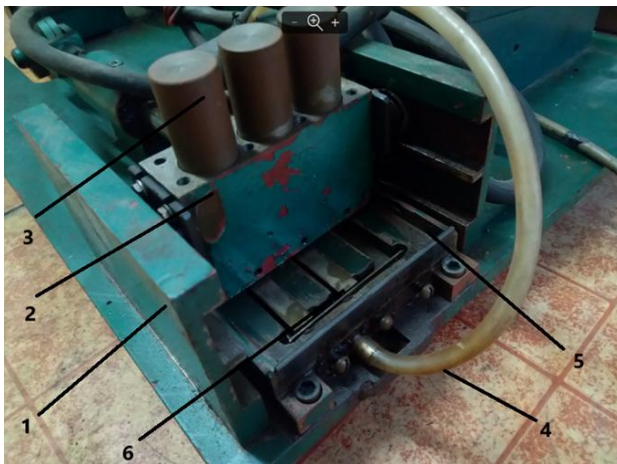


Fig. 1. General appearance of the rubbing and wear stand. 1-building; 2-body; 3-caps; 4-Oil leak hose; 5-oil bath; 6-counterbody.

The housing 1 together with the oil bath 5 are fixed. In the bathtub are located the counterbodies 6. The body 2 bears in grooves of the hull and is movable, with which it makes a stroke of 120 mm. The load on the friction pair is carried out by turning the caps 3. Below them are springs with a known deformation curve. The springs press the cylindrical specimens onto the counterbodies 6. The grooves in the housing are the other support for the implementation of the weight. Body bearings help to significantly reduce friction in the ligaments. The whole friction process takes place in an oil bath 5. The counterbodies are fixed to the bathtub by means of fixing screws at the end.

Body 2 performs the reciprocating movement through an electric motor with a washer and arm. The reverse progressive movement is carried out by an eccentrically located hole of the washer and an arm attached to it.

The oil used is CLAAS AGRIMOT Protec10W40, covering the ACEA E9 / API CK-4 standard and according to the technical specifications of MAN M3775, DEUTZ DQC III-18LA, etc. [9]. It was preheated at a temperature of 80° C and added to it the Gold Ozirol MP-8 oil anamegator in a ratio of 4.8-9.2 ml/L [3], [10].

According to literature sources, the load on the pair was chosen 50 N for the purpose of comparability of the results [1]-[2], [11]-[12].

Laboratory experiments were carried out in cat. "Materials Science and Technology of Materials" at the University of Ruse "An. Kanchev" in the period March-April 2026.

The dynamics of wear of specimens and counterbodies was investigated by determining weight loss using a Sartorius TE214S scale with 210 g and an accuracy of 0.1 mg [13].

During a period of one hour of operation, the samples and counterbodies are removed from the stand, washed with acetone and subjected to measurements.

III. RESULTS AND DISCUSSION

In this article, two factors influencing the change in the tribotechnical parameters of the friction pair are studied (Table 1).

TABLE 1 FACTORS AND LEVELS OF VARIATION

Factor	Name	Level of variation		
		-1	0	+1
X1	Quantity of anamegator, ml	4,8	7,0	9,2
X2	Type of friction pair	Br-St	Ir-St	St-St

In Table 1, for easier handling of the factors, their coded values are also given. The trials were carried out according to plan B2 with nine trials. The plan is orthogonal, centred with the need to conduct experiments at nine-star points, including the centre point [14].

One of the factors X1 is the amount of the anamegator to the oil, and the other X2 is the type of friction pair. At X1, the average value is 7.0 ml/L and a level of variation of ± 2.2 ml/L. At X2, the average value is the Ir-St cast iron-steel pair, and the variation is from the mild bronze-steel pair Br-St to the St-St hard steel. Steel specimens and counterbodies are hardened to a hardness of 50 HRC according to ISO 6508-1:2023 [15].

After completing 3h experiments for each of the variants, the results are processed statistically and given in the tables.

TABLE 2 ANALYSIS OF VARIANCE FOR SAMPLE MASS

Factor	SS	df	MS	F	p	% effect
X1	17.001	2	8.500	6647.147	0.00000	32.17

X2	5.757	2	2.878	2250.819	0.00000	10.89
Time	0.047	3	0.016	12.283	0.00156	0.09
X1*X2	29.993	4	7.498	5863.622	0.00000	56.76
X1*Time	0.013	6	0.002	1.677	0.23288	0.02
X2*Time	0.023	6	0.004	2.976	0.06908	0.04
Residual	0.012	9	0.001	nan	nan	0.02

In Table 2 are presents the Analysis of Variance (ANOVA) for the mass of the samples. It is noticed that all the main factors + the interaction $X1 \times X2$ actually affect the change in the mass of the samples. It was noticed that during the experiments, the confidence interval was too high. The duration does not have a significant impact on the change in the mass of the samples. All other factors are significant, with the greatest impact on wear being observed in $X1 \times X2$ with an efficiency of 56.76%. The amount of the anamegator factor $X1$ affects more strongly than the type of friction pair or 32.17% on the change in the mass of the samples.

The error in conducting the experiments was 0.012 or less than 0.02%. This indicates that the experiment is stable and the model explains almost everything.

TABLE 3 STATISTICS ON THE CHANGE IN THE MASS OF SAMPLES

X1	X2	Mean	Std	CV%	Min	Max
-1	-1	13.6597	0.0334	0.25	13.6364	13.7072
-1	0	12.1898	0.0723	0.59	12.1536	12.2982
-1	1	13.5556	0.0369	0.27	13.5371	13.6108
0	-1	15.0340	0.0757	0.50	14.9490	15.1191
0	0	12.2685	0.0775	0.63	12.1536	12.3237
0	1	12.4995	0.0113	0.09	12.4938	12.5165
1	-1	13.5988	0.1070	0.79	13.5371	13.7583
1	0	12.3237	0.0000	0.00	12.3237	12.3237
1	1	13.6654	0.0128	0.09	13.6590	13.6845

Table 3 shows the change in mass over the entire period of the experiment. The large change in the values of $X1$ and $X2$ is normal because different amounts of the anamegator affect different types of friction pairs. The smallest wear or minimum occurs at $X2=0$ or when the cast iron is rubbed. This is explained by the very structure of cast iron and its ability to absorb more of the oil with the anamegator in it. We know that the anamegator increases glide and reduces friction many times over. Its particles enter the pores of cast iron, and from there probably areas of reduced friction are obtained. On the other hand, hard steel samples and soft bronze have the opposite effect. The amount of the anamegator affects different friction pairs differently due to structural differences in their crystal structure. All CV% are between 0.00% and 0.79%. This is good because the measurements obtained are very stable, there is almost no noise, and at 0.00% there is almost perfect repeatability.

There is almost no randomness in the data because $R^2 = 0.9996$ and the model explains 99.96% of the variation. In this model, Adjusted $R^2 = 0.9986$. This shows the reality of the data presented.

The average prediction error is $RMSE = 0.0190$. The forecasts are extremely accurate and the error is almost zero in relation to the scale.

Residue scattering Variance = 0.0004. The pattern captures almost the entire structure and there are no hidden variations.

In the other indicator, Signal / Noise = 692.97. The signal is 692 times stronger than the noise or the pattern is very well represented.

The Shapiro residue normality test $p = 0.33249$ indicates that the residues are normally distributed, the model is statistically valid, and there are no regression problems.

The equation for the change in the mass of the specimens takes the form:

$$y = 13,142 + 0,162.X1 - 0,258.X2 + 0,970.X1.X2(1)$$

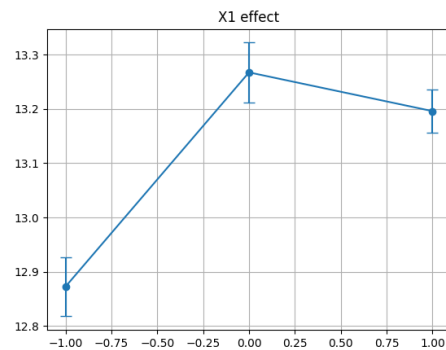


Fig. 2. The effect of $X1$ on the change in the mass of samples.

In Fig. 2 shows the effect of the application of the anamegator on the change in the mass of the samples during the experiment period. The maximum is clearly expressed at $X1=0$ and subsequently decreased. The left section of the graph shows a strongly positive effect from the growth of the anamegator to $X1=0$, and the right one shows a slight negative effect. Small amounts of the anamegator have a positive effect, which is best expressed at 7 ml/L. Preservation of sample mass is best in this range. An overdose is also not a very good option, due to a violation of the tribotechnical characteristic of the oil layer.

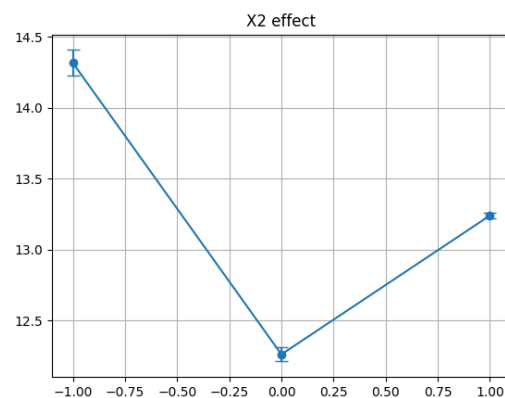


Fig. 3. Effect of $X2$ on the change in the mass of samples.

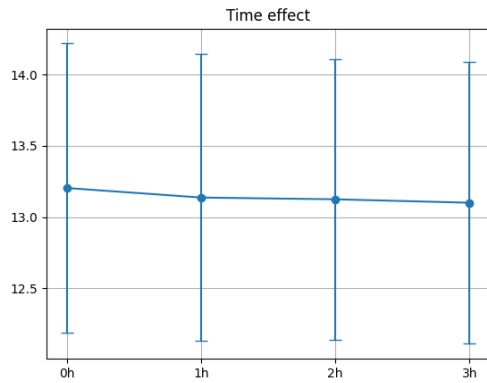


Fig. 4. Evolution of the average mass of samples.

In Fig. 3 shows the effect of the other factor X2 on the change in the mass of the samples. Here the minimum is expressed again in the zero value of the factor or in the case of a friction pair of cast iron-steel.

Figure 4 shows the dynamics of the change in the average value of the samples during the experiment. It is noticed that in the first hour the wear is the greatest, which is characteristic of the stage of operation.

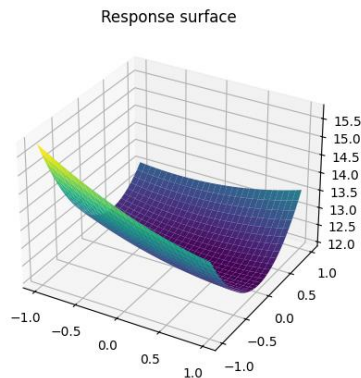


Fig. 5. 3D model of influence of factors on change in the mass of samples.

In Fig. 5 shows the three-dimensional model of influence of factors on the change in the mass of the samples. The parabola with the minimum is clearly expressed. The influence of X1 and the weaker influence of X2 is clearly expressed.

TABLE 4 ANALYSIS OF VARIANCE FOR THE MASS OF COUNTERBODIES

Factor	SS	df	MS	F	p	% effect
X1	2679.082	2	1339.5408	862071.09	0.0000	34.16
X2	2503.777	2	1251.8887	805661.94	0.0000	31.93
Time	0.034	3	0.0113	7.25	0.0089	0.00
X1*X2	2659.541	4	664.8853	427891.69	0.0000	33.91
X1*Time	0.002	6	0.0003	0.22	0.9615	0.00
X2*Time	0.006	6	0.0009	0.60	0.7231	0.00

Residual	0.014	9	0.0016	nan	nan	0.00
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Table 4 shows the ANOVA analysis of the change in the mass of the counterbodies during the experiments. The X1 factor with the high F explains 34.16% of the variations. This repeats what was said above about the mass of the samples. Due to the fact that the counterbodies are made of the same material, X2 explains 31.93% of the variations. The coefficient for the time of the experiment is statistically significant at $F=7.25$ and $p=0.008$, but its effect is very small. In contrast, the interaction $X1*X2$ explains 33.91% of the variations. The remainder is 0.014. This indicates that the model explains almost all of the variation.

Table 5 shows the statistical data from the experiment.

TABLE 5 STATISTICS ON THE CHANGE IN THE MASS OF THE COUNTERBODIES

X1	X2	Mean	Std	CV%	Min	Max
-1	-1	199.3100	0.0550	0.028	199.2500	199.3800
-1	0	197.1098	0.0428	0.02	197.0722	197.1714
-1	1	201.7386	0.0000	0.00	201.7386	201.7386
0	-1	200.2687	0.0754	0.04	200.2077	200.3778
0	0	198.8774	0.0538	0.03	198.7987	198.9206
0	1	204.1710	0.0000	0.00	204.1710	204.1710
1	-1	200.0496	0.0461	0.02	199.9894	200.0858
1	0	197.9241	0.0482	0.02	197.9000	197.9964
1	1	198.2820	0.0632	0.03	198.1920	198.3366

Factor X2 has a strong nonlinear effect. The effect of X1 is clearly expressed at $X1=0$. Here again there is a repetition with the change in the mass of the samples.

The coefficient of variation is minimal in almost all counterbodies. This confirms that the measurements obtained are noise-free and correct.

And here there is almost no randomness in the data, because $R^2 = 0.9999$ and the model explains almost 100% of the variation. In this model, Adjusted $R^2 = 0.9997$. This again shows the reality of the data presented.

The average prediction error is $RMSE = 0.0209$. The forecasts are again extremely accurate and the error is almost zero in relation to the scale.

The scattering of the residues Variance = 0.0004, the same as the samples. The pattern captures almost the entire structure and there are no hidden variations.

In the other indicator, Signal / Noise = 9557.5933. The signal is 9557 times stronger than the noise or the model is excellently represented.

The Shapiro residue normality test $p = 0.88181$ again shows that the residues are normally distributed, the model is statistically valid, and there are no regression problems.

The equation of change in the mass of the counterbodies takes the form.

$$y = 198,88 + 0,41.X1 + 1,95.X2 - 2,75.X1.X2 - 0,85.X1^2 + 2,60.X2^2 \quad (2)$$

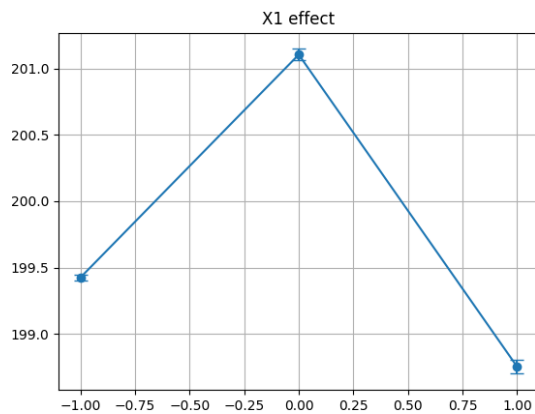


Fig. 6. The effect of X1 on the change in the mass of the counterbodies.

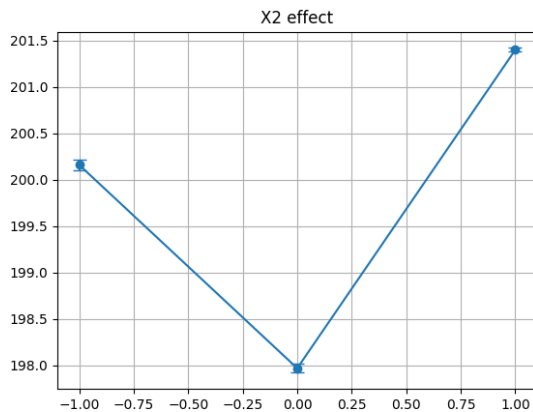


Fig. 7. Effect of X2 on the change in the mass of the counterbodies.

In Fig. 6 shows the effect of X1 on the change in the mass of the counterbodies. The factor has a strong effect and a non-linear character with an optimum in the centre. It is clearly shown that at $X1=0$ there is a pronounced maximum. With an increase in the supplement, the effect of an overdose is expressed by a decrease in the mass of the counterbodies.

In Fig. 7 shows the effect of the other factor X2 on the change in the mass of the counterbodies. A pronounced U shape is observed on the graph. A global maximum is observed at $X2=1$. The intensity of the change in the mass of the counterbodies working with cast iron is the greatest. In the case of steel counterbodies, this change is negligible, with slightly greater wear occurring in bronze counterbodies.

In Fig. 8 shows the dynamics of change in the average value of the mass of the counterbodies during the experiment. A uniform process of wear of the counterbodies is noticeable. The intervals are very wide and overlap strongly. This shows that the differences between the times are almost indistinguishable. The effect is negligible and has negligible impact on the wear process.

In Fig. 9 shows the three-dimensional model of influence of factors on the change in the mass of the counterbodies. The peak is clearly expressed in yellow, after which the values decrease. Conversely, the minimum is expressed in a blue-purple color. The system does not react linearly, but a combination of factors is taken into account.

The wear of the specimens, the counterbodies and the pair as a whole can be given with the formula:

$$I = m_i - m_f \quad (3)$$

where m_i is the initial value of the mass, g;

m_f – the final value of the mass, g.

According to the formula given in this way, the wear of the specimens, the counterbodies and the pair is determined. The result is presented in Table 6.

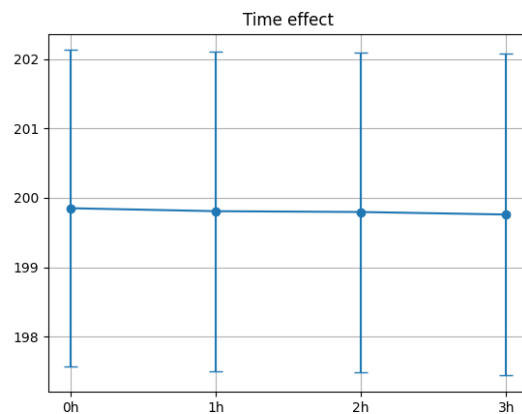


Fig. 8. Evolution of the average mass of counterbodies.

The above for the factor X1 is also confirmed by the results in Table 6. The lowest wear rate shall be obtained for specimens and counterbodies operating at a factor of $X1=0$, followed by $X1=1$.

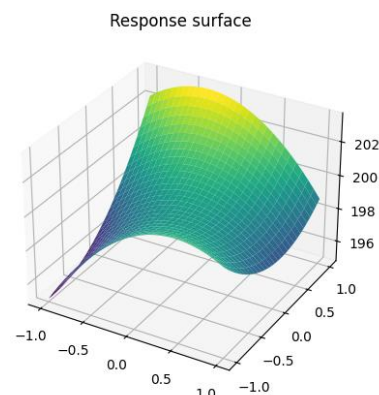


Fig. 9. 3D model of influence of factors on change in the mass of counterbodies.

TABLE 6 SIZE AND WEAR RATE OF THE PAIR

X1	X2	I _S , g	I _{CONTRA} , g	I _C , g	V, mg/s
-1	-1	0,070875	0,05103	0,121905	0,0112875
-1	0	0,144585	0,099225	0,24381	0,022575
-1	1	0,07371	0	0,07371	0,006825
0	-1	0,1701	0,1701	0,3402	0,0315
0	0	0,1701	0,121905	0,292005	0,0270375
0	1	0,02268	0	0,02268	0,0021
1	-1	0,22113	0,09639	0,31752	0,0294
1	0	0	0,09639	0,09639	0,008925
1	1	0,025515	0,144585	0,1701	0,01575

IV. CONCLUSIONS

Based on the analysed results and statistical data, the following main conclusions can be drawn:

The addition of an anamegator has a significant impact on improving lubrication performance and reducing wear. The greatest influence on wear is the interaction between the amount of anamegator (X1) and the type of friction pair (X2), which explains 56.76% of the variation in samples.

Small amounts of the anamegator have a positive effect, with the best results for maintaining the mass of specimens being observed at a concentration of 7 ml/L (zero level of factor X1). An overdose (over 7 ml/L) leads to a slight negative effect due to a violation of the characteristics of the oil layer.

The lowest wear is recorded in the friction pair of cast iron and steel (Ir-St). This is due to the porous structure of cast iron, which allows better absorption of oil with the anamegator and the creation of zones of reduced friction.

In the case of specimens, wear is most intense during the first hour of operation, which corresponds to the stage of surface operation. With counterbodies, the wear process proceeds more evenly.

The mathematical models used are extremely accurate, with a coefficient of determination R² above 0.999, which means that they explain almost 100% of the variations in the experimental data.

ACKNOWLEDGMENTS

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Improving the Accuracy of Gear Transmission by Dividing the Kinematic Error

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Abstract—This paper discusses a method for improving the kinematic accuracy of gear trains through precise analysis and decomposition of the errors of individual gears during assembly. Through mathematical modeling and analysis of collected data, the optimal meshing of the gear wheels is determined, allowing for the minimization of the total error.

Keywords—angle of rotation, gear transmission, kinematic accuracy, kinematic error.

I. INTRODUCTION

The kinematic accuracy of gear trains determines the ability of each gear to transmit rotational motion with the closest possible match between the theoretical and actual angles of rotation of the driven gear.

In a kinematic pair consisting of two gears with satisfactory accuracy, the transmission in which these gears operate may exhibit unsatisfactory accuracy. In many cases, a transmission containing two gears with satisfactory accuracy may exhibit satisfactory kinematic accuracy.

Such a comparison shows us that to ensure high kinematic accuracy of mechanisms, it is necessary to solve the complex problem of precise control both during the manufacturing stage of their components and during the assembly stage [1]. If, during the manufacturing stage, the accuracy of the gears can be guaranteed by adhering to the requirements of the manufacturing process, then the assembly stage may involve the procedure for selecting a suitable kinematic pair [2][3].

II. MATERIALS AND METHODS

When designing gear transmissions, the assembly stage can be described and summarized in two procedures:

- Analysis of the existing pair to determine its compliance with accuracy requirements;

- Synthesis of a satisfactory pair based on the results of the analysis.

The analysis procedure involves decomposing the contributions to the total kinematic error of the driving and driven links. Using this method, the decomposition can be as follows.

It is known that the kinematic error of the pair is the difference between the actual angle of rotation of the driven link θ_{act} and the nominal angle θ_{nom} .

$$\Delta\theta = \theta_{act} - \theta_{nom} \quad (1)$$

If we record the kinematic error of the pair over several revolutions of the driven link, defining the complete cycle of tooth engagement between the driving and driven links, then the number of revolutions of these links will be equal to n_1 and n_2 , respectively to (2) (3).

$$n_1 z_1 = n_2 z_2 \quad (2)$$

$$n_1 = \frac{z_2}{z}, n_2 = \frac{z_1}{z} \quad (3)$$

where z_1 and z_2 are the number of teeth on the driving and driven gears, respectively, and z is the greatest common divisor of z_1 and z_2 .

Fig. 1 shows a case where $z_1 = 12$ and $z_2 = 16$: $z = 4$, $n_1 = 4$, $n_2 = 3$, and the periods T_1 and T_2 correspond to the rotational speeds of the driving and driven links, respectively. The total number of measurements in this case will be $n_2(P/R)$, where P/R is the number of readings from the output shaft rotation transducer (Pulses per Revolution).

Further considerations are based on the obvious property of kinematic error, namely that for a centered

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kinematic error, the mathematical expectation is equal to zero (4).

$$m(\Delta\theta) = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n (\Delta\theta_i - \Delta\theta^0) = 0 \quad (4)$$

where $\Delta\theta^0$ is the initial (central) value of $\Delta\theta$.

Let us consider a specific point A on the active side surface of the drive wheel (Fig. 1). The moment of its contact with the teeth of the driving gear during the first revolution of the driven gear is characterized by point 1 and the corresponding kinematic error caused by the combined influence of errors in the driving and driven members. The moment of contact for the second rotation corresponds to point 2, and for the third rotation — to point 3, and so on. Let us consider the average value of the kinematic error $\Delta\theta$ for all contact points separated from one another by a distance T_2 (or by a number M) [4][5].

$$\frac{1}{n_2} \sum_{i=1}^{n_2} \Delta\theta \cdot (k + (i - 1) \cdot M) \quad (5)$$

where k is the number of the measured kinematic error corresponding to the position of point A within the first period T_2 ($k = 1 \dots M$), where M is the number of revolutions measured for the output shaft (corresponding to the period T_2).

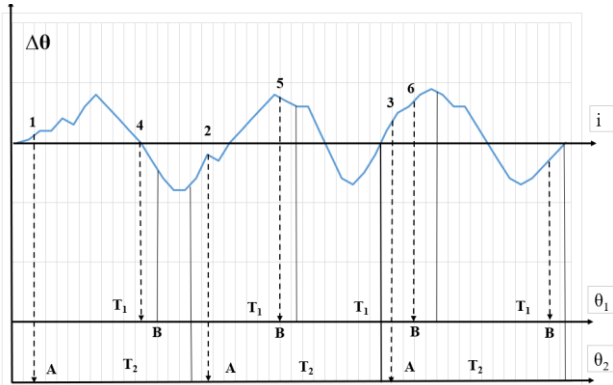


Fig. 1. Diagram illustrating the separation method

Equation (6), taking into account the contributions of the errors of the driving wheel $\Delta\theta_1$ and the driven wheel $\Delta\theta_2$, will take the form.

$$\frac{1}{n_2} \sum_{i=1}^{n_2} \Delta\theta \cdot (k + (i - 1) \cdot M) \quad (6)$$

Since the contribution of the driven wheel $\Delta\theta_2$ at point A is a constant value, then

$$\frac{1}{n_2} \sum \Delta\theta_2(r) = \Delta\theta(A) \quad (7)$$

The contribution of the drive wheel error is a random variable (since point A touches different points on the drive wheel). Therefore, taking (5) into account

$$\frac{1}{n_2} \sum \Delta\theta_1(r) \approx 0 \quad (8)$$

Taking expressions (6) and (8) into account, relation (5):

$$\begin{aligned} \Delta\theta_2(A) &= \Delta\theta(k_A) \\ &\approx \frac{1}{n_2} \sum_{i=1}^{n_2} \Delta\theta(k_A) \\ &\quad + (i - 1)M \end{aligned} \quad (9)$$

In this way, the described procedure segments the initial data and calculates the kinematic error as the average value across the segments, applying the synchronous accumulation procedure.

If we repeat the calculations for segmenting the initial data by period T_1 (i.e., by the rotation period of the drive shaft ($z_1/z_2 M$) for a specific point B on the static surface of the drive wheel (Fig. 1)), we obtain the following averaging formula:

$$\frac{1}{n_1} \sum_{j=1}^{n_1} \Delta\theta \left(k_B + (j - 1) \frac{z_1}{z_2} M \right) \quad (10)$$

where k_B is the kinematic error count corresponding to the position of point B within the first period T_1 ($k_B = 1 \dots (z_1/z_2 M)$). An expression similar to (6) is also valid for this case, but in this form

$$\frac{1}{n_1} \sum \theta_1(r_1) = \Delta\theta(B) \quad (11)$$

$$\frac{1}{n_1} \sum \theta_2(r_1) \approx 0 \quad (12)$$

$$\begin{aligned} \Delta\theta_1(B) &= \Delta\theta(k_B) \\ &\approx \frac{1}{n_1} \sum_{i=1}^{n_1} \left(k_B \right. \\ &\quad \left. + (j - 1) \frac{z_1}{z_2} M \right) \end{aligned} \quad (13)$$

Equations (9) and (13) allow us to decompose the errors of the driving and driven wheels at each kinematic error recording point ($1 \dots M$) [6][7]:

$$\Delta\theta(k) \approx \Delta\theta(k_A = k) + \Delta\theta(k_B = k) \quad (14)$$

Using (14), it is possible to convert from angular to linear units and thus model the influence of individual gear parameters on its kinematic error. Equation (14) allows for the analysis of the influence of gear mounting on their kinematic error. From the diagram in Fig. 1, it is evident that if, for two gears with $z_1 \neq z_2$, the greatest common divisor is $z > 1$ (i.e., z_1 and z_2 are not prime numbers), then contact at point A occurs only with the fixed points of the driving gear. Therefore, by “rearranging” the driving gear z_2 times, each time shifting it by 1 gear tooth — which corresponds to a phase shift of the kinematic error by a factor of M/z_2 — it is possible to find a position where the kinematic error will have a nominal value, i.e., to minimize the function

$$\sum_i \sum_j |\Delta\theta_{2j}(i, j)| \rightarrow \min \quad (15)$$

The same objective can be achieved by changing the distances between the wheel centres. The use of (14) eliminates the need for physical experiments to determine the optimal wheel mounting and, based on the synthesis of the kinematic error, immediately determines the optimal contact teeth of the pair and/or the distance between the centres.

The above considerations can be extended to the case of a multi-stage transmission. An example is a two-stage transmission (Fig. 2), for which the following relationships hold:

$$\Delta\theta_{22}^{\Sigma}(i) = \Delta\theta'_{22}(i) + \Delta\theta'_{21}(i) + \Delta\theta'_{12}(i) + \Delta\theta'_{11}(i) \quad (16)$$

where $\Delta\theta_{22}^{\Sigma}(i)$ is the kinematic error of the driven shaft; $\Delta\theta'_{ij}(i)$ are the components of the kinematic error of the driven shaft corresponding to the influence of the intermediate gear ij .

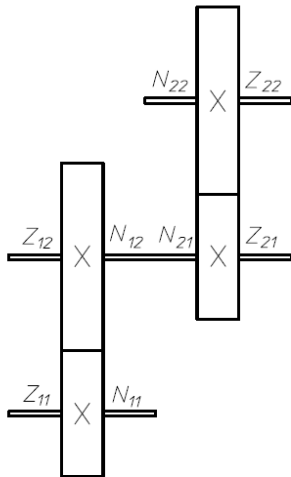


Fig. 2. Diagram of a two-stage transmission

By analogy with (9) and (13), it can be shown that

$$\Delta\theta'_{22}(i) = \frac{1}{n_{22}} \sum_{k=0}^{n_{22}-1} \Delta\theta_{22}^{\Sigma}(i + kM) \quad (17)$$

$$\Delta\theta_{21}^{\Sigma}(i) = \Delta\theta'_{21}(i) + \Delta\theta'_{12}(i) + \Delta\theta'_{11}(i) = \Delta\theta_{22}^{\Sigma}(i) - \Delta\theta'_{22}(i) \quad (18)$$

$$\Delta\theta'_{21}(i) = \frac{1}{n_{21}} \sum_{k=0}^{n_{21}-1} \Delta\theta_{21}^{\Sigma}\left(i + k \frac{n_{22}}{n_{21}} M\right) \quad (19)$$

$$\Delta\theta_{12}^{\Sigma}(i) = \Delta\theta'_{12}(i) + \Delta\theta'_{11}(i) = \Delta\theta_{21}^{\Sigma}(i) - \Delta\theta'_{21}(i) \quad (20)$$

$$\Delta\theta'_{12}(i) = \frac{1}{n_{12}} \sum_{k=0}^{n_{12}-1} \Delta\theta_{12}^{\Sigma}\left(i + k \frac{n_{22}}{n_{12}} M\right) \quad (21)$$

$$\theta_{11}^{\Sigma}(i) = \Delta\theta_{12}^{\Sigma}(i) - \Delta\theta'_{12}(i) = \Delta\theta'_{11}(i) \quad (22)$$

If it is necessary to reduce the kinematic error of the ij element to its pitch diameter, i.e., to $\Delta\theta_{ij}$, the transmission ratio between the ij component and the end link must be taken into account according to the formula:

$$\Delta\theta_{ij}^{\Sigma}(k) = \Delta\theta_{ij}(k) U_i \quad (23)$$

from which it follows that

$$\Delta\theta_{22}(k) = \Delta\theta'_{22}(k) \quad (24)$$

$$\Delta\theta_{21}(k) = \Delta\theta'_{21}(k) \cdot U_2 \quad (25)$$

$$\Delta\theta_{12}(k) = \Delta\theta'_{12}(k) \cdot U_2 \quad (26)$$

$$\Delta\theta_{11}(k) = \Delta\theta'_{11}(k) \cdot U_1 U_2 \quad (27)$$

Unfortunately, these formulas can be used in practice only if the $\Delta\theta_{22}^{\Sigma}$ measurements are performed using a sufficiently accurate angular displacement transducer and the following condition is met:

$$\Delta\theta_{ij}^{\Sigma}(k) > \Delta\omega \quad (28)$$

where $\Delta\omega$ is the absolute error of the transducer [8].

III. CONCLUSION

This article presents a theoretically grounded methodology for analyzing and decomposing the components of kinematic error in gear trains by applying the synchronous accumulation procedure. Based on the conducted research and the derived mathematical relationships, the following conclusions can be drawn:

- The proposed method allows for precise segmentation of the initial data and identification of the individual contribution of each separate component (driving and driven) to the total kinematic error. This eliminates the need for complex physical experiments to optimize the assembly.
- By mathematically modeling the phase shift of the error (through “rearrangement” of the teeth or changing the center distance), conditions are created to achieve minimum values of the kinematic error as early as the design and assembly stages.
- It has been established that the method is applicable with high accuracy for single-stage and two-stage mechanisms. For multi-stage transmissions (three or more stages), the accuracy of the calculations progressively decreases, which limits the practical application of the method to only the last one or two stages of the transmission.
- To ensure reliable results, it is critical to use high-precision angular displacement transducers (with a minimum of 2,500 counts per revolution),

whose inherent absolute error is smaller than the kinematic error of the components under investigation.

In conclusion, the described approach represents a reliable tool for the precise control and synthesis of kinematic pairs, ensuring high transmission accuracy while adhering to the defined design constraints.

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Optimization of Statistical Analysis for Gear Inspection

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Abstract— This paper presents a method for evaluating the machining accuracy and process stability of the gear cutting and gear hobbing of cylindrical gears. Through statistical analysis and the use of mathematical evaluation criteria, the stability of the machining process has been established. This makes it possible to determine the optimal setup parameters and predict the maximum number of parts that can be produced with the initial setup of the machining system.

Keywords— *manufacturing accuracy, process stability, statistical analysis.*

I. INTRODUCTION

The manufacture of gears by gear cutting and gear hobbing is widespread in mechanical engineering. To assess the process accuracy, it is advisable to monitor the length of the common normal W_k and the tooth thickness along the constant chord S_c . The preferred parameter is the length of the common normal, which reflects both the kinematic accuracy and the lateral clearance in the gear meshing.

To ensure the reliability of the inspection results, the accuracy of the machine, equipment, and workpieces must be within the specified limits for the corresponding accuracy class of the gear wheels being manufactured.

Through statistical analysis, the type of manufacturing process is identified, the target operating value is determined, and the control limits within which the mean value of the control parameter may vary are established; the progress of the technological process is monitored, and the moment is determined at which the technological system should be readjusted or the tool should be changed [1], [2] [3].

II. MATERIALS AND METHODS

The input data for the analysis is obtained by inspecting all parts produced during a single setup of the machining system. This is necessary because the tool life, expressed as the number of parts produced during a single setup, is short. The inspection of the parts is performed in a sequence corresponding to the order in which they were manufactured.

To obtain a visual representation of the course of the manufacturing process, a scatter plot is constructed based on the inspection data. In cases where it has the form shown in Fig. 1, the hypothesis can be made that the process is statistically stable, and when it has the form shown in Fig. 2, that the process is technologically stable.

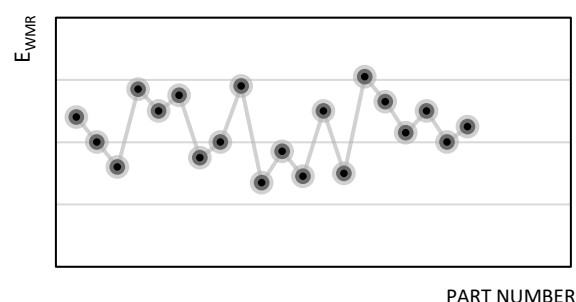


Fig. 1. A scatter plot illustrating a statistically stable process.

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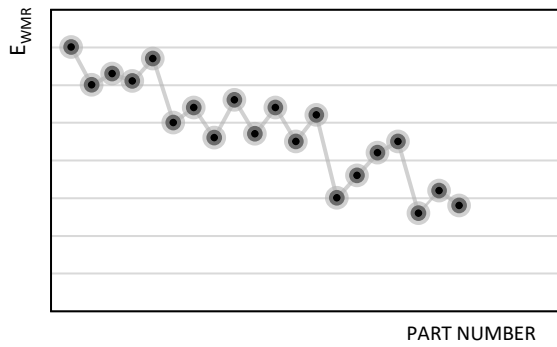


Fig. 2. A scatter plot illustrating a technologically unstable process.

In both cases, it is advisable to demonstrate the stability of the process using a uniform methodology. To simplify the analysis, the details are grouped into small samples consisting of 3 to 7 gear wheels, which are processed sequentially. The sample size is determined by the following condition:

$$3 \leq n \leq N/4 \quad (1)$$

where n is the number of gears in the sample;

N – the total number of gears produced in a single setup.

When $N < 12$, the specified method cannot be applied.

For each sample, the following statistical estimates are calculated:

E_{Wms} – mean value of the deviation from the nominal length of the general normal.

$$E_{Wms} = \frac{\sum_{i=1}^n E_{Wmri}}{n} \quad (2)$$

$$S^2 = \frac{\sum_{i=1}^n (E_{Wmri} - E_{Wms})^2}{n - 1} \quad (3)$$

If the hypothesis of statistical stability of a technological process is being tested, the homogeneity of variances and the stability of the mean values for the conditional samples are verified. For this purpose, the Cochran criterion $G_{max} < G_\alpha$, K_G and the Student's criterion $t < t_\alpha$, K_t . The tabulated values of the criteria G_α , K_G , and t_α , K_t are determined based on the accepted significance level and the degrees of freedom: $K_G = n - 1$ and $K_t = 2(n - 1)$. The values of the criteria for the manufactured parts are determined by the following expressions [4]:

$$G_{max} = \frac{S_{max}^2}{\sum_{j=1}^m S_j^2} \quad (4)$$

$$t = \sqrt{n} \frac{|E_{Wmr1} - E_{Wmr2}|}{\sqrt{S_1^2 + S_2^2}} \quad (5)$$

where m is the total number of conditional samples;

S_{max}^2 is the maximum variance across the set of samples under consideration.

The G_{max} criterion is determined for the entire set of samples, while the t criterion is applied sequentially to pairs of samples.

If the criteria of William Cochran and Student are satisfied for more than 90% of the samples, the process is considered statistically stable. In this case, the characteristics of the theoretical accuracy diagram are determined:

$\bar{E}_{Wmr}$ - Average value

$$\bar{E}_{Wmr} = \frac{\sum_{j=1}^{m-p} \bar{E}_{Wmri}}{m - p} \quad (6)$$

$\bar{s}^2$ - average variance

$$\bar{s}^2 = \frac{\sum_{j=1}^{n(m-p)} (\bar{E}_{Wmri} - \bar{E}_{Wmr})^2}{n(m - p) - 1} \quad (7)$$

ω - instantaneous scattering field

$$\omega = 2 \cdot K_w \cdot \bar{s} \quad (8)$$

Where p is the number of samples excluded from the analysis because they did not meet the Cochran or Student criteria

K_w - a coefficient that determines the practical limits of scattering.

If the hypothesis of technological stability of the process is accepted, the homogeneity of the variances of the conditional samples is tested using Cochran's criterion. Next, the linear regression equation for the mean value of the deviation from the length of the grand normal is determined, and its objectivity is tested.

The regression equation is of the form:

$$\bar{E}_{OWmrj} = a + b \cdot \tau_j \quad (9)$$

Where $\bar{E}_{OWmrj}$ is the mean value of the j th sample, determined by the regression equation;

τ_j – the sample number;

a and b – the statistical coefficients

$$a = \frac{\sum_{j=1}^m \bar{E}_{Wmrj}}{m} - b\tau \quad (10)$$

$$b = \frac{\sum_{j=1}^m \bar{E}_{Wmrj}(\tau_j - \bar{\tau})}{\sum_{j=1}^m \tau_j} \quad (11)$$

$$\bar{\tau} = \frac{\sum_{j=1}^m \tau_j}{m} \quad (12)$$

The validity of the regression equation is tested using Fisher's criterion:

$$F = \frac{S_2^2}{S_1^2} \leq F_{\alpha_{0,K_1,K_2}} \quad (13)$$

Where: F_{α_0} , K_1 , K_2 is the table value of the test statistic at a significance level of α and degrees of freedom $K_1 = m - 2$ and $K_2 = m(n - 1)$

$$s_2^2 = \frac{n \cdot \sum_{j=1}^m (\bar{E}_{Wmrj} - \bar{E}_{OWmrj})^2}{m - 2} \quad (14)$$

$$s_1^2 = \frac{\sum_{j=1}^m s_j^2}{m} \quad (15)$$

If the homogeneity of the variances is proven and the regression equation is adequate, the process is considered technologically stable. Its parameters are:

- The regression equation for $\bar{E}_{OWmrj}$

- The mean variance

$$\bar{s}^2 = \frac{\sum_{j=1}^m \sum_{i=1}^n (E_{Wmrij} - \bar{E}_{OWmrj})^2}{n(m - p) - 1} \quad (16)$$

- The instantaneous scattering field

$$\omega = 2 \cdot K_W \cdot \bar{s} \quad (17)$$

Once the stability of the process has been demonstrated, its accuracy and calibration can be analysed.

The accuracy coefficient K_T is used to evaluate accuracy.

$$K_T = \frac{W_\Sigma}{T_w} \quad (18)$$

where ω_Σ is the total scattering field resulting from the combined effect of systematic and random factors;

T_w – the tolerance for the length of the common normal.

For a statistically stable process:

$$\omega_\Sigma = \omega \quad (19)$$

For technologically stable processes:

$$\omega_\Sigma = \sqrt{\omega^2 + 3b^2 \left(\frac{N}{n} - 1 \right)^2} \quad (20)$$

The accuracy coefficient must be within the following range:

$$0,75 \leq K_T \leq 0,85 \quad (21)$$

When $K_T > 0,85$, the process does not meet the accuracy requirements.

When $K_T < 0,75$, there is an excess margin of accuracy. In this case, cutting conditions can be intensified, or, for technologically stable processes, more parts can be machined with a single dimensional setting. Their number N_{max} will be:

$$N_{max} = 1 + n \sqrt{\frac{(0,85 \cdot T_{wm})^2 - \omega^2}{3b^2}} \quad (22)$$

The tuning of the technological process is evaluated using the tuning coefficient K_H :

$$K_H = \frac{\varepsilon}{T_{Wm}} \quad (23)$$

Where: ε is the tuning deviation.

For statistically stable processes:

$$\varepsilon = \left| \bar{E}_{Wmc} - \frac{E_{Wms} + E_{Wmi}}{2} \right| \quad (24)$$

And in the case of technologically stable processes:

$$\varepsilon = |\bar{E}_{OWmr1} - E_{Wadj.}| \quad (25)$$

Here, E_{Wms} and E_{Wmi} are the tolerance limits for the length of the common normal.

$E_{Wadj.}$ – the set value for the deviation from the length of the common normal.

When adjusting the length of the common normal during the manufacturing process:

$$E_{Wadj.} = E_{Wmi} + \omega_{mes} + K_W \cdot \bar{s} \quad (26)$$

and with a downward trend

$$E_{Wadj.} = E_{Wms} - \omega_{mes} - K_W \cdot \bar{s} \quad (27)$$

Where: ω_{mes} is the measurement error in gear inspection.

The manufacturing system is well-adjusted if $K_H \leq 0,1$

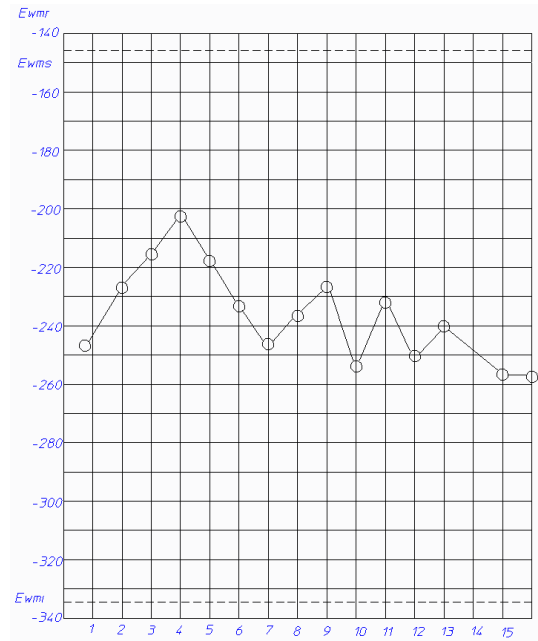


Fig. 3. A scatter plot based on an analysis of the gear-cutting process for a cylindrical gear with straight teeth

The applicability of the described methodology has been verified under production conditions. As an example, one can cite the results of an analysis of the manufacturing process for gear cutting of a cylindrical gear with straight teeth. A scatter plot was constructed based on the inspection results, shown in Fig. 3. The nature of the scatter plot provides grounds for hypothesizing the technological stability of the process. The machined parts were divided into 5 conditional samples with a size of $n = 3$ parts. The mean values $\bar{E}_{W_{mrj}}$ and variances for all samples were calculated. The Cochran criterion has a value of $G_{max} = 0.2935$. The tabulated value is $G_{0.05; 3; 10} = 3.41$. Since $G_{max} < G_{\alpha}$, K_G , the variances are homogeneous [5]. The regression equation is of the form:

$$\bar{E}_{OWmrj} = 214,5 - 7\tau_j \quad (28)$$

In this case, $s_1^2 = 234,07$ and $s_2^2 = 191,32$. The Fisher's F-statistic is $F = 1.2234$. Its critical value is $F_{0.05; 3; 10} = 3.41$. Since $F < F_{\alpha, K1, K2}$, the regression equation is adequate.

The checks performed show that the process is technologically stable. Its mean variance is $S^2 = 159.87$. The dispersion range, with a 99.73% probability that the part dimensions will fall within the specified limits and with $N = 15$ measured parts, will be: $\omega = 2.4,747 \cdot \sqrt{159,87} = 120\mu m$.

The total scattering cross section for the process with $N = 15$ particles, $\omega = 120\mu m$, $b = -7$, and $n = 3$ is:

$$\omega_{\Sigma} = 129,43 \mu m \quad (29)$$

The adjustment coefficient will be:

$$K_H = \frac{129,43}{190} = 0,68 \quad (30)$$

Since the process has a margin of accuracy, it is possible to fine-tune or replace the tool after machining a larger number of parts. This number is $N_{max} = 27$ parts.

The adjustment value of the deviation from the length of the common normal at $\omega_{mes.} = 19 \mu m$ is $E_{adj.} = -$

$224 \mu m$. The theoretical value of the deviation for the first sample is obtained from the regression equation $E_{OWmrj} = -221,5\mu m$, and the adjustment offset is $\varepsilon = 2.5 \mu m$.

The adjustment coefficient is $K_H = 2.5/190 = 0.013$, which indicates very good process adjustment.

III. CONCLUSION

A methodology for standardized statistical analysis that enables precise control over manufacturing accuracy in the production of gear wheels. By applying mathematical stability criteria, the optimal time for machine readjustment or tool replacement is determined, thereby preventing the occurrence of defects. The main benefit of the analysis is the ability to objectively and thoroughly assess precision, which allows for an increase in the number of parts processed per setup. This leads to more efficient use of resources and optimization of production modes without compromising the quality of the gear meshing. The implementation of this approach ensures high economic efficiency and stability of technological processes in mechanical engineering.

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Study of the Quality Indicators of the Surfaces of Gear Blankets After Combined Processing by Cutting and Surface Plastic Deformation

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Abstract— The continuous increase in the requirements for the quality of surface treatment of elements of mechanical engineering products from gears requires the improvement of processing and control methods. The main influence on the smoothness and noiselessness of power transmissions is exerted by the correct choice of the method for processing the base holes of the gears. The currently known methods for final processing of holes such as: countersinking, reaming, grinding, etc., do not guarantee high wear resistance, and hence, when assembling them to the journal of the shafts transmitting torque, they do not provide the prescribed kinematic accuracy in the gears. This requires conducting research on combined processing of holes in gear blanks, as well as obtaining the corresponding processing modes and their influence on roughness and microhardness.

Keywords— kinematic accuracy, machining quality, surface machining, superficial plastic deformation (SPD).

I. INTRODUCTION

A significant increase in the productivity and economy of mechanical processing during boring can be achieved if

the errors caused by the dissipation of elastic deformations of the technological system are reduced. In existing systems for controlling elastic displacements during boring, accuracy is increased by stabilizing the deformations of the support, which to the greatest extent determine the size and nature of the change in the total deformation of the system. To determine the limiting element of the system during boring, which significantly affects the deformation, it is necessary to carry out studies to determine the stability of the technological system [1] – [3].

Here, a combined approach is applied, based on the synthesis of results from real and numerical experiments. In practice, the same approach has been applied repeatedly when studying the process of surface plastic deformation (SPD).

The change in surface microhardness, as a result of mechanical impact, is due to the strengthening of the material that occurs after its drawing [4]. Given the fact that even for a one-dimensional stressed state, the deformed state is three-dimensional, the elongation is characterized by equivalent plastic deformation, i.e. there is a direct correlation between the equivalent plastic deformation and the microhardness [5], [6].

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Experimentally, based on a planned experiment, the microhardness of machined internal cylindrical surfaces is measured. The same experimental plan is used. In this way, qualitative information is obtained about the machined surface from the point of view of „microhardness of the surface layer“ [7].

Numerical modeling was performed to determine the equivalent plastic deformation of the surface layer and the depth of the reinforced layer – the layer with equivalent plastic deformation. In this way, quantitative information is obtained about the machined surface from the point of view of, respectively, „microhardness of the surface“ and „depth of the reinforced layer“ [8].

II. MATERIALS AND METHODS

Experimental setup

Technical equipment of the experiment

The figures below show the implementation, the tool used in the combined machining of holes in hydraulic cylinders.

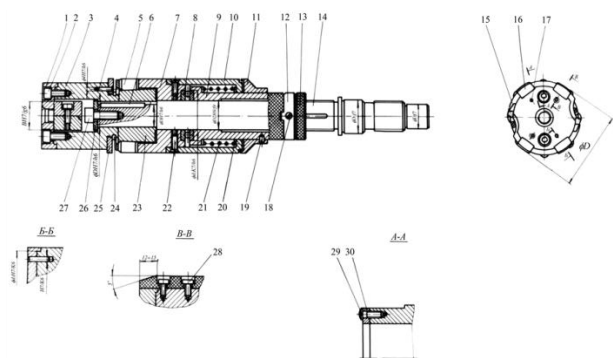


Fig. 1. Combined tool for machining a hole.

To study the roughness of the workpiece, the change in the inner and outer diameter obtained after machining by cutting and superficial plastic deformation (SPD), the based and established workpiece is machined with a pre-set tool. After machining the test specimens, we conduct measurements in three sections, equally spaced along the length (Fig. 2).

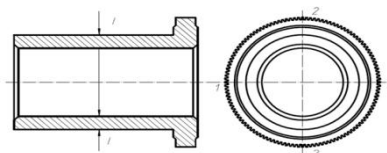


Fig. 2. Scheme for conducting control measurements.

A planned experiment was conducted to study the influence of technological parameters on the quality of the processed surfaces. The roughness measurements were performed with a Mitutoyo Surftest device, using three forming surfaces and an average value was determined [9].

The following factors were studied:

A total of 27 experiments were conducted, which corresponds to an optimal compositional plan.

Planning of experiments experimental results

Essence of planning

The purpose of planning the studied process is to solve the following main tasks [10], [11]:

- Selection of an objective function.
- Selection of the factors determining the nature of the studied process.
- Selection of the type and number of functions of the input factors that determine the actual structure of the mathematical model.



Fig. 3. Mitutoyo Surftest – 4.

Selection of an objective function

The following objective functions are selected: Y_i $i = 1, 2$:

- Obtained roughness R_a ;
- Microhardness of the surface layer HV .

Selection of factors

The following factors influencing the roughness in the spherical mandrel process are the subject of research:

- Tightness - i , [mm];
- Machine spindle speed - n_e [min^{-1}];
- Tool feed - f [mm/min];
- Initial roughness - R_a^{init} ;
- Number of transitions - n ;
- Physical and mechanical properties of the material;
- Lubrication between the tool and the workpiece.

Physico-mechanical properties of the material and the lubricant between the tool and the workpiece will not be taken into account. The main reason for this is the fact that the research is carried out on only one type of material: Steel E410. The lubricant used was selected based on research conducted during the superficial plastic deformation (SPD) research process [12].

A planned experiment was conducted. The height of the roughness was measured by two forming, and an arithmetic mean value was taken. Multifactorial variance

analysis was performed sequentially for the purpose of qualitative assessment of the influence of the factors and regression analysis for the purpose of the obtained experimental results [13].

Microhardness study

The planned experiment was carried out with 5 factors, and the levels of variation are presented in Table 1.

TABLE 1 GOVERNING FACTORS AND THE LEVELS OF VARIATION

Governing factors		Coding of factor levels		
		-1	0	1
Natural	Coded	Natural		
Tightness - i , [mm]	x_1	0,10	0,22	0,32
Submission - f [mm/min]	x_2	2000	2500	2800
Machine spindle speed - n , [min ⁻¹]	x_3	800	1100	1400
Number of transitions - n , [°p]	x_4	1	2	3
Initial roughness - R_a^{init} , [µm]	x_5	1	3	5

Table 2 shows the experimental design. Since the factors are 5, the number of experimental points is 27. An optimal compositional plan with one central point was synthesized with QStatLab.

TABLE 2 EXPERIMENTAL DESIGN

N°	x_1	x_2	x_3	x_4	x_5	R_a^{init} , µm	$R_{a,measured}^{init}$, µm	$\{R_{a,u}\}$
1	-1	-1	-1	-1	-1	1	1,24	0,36
2	-1	-1	1	-1	1	5	4,73	1,34
3	1	-1	1	1	-1	1	1,27	0,22
4	1	-1	-1	1	1	5	5,01	0,41
5	-1	1	1	1	1	5	5,04	2,32
6	-1	1	-1	1	-1	1	1,36	0,67
7	1	1	-1	-1	1	5	5,30	1,40
8	1	1	1	-1	-1	1	1,38	0,55
9	-1	-1	-1	1	1	5	5,44	1,10
10	-1	-1	1	1	-1	1	1,22	0,49
11	1	-1	1	-1	1	5	5,17	1,01
12	1	-1	-1	-1	-1	1	1,21	0,57
13	-1	1	1	-1	-1	1	1,18	0,53
14	-1	1	-1	-1	1	5	5,14	3,12
15	1	1	-1	1	-1	1	1,42	0,62
16	1	1	1	1	1	5	5,04	1,48
17	0	0	0	0	0	3	3,01	0,81
18	-1	0	0	0	0	3	2,94	1,68
19	1	0	0	0	0	3	3,16	0,79
20	0	-1	0	0	0	3	3,25	0,63
21	0	1	0	0	0	3	3,54	1,02
22	0	0	-1	0	0	3	3,22	0,84
23	0	0	1	0	0	3	3,36	0,77
24	0	0	0	-1	0	3	3,39	1,20
25	0	0	0	1	0	3	3,01	0,76

26	0	0	0	0	-1	1	1,18	0,48
27	0	0	0	0	1	5	5,23	1,29

Microhardness was measured with a Leica VMHT Auto instrument using the Vickers method.

The change in microhardness is determined by the ratio:

$$K_H = \frac{HV_{after}}{HV_{before}} \quad (1)$$

The increase in microhardness is due to strengthening of the surface layer due to plastic deformation.

III. RESULTS AND DISCUSSION

The analysis of the regression model was performed with QStatLab in two aspects: by sections of the hypersurface of the modeled roughness using hyperplanes and by scanning the resulting linear regression model [14].

Given the fact that the design is of the second order (optimal compositional), the regression model was chosen to be a second order polynomial, whose coefficients should not be more than 27 in order to perform a correct statistical analysis [15]:

$$Y_{Ra}(x_1, \dots, x_4) = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} x_i x_j + \sum_{i=1}^k b_{ii} x_i^2 \quad (2)$$

Where:

Y_{Ra} the objective function of the resulting roughness R_a with arguments the encoded factors.

The coefficient estimates $b_0, b_1, \dots, b_{44}, \dots$ are obtained from the matrix products:

$$\{b\} = ([F]^T [F])^{-1} [F]^T \{R_{a,u}\} \quad (3)$$

$$Y_{Ra} = 0.874 - 0.372x_1 + 0.323x_2 - 0.023x_3 - 0.179x_4 + 0.571x_5 + 0.519x_1x_1 - 0.336x_2x_2 - 0.095x_1x_2 + 0.074x_1x_3 + 0.008x_1x_4 - 0.259x_1x_5 \quad (4)$$

Testing the hypothesis of significance of the coefficients in the regression model

To test the hypothesis of significance of the uncorrelated coefficients, the Student distribution is used.

The magnitude is calculated $\hat{t}_k$.

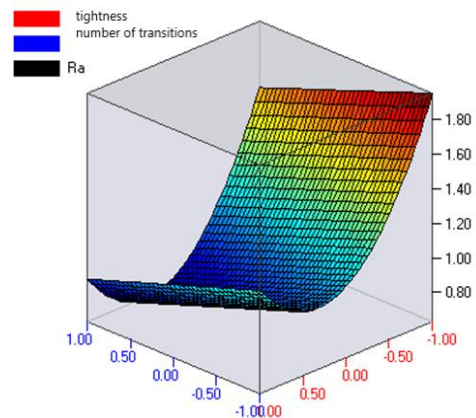


Fig. 4. Tightness, Number of transitions, R_a .

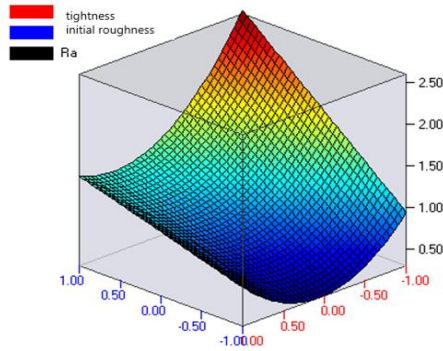


Fig. 5. Tightness, Initial roughness, R_a .

$$\hat{t}k = \frac{|b_k|}{\sqrt{c_{kk}s_{\varepsilon}^2}} \quad (5)$$

Since the regression analysis was performed with QStatLab in iterative mode, the significant coefficients were determined for each iteration using the above methodology.

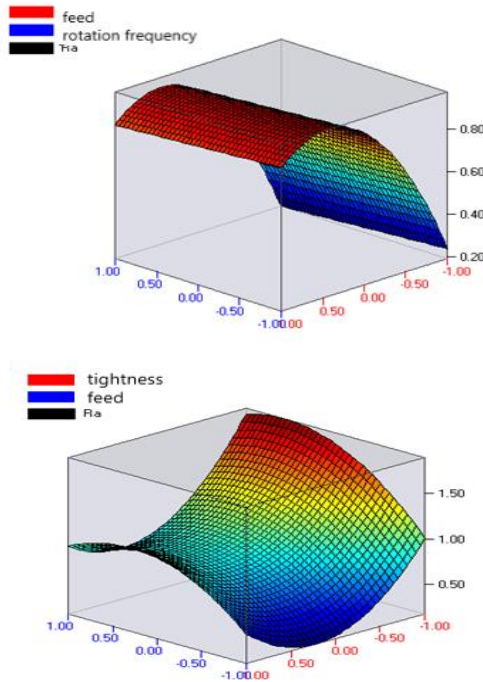


Fig. 6. Three-dimensional graphs of dependence between processing factors.

The graphical visualization of the roughness model (Fig. 5) confirms the conclusions made about the influence, significance and levels of factors on roughness. Small feeds, medium levels of tightness, and lower initial roughness lead to low obtained roughness. A detailed scan of the resulting linear regression model shows that there are no areas with negative roughness values. Using the genetic algorithm in QStatLab, the minimum of the roughness function in the full factor space was found.

Analysis of the roughness reduction coefficient

In order to study the influence of individual factors in the processing of the obtained results, a roughness reduction coefficient is introduced K_{red}^{Ra} .

The reduction factor is determined by the ratio between the initial and the roughness obtained after processing.

$$K_{red}^{Ra} = \frac{R_{a,init}}{R_{a,n}} \quad (6)$$

The results for the roughness reduction factor are shown in Table 3.

A graphical comparison between the reduction factor and the initial roughness was also performed.

A graphical comparison between the reduction coefficient K_{red}^{Ra} and the initial roughness $R_{a,n}$ for each of the controlling factors has also been made. The values in the graphs are averages.

N_0	1	2	3	4	5	6	7	8	9
$R_{a,measured}^{init}$ μm	2,24	4,73	1,27	5,01	5,04	2,56	5,30	1,38	5,44
$\{R_{a,u}\}$	0,36	1,34	0,22	0,41	2,32	0,67	1,40	0,55	1,10
K_{red}^{Ra}	6,22	3,52	5,77	12,2	2,17	4,00	3,7	2,5	4,9
N_0	10	11	12	13	14	15	16	17	18
$R_{a,measured}^{init}$ μm	2,22	5,17	1,21	1,18	5,14	1,42	5,04	3,01	2,94
$\{R_{a,u}\}$	0,49	1,01	0,57	0,53	1,12	0,62	1,48	0,81	1,68
K_{red}^{Ra}	4,53	5,1	2,1	2,2	4,58	2,3	3,4	3,7	1,8
N_0	19	20	21	22	23	24	25	26	27
$R_{a,measured}^{init}$ μm	3,16	3,25	3,54	3,22	3,36	3,39	3,01	1,18	5,23
$\{R_{a,u}\}$	0,79	0,63	1,02	0,84	0,77	1,20	0,76	0,48	0,8
K_{red}^{Ra}	4,0	5,2	3,5	3,8	4,40	2,8	3,9	2,5	6,53

Experimental results regarding the influence of tightness on the resulting roughness are illustrated in Fig. 7.

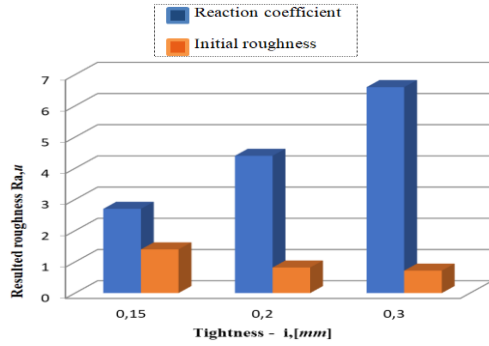


Fig. 7. Graph of K_{red}^{Ra} and $R_{a,u}$ versus factor values Tightness, i.

From the above graph it can be seen that the highest values of the reduction factor K_{red}^{Ra} , combined with the lowest values of roughness heights, are observed at a tightness of 0.32 mm. Therefore, we can define the tightness factor as significant in the formation of roughness on the surface layer.

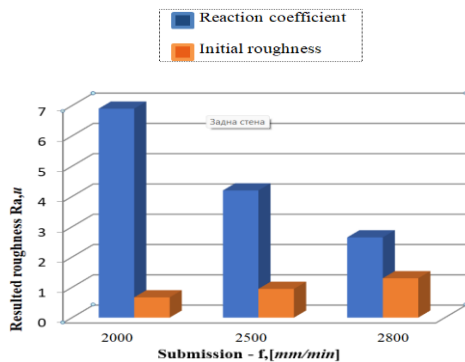


Fig. 8. Graph of K_{red}^{Ra} and $R_{a,u}$ versus factor values Submission, f.

Optimal results are observed at a feed rate of 2000 [mm/min]. The reduction factor K_{red}^{Ra} increases significantly at lower feed rates.

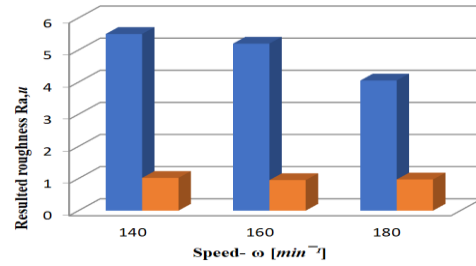
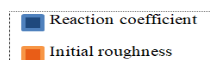


Fig. 9. Graph of K_{red}^{Ra} and $R_{a,u}$ versus factor values Speed, ω.

It is clearly seen from Figure 9 that the values of the initial roughness $R_{a,u}$ are close. Although the highest values of $R_{a,u}$ are observed at a rotation frequency of 800 min⁻¹, the lowest values of K_{red}^{Ra} are observed at a value of 1400 min⁻¹. The rotation frequency factor can be defined as a factor with low influence.

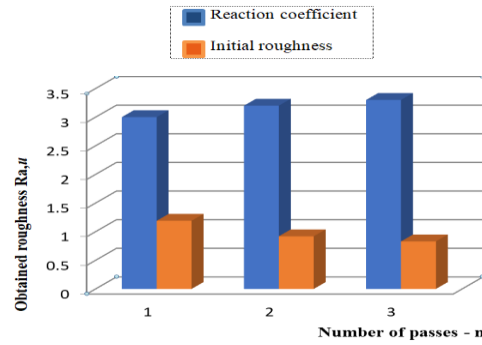


Fig. 10. Graph of K_{red}^{Ra} and $R_{a,u}$ versus factor values Number of passes.

As the number of transitions increases, K_{red}^{Ra} increases with low values.

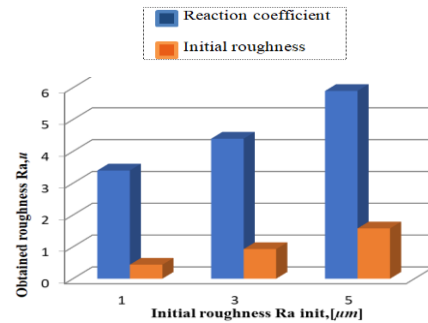


Fig. 11. Graph of K_{red}^{Ra} and $R_{a,u}$ versus factor values R_a^{init} .

It is known that the quality of machining is largely determined by the previous operation. The initial roughness is an essential parameter in determining the output roughness. Low initial roughness leads to low values of both $R_{a,u}$ and K_{red}^{Ra} .

IV. CONCLUSIONS

The experimental results show that maximum values of K_{red}^{Ra} are obtained at a tightness of 0.32 mm. This gives us reason to believe that tightness is of great importance for the combined hole machining process.

Small feeds lead to improved roughness indicators. Optimal roughness is observed at a feed of $f = 10$ [mm/min].

The machining speed is an insignificant factor for the obtained roughness of the machined surfaces.

The initial roughness R_a^{init} a factor of decisive importance for the obtained roughness. This is explained by the so-called technological heredity. The higher R_a^{init} , the lower $k_{\text{red}}^{R_a}$.

The number of passes does not significantly affect $R_{a,u}$.

Regression analysis shows that:

- increasing tightness leads to an increase in microhardness;
- small feeds give better results;
- initial roughness has a significant impact;

Graphical analysis confirms that optimal values are achieved at:

- medium tightness values;
- low feed;
- low initial roughness.

The adequacy of the regression model was checked using the Fisher test. The results show that the model is adequate and can be used to predict the results.

As a result of the conducted research, the following statements can be defined:

1. Combined processing by cutting and SPD significantly improves the quality of surfaces.
2. The most significant factors are tightness, feed and initial roughness.
3. The microhardness of the surface layer increases due to plastic deformation.
4. The developed regression models allow optimization of the technological process.
5. The method is applicable in the production of gears with high requirements for accuracy and wear resistance.

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Computer Vision Capabilities for Orthophotogrammetry and 3d Terrain Modeling

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Abstract— Orthophotogrammetry is a specialized branch of photogrammetry aimed at creating accurate, scaled orthophotographs (or orthomosaics). This paper investigates the theoretical and practical aspects of computer vision algorithms in the creation of three-dimensional models of objects and terrains in order to generate reliable reconstruction. The article discusses the capabilities of the WebODM (Web OpenDroneMap) product for application in field orthophotogrammetry and the creation of high-precision 3D models. The workflow for creating a three-dimensional model from unmanned aerial vehicle (UAV) imagery and the creation of digital elevation models (DEM/DSM), dense point clouds and textured three-dimensional models is given. A quantitative accuracy assessment was performed using the root mean square error (RMSE) of the final geospatial products, to validate their suitable relative geometric accuracy in monitoring and safety in the urban environment.

Keywords— 3D modelling, digital terrain model, orthophotogrammetry, UAV, WebODM.

I. INTRODUCTION

The rapid development of unmanned aerial systems (UAS) technologies and sensor technology over the past decade has led to a real revolution in the collection and processing of geospatial data. At the centre of this transformation is orthophotogrammetry – a specialized branch of photogrammetry that allows the transformation of perspective images into orthogonal projections of a single scale, eliminating distortions caused by terrain relief and lens aberrations [1]-[2].

Modern photogrammetry no longer relies solely on classical mathematical models, but integrates powerful Computer Vision algorithms. Processing the resulting data (geospatial imagery) increasingly relies on intelligent classification and machine learning methods that allow for high accuracy in the digital assessment of objects [3]-[4]. A key element in this process is the Structure from Motion (SfM) method, which allows automated extraction of three-dimensional information from a series of overlapping 2D images without requiring prior knowledge of camera positions [5]. Preliminary validation of our model showed deviations below 5 cm in selected control areas. This indicates acceptable precision for terrain visualization and monitoring applications.

Despite the availability of numerous commercial software solutions, open-source platforms occupy an increasingly important place in research due to their transparency and flexibility. WebODM (Web OpenDroneMap) has established itself as a leading ecosystem for photogrammetric processing based on the powerful OpenDroneMap engine [6]. It offers tools for generating high-precision products such as: digital elevation and surface models (DEM/DSM), dense point clouds (Dense Point Clouds) and textured 3D models and orthophoto maps.

This article aims to explore the theoretical foundations of computer vision in the context of orthophotogrammetry and to demonstrate the practical capabilities of WebODM in terrain modelling. The authors consider the full technological cycle – from flight planning to obtaining final geodetic products, analysing the precision of

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algorithms in relation to the established standards in geodesy [7].

The scientific and practical novelty of this study lies in the formulation and validation of an optimized, low-cost end-to-end workflow for high-precision 3D terrain modeling using consumer-grade hardware and open-source computer vision pipelines. Unlike traditional approaches that rely on pre-programmed nadir photography and expensive RTK-enabled UAVs, this work investigates the efficiency of continuous video acquisition combined with a customized Python-based frame extraction frequency. Furthermore, a comparative analysis within the WebODM environment demonstrates that leveraging the AKAZE feature detection algorithm in a triangular Structure-from-Motion (SfM) configuration yields sub-decimeter spatial accuracy (RMSE=0.104 m) even under challenging topographic variations, such as the urban protected area of Youth Hill (Plovdiv). This approach provides an accessible and reproducible methodology for rapid urban monitoring and ecological safety evaluation without heavy financial or computational overhead.

II. MATERIALS AND METHODS

In this study, a prominent recreational area in Plovdiv, Bulgaria, was selected to generate a 3D terrain model (Fig. 1).

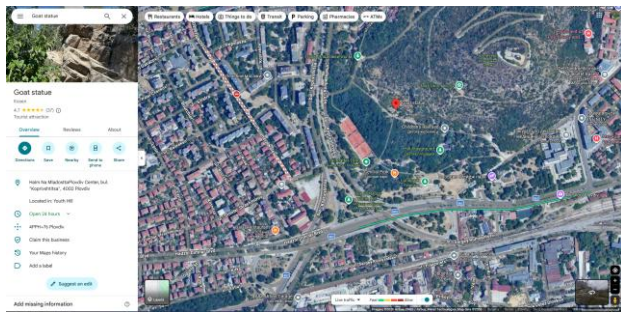


Fig. 1. Location of the terrain.

Youth Hill has been declared a natural landmark and is an extremely interesting object for photogrammetry due to its specific relief, rocky massifs and elevation change (approximately 125 meters above city level) [8]. Its coordinates are Latitude 42.13690 N and Longitude 24.73170 E [9].

It is an ideal place to test DSM (Digital Surface Model) generation algorithms, as it combines dense vegetation at the foot with bare rock structures towards the top.

For shooting in this publication, a DJI mini 3 drone was used [10]. The drone is equipped with a 48 MP camera and a 3-axis mechanical gimbal with Angular Vibration Range: $\pm 0.010^\circ$. The image sensor is 1/1.3-inch CMOS and FOV (Field of View) 82.1° on the lens. It features a wide-angle lens with a 24 mm equivalent focal length, which is comparable to those found on professional drones, making it perfectly suited for the current study.

The flight altitude was maintained at approximately 20 m, with frontal overlap of 80% and side overlap of 70%. Camera settings were fixed to ISO 100, automatic shutter

speed, and 4K video mode at 30 fps. WebODM processing was performed on a system with Intel i7 CPU, 32 GB RAM and NVIDIA T1200 GPU using medium feature-quality settings.

The drone was flown over the terrain from certain points in order to obtain a good overlap of the images. The data acquisition modes included either automated interval shooting (every 3 seconds) or high-resolution video recording.



Fig. 2. General appearance of the terrain.

When automated image capture is utilized, the extracted images from the SD card are directly ready for processing. When shooting a clip, it is necessary to divide it into frames using standard programs such as FFMPEG [11] or generate Python code. In the present study, the authors implemented custom Python code for this purpose. After splitting frames, their visual control is necessary. Numerous repetitive or low-quality frames were obtained; therefore, redundant images were filtered out, and the remaining dataset was organized into a designated folder.

To compile the 3D model of the terrain, the application Web Open Drone Map - WebODM is used [12].

III. RESULTS AND DISCUSSION

As already mentioned, the object of the study was a public recreational area in the city of Plovdiv. The experiment took place on 28 February 2026. The flight window was selected in a time interval with low attendance at the site and in compliance with all regulatory requirements of the European Union Aviation Safety Agency and the General Directorate of the Civil Aviation Administration for the operation of drone class C0, subcategory A1. The operating pilot is certified. An aerial survey of the terrain surrounding the “Goat” tourist attraction was conducted. During the flyby, recordings were made of two clips with a resolution of 4K and a total duration of 12 min and 30 s.

The video clips were processed using custom Python code. More than 800 frames were obtained from it, but subsequent editing reduced to 371 photos with a resolution of 2720x1530 pixels.

Docker is a containerization platform used for the deployment and execution of software applications in isolated environments called containers [13]. These containers include all required dependencies, libraries, and configuration files, ensuring consistent operation across

different systems. In this study, Docker Desktop (Fig. 3) was used to manage and run the containers required for the execution of the WebODM software product.

The WebODM interface was accessed through a web browser, and the folder containing the filtered frames was imported.

The processing modes and algorithms for calculating the 3D model must be configured.

The first configuration parameter is the SfM reconstruction mode. Here there is a choice between incremental, triangular and planar. The former is the default option, offering the highest versatility and robust stability. The triangular mode is better suited for drone imagery and GPS-assisted reconstruction, while Planar is fast and is used for flat scenes such as field areas. For the specific case, the triangular mode is used.

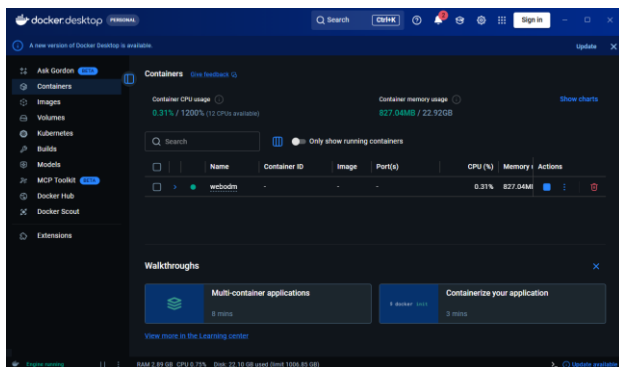


Fig. 3. General View of Docker Desktop.

WebODM allows selection among various output options, including a full 3D model (mesh and texture), a dense point cloud, a digital elevation model (DEM), a standalone orthophotograph, or a 2D map. In this article, the full 3d model has been selected.

Users can also balance processing speed against final model quality by adjusting the feature-quality configuration. It is possible to control the accuracy of the model to make only 2D or to exclude entire parts. For this development, feature-quality medium mode is used.

The product makes it possible to choose between different algorithms to obtain the computer visual model.

The first of these algorithms is Scale-Invariant Feature Transform. It looks for characteristic points (corners, edges), and is slightly affected by illumination, rotation or scaling. It gives a very accurate model and is universal.

Another algorithm based on the previous one is Accelerated KAZE AKAZE. It uses non-linear space and overlays images better. It is faster than the previous mode, but it may occasionally fail to produce an accurate reconstruction or fail to converge. It is usually applied to drone footage or when there is a wide range of shots. This algorithm was selected for the present study.

WebODM also supports the Oriented FAST and Rotated BRIEF (ORB) algorithm. Binary descriptors are

used and it is very fast and does not have a large consumption of resources. The disadvantage is that in complex scenes, objects are lost.

Another improved version of the first algorithm is the Domain-Size Pooling SIFT DSPSIFT. Very good at complex geometry and when working with different image perspectives, but it is computationally intensive.

When processing the model, it is possible to choose an algorithm - Histogram of Oriented Gradients + Hessian Affine HAHOG. Very suitable for shots from highly inclined terrain and is a combination of the others.

Other settings before modelling are mesh settings or control over the complexity of the output model. It is possible to choose between detail, number of polygons, "incomplete" 3D for bridges, cavities, etc. for faster processing. In this development, use-3dmesh = true is chosen.

There are also some automatic features like cropping scenes, removing backgrounds, and more. There is also an option for additional GPS correction.

After configuring the parameters algorithm, surface detector, model quality settings and output type, the modelling process is started.

No parameter adjustments can be made while the reconstruction process is running. Based on the selected parameters, the software recalculates the point cloud and generates the output result. The processing interface is shown in Fig. 4.

The reconstructed 3D model of 'The Goat' statue and its surroundings can be visualized, downloaded or deleted. The model covers an area of 32.43 m² and consists of 20,887,415 points, with a final file size of approximately 740.66 MB. The processing time of the model is 2 hours and 43 minutes. The visualization of the model is given in Fig. 5.



Fig. 4. Processing Output User Interface.

To validate the "high-precision" claim of the generated geospatial products, a rigorous quantitative accuracy assessment was carried out based on WebODM's internal triangulation and structural cross-validation logs (Quality Report). Because a consumer-grade UAV without RTK was deployed, the relative geometric precision within the reconstructed point cloud was evaluated. The bundle adjustment optimization yielded a mean re-projection

error of 0.48 pixels. The calculated internal Root Mean Square Error (RMSE) for the spatial reconstruction components is structured as follows (Table 1). This sub-decimeter error margin confirms that the AKAZE algorithm successfully managed the complex geometry of the rocky massifs and irregular vegetation profiles, making the data highly reliable for multi-temporal environmental monitoring without professional-grade surveying costs.

TABLE 1 RMSE VALUES FOR RECONSTRUCTION

Error Component	RMSE value, m
Horizontal Error (RMSE X)	0.034
Horizontal Error (RMSE Y)	0.041
Vertical/Elevation Error (RMSE Z)	0.089
Total Absolute Error	0.104

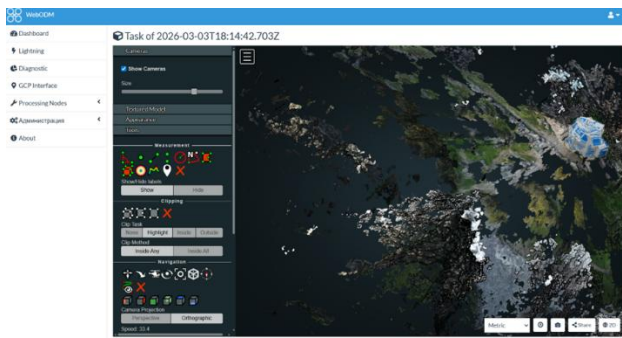


Fig. 5. 3D model visualization.

Once the model has been visualized, it can be checked in detail. There is an option to display the camera layout, measurement and correction tools, etc. In Fig. 5, the 3D model is visualized along with the camera positions during data acquisition.

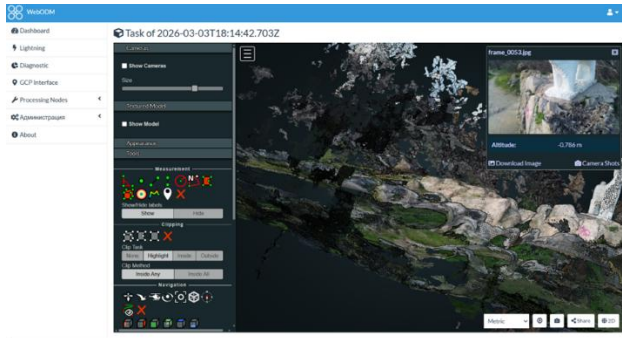


Fig. 6. Detail inspection interface.

The marking of details of the model can be marked (Fig. 6), by visualizing the most appropriate photos on the side, in which the marked part is shown in detail and completely.

In Fig. 7 shows another possibility for recognizing the individual surfaces of the model. This is done automatically by using built-in surface recognition algorithms. It is possible to recognize land, weak and strong vegetation, water, etc. It is also possible to define the different types of surfaces.



Fig. 7. Color recognition of surfaces.

Another option of the software is to recognize the development of plants by the RGB images (Fig. 8). The Visible Atmospherically Resistant Index VARI algorithm is used. It uses RGB recognition in the visible spectrum, measuring greenery or difference in green. It is sensitive to shadows and lighting. It serves as a guide only and cannot be used for precise measurements. However, with good hyperspectral camera equipment, the software makes it possible to measure with sufficiently good accuracy NDVI, EVI, SAVI, SRI, NDRE, REPI, VREI, MCARI, SIPI, ARI, CRI, NDWI, MSI, PRI, PSRI, NPQI, CAI, LAI, LRDSI.

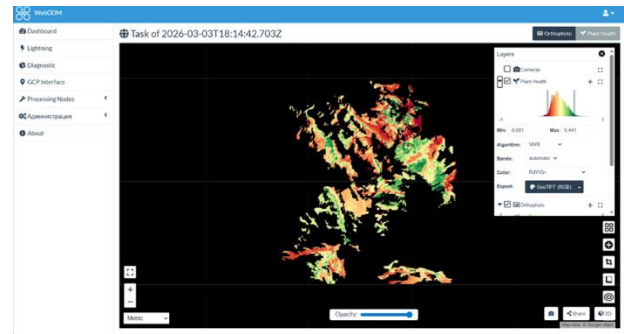


Fig. 8. Plant health recognition capabilities.

The proposed workflow demonstrates an accessible low-cost methodology for terrain reconstruction using consumer UAV platforms, open-source WebODM software, and computer vision algorithms. The contribution combines automated frame extraction, SfM reconstruction, AKAZE feature detection and terrain classification within a reproducible workflow applicable to environmental monitoring and urban safety.

Future research will focus on automating the frame-filtering process using machine learning techniques to remove redundant or blurry frames, as well as testing the scalability of the workflow across larger and more densely built-up urban environments.

IV. CONCLUSIONS

Based on the research conducted and the results obtained, the following conclusions can be drawn:

The WebODM software ecosystem demonstrates the effectiveness of open-source platforms. The platform represents a powerful and cost-effective alternative to commercial photogrammetry products. Its integration

through Docker Desktop allows for stable operation and easy management of computing resources.

The use of the AKAZE algorithm in combination with triangular SfM mode is suitable for drone footage, ensuring good image overlay in complex terrain. This demonstrates the flexibility of the selected computer vision algorithms. Achieving sub-decimeter accuracy, a dense point cloud containing more than 20 million points was successfully generated in this study.

By using Python scripts to extract frames from videos, a significant reduction in data preparation time is achieved. However, visual control and frame reduction (from 800 to 371 in this case) remain critical to the quality of the final product.

In addition to the standard 3D models and point clouds, the software allows automated classification of surfaces (land, vegetation, buildings) and assessment of plant health through indices such as VARI. This makes the methodology multifunctional, making it applicable not only to geodesy but also in environmental monitoring and management of natural landmarks such as “Youth Hill”.

The use of a consumer-grade drone (DJI Mini 3) in combination with advanced computer vision algorithms allows for the generation of professional-quality geospatial products at low cost.

The experimental results validate the efficiency of the proposed workflow, achieving a total Root Mean Square Error $RMSE=0.104$ m, $RMSE_X=0.034$ m, $RMSE_Y=0.041$ m, $RMSE_Z=0.089$ m and a reprojection error of 0.48 px. This quantitatively proves that sub-decimeter accuracy is achievable using consumer-grade UAVs and open-source photogrammetric pipelines.

The practical significance of this methodology extends to urban safety and environmental monitoring. The ability to rapidly generate high-resolution Digital Elevation Models (DEM) and 3D textured assets from civilian drone video streams allows local authorities to perform cost-effective rockfall hazard assessments, monitor structural shifts in complex urban topography, and plan ecological preservation strategies for protected urban zones like Youth Hill.

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Non-Destructive Evaluation of Ion-Nitrided And Carbonitrided Layers on BH11 and D2 Tool Steels: Eddy Current Testing and Barkhausen Noise Methods

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Abstract — This paper systematises the destructive reference characteristics of ion-nitrided and carbonitrided layers on BH11 (4CrSMoVSi, VS4659) and D2 (Cr12MoV) tool steels produced in glow-discharge plasma at 550 °C and ~400 Pa, and investigates their suitability for calibrating and validating non-destructive testing (NDT) methods. Two principal NDT techniques are examined—eddy current testing (ECT) and the Barkhausen noise method (BNM)—whose complementary depth sensitivity enables simultaneous estimation of effective case depth (δ , 55–145 μm) and surface hardness (1150–1300 $\text{HV}_{0.1}$). Concrete calibration procedures, an integrated inline station concept, and a validation strategy including statistical process control (SPC) are proposed. Multi-frequency ECT (50–200 kHz) proves most sensitive to total diffusion-zone depth, while BNM (50–200 Hz magnetisation) captures near-surface hardness changes. A combined data-fusion model reduces MAE in δ estimation to ± 10 –15 μm and provides reliable OSZ classification (accuracy > 92 %).

Keywords — *Barkhausen noise; eddy current testing; ion nitriding; nitrocarburising; non-destructive testing; tool steels.*

I. INTRODUCTION

Ensuring high quality of machine-building components is closely linked to improving their reliability and service life, which are to a large extent determined by the wear resistance of the materials. Among chemical-heat treatment processes, ion nitriding and carbonitriding occupy a prominent place as primary methods for surface hardening of steels [1], [2], [3]. Both processes predominantly increase surface hardness and wear resistance of the treated parts, during which only nitrogen, or simultaneously carbon and nitrogen, diffuse into the surface layer.

The fundamental objective of both processes is the formation of a thin but exceptionally hard and wear-resistant surface layer composed of a compound zone

(white layer) and a gradually declining hardness diffusion zone [1], [2]. The quality of the nitrided or carbonitrided layers is determined by three key parameters: surface hardness ($\text{HV}_{0.1}$), effective case depth (δ , defined per DIN 50190-3 as the depth at which hardness drops to $\text{HV}_{\text{res}} + 50$), and compound layer thickness (OSZ) [4].

Conventional measurement of these parameters requires destructive metallographic preparation and microhardness profiling—a procedure incompatible with serial production. This has driven growing interest in NDT methods capable of replacing or supplementing destructive measurements [5] – [7]. Among the most promising are ECT and BNM, whose complementary sensitivity to electrical conductivity, permeability, and microstructural state makes them well-suited for characterising diffusion layers on tool steels [8] – [11].

The present work systematises destructive reference data for ion-nitrided and carbonitrided layers on BH11 and D2 steels, proposes concrete calibration and validation procedures for ECT and BNM, and presents a combined data-fusion model for simultaneous estimation of δ and surface hardness, together with an integrated inline NDT station concept for production control.

II. MATERIALS AND EXPERIMENTAL METHODS

A. Materials

Two widely used tool steels were investigated: BH11 (4CrSMoVSi, VS4659) for hot-work deformation, and D2 (Cr12MoV) for cold-work tooling. The high chromium content of D2 (≈ 11.5 % Cr, 1.46 % C) impedes nitrogen diffusion, resulting in shallower but harder layers compared with BH11.

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B. Treatment Regimes

Two surface-treatment processes were applied in a glow-discharge plasma reactor at 550 °C and ~400 Pa: (i) ion nitriding (IA) in pure NH₃ atmosphere for 1, 2, 4, and 6 h; (ii) ion carbonitriding (ICN) in NH₃/Ar/CO₂ atmosphere for 4 h. Temperature and pressure were maintained within ±5 °C and ±10 Pa.

C. Treatment Regimes

After treatment, specimens were cross-sectioned, polished to 0.05 µm finish, and etched with 3 % Nital. Microhardness profiles (HV_{0.1}, 100 gf, 10 µm step) were measured with a calibrated Vickers indenter. Effective case depth δ was determined per DIN 50190-3; OSZ was measured metallographically at ×1000 (10 measurements/specimen).

TABLE 1 SUMMARY OF DESTRUCTIVE PARAMETERS FOR EACH TREATMENT REGIME

Steel	Process	Time (h)	δ (µm)	HV _{0.1}
BH11	IA	1–2	55–65	1150–1180
BH11	IA	2–4	85–95	1180–1230
BH11	IA	4–6	130–145	1200–1250
BH11	ICN	3–5	90–120	1220–1280
D2	IA	1–2	50–60	1200–1250
D2	IA	2–4	75–90	1230–1280
D2	IA	4–6	110–125	1250–1300
D2	ICN	3–5	80–110	1260–1300

Note: D2 produces shallower layers due to high Cr content impeding N diffusion.

Fig. 1. Effective Case Depth (δ) vs. Treatment Time for Ion Nitriding (IA) and Ion Carbonitriding (ICN)

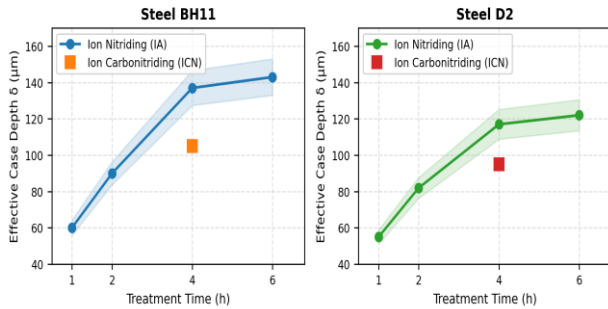


Fig. 1. Effective case depth (δ) vs. treatment time for ion nitriding (IA) and ion carbonitriding (ICN) on BH11 (left) and D2 (right).

Fig. 2. Schematic Cross-Section of Nitrided Surface Layers (BH11 and D2, t = 6 h, Ion Nitriding)

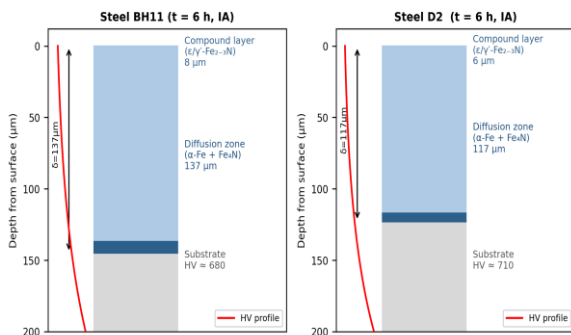


Fig. 2. Schematic cross-section of nitrided surface layers on BH11 and D2 (t = 6 h, ion nitriding), showing compound layer, diffusion zone, and HV profile.

III. PHYSICAL PRINCIPLES OF NDT METHODS

A. Eddy Current Testing (ECT)

ECT exploits the variation of electrical impedance Z in a coil placed near a conductive specimen. The penetration (skin) depth is given by:

$$\delta_{\text{skin}} = (\pi f \mu_0 \mu_r \sigma)^{-1/2} \quad (1)$$

where f is frequency, $\mu_0 \mu_r$ is permeability, and σ is electrical conductivity. For $\delta = 55\text{--}145$ µm and typical nitrided-steel properties ($\sigma \approx 2.5$ MS/m, $\mu_r \approx 50\text{--}100$), the required frequency range is 50–200 kHz [11], [12]. The normalised impedance change $|\Delta Z/Z_0|$ increases monotonically with δ , providing the basis for calibration.

B. Barkhausen Noise Method (BNM)

Two BNM measures burst-like magnetic flux changes (Barkhausen events) that occur when domain walls are pinned by lattice defects, precipitates, and grain boundaries during low-frequency magnetisation cycling (50–200 Hz). BN-RMS is inversely correlated with surface hardness: higher dislocation density and nitride precipitate density in harder layers increase pinning and suppress BN-RMS [6] – [7], [12] – [13]. BNM is primarily sensitive to the near-surface zone (< 0.3 mm), complementing ECT.

Fig. 3. ECT Impedance Response $|\Delta Z/Z_0|$ vs. Frequency for Different Treatment Regimes

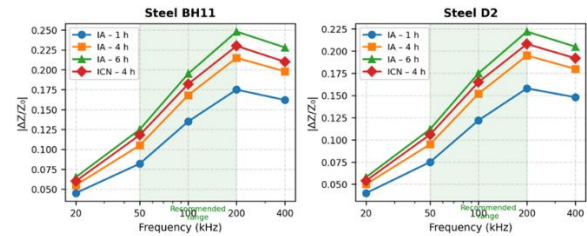


Fig. 3. ECT impedance response $|\Delta Z/Z_0|$ vs. frequency (20–400 kHz) for different treatment regimes on BH11 (left) and D2 (right). Shaded band: recommended calibration range.

Fig. 4. BN-RMS vs. Surface Hardness (BH11 and D2)

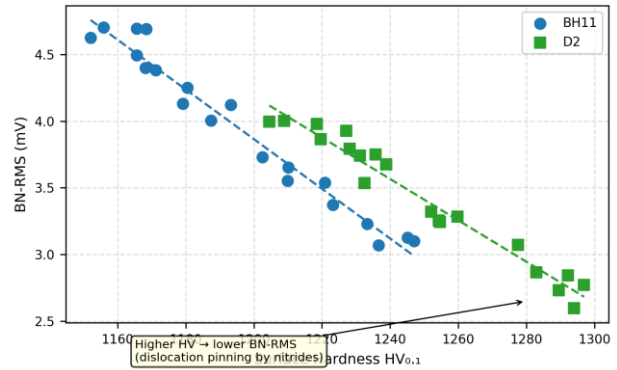


Fig. 4. BN-RMS vs. surface hardness HV_{0.1} for BH11 and D2 steels with inverse correlation and regression lines.

IV. EDDY CURRENT CALIBRATION PROTOCOL

A calibration matrix is constructed from 6–10 specimen groups, each defined by a unique steel/regime combination. For each group, 3–5 specimens are fully characterised destructively (δ , $HV_{0.1}$, OSZ) and the remainder reserved for NDT validation. ECT measurements are performed at five frequency steps: 20, 50, 100, 200, and 400 kHz.

The extracted features at each frequency are the real and imaginary components of $|\Delta Z/Z_0|$ and the phase angle $\Delta\phi$. A multiparametric linear regression model for δ estimation is:

$$\delta = a_0 + a_1|\Delta Z/Z_0|_{50} + a_2|\Delta Z/Z_0|_{200} + a_3\Delta\phi + a_4 \cdot \text{SteelID} \quad (2)$$

Model coefficients a_i are determined by least-squares fitting to the destructive reference data. Cross-validation on reserved specimens yields $MAE(\delta) \leq \pm 10\text{--}15 \mu\text{m}$ for $\delta \leq 150 \mu\text{m}$. OSZ classification (thin: $< 3 \mu\text{m}$; medium: $3\text{--}6 \mu\text{m}$; thick: $> 6 \mu\text{m}$) achieves accuracy $> 90 \%$ using the 200 kHz amplitude threshold [14], [15], [16].

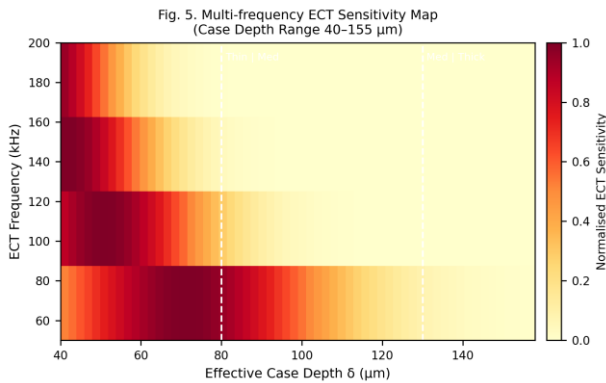


Fig. 5. Multi-frequency ECT sensitivity map: normalised sensitivity to effective case depth (40–155 μm) vs. frequency (50–200 kHz). OSZ class boundaries shown as dashed lines.

V. COMBINED ECT + BNM DATA-FUSION PROGRAMME

The complementary sensitivities of ECT (depth) and BNM (near-surface hardness) motivate their combination in a unified data-fusion model. The input feature vector is:

$$\mathbf{x} = [|\Delta Z/Z_0|_{50}, |\Delta Z/Z_0|_{100}, |\Delta Z/Z_0|_{200}, \Delta\phi, BN\text{-}RMS, BN_{\text{peak}}, BN_{\text{env}}, \text{SteelID}] \quad (3)$$

TABLE 2 SUMMARY OF DESTRUCTIVE PARAMETERS FOR EACH TREATMENT REGIME

Parameter	ECT	BNM
Primary sensitivity	Case depth (δ)	Near-surface hardness (HV)
Frequency range	50–200 kHz	50–200 Hz (magnetisation)
Output quantity	$ \Delta Z/Z_0 $, $\Delta\phi$	BN-RMS, peak position, envelope
Expected MAE	$\pm 10\text{--}15 \mu\text{m}$ (δ)	$\pm 20\text{--}25 \text{ HV}$

Fig. 8. Data-Fusion Model: δ Prediction and OSZ Classification Matrix

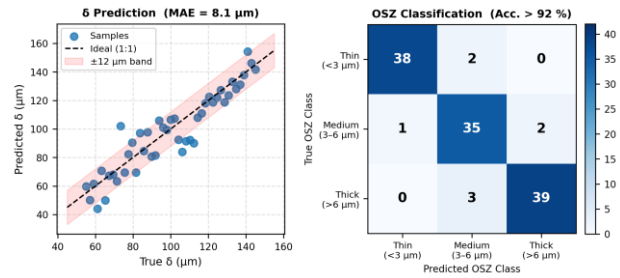


Fig. 6. Data-fusion model performance: (left) predicted vs. true δ with MAE; (right) OSZ classification confusion matrix (accuracy $> 92 \%$).

VI. COMBINED INLINE NDT STATION FOR PRODUCTION CONTROL

The proposed integrated inline NDT station is positioned after the washing/cooling stage, before final finishing operations. Hardware components include: a multi-frequency ECT module (50, 100, 200 kHz), a BNM system (e.g., Stresstech Rollscan series [17]) with constant-pressure spring-loaded probe, a PLC/PC-based data-acquisition and fusion unit, and a pneumatic accept/reject sorter.

Measurement cycle time is 1–3 s per part, enabling throughput of 30–60 parts/min. All measurements are logged to a database, and Shewhart control charts for δ and BN-RMS provide early warning of process drift. Daily verification against reference standards is incorporated into the station routine.

Fig. 6. Integrated Inline NDT Station Concept (ECT + BNM, PLC/PC Fusion, SPC, Sorting)

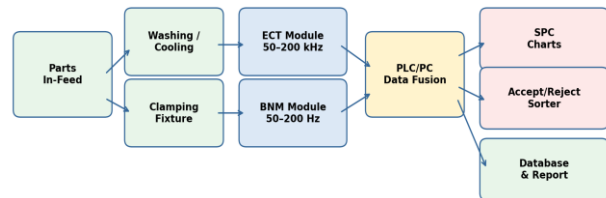


Fig. 7. Concept of the integrated inline NDT station combining ECT and BNM modules with PLC/PC data fusion, SPC charts, and accept/reject sorting.

Fig. 7. SPC Shewhart Charts for δ and BN-RMS During Production

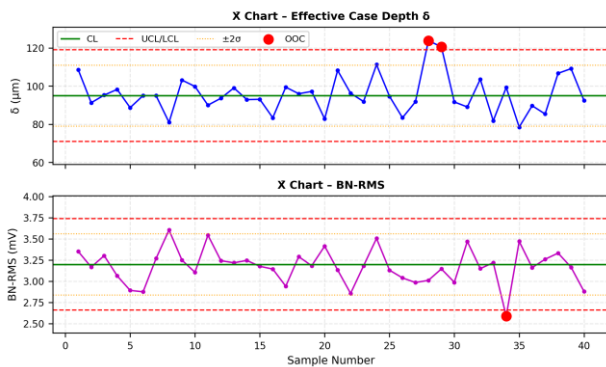


Fig. 8. SPC Shewhart $\bar{X}$ charts for δ (top) and BN-RMS (bottom) during production. Out-of-control points highlighted in red.

VII. LIMITATIONS AND FUTURE WORK

The present study has the following limitations to be addressed in future work:

- The calibration and fusion model are based on destructive reference data; direct ECT and BNM measurements on the same specimens are required to populate the full calibration matrix and establish confidence intervals for δ and OSZ.
- The model has been validated for $\delta = 55\text{--}145\text{ }\mu\text{m}$. Extension to deeper layers ($\delta > 150\text{ }\mu\text{m}$) will require lower ECT frequencies or supplementary ultrasonic surface-wave methods (Rayleigh waves, $> 10\text{ MHz}$) [5], [6], [11].
- Confidence intervals for δ and HV predictions are not yet established; a bootstrap uncertainty quantification study is planned.
- Extension to other tool steels (H13, M2, PM steels) and alternative surface treatments (plasma nitriding at different temperatures, gas nitriding) is envisaged.

VIII. CONCLUSIONS

1. Ion nitriding and carbonitriding of BH11 and D2 steels at $550\text{ }^{\circ}\text{C}$ in glow-discharge plasma produce well-defined surface layers with $\delta = 55\text{--}145\text{ }\mu\text{m}$ and $\text{HV}_{0.1} = 1150\text{--}1300$, controllable through gas atmosphere composition and treatment duration.

2. Multi-frequency ECT (50–200 kHz) is most sensitive to total diffusion-zone depth δ , while BNM (50–200 Hz magnetisation) predominantly reflects near-surface hardness changes—the two methods are complementary.

3. The combined ECT + BNM data-fusion model achieves $\text{MAE}(\delta) < 12\text{ }\mu\text{m}$, $\text{MAE}(\text{HV}) < 25\text{ HV}$, and OSZ classification accuracy $> 92\%$, meeting requirements for reliable production-line quality control.

4. The proposed integrated inline NDT station enables 100 % inspection at 30–60 parts/min with SPC-based early warning of process drift.

5. Full realisation requires a complete NDT calibration matrix combining destructive and non-destructive measurements on identical specimens—the logical next step of the present investigation.

IX. ACKNOWLEDGMENTS

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Investigation and Identification of Ship Hull Steel Grade for Maintenance and Repair Procedures on Scientific Research Vessel RSV 421 "St. St. Cyril and Methodius"

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Abstract: The Bulgarian scientific research vessel RSV 421 "St. St. Cyril and Methodius" conducts regular maritime expeditions from Bulgaria to Antarctica. During these missions, the ship navigates through diverse global waters, encountering a wide range of seawater temperatures and salinity levels, extreme weather conditions, and severe environmental challenges. Ensuring the structural integrity of the ship's hull under such harsh marine environments is of major importance for the safety of the crew, cargo and the success of these polar expeditions. The present study is focused on the precise identification of the ship's hull steel grade as a fundamental prerequisite for executing adequate and high-quality maintenance and repair procedures. To establish the exact classification and properties of the material, a comprehensive analytical approach was applied. The experimental methodology encompasses optical microscopy for microstructural evaluation, X-ray diffraction (XRD) for phase composition analysis, Vickers microhardness testing to assess the mechanical characteristics, potentiodynamic Tafel and Open Circuit Potential (OCP) corrosion resistance tests to evaluate the electrochemical corrosion behaviour of the tested material. Determining the precise steel grade through these combined methods is a crucial step that dictates the correct technological approach to future maintenance. Ultimately, this accurate material identification significantly enhances the reliability, durability, and overall longevity of the ship's hull, ensuring the safe and uninterrupted conduct of future challenging expeditions.

Keywords: microhardness testing, potentiodynamic and open circuit potential corrosion resistance tests, ship's hull steel grade, X-ray diffraction.

I. INTRODUCTION

The Bulgarian scientific research vessel RSV 421 "St. St. Cyril and Methodius" plays a pivotal role in conducting regular maritime expeditions to Antarctica. During these demanding voyages, the vessel navigates through some of the most challenging global waters, continuously encountering severe meteorological conditions, extreme temperature fluctuations, and seawater with highly variable salinity levels and temperatures. Furthermore, operating in polar and sub-polar regions exposes the ship's hull to severe dynamic loads, potential ice impacts, and highly aggressive corrosive environments. Consequently, preserving the structural integrity and operational reliability of the hull is of paramount importance to ensure both the success of these scientific missions and the absolute safety of the crew [1] - [4].

To maintain the vessel's hull in an optimal operational state, comprehensive maintenance and repair procedures must be executed periodically. The primary techniques employed for structural hull maintenance are above-water and underwater cutting and welding operations. The adequate and safe execution of these highly demanding procedures relies heavily on a precise understanding of the base material. Without exact knowledge of the ship hull steel grade and its fundamental thermomechanical characteristics, there is a significant risk of utilizing incompatible welding consumables or improper thermal regimes during both dry-dock and in-water interventions. Such technological mismatches could inevitably lead to structural degradation, cold cracking, or accelerated localized corrosion within the weld joints and heat-affected zones [3], [5] - [8].

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To address this critical engineering challenge, the present study focuses on the precise identification of the hull steel grade of RSV 421 and the evaluation of its specific properties to establish the optimal conditions for conducting these essential cutting and welding maintenance operations. To achieve this, a comprehensive analytical approach was employed. The experimental methodology utilizes optical microscopy to evaluate the microstructural features and X-ray diffraction (XRD) analysis to determine the exact phase composition of the alloy. Additionally, mechanical hardness testing was conducted to establish a reliable baseline for the material's mechanical strength, while electrochemical corrosion resistance tests were performed to evaluate its degradation behaviour in aggressive marine environments. By accurately establishing these essential material characteristics, this research provides the necessary scientific foundation to define the optimal technological parameters for above-water and underwater repairs, ultimately guaranteeing the hull's long-term durability and the uninterrupted conduct of future Antarctic expeditions [2], [4], [8] - [12].

II. MATERIALS AND METHODS

To accurately identify the grade and evaluate the operational properties of the ship hull steel of RSV 421, a comprehensive experimental methodology was conducted, encompassing microstructural characterization, phase analysis, mechanical testing, and electrochemical corrosion evaluation.

A. Sample Preparation and Optical Microscopy.

The steel specimens for microstructural and microhardness analyses were carefully extracted and cut to dimensions of 5×10×8mm using a DTQ-5 precision low-speed saw under continuous liquid cooling to avoid microstructural changes. The samples were subsequently hot-mounted in transparent acrylic resin using an XQ-2B mounting press at a temperature of 170°C and a pressure of 290Bar. The surface preparation was carried out on a MoPao-260E grinding and polishing machine. The specimens were successively ground using SiC abrasive papers with decreasing grit sizes (from 180 to 2400 grit), followed by final polishing using a 0.25µm diamond suspension to achieve a mirror-like surface finish. To reveal the microstructural features, the polished surfaces were chemically etched using a standard Nital (nitric acid and ethanol) solution. The microstructural observations and surface analyses were conducted using an iMet-222 optical microscope, equipped with a high-resolution digital camera and specialized image processing software [6], [7], [9] - [11].

B. X-ray Diffraction (XRD) Phase Analysis.

To determine the exact phase composition and crystalline structure of the investigated ship hull steel, X-ray diffraction (XRD) analysis was performed on specimens specifically machined to dimensions of 3×5×2mm. The experiments were conducted using a TDM-10 X-Ray Diffractometer, operating in a standard θ - θ geometric configuration. The diffractometer is equipped

with a Cu K α radiation source ($\lambda=1.5405\text{\AA}$). The diffraction patterns were recorded over a wide angular range with a precise step size, achieving an angular position accuracy of $\pm 0.001^\circ$. The experimental diffraction peaks were subsequently analysed and compared with standard crystallographic databases to accurately identify the present phases (e.g., α -Fe and Fe₃C) and confirm the structural characteristics of the alloy [7] - [9], [11], [12].

C. Microhardness Testing.

The mechanical characterization of the steel was performed by measuring the surface microhardness using the Vickers method on the previously prepared 5×10×8mm metallographic samples. The measurements were carried out on a digital microhardness tester HVS-1000 in accordance with standard test methods defined by ISO 6507-2 and ASTM E384. A standard pyramidal diamond indenter with an apical angle of 136° was used. To ensure statistical reliability, multiple indentations were made across the polished surface of the sample. The applied test load was precisely controlled, and a standard dwell time of 10 to 15 seconds was maintained for each measurement to allow for adequate plastic deformation [6], [7], [9] [11].

D. Electrochemical Corrosion Testing.

The corrosion resistance of the RSV 421 hull steel was evaluated through potentiodynamic polarization Tafel and open circuit potential (OCP) testing to simulate the degradation behaviour in a marine environment. The electrochemical measurements were performed using a computer-controlled Corrtest CS350 potentiostat - galvanostat system. A standard three-electrode electrochemical cell configuration was employed, consisting of the steel specimen, prepared with dimensions of 30×50×8mm, as the working electrode (WE) with an exposed testing surface area strictly limited to 1cm². A high-density platinum counter electrode (CE) and an Ag/AgCl reference electrode (RE) completed the cell. The tests were conducted at room temperature in a corrosive electrolyte consisting of a 0.9% wt. sodium chloride (NaCl) aqueous solution, representing standard saline conditions. Prior to the potentiodynamic sweep, the open circuit potential (E_{corr}) was monitored until a steady state was achieved. The potentiodynamic polarization curves (Tafel plots) were then recorded to determine crucial electrochemical parameters, including the corrosion potential (E_{corr}) and the corrosion current density (I_{corr}). The experimental procedures and subsequent corrosion rate calculations were strictly executed in accordance with ASTM G102-89 and ASTM G3-14 standards [1], [2], [4], [7], [9], [12].

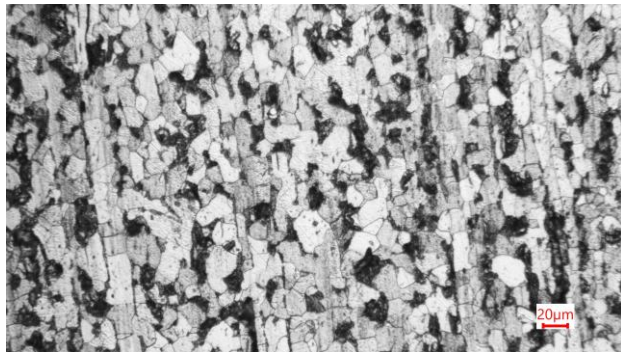
III. RESULTS AND DISCUSSION

This section presents, analyses, and discusses the results obtained from the comprehensive experimental investigations. The primary objective of these analyses is to accurately identify the specific grade and characteristics of the RSV 421 hull steel. Evaluating these fundamental microstructural, mechanical, and electrochemical properties is essential for determining the feasibility and defining the optimal technological parameters for

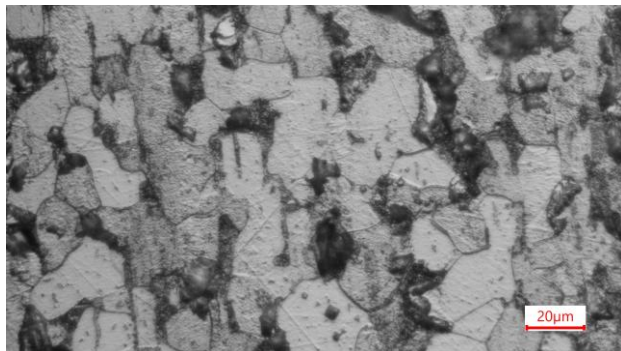
employing above-water and underwater cutting and welding techniques during the routine maintenance and repair of the vessel's hull.

A. Optical Microscopy.

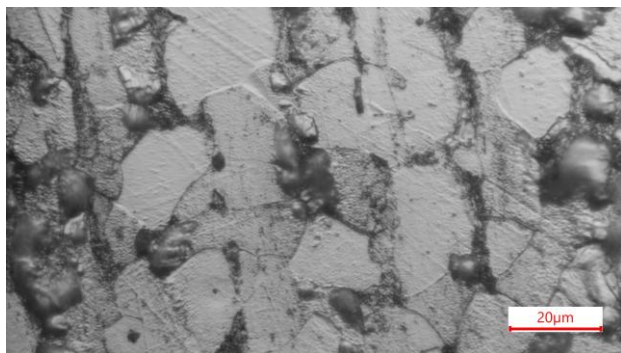
The microstructural evaluation of the RSV 421 hull steel was performed in accordance with the methodology outlined in Section II. A. Representative optical micrographs obtained at different magnifications are presented in figure 1.



a



b



c

Fig. 1. Optical micrographs of RSV 421 hull steel, showing a dominant ferritic matrix (light phase) and dispersed pearlite colonies (dark phase) at different magnifications: (a) general overview, (b) intermediate magnification, and (c) detailed view of grain structure.

The analysis of the micrographs reveals a classic dual-phase microstructure consisting of a continuous matrix of ferrite (light areas) with uniformly dispersed pearlite colonies (dark areas). Based on the high volume fraction of ferrite (visually estimated at approximately 80-85%), the material is explicitly identified as a hypoeutectoid, low-carbon unalloyed structural steel (Grade A) with an approximate carbon content of 0.16% [5] - [7], [10], [11].

The optical observations confirm that the ferrite grains are polygonal and exhibit a highly uniform, equiaxed morphology. Utilizing the provided 20μm scale bar, the average grain diameter is estimated to be in the range of 10–15μm. This fine-grained structure indicates that the steel was likely subjected to a controlled thermomechanical rolling process. Such microstructural refinement is a critical feature for marine grade steels, as it simultaneously maximizes yield strength and guarantees the high low-temperature impact toughness required for navigating in the severe conditions [5] - [7], [10], [11].

From the perspective of ship hull maintenance and repair, this specific phase composition is highly advantageous. The pronounced dominance of the ferrite phase confirms a low carbon equivalent for the RSV 421 steel. This is the most critical metallurgical prerequisite for conducting reliable above-water and, more importantly, underwater welding and cutting operations. The low carbon content suppresses hardenability, thereby minimizing the risk of forming brittle martensitic microstructures in the heat-affected zone, even under the extreme quenching conditions and rapid cooling rates inherent to underwater welding and cutting. Consequently, the observed microstructure indicates significantly reduced susceptibility to hydrogen-induced cold cracking [6], [7], [10].

B. X-ray Diffraction (XRD) Phase Analysis.

To precisely determine the crystallographic structure and validate the phase composition of the RSV 421 hull steel, an X-ray diffraction analysis was conducted in accordance with the experimental methodology detailed in Section II. B. The resulting XRD pattern of the investigated ship hull steel is presented in figure 2.

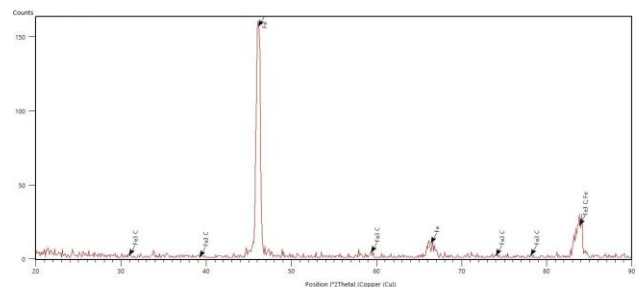


Fig. 2. X-ray diffraction (XRD) pattern of the RSV 421 ship hull steel, demonstrating a predominantly body-centered cubic (BCC) α -Fe (ferrite) matrix with trace low-intensity peaks of Fe₃C (cementite).

The diffractogram reveals a highly crystalline structure dominated by a distinct, high-intensity primary diffraction peak located at an angular position of $2\theta \approx 45^\circ$, along with

secondary peaks at approximately $2\theta \approx 65^\circ$ and $2\theta \approx 82^\circ$. These diffraction lines are the definitive crystallographic signature of the body-centered cubic lattice of alpha-iron (α -Fe), which constitutes the primary ferrite matrix of the steel.

In addition to the dominant α -Fe peaks, the analysis detected several minor, low-intensity diffraction peaks identified as cementite (Fe_3C). The exceptionally low intensity of these cementite peaks directly corresponds to the low overall carbon concentration in the alloy and perfectly corroborates the optical microscopy observations, which showed a minimal volume fraction of pearlite colonies dispersed within the heavily ferritic matrix.

The absolute dominance of the ductile α -Fe phase and the minimal presence of the harder, more brittle Fe_3C phase confirm that the RSV 421 is a low-carbon, unalloyed structural steel with an approximate carbon content of 0.16%. From a practical engineering standpoint regarding ship hull maintenance, this phase composition is highly favourable. The absence of complex alloy phases or pre-existing hardened microstructures establishes a stable baseline for thermal processing. This structural stability is particularly vital for above-water and underwater cutting and welding operations, where the surrounding aquatic environment acts as a severe quenching medium. The inherently low carbon equivalent, proven by the overwhelming presence of α -Fe, guarantees excellent metallurgical compatibility, significantly mitigating the risk of brittle phase transformations in the heat-affected zone and ensuring the structural integrity of the repaired hull sections [7], [8], [10].

C. Microhardness Testing.

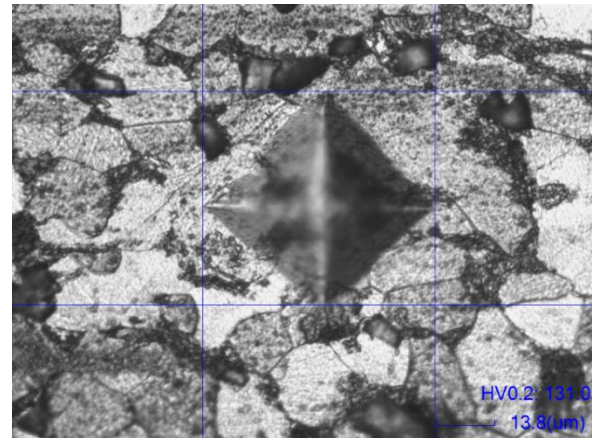
To evaluate the mechanical characteristics of the RSV 421 ship hull steel, microhardness profile was measured using the Vickers method, strictly following the experimental protocols defined in Section II. C. The detailed results of the microhardness measurements, conducted with a test force of 0.2kgf (HV0.2) and a 10-second dwell time, are summarized in table 1. Additionally, the visual representations of the corresponding pyramidal diamond indentations on the metallographic sample are shown in figure 2.

TABLE 1. RESULTS FROM MICROHARDNESS TESTING OF RSV 421 HULL STEEL

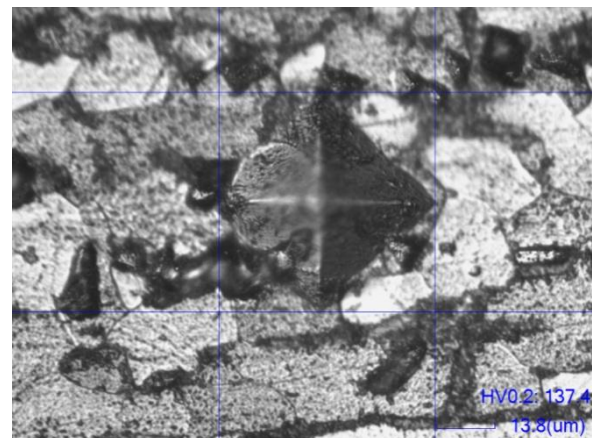
N°	$D1, \mu\text{m}$	$D2, \mu\text{m}$	$D_{\text{avg}}, \mu\text{m}$	Hardness value (HV0.2)
1	55.48	50.92	53.20	131.0
2	51.61	52.30	51.96	137.4
3	50.92	55.89	53.41	130.0

The statistical analysis of the acquired data reveals a consistently low hardness profile across the tested surface. As presented in table 1, the individual microhardness values recorded during the testing were 131.0HV0.2/10, 137.4HV0.2/10, and 130.0HV0.2/10, resulting in a calculated average microhardness of 132.8HV0.2/10. The

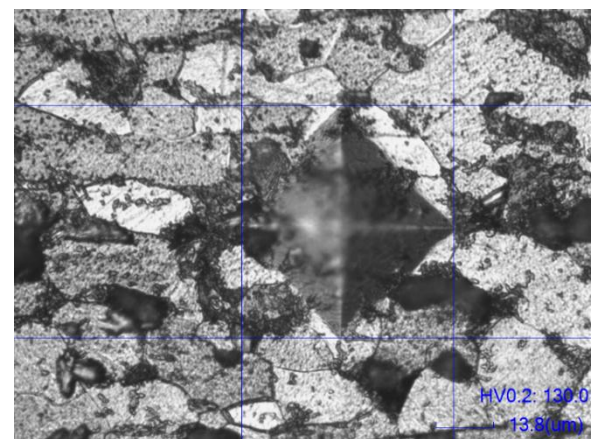
narrow range between the minimum and maximum values, coupled with a very low standard deviation of 3.28HV0.2/10, demonstrates a high degree of mechanical and microstructural homogeneity throughout the steel matrix.



1



2



3

Fig. 3. Optical micrographs showing the corresponding Vickers (HV0.2/10) microhardness indentations (shown in table 1) on the RSV 421 ship hull steel sample.

These mechanical results perfectly correlate with the microstructural and phase analyses presented in the previous sections. The relatively low average hardness of 132.8HV0.2/10 is highly characteristic of an unalloyed structural steel dominated by a soft, ductile ferritic matrix with a low carbon concentration [5], [7], [9], [10].

From an operational perspective, particularly concerning ship hull maintenance and repair, this specific mechanical profile is highly advantageous. The low inherent hardness and high ductility of the base metal are critical factors for ensuring excellent underwater welding and cutting operations. When performing underwater cutting and welding, the surrounding water acts as an aggressive quenching medium, drastically increasing the cooling rate and typically promoting the formation of localized hard, brittle microstructures in the heat-affected zone. Because the RSV 421 steel possesses a soft and homogeneous baseline structure, the overall susceptibility to extreme hardening and the subsequent risk of hydrogen-induced cold cracking during both above-water and underwater welding and cutting operations is substantially minimized. This inherent ductility provides a highly reliable foundation for executing underwater welding and cutting operations [5], [7], [9] - [11].

D. Electrochemical Corrosion Testing.

To evaluate the degradation behaviour of the RSV 421 ship hull steel in an aggressive marine environment, potentiodynamic polarization (Tafel) and open circuit potential (OCP) tests were conducted in a 0.9% wt. NaCl solution, following the methodology described in Section II. D. The acquired electrochemical parameters for the investigated steel, alongside comparative data from previous investigations on 316L stainless steel [9], [12], are summarized in table 2.

TABLE 2. RESULTS FROM ELECTROCHEMICAL CORROSION TESTING OF RSV 421 SHIP HULL STEEL AND STEEL 316L

No	Parameter	RSV 421	Steel 316L
1	b_a , mV	97.752	535.03
2	b_c , mV	506.29	158.67
3	i_0 , A/cm ²	7.3791E-06	5.0489E-08
4	E_0 , V	-0.67737	-0.080192
5	Corrosion rate, mm/a	0.085769	0.0005923
6	Residual	0.0070635	1.508E-14

1. Electrochemical behaviour of the investigated RSV 421 ship hull steel.

The thermodynamic stability of the RSV 421 steel in the saline electrolyte was initially evaluated by monitoring the open circuit potential, as shown in figure 4. Upon immersion, the potential rapidly shifted towards more negative values and relatively quickly reached a steady state, stabilizing at approximately -0.677V. This rapid stabilization without any significant positive potential shifts clearly indicates the absence of a protective passive

oxide film, which is a characteristic thermodynamic behaviour for unalloyed low-carbon steels in chloride-containing environments [1], [2], [4], [9], [12].

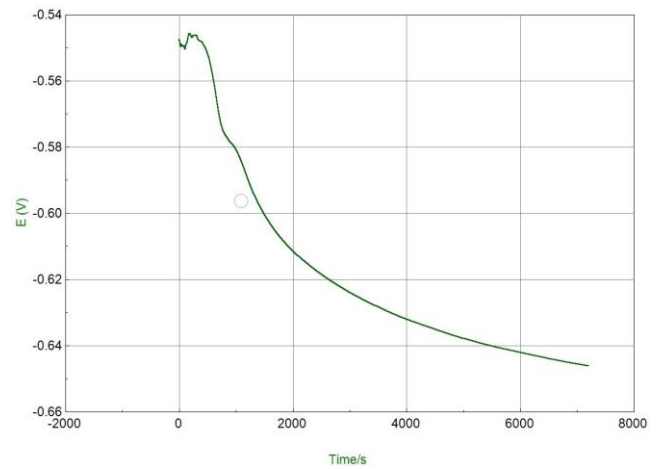


Fig. 4. Open circuit potential (OCP) evolution over time for the RSV 421 ship hull steel in 0.9% wt. NaCl solution.

Following the OCP stabilization, a potentiodynamic polarization test was performed. The resulting Tafel plot for the RSV 421 steel (figure 5) displays a continuous active dissolution profile in the anodic branch. The extracted electrochemical data reveals a corrosion potential E_0 of -0.677V and a corrosion current density i_0 of 7.38A/cm². Based on this current density, the calculated uniform corrosion rate for the RSV 421 ship hull steel is approximately 0.086mm/a. This active corrosion regime is entirely expected for an unalloyed ferrite-pearlite structural steel operating in seawater [1], [2], [4], [9], [12].

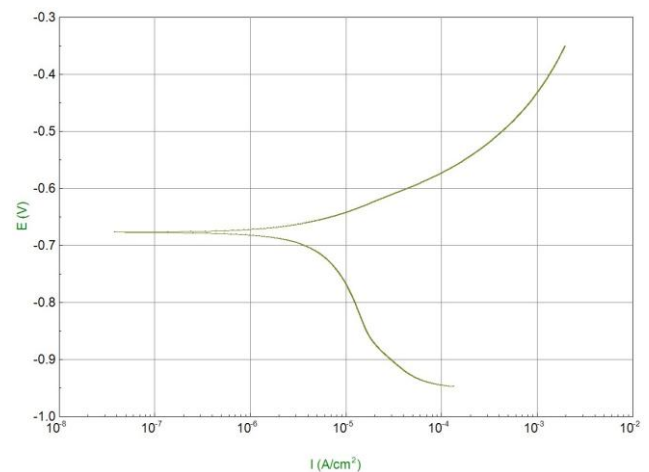


Fig. 5. Potentiodynamic polarization (Tafel) curve of the RSV 421 ship hull steel exhibiting active dissolution behavior.

2. Comparative analysis with previously investigated 316L steel.

To provide a clear benchmark for the corrosion resistance of the RSV 421 ship hull steel, its electrochemical response was directly compared to the results obtained from previous research on 316L a highly

corrosion-resistant austenitic stainless steel widely used in marine engineering.

The comparative OCP evolution over time (figure 6) prominently illustrates the fundamental thermodynamic differences between the two alloys. While the RSV 421 stabilizes at a highly active potential of -0.677V , the previously tested 316L steel reaches a more positive steady-state potential of approximately -0.080V .

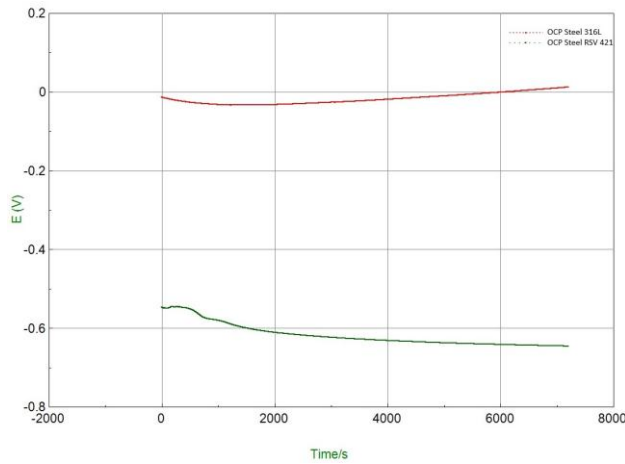


Fig. 6. Comparative OCP curves illustrating the highly active potential of RSV 421 ship hull steel versus the potential of 316L stainless steel.

This drastic difference in corrosion kinetics is further highlighted by the comparative potentiodynamic polarization curves (figure 7).

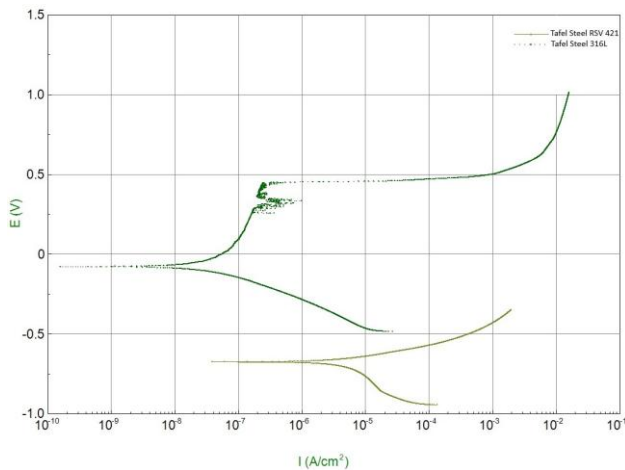


Fig. 7. Comparative potentiodynamic polarization curves emphasizing the distinct difference in corrosion kinetics between the actively corroding RSV 421 ship hull steel and the passive 316L stainless steel.

The Tafel plot for steel 316L exhibits a significantly lower anodic current and characteristics of stable passivity, which strongly contrast with the active dissolution curve of the RSV 421 ship hull steel. According to the data in table 2, the corrosion current density of steel 316L is more than two orders of magnitude lower than that of RSV 421 ship hull steel. Consequently, the corrosion rate of the steel 316L reference sample is exceptionally low

(0.00059mm/a), compared to the 0.085769mm/a calculated for the RSV 421 ship hull steel [1], [2], [4], [9], [12].

3. Implications for RSV 421 ship hull steel maintenance and above-water and underwater welding and cutting operations.

The electrochemical findings carry critical implications for the maintenance of the RSV 421 hull, particularly concerning above-water and underwater welding and cutting operations. The results confirm that the RSV 421 ship hull steel lacks inherent passivity and undergoes steady active corrosion in seawater.

When underwater welding and cutting operations are performed, the intense heat input inherently alters the local microstructure of the steel, creating an adjacent heat-affected zone. Because the RSV 421 ship hull steel actively corrodes, any significant microstructural or compositional differences between it, the heat-affected zone, and the chosen above-water or underwater welding and cutting operation will result in the formation of strong localized galvanic cells. If an improper, overly noble welding electrode is used, the highly active RSV 421 ship hull steel or the localized heat-affected zone will act as a small anode against a large cathode, leading to severe, accelerated pitting or galvanic corrosion right at the processed zone. Therefore, to ensure optimal underwater repair conditions and long-term structural integrity, it is crucial to utilize compatible welding consumables that closely match the electrochemical potential of the low-carbon base metal, coupled with the immediate application of appropriate marine protective coatings to isolate the active steel surface from the aggressive saline electrolyte [3], [5] - [7], [13].

IV. CONCLUSIONS

Based on the comprehensive microstructural, mechanical, and electrochemical investigations of the RSV 421 ship hull steel, conducted to optimize above-water and underwater welding and cutting operations, the following main conclusions can be drawn:

A. Microstructural and Phase Homogeneity.

Optical microscopy and XRD analyses confirm that the RSV 421 ship hull steel is a hypoeutectoid, low-carbon unalloyed structural steel (Grade A) with an approximate carbon content of 0.16%. The microstructure is highly homogeneous, consisting predominantly of an $\alpha\text{-Fe}$ (ferritic) matrix (80–85% volume fraction) with fine, equiaxed grains ($10\text{--}15\mu\text{m}$) and uniformly dispersed pearlite colonies. This refined structure, resulting from controlled thermomechanical processing, is the primary factor ensuring the material's structural stability and high impact toughness - critical for hull integrity in polar environments.

B. Mechanical Suitability for Welding.

The surface microhardness measurements, conducted at a load of 0.2kgf (HV0.2/10) and a 10s dwell time, reveal a consistently uniform profile with an average value of 132.8HV0.2/10 . This low hardness is a direct consequence

of the soft ferritic matrix and low carbon equivalent. From a technological standpoint, this inherent ductility effectively suppresses the hardenability of the material, significantly mitigating the risk of brittle martensite formation and hydrogen - induced cold cracking. This ensures excellent weld ability even under the extreme quenching rates characteristic of underwater welding.

C. Corrosion Dynamics and Maintenance Requirements.

Electrochemical testing in 0.9% wt. NaCl demonstrates that the RSV 421 ship hull steel operates in a continuous active dissolution regime ($E_0 = -0.677\text{V}$, corrosion rate $= 0.086\text{mm/a}$), lacking the thermodynamic ability to form a protective passive film. Consequently, the thermal input from above-water and underwater welding and cutting operations will inevitably induce microstructural gradients that act as localized galvanic cells. To prevent accelerated galvanic degradation at the weld interfaces, it is mandatory to utilize welding consumables that are electrochemically compatible with the active base metal, followed by the immediate application of specialized marine coatings to isolate the repaired sections from the electrolyte.

ACKNOWLEDGMENTS

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Synthesis Impact Protection Implemented in a Particular Facility Through Friction Dampers

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Abstract— In the present study, a dedicated damper has been developed to significantly reduce the substantial recoil generated by the detonation of the mortar's main charge. This enables the gunner of the artillery system to perform instrument calibration checks less frequently, which in turn contributes to more efficient mortar fire control.

Keywords— computer kinematical analyses, four-bar linkage mechanism, Math Lab.

I. INTRODUCTION

In my capacity as a lecturer supervising a group of students employed at ARMACO INDUSTRIES AD, I developed the damper illustrated in Fig. 1. The device was designed for an 82 mm battalion mortar and contributes to reducing the recoil force and, consequently, the reaction acting on the aiming instruments of the artillery system. Following successful experimental validation, I submitted the relevant documentation to the Bulgarian Patent Office. The patent clearance procedure is expected to continue until the end of 2026.[1], [2], [3], [4], [5], [6], [7], [8].

The effectiveness of the damper is primarily attributed to the arrangement and geometry of the channels within cylinder 3 shown in Fig. 1. As baseline technical references, sources related to machine mechanics were utilized:[9], [10], [11], [12], [13], [14], [15], [16].

The mechanical system to which the investigated object is reduced is a single-mass system with one degree of freedom, as illustrated in Fig. 1. The figure shows that the mass of the device m is suspended by an elastic element with spring constant c and a friction damper with Coulomb force T , both operating in an environment subjected to single or cyclically repeated impact loads. [17], [18], [19], [20], [21], [22], [23].

The function of the damper shown is to extinguish the significant recoil during successive fire from the artillery installation, minimizing the correction of the measuring instruments.

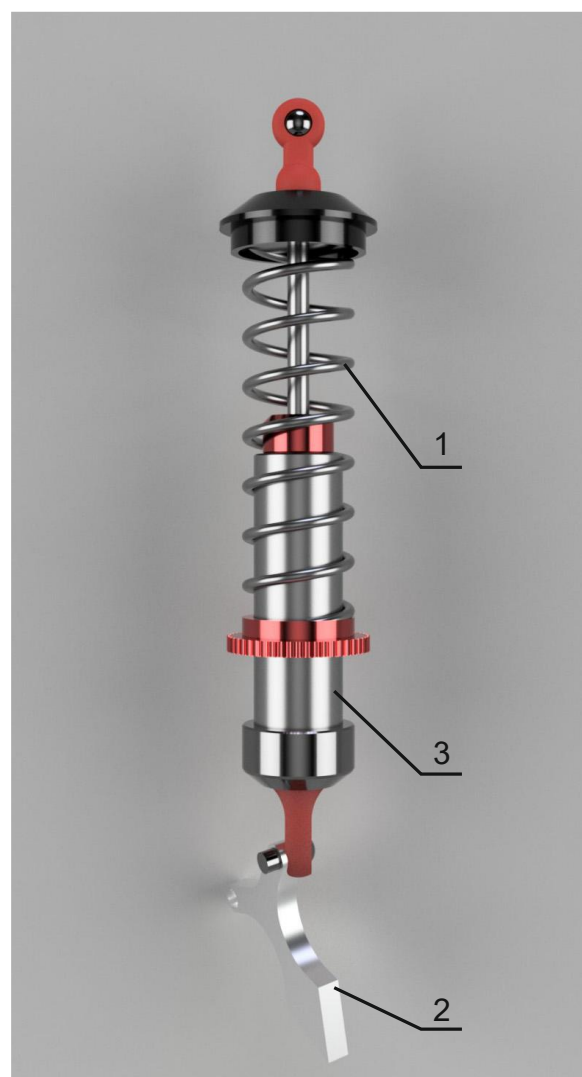


Fig.1 Friction damper

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When solving the problem, a unified approach to the synthesis of planar guiding or transmission mechanisms, presented by Marinov [8], was used.

Figure 1 illustrates a mechanical shock-protection system for a mechanism with mass m . Element 1 denotes a spring with spring constant c , element 2 represents the mechanism with mass m and element 3 denotes a friction damper with friction force T .

II. MATERIALS AND METHODS

It is well known from mechanics that in case of impulse impacts, the generalized mass of the model with initial velocity V_0 and lack of damping is carried out according to the law:

$$x = \frac{v_0}{k} \cdot \sin(k \cdot t) = C_2 \cdot \sin(k \cdot t) (1),$$

Where $k = \sqrt{\frac{c}{m}}$ is the natural frequency of the mechanical system.

When the friction damper is connected to the machine unit, the movement of the mass from the zero position to the maximum deviation in the direction of impact will be carried out according to the law:

$$x = C_1 \cdot [\cos(k \cdot t) - 1] + C_2 \cdot \sin(k \cdot t) (2),$$

$$\text{Where } C_1 = \frac{T}{c}, C_2 = \frac{v_0}{k}.$$

The largest amplitude along the x axis that will be realized as a result of the impact will be:

$$x_1 = C_1 \cdot \left[\cos \arctg \left(\frac{C_2}{C_1} \right) - 1 \right] + C_2 \cdot \sin \arctg \left(\frac{C_2}{C_1} \right) (3)$$

If known trigonometric relationships are used, equation (3) can be represented as:

$$x_1 = \sqrt{C_1^2 + C_2^2} - C_1. \quad (4).$$

The time from the moment the impact is applied to the moment the amplitude of the mass in the direction of impact reaches x_1 will be:

$$t_1 = \frac{1}{k} \cdot \arctg \frac{C_2}{C_1} (5)$$

After the mass of the device reaches the maximum deflection x_1 in the direction of impact, its motion changes direction, and from that moment until the moment when it reaches the maximum deflection in the direction opposite to the impact, the equation of motion will have the form:

$$x = D_1 \cdot \cos(k \cdot t) + D_2 \cdot \sin(k \cdot t) + C_1 (6),$$

$$\text{Where } D_1 = \frac{C_1(x_1 - C_1)}{\sqrt{C_1^2 + C_2^2}}, \quad D_2 = \frac{C_2(x_1 - C_1)}{\sqrt{C_1^2 + C_2^2}}.$$

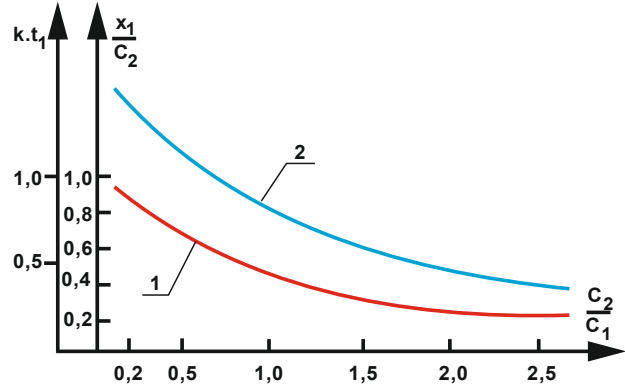


Fig.2

Fig. 2 shows a graph of the change in the amplitude x_1 , depending on the change in the amplitude of the free oscillations C_2 of the system and the time t_1 , depending on the natural frequency k , at different deviations $\frac{C_2}{C_1}$.

The largest deflection that the mass of the device will make in the direction opposite to the direction of impact will be:

$$x_2 = -x_1 + 2 \cdot C_1 \quad (7),$$

The time from the moment the impact is applied to the moment the deflection of the mass of the device in the direction opposite to the impact reaches x_2 can be determined from the equation:

$$t_2 = \frac{1}{k} \left(\arctg \frac{C_2}{C_1} + \pi \right) \quad (8),$$

The motion of the mass, from the moment t_2 , to the next maximum deflection in the direction of impact, can be expressed by the equation:

$$x_1 = E_1 \cdot \cos(k \cdot t) + E_2 \cdot \sin(k \cdot t) - C_1 \quad (9),$$

$$\text{Where } E_1 = -\frac{C_1(x_1 - 3 \cdot C_1)}{\sqrt{C_1^2 + C_2^2}}, \quad E_2 = -\frac{C_2(x_1 - 3 \cdot C_1)}{\sqrt{C_1^2 + C_2^2}}$$

The second maximum mass deflection, in the direction of impact, will be:

$$x_3 = x_1 - 4 \cdot C_1 \quad (10).$$

From expressions (2), (4), (6), (7), (9) and (2.10) it is seen that the mass of the device after the impact performs a damped mechanical oscillation. The change in amplitude for one period is $\Delta x = \mp 4 \cdot C_1$. The oscillations of the system will continue until the next deviation is between the points with coordinates $x = \pm C_1$. In this zone the elastic force is less than the friction force T .

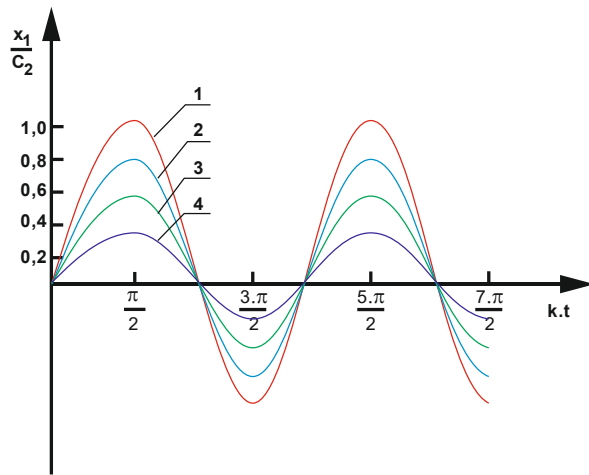


Fig.3 shows the motion of a mass subjected to a single impact at different ratios $\frac{C_2}{C_1}$.

The change in velocity and acceleration of the object's mass, for the period from the beginning of the impact until the moment it reaches the largest deviation x_1 in the direction of impact, follow from expression (2), namely:

$$\dot{x} = -C_1 \cdot k \cdot \sin(k \cdot t) + C_2 \cdot k \cdot \cos(k \cdot t) \quad (11),$$

$$\ddot{x} = -C_1 \cdot k^2 \cdot \cos(k \cdot t) + C_2 \cdot k \cdot \sin(k \cdot t) \quad (12),$$

and their maximum values will be:

$$\max \dot{x} = k \cdot \sqrt{C_1^2 + C_2^2} \quad (13) ,$$

$$\max \ddot{x} = -k^2 \cdot \sqrt{C_1^2 + C_2^2} \quad (14) .$$

When synthesizing shock protection for a device or other object, using a mechanical system of an elastic element (spring) and a friction damper from the GERWAH company, it is necessary to clarify in advance what are the permissible kinematic characteristics (mass deviation, as well as permissible linear and angular velocities and accelerations) at which the object of protection will operate reliably, i.e. it will not give a series of failures or the strength of the units and the kinematic connections between them will not be impaired.

III. RESULTS AND DISCUSSIONS

The mortar is a type of artillery weapon intended for high-angle fire against concealed targets, as well as for the destruction of field fortifications.

The main combat qualities of the mortar are: the high power of the ammunition (mines), the high rate of fire, the relatively low mass, the elementary arrangement of the mechanisms during combat use, the constant readiness to open fire, without special training of the service crew.

A characteristic feature of the mortar is: the large trajectory of the mines' flight (the firing angle allows a change from 45° to 85°) allows the destruction of concealed targets, indestructible by automatic and artillery fire.

Fig.4 shows a photo of an American field mortar M224. A characteristic feature of this type of artillery installation is the lack of any kind of damping, due to the fact that the

barrel of the gun, in its lower part, is based on the so-called a plate whose purpose is to distribute the impact of the mine detonation, transmitting it to the surface of the earth, possibly over a larger area. With each shot, the optical measuring device loses the main direction of the shot, if there is no special anti-shock protection.

This publication proposes a methodology for calculating the anti-shock protection of the measuring device, using a helical cylindrical spring and a friction damper.



Fig.4 Mortar with application of the developed damper.

The spring is made of 4X13 spring steel with a cross section of Ø5mm, number of coils $n=8$ and length $L=120\text{mm}$. The friction damper is made of a stem made of 40X steel and contacting along its length with a rubber filler.

IV. CONCLUSION

The present publication proposes a model of a single-mass anti-shock mechanism that can successfully protect the measuring instrument of any small-caliber artillery installation, such as the American model 60 mm M224, and the Russian model 82 mm battalion mortar MX82. The orientation of the anti-shock protection shown in Fig. 1 should be in a direction parallel to the body of the mortar, in order for the protection to be maximally effective, i.e.: after each detonated mine, the impact that is directed towards the plate based on the ground and the residual vibrations that cannot be absorbed by the plate, should be absorbed for one cycle by the friction damper and the spring.

In artillery installations with a large caliber, for example 120 mm or larger, this type of impact protection is ineffective and hydraulic or gas vibration dampers are used. They are mounted parallel to the body of the mortar, with the dampers usually being two, placed 180° around the barrel of the artillery unit. In self-propelled artillery units, hydraulic dampers are mandatory, which are extremely effective in preserving the integrity of the chassis of the self-propelled unit. Such a damper is mounted on the Bulgarian self-propelled mortars 2S9 "Tundzha" 120mm, manufactured in 1986-1987. which are currently in service with the Bulgarian Army.

ACKNOWLEDGMENTS

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Hybrid Plasma-Sol-Gel Technologies for Flame Retardancy and NIR Camouflage of Military Textiles: Review

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Abstract— This review examines hybrid technologies combining dielectric barrier discharge (DBD) plasma treatment and sol-gel nanocomposite coatings to improve the performance of military textiles. The paper examines cotton/polyester (CO/PES) blended fabrics that exhibit good physicochemical and comfort properties but limited thermal resistance. The reviewed literature identifies DBD plasma as an effective surface activation method that improves textile adhesion and chemical reactivity through the formation of active functional groups. The sol-gel silica matrix serves as a stable carrier for halogen-free phosphorus-nitrogen refractory systems and functional additives, contributing to improved limiting oxygen index (LOI) values and increased coating wash durability. In addition to fire protection, the reviewed studies demonstrate the potential for controlling spectral reflectance in the near-infrared (NIR) region by incorporating selected pigments, carbon-based materials, and metal oxide additives into the hybrid coating system. Such modifications can reduce the optical detectability of military textiles while maintaining the flexibility and comfort of the fabric. Based on the reviewed studies, the paper proposes a conceptual technological model for multifunctional military textiles with controlled spectral properties and improved thermomechanical performance. The review also outlines key performance indicators and future experimental directions for validating the proposed hybrid plasma-sol-gel concept on CO/PES military fabrics.

Keywords— DBD plasma; flame retardancy; military textiles; NIR camouflage.

I. INTRODUCTION

The operational environment of military personnel exposes uniforms and protective textile systems to multiple thermal hazards, including open flames, incendiary devices, explosions, and high temperatures. Consequently, flame-retardant (FR) treatments have become a strategic requirement in military textile engineering. These treatments must provide effective resistance to ignition and flame propagation and maintain protective functionality

throughout prolonged use. However, repeated laundering, mechanical abrasion, and environmental exposure can significantly alter the physicochemical properties, color stability, and overall performance of FR-treated fabrics, reducing their long-term protective efficiency [1]–[4]. Thus, washing durability and mechanical stability are critical design parameters for modern military protective textiles.

Furthermore, combining functional coatings, including nanostructured additives and metal oxide-based treatments, has shown potential to improve fire resistance and additional protective properties, such as antimicrobial activity or infrared (IR) camouflage, without damaging the mechanical integrity or comfort of textile layers [5], [6]. Chemically stabilized fire-resistant treatments, plasma or sol-gel surface alterations, and optimized fiber blends (e.g., cotton/polyester or high-performance aramids) represent a multi-faceted approach to achieving durable, operationally effective uniforms that withstand both thermal and mechanical stress. Overall, the evidence emphasizes that protective military textiles must be designed as integrated systems in which material selection, functional coatings, and durability converge under real-world stressors to maintain life-saving performance and mission readiness in extreme warfare settings.

This article does not present original experimental results. Instead, it provides a literature-based conceptual review. It presents a hybrid technological framework for the future development of multifunctional military textiles, combining plasma activation, sol-gel coatings, flame-retardant systems, and NIR signature management.

II. LITERATURE REVIEW, METHODOLOGY, AND TECHNOLOGICAL BACKGROUND

The present study is based on a qualitative literature review of scientific publications related to dielectric barrier discharge (DBD) plasma treatment, sol-gel textile coatings,

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halogen-free phosphorus–nitrogen flame-retardant systems, and near-infrared (NIR) camouflage technologies for military textiles. The analyzed sources include peer-reviewed journals, books, and conference proceedings in textile engineering, plasma processing, flame retardancy, and smart camouflage materials. The review focuses on identifying technological synergies, functional processes, and performance indicators relevant to multifunctional cotton/polyester military fabrics. The analysis focused on studies reporting working mechanisms, coating durability, flame-retardant performance, and spectral-related behavior in the NIR region.

A. Dielectric Barrier Discharge (DBD)

Dielectric Barrier Discharge (DBD) represents a form of cold atmospheric plasma generated between two electrodes separated by one or more dielectric layers, such as glass, ceramic, or quartz. This plasma can operate at atmospheric pressure, offering a versatile, energy-efficient, and environmentally friendly approach to surface modification of textile substrates [4], [5].

In textile engineering, DBD plasma treatment has been widely investigated as an effective approach to increase surface energy, improve wettability, and facilitate the deposition of functional compounds, including flame-retardant agents, hydrophobic layers, and antimicrobial finishes. Plasma-assisted activation has been shown to improve chemical uptake while preserving the mechanical integrity of textile substrates during conventional high-temperature pad–dry–cure processing [5].

Similarly, atmospheric DBD treatment has been successfully applied to cotton fabrics prior to the deposition of phosphorus-based flame-retardant systems, such as Pyrovatex CP New, in combination with the crosslinking agent Knittex FFRC. These studies show improved flame-retardant performance and higher residual tensile strength compared with conventional impregnation–drying–thermal fixation processes, thereby demonstrating the technological significance of plasma activation as a process-optimization strategy that reduces thermally induced fiber degradation [6].

DBD plasma treatment promotes the formation of reactive surface functionalities, including hydroxyl (–OH), carboxyl (–COOH), and carbonyl (–C=O) groups, which improve the interfacial adhesion, homogeneity, and durability of subsequently applied chemical and sol-gel coatings. Furthermore, plasma pre-treatment has been shown to improve capillary behavior and facilitate more efficient flame-retardant functionalization of polyester-based textile substrates [7].

It is important to emphasize that the role of DBD plasma in hybrid textile treatment systems is not to provide complete flame resistance on its own, but rather to generate a chemically active fiber surface that improves the effectiveness and durability of subsequent multifunctional coatings. Through increased surface energy and improved interfacial bonds, DBD treatment promotes uniform coating deposition and contributes to the formation of

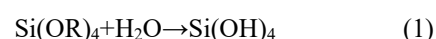
advanced textile systems with flame-retardant, ultraviolet-protective, hydrophobic, and antimicrobial properties [8].

B. Halogen-Free Phosphorus–Nitrogen Flame-Retardant Systems

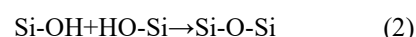
Contemporary research on textile flame retardance increasingly focuses on halogen-free systems based on phosphorus (P) and nitrogen (N). These systems are favored for their success in retarding combustion through both condensed-phase and, in some formulations, gas-phase mechanisms. In the condensed phase, phosphorus compounds promote the formation of a protective char layer that limits the heat and mass transfer between the flame and the substrate [9]. Nitrogen-containing components can enhance this effect through intumescent expansion or by synergistically stabilizing the char structure. Consequently, P/N/Si combinations are considered particularly promising for developing thin, multifunctional coatings with durable flame-retardant performance [9], [10]. For cotton-polyester blends, untreated fabrics typically exhibit low limited oxygen index (LOI) values (17%), indicating high flammability. The application of phosphorus–nitrogen sol-gel coatings can substantially increase LOI values, e.g., to 27.3–31.8%, depending on the coating composition and application parameters. Integration of plasma surface activation before coating further enhances performance by generating reactive surface groups, improving chemical bonding between the flame retardant and the fiber, and increasing washing durability—a key limitation of conventional impregnation-based treatments [7].

C. Sol-Gel Technologies

Sol-Gel technologies for textile surface modification. The sol-gel process constitutes a transition from a liquid phase (sol) to a solid three-dimensional network (gel) through hydrolysis and condensation reactions:



Condensation:



In the textile field, sol-gel technology has become an established platform for depositing thin, multifunctional coatings that impart flame-retardant, hydrophobic, ultraviolet-protective, and other advanced functional properties to textile substrates [8]. During the sol-gel process, the formation of a silicate network creates a stable inorganic matrix that improves the fixation and distribution of refractory compounds and other active additives within the coating structure. Among the most widely used precursors in textile sol-gel processing is tetraethyl orthosilicate (TEOS), owing to its high chemical reactivity, compatibility with low-temperature processing, and ability to generate homogeneous silica-based networks on fiber surfaces [11].

A major advantage of sol-gel systems is their ability to serve as carrier matrices for additional functional components, including phosphorus–nitrogen flame-retardant agents and nanoscale or microscale particles that modify surface morphology and optical behavior. The final properties of sol-gel coatings, including thickness, uniformity, flexibility, vapor permeability, and surface appearance, are strongly influenced by precursor composition, additive concentration, deposition technique, and curing conditions. Therefore, careful optimization of these parameters is required to achieve an effective balance between protective performance and physiological comfort [12].

Recent developments in UV-curable sol-gel systems have additionally expanded the applicability of this technology to temperature-sensitive textile substrates. Unlike conventional thermal curing processes, ultraviolet-assisted crosslinking allows coating stabilization at near-ambient temperatures using UV-sensitive photoinitiators. Although localized outer temperatures may increase during irradiation, they remain below the thermal degradation thresholds for cotton and polyester fibres, thereby minimizing structural damage and reducing the overall energy consumption of the coating process [12].

In addition to their flame-retardant properties, sol-gel coatings can greatly improve the hydrophobicity of textile materials. Cotton fabrics treated with silica nanoparticles and water-repellent agents have been reported to exhibit superhydrophobic characteristics, with liquid contact angles exceeding 130°, indicating substantially reduced surface wettability [13]. Such functionality is particularly important in military textile systems, where moisture accumulation may alter thermal transport properties, reduce wearer comfort, and modify the infrared radiation emitted from the clothing surface, thus affecting the near-infrared (NIR) and thermal camouflage performance of military garments under service conditions [14], [15].

D. Near-Infrared Signature Management (NIR Signature Management)

Protective military textiles are not solely mechanical or thermal barriers; control of near-infrared (NIR) reflectance is essential for operational concealment [14], [15]. NIR camouflage focuses on modifying the reflective properties of textile surfaces in the 700–1200 nm range to reduce contrast with environmental backgrounds when observed with NIR-sensitive devices. The objective is not absolute invisibility, but the reduction of spectral detectability. Pigments, coatings, and functional additives can modulate the NIR reflectivity. Approaches in “smart textiles” include incorporating carbon-based materials, metal or metal-oxide nanoparticles, and conductive polymers to tune spectral characteristics. Carbon black dispersions, for example, have been shown to effectively adjust the NIR reflectance of camouflage fabrics [16]. Sol-gel matrices can serve as carriers and stabilizing environments for such

additives, enabling the embedding of multifunctional properties—including flame retardance, water repellency, and NIR signature modulation—into a single coating system. Additionally, recent studies highlight that repeated laundering and environmental exposure can influence both the functional and aesthetic performance of treated textiles. Investigations into flame-resistant fabrics and antibacterial finishes show that appropriate sol-gel matrices, combined with plasma activation, can preserve physico-mechanical properties and maintain functional efficacy after multiple wash cycles [17], which is critical for operational dependability in military applications [18], [19].

III. STRUCTURE–PROPERTY RELATIONSHIPS IN HYBRID PLASMA–SOL–GEL COATINGS FOR MULTIFUNCTIONAL MILITARY TEXTILE APPLIC

The literature data analysed in the present study indicate that the development of multifunctional protective textiles for military applications requires the synergistic integration of surface activation technologies, inorganic/organic hybrid coatings, and halogen-free flame-retardant systems, while simultaneously preserving the near-infrared (NIR) camouflage performance and the physico-mechanical integrity of the textile substrate.

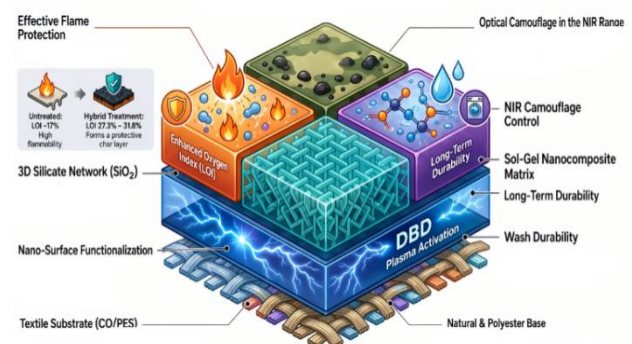


Fig. 1. Hybrid protection technologies for military textiles.

Based on the analysed literature, a conceptual hybrid technology system can be proposed to develop multifunctional military textiles that combine plasma-assisted surface activation, sol-gel nanocomposite coatings, flame-retardant additives, and NIR signature management components. The proposed system integrates complementary functional elements intended to improve thermal protection, coating durability, moisture resistance, and spectral camouflage performance, while preserving the mechanical flexibility and operational comfort of the textile substrate. Table 1 summarizes the principal components of the proposed hybrid system, their technological roles, and expected functional effects.

TABLE 1 PROPOSED HYBRID PLASMA–SOL–GEL SYSTEM FOR MULTIFUNCTIONAL MILITARY TEXTILES

Component	Function	Expected Effect
CO/PES fabric	Base textile substrate	Mechanical flexibility and wear comfort

DBD plasma treatment	Surface activation	Improved wettability and coating adhesion
Silica sol-gel matrix (TEOS)	Carrier network	Stabilization of functional additives
Phosphorus–nitrogen FR additives	Flame retardancy	Increased LOI and char formation
Carbon-based and metal-oxide additives	NIR modulation	Controlled reflectance in 700–1200 nm
Hydrophobic additives	Moisture control	Reduced water uptake
UV curing	Low-temperature crosslinking	Reduced thermal degradation

The data presented in Table 1 demonstrate that the proposed hybrid plasma-sol-gel system relies on the synergistic interaction of multiple functional components rather than on a single protective treatment. The CO/PES blended fabric serves as a mechanically flexible and operationally suitable substrate, while DBD plasma treatment serves as a surface-activation step that improves wettability and promotes stronger interfacial adhesion between the textile fibers and the subsequently deposited coating layers.

The silica-based sol-gel matrix, primarily derived from TEOS precursors, serves as a stabilizing carrier network that can incorporate multiple categories of functional additives into a unified coating architecture. In this system, phosphorus–nitrogen flame-retardant systems improve thermal stability and increase the limiting oxygen index (LOI) values by enhancing char-formation mechanisms. Simultaneously, carbon-based and metal-oxide additives enable modulation of near-infrared reflectance, which is necessary to reduce spectral detectability in NIR surveillance systems.

Hydrophobic agents further enhance operational performance by reducing water uptake and lessening moisture-related changes in thermal exchange and optical behavior. In addition, UV-curing technology provides an important processing advantage by enabling low-temperature crosslinking of the coating system, thereby reducing thermal stress and minimizing degradation of the textile substrate during finishing.

IV. OTHER RECOMMENDATIONS

A. Programs Key Performance Indicators for Future Validation

The reviewed literature indicates that future validation of hybrid plasma–sol-gel military textile systems should include both protective and operational performance criteria. The most important indicators include:

- Limiting Oxygen Index (LOI);
- Vertical flame test performance;
- Char length;
- Afterflame and afterglow time;
- Washingdurability;
- Tensile ad tear strength;
- Air permeability;

- Bending stiffness;
- Mass add-on;
- Color stability;
- Near-infrared reflectance in the 700–1200 nm range.

B. Effect of Dielectric Barrier Discharge (DBD) Plasma on Textile Surface Reactivity

One of the most significant findings from recent research is that dielectric barrier discharge (DBD) plasma treatment offers an effective, relatively mild means of tailoring the surface chemistry of textile materials without inducing bulk fiber degradation. DBD plasma, generated at atmospheric pressure between electrodes separated by dielectric barriers, produces a chemically active environment containing ions, radicals, metastable species, and UV photons, all of which can interact with the outermost molecular layers of the textile substrate [4], [5].

For both cellulosic and synthetic textile materials, plasma exposure forms oxygen-containing polar functional groups, such as hydroxyl (–OH), carbonyl (–C=O), and carboxyl (–COOH), while also partially cleaning and micro-roughening the fiber surface. These modifications increase surface free energy, improving wettability, capillary transport, and substrate affinity for subsequent chemical treatments [7]. Technologically, this is important because a persistent limitation in conventional textile finishing is incomplete penetration and weak fixation of functional agents on relatively inert or hydrophobic surfaces, especially in polyester-containing blends. For polyester and polyester-rich blended fabrics, plasma pre-treatment facilitates the uptake and distribution of flame-retardant formulations by enhancing fiber surface accessibility and improving the uniformity of coating deposition. This effect is valuable in systems that would otherwise require aggressive thermal fixation for acceptable bonding. DBD plasma acts not only as a surface-cleaning technique but also as a chemical activation step that partially compensates for polyester's intrinsic low reactivity. For cotton-based systems, plasma activation is equally important, though the rationale differs. Since cotton already has abundant hydroxyl groups, the benefit of DBD treatment lies less in creating new reactive chemistry and more in increasing accessibility and energetic state of the fiber surface, while improving homogeneity of subsequent deposition. Studies with phosphorus-based flame-retardant formulations, such as Pyrovatex CP New, show plasma-assisted pretreatment can improve finishing efficiency and may reduce the severity of post-application curing conditions needed for acceptable flame-retardant performance [7].

Therefore, within the framework of advanced military textile finishing, DBD plasma should not be regarded as a stand-alone flame-retardant treatment, but rather as a strategic enabling technology that improves the interfacial compatibility between the textile substrate and the functional coating. This role is particularly relevant in

hybrid treatment concepts, where coating adhesion, wash resistance, and minimization of mechanical damage are decisive parameters for long-term field performance.

C. Sol-Gel Coatings as Hybrid Platforms for Functional Surface Engineering.

The reviewed literature strongly supports the conclusion that sol-gel technology is one of the most versatile and scientifically robust approaches for functionalizing textile surfaces. From a materials engineering perspective, the importance of sol-gel coatings does not lie in their ability to form thin films, but in the fact that these films can serve as multifunctional carrier matrices. In other words, the silica-based network is not only a protective shell but also a structurally tunable host phase that can immobilize flame-retardant molecules, nanoparticles, pigments, and other performance-enhancing additives. This gives sol-gel systems a clear advantage over conventional monofunctional finishes, which are often limited by poor durability or additive incompatibility when applied in a single bath [9], [20].

The effectiveness of sol-gel systems for textile applications depends on network architecture, crosslink density, and interfacial bonding with the substrate. When optimized, these coatings provide uniform coverage without excessively affecting textile flexibility or handle. However, sol-gel performance depends heavily on formulation. Excessively dense or brittle silica networks may reduce drapeability, increase stiffness, or cause cracks upon repeated deformation, especially in woven fabrics under flexural stress. Successful implementation requires balancing inorganic network formation with textile-specific requirements such as softness, breathability, and laundering resistance. An important finding from the reviewed studies is that sol-gel-derived coatings can simultaneously enhance flame retardancy, hydrophobicity, UV protection, and surface durability, making them particularly attractive for defence textiles exposed to complex environmental and operational stressors. This multifunctionality is highly relevant in military environments where separate finishing steps for each property would increase process complexity, weight, and cost [8].

The sol-gel process, based on the hydrolysis and condensation of alkoxide precursors such as tetraethyl orthosilicate (TEOS), enables the formation of three-dimensional inorganic or hybrid inorganic-organic networks at comparatively low processing temperatures [11].

Another important technological implication concerns UV-curable solgel systems. The use of photo-initiated curing, rather than conventional thermal curing, is particularly attractive for heat-sensitive or dimensionally unstable textile substrates. Rico et al. (2023) demonstrated that UV-induced sol-gel curing can proceed under relatively mild thermal conditions, thereby lowering

thermal stress on the substrate while maintaining coating functionality [12]. This is of considerable industrial significance because it opens the possibility of lower energy, higher-throughput finishing processes compatible with blended and synthetic military fabrics.

Particularly noteworthy is the observation that silica-based sol-gel layers can significantly modify surface wetting behavior. Bae et al. (2009) demonstrated that cotton fabrics treated with silica nanoparticles and a water-repellent agent exhibited contact angles exceeding 130°, indicating strong hydrophobicity [13]. From a military perspective, this is not merely a comfort-related feature. Moisture accumulation in garments can alter thermal exchange, increase garment mass, compromise wearability, and potentially affect the optical and infrared behavior of the textile surface. Thus, hydrophobic sol-gel systems may indirectly contribute to both operational comfort and signature stability under field conditions.

Taken together, the literature suggests that sol-gel technology should be interpreted not simply as a coating method but as a materials design platform for engineering textile surfaces with customized multifunctionality.

D. Flame-Retardant Performance of Halogen-Free Phosphorus–Nitrogen Systems

The literature reports that untreated CO/PES blends typically have low oxygen index (LOI) values, often around 17%, confirming their pronounced flammability. In contrast, incorporating phosphorus–nitrogen flame-retardant systems via sol-gel or related hybrid deposition routes can substantially increase LOI values, in some cases reaching approximately 27.3–31.8%, depending on the exact formulation, add-on level, and processing conditions [6]. From a fire safety perspective, this increase is highly significant, as it indicates a transition from easily combustible behaviour toward markedly improved resistance to fire spread.

A major result emerging from the analysed literature is the clear shift towards halogen-free flame-retardant systems, particularly those based on phosphorus (P) and nitrogen (N) chemistry. This transition is driven not only by environmental and toxicological considerations, but also by growing evidence that P/N systems can provide effective fire protection in textiles through multiple, complementary mechanisms [10].

This mechanism is especially important in cotton/polyester (CO/PES) blends, which are widely used in military clothing but exhibit notably difficult fire behavior. Cotton contributes to rapid ignition and afterglow due to its cellulosic nature, whereas polyester tends to melt, shrink, and drip, which may exacerbate burn injuries. The combined flammability of these blended systems makes them highly relevant targets for advanced flame-resistant engineering. However, a critical point that repeatedly emerges in the literature is that initial flame-retardant efficacy alone is insufficient if the treatment lacks durability. A coating or finish that performs well only before washing has limited practical value for military

uniforms intended for prolonged field use. In this context, the combination of plasma activation with phosphorus–nitrogen systems appears particularly promising. Plasma-generated reactive groups can enhance the chemical anchoring of flame-retardant formulations or sol-gel matrices to the fibre surface, thereby reducing wash-off and improving long-term functional retention [7]. This strength issue is reinforced by recent work on flame-resistant military fabrics, which reported that repeated washing can cause measurable changes in both physico-mechanical properties and color characteristics, underscoring the need to evaluate flame-retardant systems not just under ideal laboratory conditions but also under realistic maintenance scenarios. These conclusions are particularly relevant for military textiles, where performance retention after repeated laundering is not optional, but operationally mandatory.

The flame-retardant action of phosphorus-containing compounds is primarily attributed to the condensed phase, where they promote dehydration, cyclization, and carbonization, thereby facilitating the formation of a coherent char layer on the textile surface. This carbonaceous barrier acts as a thermally insulating, mass-transfer-limiting shield, reducing the release of flammable volatiles and slowing heat feedback from the flame to the substrate. Nitrogen-containing components can reinforce this effect through intumescent expansion, gas release, and synergistic stabilization of the developing char structure [8].

Accordingly, the most hopeful direction is not simply the application of an isolated flame-retardant chemistry, but the construction of durable hybrid protective systems in which phosphorus-nitrogen chemistry is structurally integrated into an inorganic or hybrid matrix and further stabilized by controlled surface activation.

E. Implications for Near-Infrared (NIR) Signature Management

A further important conclusion drawn from the reviewed literature is that the design of military protective textiles should not focus solely on reducing flammability. In contemporary operational environments, military uniforms must also provide effective spectral concealment, particularly in the near-infrared (NIR) region, where night vision devices and advanced surveillance systems operate [14], [15]. The NIR spectral region relevant to textile camouflage generally spans approximately 700–1200 nm. The main goal is not complete invisibility, but rather to adjust the textile's reflectance profile to more closely match the surrounding environment. This achievement requires accurate control not only of visible coloration but also of pigment composition, surface morphology, and optical effects arising from coatings and functional additives.

In this context, the literature emphasizes the key role of carbon-based materials and metal or metal-oxide additives in spectral-tuning applications. Carbon in particular is widely recognized as an efficient electromagnetic absorber and has been investigated for its influence on the reflective behavior of textile materials in the visible and near-infrared

regions. Conductive or semiconductive particulate phases can greatly alter electromagnetic dynamics and may therefore contribute to NIR signature management when appropriately incorporated into textile-compatible matrices [16].

These findings provide a strong scientific rationale for using sol-gel matrices as multifunctional carriers for NIR-active additives. Within such systems, the inorganic network can improve the physical stabilization and homogeneous distribution of carbonaceous or oxide-based particles while simultaneously providing additional protective functionalities, including flame retardancy and water repellency. The scientific significance of this approach lies in its potential to integrate traditionally separate defense requirements—thermal protection and spectral camouflage—into a single multifunctional material platform. At the same time, the literature indicates that factors such as surface moisture, repeated laundering, and progressive coating degradation may significantly affect NIR performance over time [17]. Therefore, the development of military camouflage textiles for NIR applications must incorporate durability considerations alongside spectral optimization. This further stresses the relevance of combined plasma-sol-gel flame-retardant systems, whose performance should be evaluated not only under initial laboratory conditions but also under repeated environmental exposure and maintenance-related stress. Future optimization of NIR camouflage systems should focus on tailoring the spectral reflectance characteristics of treated fabrics to specific operational environments, including woodland, desert, and urban terrains. This requires careful adjustment of parameters such as pigment concentration, particle size distribution, and coating thickness. In addition, potential trade-offs between flame-retardant efficiency and NIR camouflage performance must be carefully considered, as certain phosphorus-containing or inorganic additives may alter optical reflectance across both the visible and near-infrared spectral regions.

F. Relationship Between Surface Functionalization and Mechanical Integrity.

An important scientific and practical issue in advanced textile finishing is the balance between functional enhancement and preservation of substrate integrity. High-performance coatings are of limited utility if they induce unacceptable deterioration in tensile strength, flexibility, abrasion resistance, or color stability. According to established fiber chemistry principles, the mechanical performance and functional response of textile substrates are strongly governed by fiber morphology, polymer composition, and intermolecular interactions. The reviewed studies show that the application of inorganic particles or metal-oxide-based functional systems can affect physical and mechanical performance, as well as ergonomics and comfort, in different ways, depending on particle chemistry and deposition uniformity. A study of antibacterial coatings for shoe lining materials reported that

different metal oxide systems affect the substrate's physicochemical properties to varying degrees, indicating that functionality cannot be considered independently of structural characteristics [18], [21].

Studies involving the addition of silica or metal oxide-based coatings can improve fire resistance, antimicrobial resistance, or signature control, but can also modify flexural stiffness, tear resistance, and interfiber friction. Therefore, the formulation should be treated as a multifactorial optimization task in which protective properties, comfort, and mechanical resistance are optimized simultaneously. In this context, DBD plasma and sol-gel technologies offer a significant advantage, as they enable modifications confined primarily to the fiber surface without substantially altering the fiber's bulk structure. By localizing functionalization at or near the external fiber interface, these approaches minimize mechanical and chemical stress on the textile substrate. As a result, the likelihood of increased brittleness, deterioration of mechanical properties, or undesirable weight gain is reduced. This represents a substantial advantage over more invasive finishing methods, which typically rely on high add-on levels or repeated impregnation cycles.

IV. CONCLUSION

The reviewed literature demonstrates that advanced protective military textiles must be engineered using an integrated, multi-parameter design strategy that simultaneously targets flame retardancy, long-term durability, and spectral management. Dielectric barrier discharge (DBD) plasma has been shown to be an efficient surface activation technology that increases surface energy and reactivity by generating polar functional groups and microscale surface modifications, thereby significantly improving interfacial adhesion and the stability of subsequent functional coatings. In parallel, sol-gel processing provides a highly adaptable inorganic-organic hybrid platform that can structurally embed halogen-free phosphorus-nitrogen flame-retardant systems, as well as hydrophobic agents and near-infrared (NIR)-active additives, within a unified coating architecture.

For CO/PES military fabrics, the synergistic combination of plasma pre-treatment and phosphorus-nitrogen-based sol-gel systems enables a coordinated enhancement of critical performance metrics, including limiting oxygen index (LOI), laundering resistance, and mechanical integrity, while enabling controlled tuning of NIR reflectance in the 700–1200 nm spectral window. The proposed framework integrates substrate engineering, plasma activation, sol-gel formulation design, and standardized multifunctional performance metrics, establishing a coherent methodological basis for systematic optimization and experimental validation. Collectively, the hybrid plasma-sol-gel approach constitutes a robust materials engineering paradigm for

next-generation multifunctional military textiles, enabling the concurrent realization of fire safety, environmental resilience, and adaptive near-infrared signature control within a single integrated functional system.

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On the Vibrations of Multi-Cylinder Marine Diesel Generators

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Abstract— In modern ship power plants with electric propulsion motors, the main ship power system consists of powerful multi-cylinder diesel generators. The engine and the generator are mounted on a common frame, which is attached to the ship's hull through resilient (elastic) elements.

Minimizing the vibrations induced in the ship's hull is achieved by refining the mechano-mathematical models. In the present work, this is performed using a mechano-mathematical model in which the diesel-generator-frame system is modeled as an elastic body with distributed parameters.

A model has been developed in which the ship's power plant undergoes vibrations in a single plane. The resulting system of differential equations describes the forced vibrations of the proposed dynamic model.

The natural frequencies of free vibrations have been obtained. Forced vibrations excited by the imbalance of the generator rotor are investigated.

Results from experimental studies of a nine-cylinder diesel generator are presented.

The presented theoretical and experimental results demonstrate the necessity of accounting for bending vibrations when investigating the overall vibrations of resiliently mounted multi-cylinder diesel generators.

Keywords— diesel generators; natural frequencies; oscillation.

I. INTRODUCTION

Marine diesel generators are mounted elastically to minimize the vibrations that excite the ship's hull. The vibration exciters are the unbalanced inertial forces of the diesel engine and the unbalance of the generator rotor. The vibrations are studied using mathematical models [1-3] with varying degrees of complexity. Typically, the object is modeled as a rigid body with one, two or six degrees of

freedom. Attempts to minimize the weight of industrial units through various optimization procedures have led to the influence of the elasticity of the machine body on the vibration state [4-8]. The effect is most pronounced in powerful elastically mounted industrial fans. The frame on which the fan and engine are mounted performs bending vibrations [4, 6, 7, 8]. These vibrations can be of high intensity at resonance, despite the elastic mounting. The elasticity of the main ship engines in large ships [7] is a cause of excitation of vibrations because of the elastic anisotropy of the crankshaft. When the ship is loaded, the multi-cylinder engine is deformed because of the deformation of the ship hull. The misalignment of the bearings caused by the elastic deformation of the engine is the cause that leads to excitation of vibrations from the crankshaft. In modern ship power systems with rowing electric motors, the main ship power system consists of powerful multi-cylinder diesel generators. The engines have fully balanced inertial forces. The excitation of vibrations can be an imbalance of the generator rotor or inhomogeneity of the magnetic field. The engine and generator are mounted on a common frame, which is attached to the ship hull by elastic elements. Minimization of vibrations excited on the ship hull is achieved by improving the mechano-mathematical models. In the present work this is done through a mathematical model in which the system - diesel generator - frame is modeled as an elastic body (Fig. 1).

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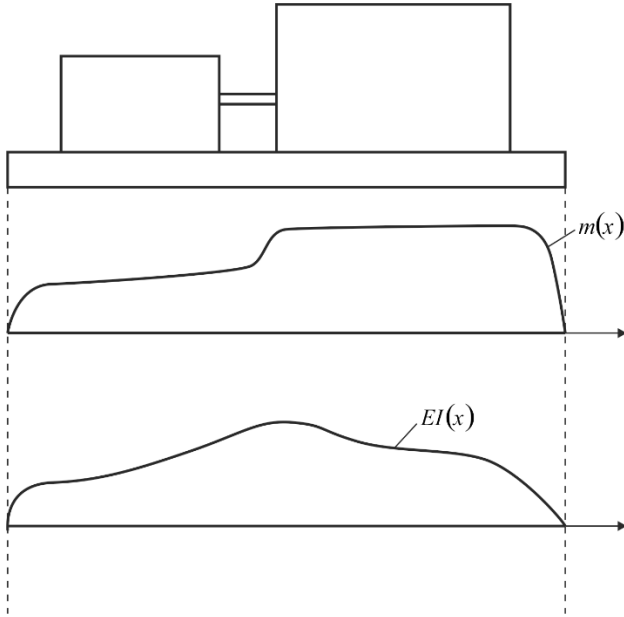


Fig.1. System frame.

The machine unit is a body with distributed parameters. The elastic properties are given by the function $EJ(x)$, and the mass ones through the function $m(x)$. C E is denoted by the modulus of elasticity, and by $J(x)$ the moment of inertia of the geometric sections. In the model presented in Fig. 1, the elastic suspension is not represented. It consists of n - number of elastic elements (Fig. 2) with stiffness $C_i (i = 1, 2, \dots, n)$.

We will build a model in which the ship's power system performs vertical oscillations in one plane (Fig.2).

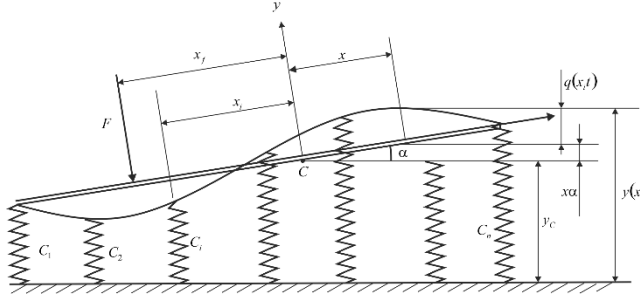


Fig.2. Vertical oscillations.

Oscillations of the center of mass C are marked with y_c , and the angular oscillations about an axis passing through the center of mass (orthogonal to the plane) are denoted by α . The elastic beam with distributed parameters $m(x)$ and $EJ(x)$ through which the diesel generator is modeled together with the frame performs oscillations, which are indicated by $q(x,t)$. With F is the force that excites oscillations as a result of unbalance of the rotor of the electric motor or inhomogeneity of the electromagnetic field. The force is applied in a cross section x_f .

The transverse displacement during vibrations of the beam with distributed parameters will be represented in the form

$$(1) \quad q(x,t) = \mathcal{G}(x)\varphi(t)$$

where $\mathcal{G}(x)$ is the form of the free vibrations of the elastic beam, and $\varphi(t)$ is an unknown function of time. The displacement resulting from the oscillations of the cross-section with coordinate x we mean by $y(x,t)$ (Fig. 2). It is the result of the transverse vibrations of the beam as an elastic body.

$q(x,t)$ and the vibrations of the beam as a rigid body defined by $y_c(t)$ and $\alpha(t)$:

$$(2) \quad y(x,t) = q(x,t) + y_c(t) + x\alpha(t)$$

Assuming generalized coordinates $\varphi(t), y_c(t), \alpha(t)$ we will compose the differential equations describing oscillations, applying the Lagrange formalism

Kinetic energy has the form:

$$(3) \quad T = \frac{1}{2} \int_0^L \dot{y}^2(x,t) m(x) dx$$

we substitute (2) into (3) and obtain

$$(4)$$

$$T = \frac{1}{2} M \dot{\varphi}^2 + \frac{1}{2} m \dot{y}_c^2 + \frac{1}{2} J_z \dot{\alpha}^2 + m_1 \dot{\varphi} \dot{y}_c + m_2 \dot{\varphi} \dot{\alpha} + m_3 \dot{y}_c \dot{\alpha}$$

where:

$$(5)$$

$$(5.1) \quad M = \int_0^L \mathcal{G}^2(x) m(x) dx$$

$$(5.2) \quad J_z = \int_0^L x^2 m(x) dx$$

$$(5.3) \quad m_1 = \int_0^L \mathcal{G}(x) m(x) dx$$

$$(5.4) \quad m_2 = \int_0^L \mathcal{G}(x) x m(x) dx$$

$$(5.5) \quad m_3 = \int_0^L x m(x) dx$$

Potential energy has the form:

$$(6) \quad \Pi = \frac{1}{2} \int_0^L EJ(x) y''(x,t) dx + \frac{1}{2} \sum_{i=1}^n C_i y_i^2(x,t)$$

$$\text{here } y'' = \frac{d^2 y}{dx^2}$$

x_i - coordinate of i - elastic element of the suspension with stiffness C_i .

After substituting (2) into (6) we obtain

$$(7) \quad \Pi = \frac{1}{2} C \varphi^2 + \frac{1}{2} \sum_{i=1}^n C_i [\mathcal{G}(x_i) \varphi + y_c + x \alpha]^2$$

where

$$(8) \quad C = \int_0^L EJ(x) \mathcal{G}''(x)^2 dx$$

$$\mathcal{G}'' = \frac{d^2 \mathcal{G}}{dx^2}$$

The possible work is determined by

$$\delta A = F \delta y = F [\mathcal{G}(x_f) \delta \varphi + \delta y_c + x_f \delta \alpha]$$

from here we get the generalized forces

$$Q_\varphi = F(t) \mathcal{G}(x_f), \quad Q_{y_c} = F(t), \quad Q_\alpha = F(t) x_f$$

Applying Lagrange's formalism, the equations are obtained:

$$(9) \quad \begin{cases} M \ddot{\varphi} + m_1 \ddot{y}_c + m_2 \ddot{\alpha} + C \varphi + \sum C_i [\mathcal{G}(x_i) \varphi + y_c + x_i \alpha] \mathcal{G}(x_i) = F \mathcal{G}(x_f) \\ m \ddot{y}_c + m_1 \ddot{\varphi} + m_3 \ddot{\alpha} + \sum C_i [\mathcal{G}(x_i) \varphi + y_c + x_i \alpha] = F \\ J \ddot{\alpha} + m_2 \ddot{\varphi} + m_3 \ddot{y}_c + \sum C_i [\mathcal{G}(x_i) \varphi + y_c + x_i \alpha] x_i = F x_f \end{cases}$$

The system of differential equations (9) describes the forced oscillations of the dynamic model in Fig. 2, through which the oscillations of the diesel generator are modeled. The function $\mathcal{G}(x)$ defines the form of free oscillations of the elastic beam with distributed parameters. The principal vector of the vertical inertial forces must be equal to zero

$$(10) \quad \int_0^L m(x) \ddot{q} dx = 0$$

The principal moment of inertia forces must also be equal to zero:

$$(11) \quad \int_0^L m(x) \ddot{q} x dx = 0$$

After substituting (1) into (10) and (11) we obtain:

$$(12) \quad \begin{cases} \int_0^L m(x) \mathcal{G}(x) dx = 0 \\ \int_0^L m(x) \mathcal{G}(x) x dx = 0 \end{cases}$$

It follows from this that for (5.3) and (5.4) we obtain

$$(13) \quad m_1 = 0, \quad m_2 = 0$$

The coordinate system (XY) is with origin at the center of mass. It follows that for (5.5) is satisfied.

$$(14) \quad m_3 = \int_0^L x m(x) dx = X_c m = 0$$

Based on (13) and (14), the system of differential equations (9) takes the form:

$$(15) \quad \begin{cases} M \ddot{\varphi} + C \varphi + \sum C_i [\mathcal{G}(x_i) \varphi + y_c + x_i \alpha] \mathcal{G}(x_i) = F \mathcal{G}(x_f) \\ m \ddot{y}_c + \sum C_i [\mathcal{G}(x_i) \varphi + y_c + x_i \alpha] = F \\ J \ddot{\alpha} + \sum C_i [\mathcal{G}(x_i) \varphi + y_c + x_i \alpha] x_i = F x_f \end{cases}$$

The free (bending) vibrations of the elastic beam with distributed parameters are described by the equation

$$(16) \quad M \ddot{\varphi} + C \varphi = 0$$

Free vibrations are of the form

$$(17) \quad \varphi = \Phi \sin p_c t$$

Substituting (17) into (16) we obtain the frequency of free (bending) vibrations.

$$(18) \quad p_c^2 = \frac{C}{M} = \frac{\int_0^L EJ(x) (\mathcal{G}''(x))^2 dx}{\int_0^L m(x) \mathcal{G}^2(x) dx}$$

This is the frequency of (bending) vibrations of the free (unsupported) beam.

The actual forms of the free vibrations are not known. For any given function $\mathcal{G}(x)$ corresponds to a certain value of P_c . According to Rayleigh's theorem, the functional (18) is minimized for the true form of oscillation. The lowest (first) eigenfrequency corresponds to a two-node form of oscillation, the second to a three-node form (Fig. 3), and so on.

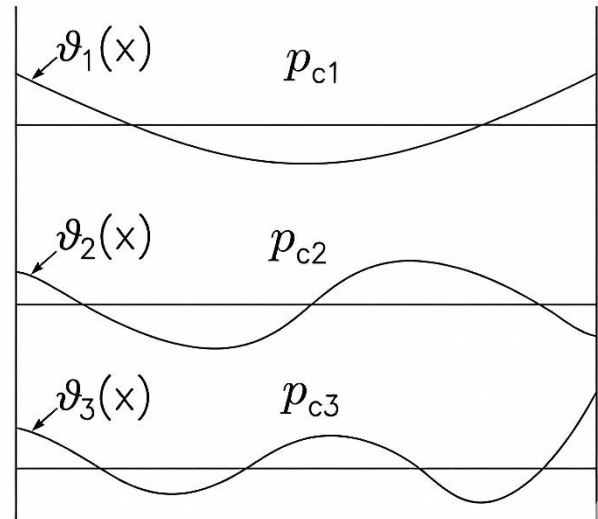


Fig.3. Node forms of oscillation.

The free (bending) vibrations of the elastically mounted beam are described by the equation (19)

$$M \ddot{\varphi} + \left[C + \sum C_i \mathcal{G}^2(x_i) \right] \varphi = 0$$

From here we obtain the frequency of free (bending) vibrations of the elastically mounted beam

$$(20) \quad p^2 = \frac{C + \sum C_i \mathcal{G}^2(x_i)}{M} = p_c^2 + \frac{\sum C_i \mathcal{G}^2(x_i)}{M}$$

The vibrations of the beam as a rigid body are described by the equations

$$(21) \quad \begin{cases} m \ddot{y}_c + C_0 y_c + C_x \alpha = 0 \\ J \ddot{\alpha} + C_x y_c + K \alpha = 0 \end{cases}$$

where

$$C_0 = \sum C_i, \quad C_x = \sum C_i x_i, \quad K = \sum C_i x_i^2$$

free vibrations are of the form

$$y_c = A \sin p_r t, \quad \alpha = B \sin p_r t$$

After substitution in (21) we obtain the frequency equation

$$(22) \Delta = \begin{vmatrix} -mP_T^2 + C_0 & C_x \\ C_x & -IP_T^2 + K \end{vmatrix} = 0$$

$$\Delta = mIP_T^4 - (mK + IC_0)P_T^2 + C_0K - C_x^2 = 0$$

The solution of the biquadratic equation defines the values of the free vibration frequencies of the "rigid" elastically mounted beam. These are the free vibration frequencies of the elastically mounted diesel generator, which do not consider the elastic properties of the diesel generator - frame structure. These frequencies are obtained by applying existing calculation methods.

Forced oscillations are described by the system of differential equations (15), with F is the force that excites oscillations.

Multi-cylinder internal combustion engines have balanced inertial forces. Oscillations are excited by an imbalance of the generator rotor or because of inhomogeneity of the stator magnetic field. These forces, regardless of their different nature, are harmonic functions of the rotational frequency.

$$(23) F = F_0 \sin \omega t$$

Based on (23), the system of differential equations (15) takes the form:

$$M\ddot{\varphi} + C_1\varphi + C_2y_c + C_3\alpha = F_0I(x_f)\sin \omega t$$

$$(24) m\ddot{y}_c + C_2\varphi + C_0y_c + C_x\alpha = F_0 \sin \omega t$$

$$I\ddot{\alpha} + C_3\varphi + C_xy_c + K\alpha = F_0x_f \sin \omega t$$

where:

$$C_1 = C + \sum C_i g^2(x_i)$$

$$(25) C_2 = \sum C_i g(x_i)$$

$$C_3 = \sum C_i g(x_i)x_i$$

The solution of (24) is of the form

$$\varphi = A_\varphi \sin \omega t$$

$$y_c = A_y \sin \omega t$$

$$\alpha = A_\alpha \sin \omega t$$

The amplitudes of oscillations are obtained as a result of solving the algebraic system of equations:

$$(26) \begin{cases} (C_1 - M\omega^2)A_\varphi + C_2A_y + C_3A_\alpha = F_0g(X_f) \\ (C_y - m\omega^2)A_y + C_2A_\varphi + C_x\alpha = F_0 \\ (K - J\omega^2)A_\alpha + C_3A_\varphi + C_xA_y = F_0X_f \end{cases}$$

The bending vibrations of the elastically mounted beam with distributed parameters are described by the equation:

$$(27) M\ddot{\varphi} + C_1\varphi = F_0g(X_f)\sin \omega t$$

When the frequency of free bending vibrations is satisfied $p = \omega$

resonant bending vibrations occur.

The vibrations of the aggregate as a rigid body are described by the equations

$$(28) \begin{cases} m\ddot{y}_c + c_yy_c + C_x\alpha = F_0 \sin \omega t \\ J\ddot{\alpha} + C_xy_c + K\alpha = F_0X_f \sin \omega t \end{cases}$$

When it is fulfilled

$$p_T = \omega$$

resonant vibrations occur on the "rigid" elastically mounted beam, which is used to model the aggregate. The intensity of the bending vibrations depends on the value of the shape of the bending vibrations $g(x_f)$ in the cross section where the force is applied F . If $g(x_f) = 0$, then regardless of the magnitude of the exciting force, it will not excite oscillations. At a large value of $g(x_f)$, a small force can excite substantial vibrations. Between bending vibrations and vibrations of the aggregate as a rigid body $(y_c(t), \alpha(t))$ there is only deformation connectivity. Unlike dynamic (inertial) connectivity, it is weak. That is why it is essential to consider partial subsystems:

- bending vibrations $\varphi(t)$
- oscillations like a rigid body $(y_c(t), \alpha(t))$.

and the ratio of the partial natural frequencies p and p_T with the excitation frequency ω .

The proximity of p to ω causes the excitation of intense bending vibrations, and the proximity of p_T to ω causes excitation of intense general oscillations.

Experimental results.

The object of the experimental research is a two-cylinder diesel generator with a power of kW at 720 rpm.

The vibrations were measured at 27 equally spaced points along the length of the frame.

The oscillation spectrum is dominated by a harmonic with a rotational frequency (720 rpm).

Point	RMS	point	RMS	point	RMS
1	14,5	10	12	19	6,6
2		11	11,8	20	6
3		12	10,5	21	5,6
4	15,6	13	10,5	22	5
5	16	14	9,8	23	4,6
6	15	15	8,8	24	4,25
7	15	16	8,6	25	4
8	15	17	7,6	26	4
9	13	18	7	27	3,8

The table presents data on the oscillations with a rotational frequency, and Fig. 4 presents a graphical representation

of the law of variation of the fundamental harmonic along the length of the frame.

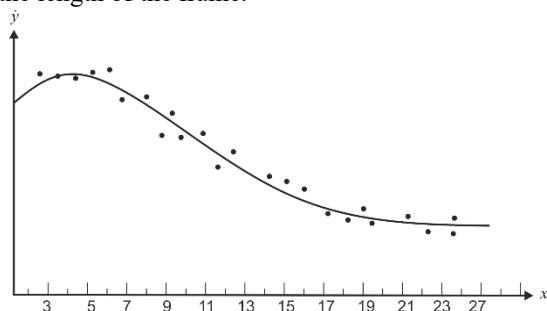


Fig.4. The law of variation of the fundamental harmonic along the length of the frame.

Fig. 5-a shows the experimentally obtained bending oscillations. The shape of the bending oscillations is visible.

Fig. 5-b shows the experimentally obtained total oscillations (oscillations as a rigid body). There is a large difference in the oscillations at both ends as a result of the uneven distribution of the mass.

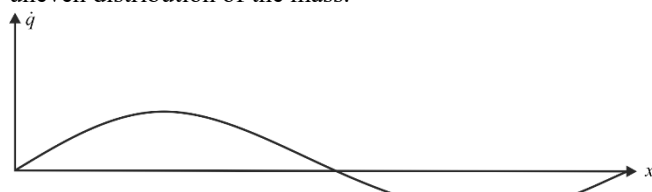


Fig.5-a. Experimentally obtained bending oscillations.

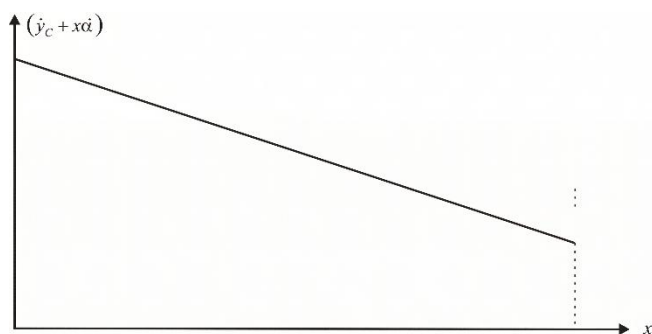


Fig.5-b. Experimentally obtained total oscillations.

Fig. 6 presents some spectra of the oscillations at several points of the frame.

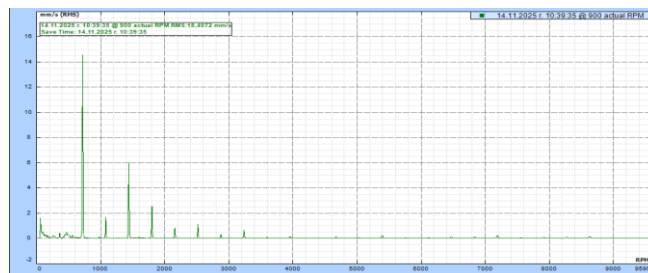


Fig.6-1. Spectra of the oscillations at several points of the frame, example-1.

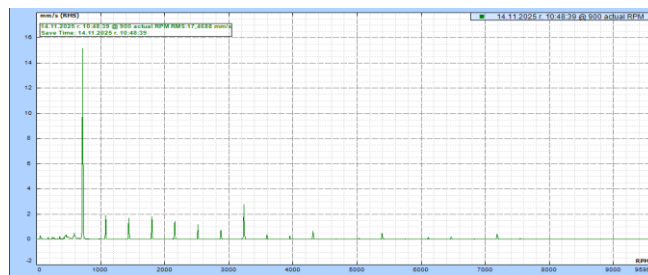


Fig.6-2. Spectra of the oscillations at several points of the frame, example-2.

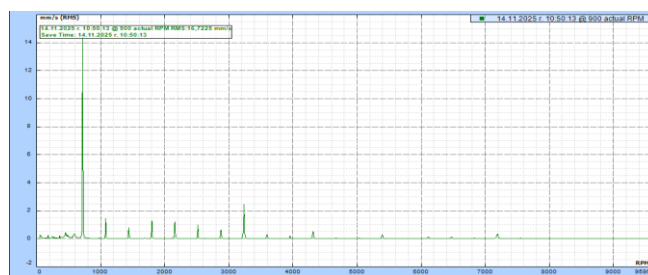


Fig.6-3. Spectra of the oscillations at several points of the frame, example-3.



Fig.6-4. Spectra of the oscillations at several points of the frame, example-4.

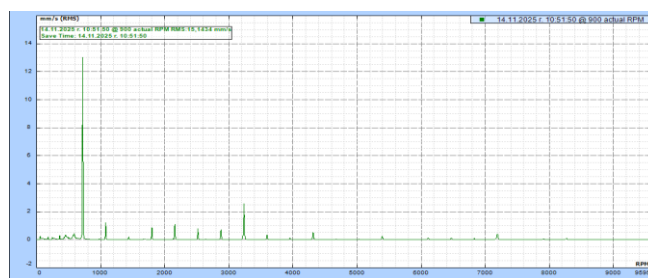


Fig.6-5. Spectra of the oscillations at several points of the frame, example-5.

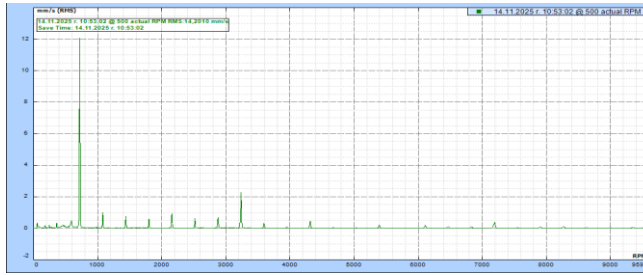


Fig.6-6. Spectra of the oscillations at several points of the frame, example-6

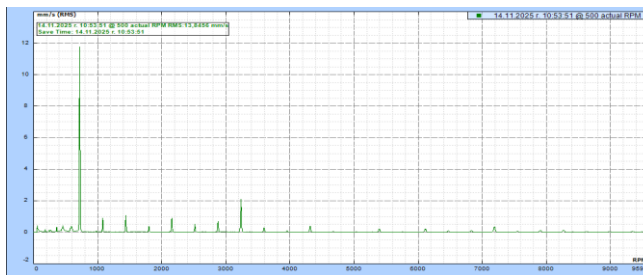


Fig.6-7. Spectra of the oscillations at several points of the frame, example-7.

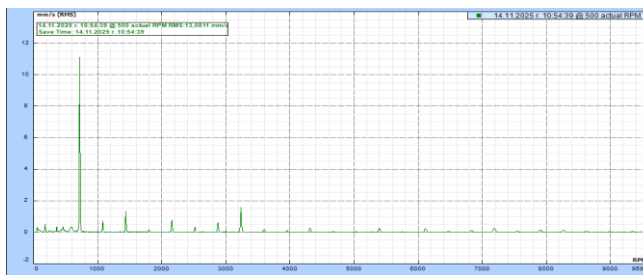


Fig.6-8. Spectra of the oscillations at several points of the frame, example-8.

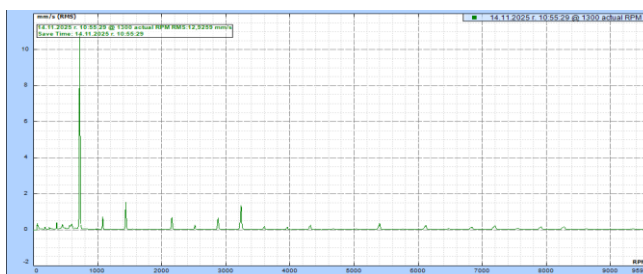


Fig.6-9. Spectra of the oscillations at several points of the frame, example-9.

CONCLUSION

The presented theoretical and experimental results determine the need to take into account the bending oscillations when studying the total oscillations of elastically mounted multi-cylinder diesel generators.

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Automated Loading and Unloading of CNC Vertical Milling Centers

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Abstract—The automation of loading and unloading operations for CNC vertical milling centers has become increasingly important due to rising production costs, labor shortages, and the pursuit of higher productivity and efficiency. This paper investigates the challenges associated with automating these processes, particularly focusing on optimizing workspace utilization, reducing auxiliary times, and improving overall workflow in CNC production environments. An overview of CNC technology development and its current capabilities is provided, highlighting the essential role of G-code programming and the transition from manual to computer-aided manufacturing. Key issues such as the high cost of programming for small batches, difficulty in recruiting skilled operators, and the economic factors influencing automation decisions are analyzed. The study emphasizes the critical importance of careful investment planning, including return on investment (ROI) considerations, productivity gains, and quality improvements. Practical guidelines for robot selection, end-effector design, and CNC-machine communication integration are proposed, along with a workflow model for automating part handling tasks. An experimental application on a VMC 1000L vertical milling center demonstrates the practical aspects and challenges of implementing an automated loading/unloading system, including necessary

machine modifications like door automation. The paper concludes that although automation offers significant benefits, it is not universally applicable; a detailed feasibility study based on batch sizes, product complexity, and financial evaluation is crucial for success. Hybrid approaches combining manual and automated operations are suggested for flexible and cost-effective manufacturing strategies. The study highlights the growing role of intelligent automation as a response to market dynamics, labor trends, and technological advancements in the CNC manufacturing sector.

Keywords— CNC machines, part loading, part unloading, robot integration

I. INTRODUCTION

This paper suggests some considerations regarding CNC vertical milling centers and their loading and unloading operations in an automated manner.

CNC machines have gone through rapid development in the past 20-30 years from basic NC controls up to modern, 5-axis and more automated solutions. They are irreplaceable since most of the advanced parts are processed on such machines. On the market, there are 2.5D,

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3-axis, 3+2-axis and 5-axis machines. The difference between 3+2-axis and 5-axis is the simultaneous control of all axes on the 5-axis machine whereas the 3+2-axis only allows for indexing movements with the head that are not coordinated with the other axes.

A typical CNC machine has a steel table with slots for fixing parts, vices and other accessories, optionally a tool measuring system [1]. A rotary tool magazine with 16-30 tool slots is a nice automation solution. The CNC control varies from machine to machine with the most popular ones being Sinumerik 808D from Siemens, others are from the companies Fanuc, Heidenhain, Mazak, etc. The CNC system communicates with each CNC axis and sends commands to the drives, preferably via an Ethernet-based protocol.

CNC machines understand G-code, their native language. While there are some dialects of the language, generally all instructions are common with only minor differences. G-code could be typed manually. However, this is the old-fashioned way and nowadays CAM products are used. They obtain the part geometry from CAD models and the engineer has to define the corresponding operations (e.g. contour milling, pocket, profile) with their corresponding settings such as feed rate, spindle RPM, depth per pass, etc.). For each operation, the tool diameter and machining parameters must also be defined. Based on that, the CAM software product generates a file with G-code that could be transferred to the machine for direct processing. CAM products may be costly so the alternatives are manual typing and dialog-based programming, on the machine directly. The latter requires some experience but it is beneficial to invest in building these skills since this option most commonly is already provided with the machine delivery. Once the program is ready regardless of the way it is built, the machine needs a CNC operator who can start the cycle and observe the process for problems. There are no specific requirements for CNC operators as their sole job is to control the machine.

Universal machines on the other hand have no numerical control system. They require a machinist worker (which may also be referred to as an operator but it will not relate correctly to the CNC operators who tend to only observe while the machine is working). Some research papers indicate that in 2025 universal machines are not used or their use is limited. In fact, there is no place for comparison as there are certain operations that are much faster to process on universal machines rather than CNC machines. This is because a program is always necessary while with the universal machines one could directly start working. Despite the fact that no special skills are generally required for being a CNC operator, some companies struggle to find such workers and due to this shortage, they switch their focus on automation of loading, unloading processes as integration of automation solutions generally yields better productivity, quality and lower production costs.

The automation of loading and unloading is a process which makes use of robots (Cartesian, SCARA, six axis,

delta) for the process of loading workpieces and unloading ready parts to/from the CNC machine.

II. MATERIALS AND METHODS

A. Problem definition

The major issues with CNC machines are related to the costs of program preparation. In fact, for single parts or small batches it is not cost-effective due to the hour rate being paid to CNC programmers and/or CNC operators. In the general case, they are different people although in certain cases the role may be taken by a single person. In order to achieve efficiency, a certain machine has to produce parts as quickly as possible, to maintain high utilization throughout the workday, to be reliable and maintenance-free when there is work to be processed. If even one of these requirements fails, this immediately leads to production delays and triggers a chain of events failing other connected processes. Moreover, the loss of machine uptime directly affects overall shop productivity and customer satisfaction. Therefore, minimizing auxiliary times and optimizing setup operations are crucial for maintaining a competitive manufacturing process.

TABLE 1. SALARIES OF CNC PROGRAMMERS AND OPERATORS BY COUNTRY

Country	Average hour rate, EUR	Average hour rate, original currency
Austria	18,67	same
Bulgaria	5	10,02 BGN
Czech Republic	7,98	199,65 CZK
Germany	19,41	same

The data in Table 1 shows the average hour rate that is paid in different countries for CNC programmers and operators [2]. As it could be noted from this example, sometimes two roles could be merged into a single job. The tendency is that more and more it becomes harder to produce by manual labor in Europe. This is especially true for Western Europe and still not so much in Eastern Europe. For this reason, automation is greatly involved in this area of the world and manual labor is only present with more technologically challenging processes which are hard to automate or it is not cost-effective.

The rise in costs is one of the general issues of production worldwide and solutions are constantly searched in the area of automation of the functions of CNC operators. It is unlikely that automation can fully replace CNC programmers, however it is not impossible with the recent development of AI tools. Perhaps it is powerful enough to do this by now but programs may need editing before running on the machine or costly failures may occur such as breaking of the spindle axis.

Automation and universality are normally mutually-exclusive terms. In other words, when a human CNC operator works, they could think and analyze and react in various situations. The automated system is programmed to

perform a fixed number of operations, according to its algorithm (robot program, PLC program, etc.), in a fixed sequence. To achieve cost-effectiveness, medium to large batches (lots) are required. Automating the loading of a batch of only five consecutive parts is totally economically unjustified. Another motivation for installation of automatic loading/unloading solutions may be just for technological advancement of the company and not for financial reasons.

Perhaps a hybrid strategy may be employed - CNC operators may be available in the company, working at other positions, or at least on other machines. If a larger-series product (larger batch) is to be worked that could be handled by the automation system, then it may be loaded and unloaded automatically. However, if small batches of parts are present, it is better to work manually.

$$TC = MC + AT \quad (1)$$

TC – total cycle; MC – machine cycle; AT – auxiliary time, not overlapped

In (1) is shown the basic equation related to the calculation of the total cycle for one ready part. The machine cycle (MC) is normally not an object of optimizations, though sometimes this is also possible. The main focus goes on the auxiliary time that is not overlapped. In other words, it is production time that is spent while the CNC machine has stopped and there is no production process. AT consists of the sum of all activity durations such as door opening, part gripping/release, movement for loading/unloading, door closing. Regardless of the way these operations are handled, they are always not overlapped, they sum up and usually constitute a big portion of TC.

Business logic says that any investment should have a return on investment (ROI) period of about 2 years, on average. This is something like a rule of thumb that is considered. As a result, an estimation is to be made on the investment for consideration whether it would be effective.

$$I_{G1} = (SC_0 - SC_a)QTY \quad (2)$$

I_{G1} – effect based on the difference in production costs; SC_0 – costs before the automation; SC_a – costs after the integration of the automation; QTY – year planned quantity.

$$I_G = I_{G1} + I_{G1} \left(\frac{K_1 + K_2}{100} \right) \quad (3)$$

K_1 – rise of productivity; K_2 – decrease of failed products

$$A_M = \frac{K}{N} \quad (4)$$

A_M - Amortization; K – investment size; N – period of use of the equipment

$$n = \frac{K}{I_G + A_M} \quad (5)$$

n – period for return of investment

So equations (2), (3), (4), (5) are important in the decision-making process from economic point of view [3]. As already highlighted, ROI should be about 2 years. If we consider the influenced parameters, these are:

- costs after the integration of automation – it all depends on the level of automation and whether a human operator still has some role.
- yearly planned quantity – nowadays it is very rare that companies receive even frame purchase orders for a whole year ahead. The market is dynamic and not many producers could allow themselves to behave this way.
- Investment size – the amount of funds that the automated system costs. Perhaps a more cost-effective robot is better depending on its service life.

In the context of quality improvement, it may be considered that there will be significant values of coefficients K_1 and K_2 since it is expected that productivity will be increased. For K_2 it may not be so significant, however there may still be improvement. It is important to note that robots in comparison to humans are much better in repetitive tasks:

- no service breaks
- continuous operation without scheduled breaks (coffee and lunch breaks)
- efficiency $\geq 95\%$ when programmed effectively
- high reliability when used according to the manufacturer's recommendations

B. Possible solutions

Automation of loading and unloading is generally fulfilled with the help of robotic arms. Robots alone are insufficient unless combined with properly designed end effectors and suitable part magazines. The main parameters that have to be considered when integrating robots are:

- arm reach in relation to the CNC machine
- payload
- communications
- standard cycle time

Based on these, a suitable robot may be selected [4], [5]. Non-technical parameters include price, lead time and payment terms. Further technical considerations may include that the CNC machine must have capabilities for communication with external devices in order to exchange signals such as statuses, commands for start/stop/pause, etc. Luckily, most machines are robot integration ready due to the aforementioned economical factors.

A typical work cycle is shown in “Fig. 1”.

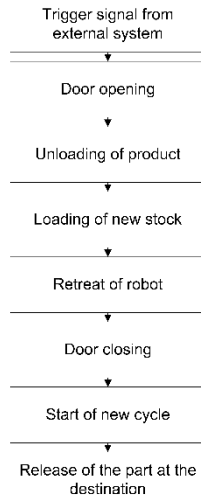


Fig. 1. Workflow related to CNC machine processing

The shown algorithm is limited to only the main stages. It could be definitely further developed to reflect some minor stages such as part fixing/release. It is considered that these processes are part of the loading/unloading processes. It is to be noted that the process of loading/unloading is identical regardless of the way it is carried out – by a human operator or by an automated system.

III. RESULTS AND DISCUSSION

A. Experimental application

The decision making recommendations will be used for considerations on a VMC 1000L vertical milling center and it would be considered if it could be automated.



Fig. 2. CNC machine VMC 1000L

In “Fig. 2” is shown the general front view of the VMC 1000L machine. It features a Sinumerik 808D control from Siemens and all axes are based on servo drivers [6]. The machine features a 4th rotary axis that is inside the working area and a turret rotary magazine for tools. Furthermore, it has a chip removal conveyor [7],[8].



Fig. 3. Table, vise and 4th axis

In the current state parts are loaded manually in a vise (“Fig. 3”) and the machine processes a hole on them. It is a simple operation that takes about 25 seconds. The auxiliary time would be much bigger.

One of the key issues related to the automation of this particular machine with a robot is that the door is not automatic and this requires the machine to be upgraded with actuators for opening and closing of the door. This should be done by means of electrical signals. The CNC controller is shown in “Fig. 4”, it is a modern solution that is reliably established on the market. Many units are sold on a yearly basis. It is a high-quality industrial controller widely adopted in industrial practice, featuring many advanced features such as machine cycles, greatly reducing cycle times for repetitive operations. A few examples are – pocket milling, profile milling, drilling with cycles, etc. Many parameters could be customized and the CNC program takes only one row instead of multiple rows, based on simple G-code instructions.



Fig. 4. Control system

If the issue with the door is solved, the next step is to select a suitable robot. In order to have sufficient space for maintenance, it is advisable that the robot has an arm reach of at least 1200 mm which requires that a slightly bigger robot is integrated [9]. The example operation requires that the parts are stacked in a magazine next to the robot which involves hand labor [10]. This part is not prone to automatic feeding and orienting due to its dimensions and weight, regardless of the fact it is made from aluminum.

To provide an approximate quantitative assessment of the proposed automation concept, an engineering estimation of the cycle components was performed and presented in Table 2. The machine cycle remains unchanged at approximately 25 s, while the auxiliary time could potentially be reduced from approximately 20 s in manual operation to about 8 s under automated loading and unloading conditions. This results in an estimated reduction of total cycle time from 45 s to 33 s, corresponding to a productivity increase of approximately 36%. These values are indicative and depend on robot type, gripper design, communication delays, and part handling strategy.

TABLE 2. COMPARISON BETWEEN MANUAL AND ESTIMATED AUTOMATED OPERATION

Parameter	Manual operation	Estimated automated operation
Machine cycle, s	25	25
Auxiliary time, s	20	8
Total cycle time, s	45	33
Productivity increase, %	-	36.4%

IV. CONCLUSIONS

The automation of loading and unloading of CNC machines is still a highly relevant topic in 2026. However, not every task is worth automating and the feasibility greatly depends on various factors including economical ones. Sometimes one automation solution fails and the end result is negative (the process automation decreases productivity, quality and increases production costs). The decision making process should be carried out carefully and predictively, after evaluation of all aspects of the task [11]. Sometimes shop owners decide to automate not because of costs but due to the lack of personnel (in the scope of this paper that is CNC programmers and operators) and sometimes they do it due to the wish to have the latest technology in their facilities in order to present it in front of potential customers. The problem with personnel that has already emerged and there are multiple reasons behind it starting from school education and universities.

Miniature CNC machines are also very popular in jewelry processing and cost-effectiveness is more easily achieved in this sector of the industry due to the high-value products [12].

Precision and error handling are really important aspects of the process as feeding systems are demanding. Measures should be taken for repeatability and reliability in time using the methods presented in [13]–[15].

The physical parameters of machine parts affect the reliability of the developed feeding systems [16].

The provided methods and design suggestions in [17]–[18] are applicable to the development of automated robotic systems for loading and unloading operations in machining environments, where structural optimization

and modular design play a key role in improving system efficiency and flexibility.

The hybrid stochastic-machine learning framework proposed in [19], although applied in a biomedical context, demonstrates a flexible data-driven approach that can be adapted for modeling, prediction, and optimization tasks in automated manufacturing systems.

The automation of CNC machines is a process that needs to go through the following steps:

- Evaluation of the economical effects and yearly quantity of parts.
- In case of positive results from the previous stage, a suitable robot has to be selected.
- A concept related to the automatic gripping and release of the workpiece on the machine table is to be considered.
- A robot with a sufficient arm reach has to be selected considering some extra reach.
- Analysis of the CNC machine and its features for automation – exchange of signals, reprogramming, etc.

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Benchmarking for Integration of Artificial Intelligence in Strategic Firm Management

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Abstract—The article focuses on conducting a benchmarking study to identify and analyze good practices for integrating artificial intelligence into strategic management at the company level. By comparing and evaluating effective models, tools, and approaches, key success factors, benefits, and risks in implementing AI in strategic planning processes, making informed management decisions, and achieving sustainable competitive advantage have been identified. Benchmarking is considered an effective tool for reducing risk, optimizing resources, and increasing efficiency. The conclusions and recommendations made are applicable to improving strategic planning processes and increasing the competitiveness of organizations in the digital business environment.

Keywords—Artificial intelligence, benchmarking, good practices, strategic management

I. INTRODUCTION

In the conditions of the fifth industrial revolution, business and non-profit organizations [1], [2] are faced with the challenge of improving the efficiency and quality of their production, reducing production costs and cycles. The topic is extremely relevant in view of the penetration of artificial intelligence (AI) both into the activities of a number of organizations and into public life, considered in the publications [3], [4], [5] of a number of authors. Research [6], [7], [8] on the integration of artificial intelligence AI into strategic corporate management is an active and rapidly developing scientific field that covers many aspects: from strategic planning and decision-making to organizational capabilities, adaptability, innovation and sustainable competitive advantage. AI continues to change business management, industrial practices and organizational strategies.

The aim is to perform a benchmarking analysis of leading practices for integrating AI into strategic corporate management regarding the identification, comparison and

evaluation of effective models, tools and approaches, while identifying key success factors, benefits and risks in implementing AI in the processes of strategic planning, management decision-making and sustainable competitive advantage. Based on the considerations, recommendations have been formulated for their application in a specific organizational environment.

To achieve the goal, the following tasks have been solved:

- Analysis of the nature and role of artificial intelligence in modern strategic corporate management.
- Research of basic concepts, models and tools for integrating AI into management processes.
- Selection of leading organizations and/or practices as the object of benchmarking analysis.
- Identification and comparison of good practices for using artificial intelligence in strategic planning and decision-making.
- Assessment of the effects of AI implementation on the efficiency, competitiveness and sustainable development of companies.
- Analysis of risks, limitations and ethical aspects in integrating AI into strategic management.
- Diagnosis of key success factors and indicators for assessing the effectiveness of AI solutions.

Integrating AI into management allows for the automation of routine and repetitive tasks, freeing up time for higher-level strategic thinking and innovation. This effect is observed in technology giants, whose practices can also be adapted in traditional industries, based on

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technological and organizational benchmarking to integrate AI in order to optimize processes, operations and make strategic decisions for product development and improving the customer experience. With the help of AI, companies will be able to increase their efficiency and productivity by analyzing huge data sets, discovering patterns and trends, and providing high-accuracy forecasts — making managers more informed and adaptable to market changes.

There are numerous classifications of benchmarking and its forms of manifestation in literary and online sources. One of the most famous and widely used classifications is that of Robert Kamp [9], who defines benchmarking as: "... the search in industrial development for that best practice, the application of which leads to a more effective and perfect form of business performance." Benchmarking is perceived as an element of the strategy of companies, organizations and institutions. It is carried out in five main phases [10]: planning of activities, integration with corporate strategy and business interests, specific models and indicators for application, analysis of results, introduction of best practice (maturity phase). Benchmarking is seen as an effective tool to reduce risk, optimize resources, and accelerate the AI implementation process, especially in environments with limited capacity and experience. Benchmarking is a management approach for sustainable development that involves studying and implementing best practices from leading companies to increase efficiency, quality, and productivity.

II. MATERIALS AND METHODS

The benchmarking conducted includes five Bulgarian companies with implemented or clearly developed AI practices. **Payhawk** is a prime example of a company with Bulgarian roots and active operations in Bulgaria that has implemented artificial intelligence not as an isolated technological module, but as part of its core product, management and organizational logic. In parallel, a comparative benchmarking was established with four more companies operating in Bulgaria – **TBI bank, DSK Bank, Sirma Group and Yettel Bulgaria**, in which artificial intelligence contributes to more effective strategic management, digital transformation, risk management, process automation and organizational adaptation. The selection of companies was carried out according to strict criteria: presence of active activity in Bulgaria, publicly available and sufficiently reliable data for real implementation of AI, presence of a connection between AI and strategic management, data on management model and organizational adaptation, as well as the ability to conduct a sufficiently substantiated comparative analysis.

The study shows that the five companies use AI differently. Payhawk is a strong example of AI embedded in the core product and in the work of the CFO function. Tbi bank uses AI in credit analysis, pricing, digital application and risk management. DSK Bank is developing AI in customer service and in the management framework for AI governance as part of a broader digital transformation. Sirma Group is developing AI both as its own internal strategic direction and as a corporate AI

platform for customers, which distinguishes it with the most pronounced AI-centric identity at the group level.

The main conclusion is that the most successful practices are not limited to the implementation of models or agents. They are based on a combination of a clear role of senior management, manageable risk, appropriate infrastructure, organizational learning, precise control over data and the ability to connect AI to measurable business value. This is precisely why benchmarking should be seen not only as a technology comparison, but as a comparison of management models.

The methodological approach combines descriptive analysis, comparative analysis (benchmarking) and management interpretation. The basis of the study are official company sources – company websites, official newsroom publications, publications about the management team, career roles, investor materials and public corporate reports. Where necessary, independent business publications were also used, but only as a supplementary source, and not as the main carrier of the facts.

The criteria for inclusion in the benchmarking are the following:

- first, the company must be Bulgarian or have Bulgarian roots and have active activities in Bulgaria;
- second, there must be public evidence of implemented AI;
- third, the use of AI must be related to strategic management, risk management, efficiency, product development or organizational adaptation;
- fourth, it must be possible to trace the roles of senior management and the management logic behind the implementation;
- fifth, the company must provide sufficient information for a more detailed and defensible analysis.

It should be explicitly noted that public data is not equally detailed for all companies. Payhawk and Sirma Group provide more complete and conceptually developed public materials on their AI direction. At tbi bank and DSK Bank, the information is more fragmented, but still sufficient to draw reliable conclusions about the strategic and managerial role of AI. This is not a weakness of the analysis itself, but a limitation of the publicly available facts:

- Connection between AI and strategic management, and not just local automation.
- Availability of specific examples of AI applications, agents, scoring models, governance mechanisms or AI platforms.
- Ability to track the role of the CEO, CFO, CTO or other senior managers in the company's adaptation.
- Availability of organizational signals of sustainability: specialized teams, governance

roles, process changes, new competencies and investments.

The main subject of the benchmarking study and a leading example of embedded AI in core product logic is Payhawk, founded in 2018. By 2026, it is positioned as an AI-native platform for managing corporate expenses, payments, invoices, business cards, travel and procurement. The company publicly lists over 400 employees, over 5,000 customers, presence in 32 countries and 9 offices, with Sofia remaining a key location for engineering, product, AI and strategic functions. From a management perspective, Payhawk is particularly important for the study because AI is not presented as an external integration or marketing addition, but as a factor that changes the way the company creates value. The management team is represented by three co-founders. This triad is important because at Payhawk, the strategic direction, financial logic and technological infrastructure are connected in a common line of development. The company's most significant publicly announced AI initiative is the "AI Office of the CFO," unveiled in April 2025. It includes specialized AI agents such as the Financial Controller Agent, Procurement Agent, Travel Agent, and Payments Agent. Their function is not simply to answer questions, but to perform specific processes – collecting documents, processing requests, supporting expense procedures, tracking approvals, and other repetitive activities in the finance function.

The essence of Payhawk's model [11] is that agents are framed by existing company rules, permissions, workflows, spend controls and audit trails. This means that AI is not left to operate freely outside of management control. Quite the opposite – autonomy is limited by company policies, access rights and control mechanisms. Thus, Payhawk chooses a model of controlled autonomy, which is particularly relevant in a financial environment.

The company is further developing its AI capacity through specialized roles in Sofia. Advertisements for Applied AI Engineer and related engineering roles show work on autonomous agents, evaluation pipelines, retrieval approaches, context handling, observability and production deployment. This is an important indicator that AI is not a temporary project, but a permanently built organizational competence.

An even stronger signal of the managerial nature of the change is provided by the Founder's Associate role in the CEO Office. There, the company describes real-time visibility into performance metrics, OKR automation, pricing and monetization analyses, as well as work on cross-functional execution. Therefore, the adaptation is not only product-related, but also affects the company's management operating system. In his published positions, one of its founders describes AI as a force that requires rethinking the strategy, product and organization. This is important because it shows a managerial understanding according to which competitive advantage no longer comes only from code, but from a combination of data, regulatory readiness, customers, contractual relations, culture and the ability to change. In this sense, Payhawk can be seen as an

example of a company that understands AI not only technologically, but also strategically. The effect on work is twofold. On the one hand, the company claims that AI agents reduce administrative actions and accelerate financial cycles. On the other hand, the work of teams shifts towards analysis, control, exception handling and higher added value. For strategic management, this means that the CFO function is moving from an operational workload to a stronger role in managing resources and decisions.

The role of the CEO (Chief Executive Officer) is strategic and integrative. As the top manager, he or she guides the company toward a model where AI doesn't just accelerate existing processes, but transforms the product offering itself. This is a classic form of strategic adaptation: instead of adding limited automation, the company restructures its value proposition around the ability to eliminate work, free up time, and support decision-making in finance teams.

The CEO's role is key because at Payhawk, AI is directly tied to the finance function and its transformation. Top executives consistently link cost management, real-time visibility, and automation to better managing growth. This means that AI is not seen as a separate IT initiative, but as a tool for more mature financial discipline and stronger strategic involvement of finance leadership. It provides the infrastructure, security, and scalability, pointing out that AI can only deliver value when built on a solid technology foundation. This puts technology management at the service of business strategy, not the other way around. Such a logic reduces the risk of chaotic implementation and supports long-term sustainability.

Among Payhawk's strengths is the deep integration of AI into the core product. This creates a more difficult to replicate competitive advantage compared to companies that use AI only for customer service or single internal activities. An additional advantage is that autonomy is limited by permissions, workflows and control mechanisms, which is especially valuable in a financial context.

Another strength is organizational consistency. There are signs of AI engineering capability, strategic engagement of the CEO Office and a connection with the CFO function. This means that the company does not rely on separate technical experiments, but on a coordinated management transformation.

Among the weaknesses and risks, it should be noted the high dependence on data quality, the correct configuration of access and control over delegated actions. The more agents move from assistance to actual execution of actions, the greater the importance of governance mechanisms, verification and liability in case of error. In addition, some of the published benefits are at the level of company claims and early results, which means that they should be formulated cautiously in academic presentations.

TBI bank - a Bulgarian bank with a clear connection between AI, credit process, risk and digital growth.

TBI bank is an active bank with a center of activity in Southeastern Europe and a strong presence in Bulgaria. Its official publications for 2024 [12] show over 1 million loans issued, over 2.2 million loan applications, total assets of 1.77 billion euros and a share of digital applications of about 70%. The bank explicitly states that it continues to invest in technology and AI solutions, which links financial results with technological innovation.

From a management perspective, tbi bank offers an interesting model because AI is not so much related to user assistants, but to the economics of the credit process. Particularly strong evidence of implemented AI is contained in the public prospectus for the bank's MREL bonds. There, a new customer credit scoring model is explicitly described, which updates the customer's credit rating in real time in the mobile application and is created with AI technology. In parallel, a risk-based pricing model and automation in customer operations and risk management are described, aimed at preventing fraud and money laundering. This combination is particularly important for strategic management, because it shows that AI is connected to the core of the banking economy: credit decision, pricing, risk, speed of approval, digital customer experience and process efficiency. TBI bank uses AI where it directly affects revenue, risk and competitiveness. In official interviews, bank representatives indicate that AI and machine learning are used in onboarding and risk assessment, and the bank describes itself as having transformed from a traditional bank to a challenger bank. This is managerially important because it shows that technological change is part of a broader strategic transformation, not just a local process improvement. The effect on the organization can be interpreted as moving key decisions to more centralized and automated decision points. In the credit business, this means faster decisions, more precise customer segmentation, personalized offers and potentially a better risk-reward ratio. With proper management, such a model increases the manageability of growth.

At TBI bank, the adaptation is manifested in the fact that AI management is not limited to the IT department. The presence of a Chief Data, AI & Monetization Officer, as well as clearly defined risk and credit business departments, suggest that data and AI solutions are considered part of the bank's overall business architecture. This is a mature model because credit risk, compliance and monetization are interconnected. The CEO role is related to the transformation of the business model towards a more digital bank. Public statements by Petar Baron describe a transition from branch-based banking to more centralized automated decision-making points. This shows that AI is part of a management philosophy of scaling, not just a technological infrastructure. From a strategic management perspective, tbi bank is a strong example of how AI can be used to improve a core revenue activity. This is different from models in which AI is primarily focused on customer communication or internal office productivity.

A strength of TBI bank is that AI is implemented in processes with direct strategic importance: credit decision, risk, pricing and digital application. This provides great potential for real economic impact and for better growth

management. Another strength is the institutionalization of AI and data functions in the management model. This reduces the likelihood that AI will be used fragmentarily or without sufficient connection to business results. A major risk is that the banking sector is highly regulated and errors in scoring, pricing or fraud detection can have direct financial and reputational consequences. Therefore, success depends not only on the quality of the models, but also on governance, explainability, compliance and continuous control.

DSK Bank is an example of AI in customer service, digital transformation and AI governance. It is one of the largest banks in Bulgaria and officially declares a long-term growth strategy combined with a large-scale digital transformation. The public description of the bank emphasizes investments in digitalization of operations, development of digital channels and innovative banking services. [13].

The management model of DSK Bank is particularly interesting for benchmarking, because in addition to the classic financial and operational logic, it clearly shows functions such as Head of Digital, Data and Technologies, Head of Strategy, Finance and Operations and Head of Transformation and Change Management. This is indicative that digital change and adaptation are institutionalized management priorities.

The bank's most visible public AI solution is the officially announced AI assistant, unveiled in July 2025. The bank describes it as the first fully AI-based assistant in Bulgaria, built on OpenAI's generative AI, trained on the DSK context and capable of understanding natural language and responding within seconds. The assistant is part of the bank's ongoing digital transformation. At first glance, this solution seems more limited than the Payhawk and tbi bank models, as it is primarily focused on customer communication. A deeper analysis shows that the bank also has an Innovation & AI Office, with which AI is viewed not only as a front-end tool, but also builds a framework for risk management and compliance.

This management direction is very important for strategic management. In a highly regulated bank, sustainable implementation of AI cannot be based on technological enthusiasm alone. It requires rules, responsibilities, policy frameworks, documentation, risk assessment and clear organizational ownership. In this sense, DSK Bank is a valuable benchmark for AI governance in the Bulgarian environment. The effect on work can be sought in several directions: improving the speed and accessibility of customer information, offloading standard service activities, enhancing the digital experience and building internal capacity for further implementation of AI. Although public metrics are more limited, available data show that the bank is moving towards a more systematic, rather than occasional, use of AI.

At DSK Bank, adaptation is manifested through organizational design. The presence of separate senior roles for digitalization, strategy, finance, operations and change shows that AI initiatives can be integrated into a broader transformational framework. This is different from the

approach of smaller technology companies, where the same leader often combines multiple functions. The CEO and C-level management work in an environment where the implementation of AI must be compatible with banking regulation, security and trust. Therefore, the adaptation here is more cautious, but potentially more sustainable. The management emphasis is not only on rapid implementation, but on controlled implementation. From a benchmarking perspective, this makes DSK Bank a useful counterpoint to Payhawk. While Payhawk is strong in product-native AI, DSK Bank is strong in the management question of how to implement AI in a large, highly regulated institution without disrupting manageability.

A strength of DSK Bank is its institutional maturity. The bank builds AI solutions in an environment of clear management, digital transformation and governance mechanisms. This is especially important in the context of trust, regulations and customer security. Another plus is that the AI assistant is a visible entry point for broader organizational learning. Such initiatives often also work as a tool for accumulating experience, data and organizational habits when working with AI. As a relative weakness, it can be pointed out that the available public information shows a more limited deployment of AI in the core banking logic compared to Payhawk or TBI bank. Therefore, in its publicly visible part, DSK Bank seems stronger in governance and customer front-end than in a proven large-scale restructuring of the core product economy through AI.

Sirma Group [14], [15] - a Bulgarian technology group with an AI-centric identity, corporate governance and enterprise AI platform has a special place in this benchmarking, because its very history is connected with artificial intelligence. The group was founded in 1992 as Sirma AI and over the years has developed into one of the largest Bulgarian software groups. By 2026, the company publicly lists over 800 employees, a dual listing on the Bulgarian Stock Exchange and the Frankfurt Stock Exchange, and a pronounced focus on AI-driven transformation.

Unlike the other companies under consideration, Sirma Group is not just a user of AI for its own processes. It develops AI both as a corporate product and as a strategic transformation direction of the group itself. The Sirma.AI Enterprise platform is presented as a means to build, deploy and scale AI agents, agent teams and agentic workflows in cloud and on-premise environments with full control over data and AI operations. This model has strong management value because it places Sirma in the role of both a producer and operator of AI capabilities. The company's public materials show not only AI engineers, AI architects, MLOps, data science, RAG and orchestration capabilities, but also roles such as AI Ethics & Safety. Therefore, the organizational capacity is built much more broadly than the typical company that simply uses an external AI tool.

At the corporate governance level, Sirma Group has a clearly defined board and committees, including Investment, Risk and Sustainability, Remuneration Committee and Disclosure Committee. This is particularly

important for benchmarking, as it allows the AI strategy to be interpreted not only from a technological or product perspective, but also from a formal governance perspective.

In its investor materials, the company explicitly links its long-term strategy to AI-driven transformation. In publications from 2025, it describes restructuring and consolidation aimed at synergies and a stronger focus on high added value, especially in AI and the automation of financial and administrative processes. This is a direct link between AI and the strategic reorientation of the company.

Sirma Group has clearly defined board roles, C-level responsibilities and specialized AI positions. CEO (Chief Executive Officer), CFO (Chief Financial Officer) and CTO (Chief Technology Officer) are clearly part of a model where AI is not a peripheral topic, but an axis of long-term development, capital market narrative and product evolution. Particularly valuable is the fact that the group combines enterprise software logic with management mechanisms of a public company. This means that the AI direction must be aligned simultaneously with market, risk, sustainability, accountability and investor expectations. This combination makes Sirma Group perhaps the strongest Bulgarian example of formalized AI governance at the group level.

Organizational adaptation is also visible in the development of competencies: AI engineering, data science, ethics, RAG (Retrieval-augmented generation), orchestration and enterprise deployment. Here, AI is seen not only as a tool, but as a whole set of capabilities that must be constantly developed. This is a sign of high organizational maturity.

Sirma Group's core strength is its strategic consistency. AI is present in the company's history, products, investor narrative, leadership structure, and skill set. This creates a deeper AI identity than companies that implement AI in only a few processes. Another strength is its enterprise orientation – a focus on security, on-premise options, data control, multi-LLM (Large Language Model) and AI operations. This is especially important for corporate clients and strategic management in sensitive environments. A potential weakness is the higher complexity of the model. When a group simultaneously builds AI platforms, AI services, and its own internal transformation, it must manage a wider range of technological, market, and execution risks. In addition, enterprise AI sales typically have longer cycles and higher expectations for reliability.

Yettel Bulgaria [16], is developing an AI line mainly in its B2B (Business-to-Business) solutions. They are products, services or software sold by one company to another, aimed at optimizing operations, increasing efficiency and increasing profitability. They are characterized by longer sales cycles, high order value and needs for a personalized approach. The company presents Smart CRM and Smart Drive, which use cloud technologies and artificial intelligence to manage customers, documents and processes. Smart Drive is particularly indicative – a solution with integrated AI for

scanning, extracting, analyzing and categorizing information from files. Thus, Yettel shows how AI can be used for practical digitalization and operational efficiency in small and medium-sized enterprises.

III. RESULTS AND DISCUSSION

TABLE 1 BENCHMARKING STRUCTURE

Company Driving Force	Main AI Focus	Role in Strategic Management	Organizational Adaptation	Main Risk / Weakness
Payhawk Deep integration of AI with permissions and workflow	AI agents for the CFO function, expenses, invoices, procurement, and payments	Turns AI into part of the core product and financial management	AI engineering, CEO Office analytics, control-by-design	Dependence on data quality, access control, and governance for autonomous actions
TBI bank AI is embedded in processes with direct financial impact	Credit scoring, risk-based pricing, onboarding, risk management	Improves lending economics and growth manageability	Senior-level AI/Data functions, connection between risk and monetization	Regulatory risk, explainability, and sensitivity to model errors
Bank DSK Strong institutional framework for controlled implementation	Generative AI assistant customer service, governance framework	Supports digital transformation and creates a foundation for systematic AI adoption	Innovation & AI Office, governance roles, and change management	More limited publicly visible connection between AI and core banking economics
Sirma Group Most formalized AI identity and governance at group level	Enterprise AI platform, AI agents, RAG, orchestration, AI services	Connects AI with long-term strategy, restructuring, and high-margin services	Board-level governance, committees, AI teams, ethics & safety	High execution complexity and longer enterprise cycles
Yettel Bulgaria Diversification and higher-margin B2B services. Need for smarter growth in a saturated telecom market	Customer experience automation (chatbots, digital support, personalization)	Supports evidence-based strategy better pricing, targeted offers, customer lifetime value growth Uses AI to improve productivity, creativity, and internal processes	Shift toward digital-first operating model; more cross-functional teams across IT, marketing, customer care	Privacy concerns, regulatory scrutiny, biased models Employee resistance, skills gaps, unclear return on investment

The comparative analysis shows that the five companies use AI according to different strategic logics. To avoid simplification, the benchmarking is structured

simultaneously according to functional focus, management logic, organizational adaptation, and risk framework.

Analytical conclusions from the comparison

Payhawk is the strongest example of a company that embeds AI in its core product and thereby changes its own value logic. In this case, the strategic effect comes from product-native AI and from the transformation of the CFO function.

TBI bank is the strongest example of AI implemented in processes with a direct impact on the credit economy. This makes its model particularly valuable when looking for a connection between AI, risk, revenue and digital growth.

DSK Bank is the strongest example of institutional and governance-oriented implementation of AI in a large bank. Its role in benchmarking is to show that sustainable implementation does not necessarily mean the most aggressive automation, but sometimes the best management framework.

Sirma Group is the strongest example of AI-centric corporate identity and formalized governance in a Bulgarian technology group. It shows how AI can be both a product, an internal strategic direction and a topic of board management.

Based on the benchmarking conducted with the banks in Bulgaria, Yettel Bulgaria is positioned above the average level in practical use of artificial intelligence, especially in the commercialization of AI services for business customers.

Common Strengths

First, in all five companies, AI is linked to real business processes, not just communication campaigns. This is a significant sign of maturity. Even if the publicly visible form is different, in all cases AI is linked to activities that affect efficiency, decisions, risk or service quality.

Second, in all the companies examined, there are signs that senior management is involved in the adaptation. This may be through the CEO Office and product strategy, through data/AI leadership, through transformation functions or through formal governance structures. This management involvement significantly increases the chance that AI will become a sustainable competitive advantage.

Third, organizational adaptation is not limited to the purchase of technology. There are new roles, new competencies, new processes and in some cases new control frameworks. This is particularly important because it shows that AI transformation is both technological and organizational.

Common Weaknesses and Risks

The biggest common risk is that the closer AI gets to decision-making or execution, the more important governance, access control, data quality, explainability, and accountability become. This risk is most visible in finance and banking processes, but is also relevant to enterprise AI platforms.

A second significant risk is the unevenness of publicly demonstrable results. Many companies report effects and acceleration, but independent external validation of these results is often limited. Therefore, in an academic context, a distinction should be made between publicly claimed effects and independently verified effects.

A third risk is related to organizational readiness. Even with good technology, companies can encounter difficulties if employees are not trained, if there is a lack of clarity about process ownership, or if AI initiatives are not aligned with management priorities. In this sense, organizational learning remains a key factor for success.

Leading practices that stand out in benchmarking

The first leading practice is connecting AI to a core business process, rather than a peripheral function. Payhawk and tbi bank show that the strongest effect is achieved when AI affects the core economy of the company – on CFO operations and on lending, respectively.

The second leading practice is the construction of control-by-design. This is particularly clear in Payhawk and in the governance direction of DSK Bank. Successful implementation of AI requires that it be subject to rules, rights, documentation and verifiability.

The third leading practice is the institutionalization of AI competencies. Sirma Group is the most striking example of this, but there are signals in other companies as well. When AI is supported by a sustainable set of roles, knowledge and management mechanisms, the likelihood of a long-term effect is greater.

The fourth leading practice is senior management commitment. AI does not succeed where it remains locked into a technology team. Success comes where there is management ownership – with the CEO, CFO, CTO, data leadership, transformation offices or board committees.

Payhawk	5	5	4	5	5
TBI bank	4	4	3	4	4
Bank DSK	4	3	5	4	4
Sirma Group	5	4	3	5	4
Yettel Bulgaria	3	4	3	3	4
	strategic interaction	operational automation	customer integration	management and control	scalability
	Criterion				

Fig.1. Comparative analysis of 5 Bulgarian companies by key AI criteria

The graphic matrix represents an analytical assessment on a 5-point scale (1 = low level, 5 = very high level), prepared on the basis of publicly available information for each company. The matrix is of a comparative nature and

serves to visualize the overall picture. Therefore, the most important conclusion is not which company “uses AI the most”, but which company uses it in the most manageable, strategically relevant and organizationally sustainable way. This question is the real subject of benchmarking. If we are looking for an example of deep product integration – this is Payhawk; for AI in the revenue-generating core of banking is TBI bank; for controlled institutional implementation – DSK Bank; for formalized corporate identity of AI – Sirma Group and for practical digitalization and operational efficiency – Yettel Bulgaria.

IV. CONCLUSIONS

Integrating AI into management is a strategic necessity for companies that want to remain adaptable, innovative and competitive in the global economy.

The current benchmarking shows that the Bulgarian business environment already offers sufficiently mature examples of companies that use artificial intelligence in a way relevant to strategic management. The differences between the companies are significant, but it is in them that the analytical value of the comparison lies.

Payhawk stands out as the strongest example of deeply embedded AI in the core product and in CFO-oriented processes. tbi bank is a strong example of AI in credit logic, risk and digital growth. DSK Bank shows how a large financial institution can approach AI through digital transformation and governance. Sirma Group demonstrates the most formalized AI identity and the clearest connection between AI strategy, corporate governance, and enterprise capabilities.

The first important conclusion is that the use of AI in Bulgaria is growing rapidly, but still remains below the EU average. The second conclusion is that the most successful companies do not use AI only as a separate tool, but connect it with the management model, control and long-term strategy.

The third conclusion is that different sectors use AI in different ways: fintech and banks use it for risk, financial control and customer service, software companies – as a strategic product, and telecommunications companies – for the digitalization of business processes.

In summary, it can be said that Payhawk, TBI bank, DSK Bank, Sirma Group and Yettel Bulgaria represent a useful set of examples for benchmarking. They describe different but complementary models of using artificial intelligence in the Bulgarian business environment.

More broadly, the analysis shows that artificial intelligence makes a sustainable contribution to strategic management only when it is combined with leadership, governance, organizational adaptation, infrastructure, training and a clear connection to business value. Without these conditions, AI remains a tool; with them, it becomes a strategic resource.

The report is based on publicly available sources and therefore does not include internal (KPIs - Key Performance Indicators), non-public policies, contractual

relationships with model providers or internal assessments of returns. Therefore, some of the conclusions are interpretive and rely on reliable but incomplete public data.

Public visibility of AI results is uneven across companies. Some companies report in more detail on architecture and roles, others on governance framework or product usage. This means that the comparison is strongest along the lines of governance models and leading practices, rather than as a strict quantitative measurement of impact.

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Analysis of Braking Deceleration and the Efficiency of Automotive Braking Systems Using MATLAB

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Abstract—This study presents an analytical and computational methodology for determining vehicle braking deceleration and evaluating the efficiency of braking systems based on measured skid marks. Based on classical kinematic relationships and the physical limitations of tire–road adhesion, the actual braking deceleration j , the maximum possible deceleration j_{max} , and the efficiency coefficient η are defined. A MATLAB-based model has been developed to enable interactive and three-dimensional analysis of the relationships between vehicle speed, braking distance, and available traction. The resulting visualizations allow the identification of critical braking regimes and the assessment of the extent to which the braking system utilizes the physical potential of the road surface. The proposed methodology is applicable to traffic accident reconstruction, engineering evaluation of braking systems, and educational purposes in the field of vehicle dynamics. The experimental results are validated through comparative graphical analysis of acceleration–time histories at different speeds.

Keywords— 3D visualization, braking deceleration, braking efficiency, MATLAB, tire–road adhesion, vehicle dynamics

I. INTRODUCTION

The braking process is one of the most critical factors for traffic safety, as it determines the ability to reduce speed in a timely manner and prevent road traffic accidents. The analysis of braking deceleration and braking distance is of significant importance both for accident reconstruction and for engineering assessment of the technical condition and efficiency of braking systems.

The literature provides well-established analytical relationships describing the connection between initial speed, braking distance, and vehicle deceleration [1], [2]. However, in practice, there is often a need to integrate these relationships into a computational environment [3], [4] that enables rapid analysis of multiple scenarios and clear visualization of the physical limitations of the process.

The aim of this study is to develop a methodology for the quantitative evaluation of braking deceleration and braking system efficiency through MATLAB-based modeling and three-dimensional visualization. The scientific contribution of the research lies in integrating classical analytical relationships with a graphical computational tool that enables systematic analysis of traction limit conditions and supports expert assessment under various road conditions.

The research hypothesis of this study is that the integration of classical kinematic relationships with MATLAB-based computational modeling enables accurate estimation and effective visualization of vehicle braking deceleration and braking system efficiency under varying road conditions.

II. GENERAL REGULATIONS

Additional Theoretical Considerations

In real braking conditions, the deceleration process is influenced not only by the initial speed and braking distance but also by transient effects such as brake force build-up and dynamic load transfer between the axles.

The dynamic redistribution of vertical load during braking leads to increased normal force on the front axle and reduced force on the rear axle. This phenomenon directly affects the maximum achievable friction force and may lead to premature wheel lock if not properly controlled.

Furthermore, the braking process is inherently non-linear due to:

- tire slip characteristics;
- variation of friction coefficient with slip ratio;
- influence of road surface microtexture and macrotexture.

For a more precise analysis, the instantaneous deceleration can be expressed as a function of time:

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$$a(t) = \frac{dv(t)}{dt}$$

which allows evaluation of transient braking regimes and identification of peak deceleration values.

III. FIGURES, TABLES AND EQUATIONS

This section presents the fundamental physical relationships and constraints governing the braking process.

A. Determination of Actual Braking Deceleration

Assuming uniform deceleration, the actual braking deceleration is determined by:

$$j = \frac{v^2}{2s} \quad (1)$$

where:

V is the initial vehicle speed [m/s],
 s is the braking distance [m].

This relationship is widely used in vehicle dynamics analysis [1].

When the brake force build-up time t_3 is taken into account, the deceleration can be determined using:

$$j = \frac{2s + t_3 V - \sqrt{(2s + t_3 V)^2 - t_3^2 V^2}}{0.5 t_3^2} \quad (2)$$

This approach provides a more realistic description of the braking process in cases where the braking force is not applied instantaneously.

B. Maximum Physically Possible Deceleration

The maximum possible deceleration is limited by the tire–road adhesion and is expressed as:

$$j_{max} = \mu_{max} g \quad (3)$$

where:

μ_{max} is the maximum coefficient of adhesion,
 $g = 9.81 \text{ m/s}^2$ - is the gravitational acceleration.

This limitation is governed by tire–road interaction properties [5], [6].

Typical values of μ_{max} for different road surfaces are presented in Table I.

TABLE I TYPICAL VALUES OF MAXIMUM ADHESION COEFFICIENT

Surface	Dry	Wet
Asphalt	0.9	0.6
Concrete	0.8	0.5

Surface	Dry	Wet
Mud/Soil	0.6	0.4
Ice/Snow	0.2	0.1

C. Braking Efficiency Coefficient

To quantitatively assess how effectively the braking system utilizes the available traction, the braking efficiency coefficient is defined as:

$$\eta = \frac{j_{actual}}{j_{max}}, 0 \leq \eta \leq 1 \quad (4)$$

where j_{actual} is the actual braking deceleration.

The concept of braking efficiency is commonly used in vehicle performance evaluation [7].

A value of $\eta = 1$ indicates full utilization of the available adhesion, while $\eta < 1$ indicates partial utilization of the braking potential.

D. Energy-Based Analysis of Braking

In addition to the kinematic approach, the braking process can be analyzed from an energy perspective. The initial kinetic energy of the vehicle is dissipated through the braking system and tire–road interaction.

The kinetic energy of the vehicle is expressed as:

$$E_k = \frac{1}{2} m v^2$$

During braking, this energy is transformed into heat due to friction forces. The work done by the braking force over the braking distance s can be expressed as:

$$A = F_b s$$

By equating the kinetic energy to the work done by the braking force, the following relationship is obtained:

$$F_b s = \frac{1}{2} m v^2$$

From this, the braking force can be estimated as:

$$F_b = (m v^2) / (2s)$$

This formulation provides an alternative interpretation of the braking process and complements the kinematic model used in the present study.

E. Experimental Results

The analysis of the experimental data shows that the braking process is characterized by distinct peaks in longitudinal deceleration.

The experimental results obtained for different vehicle speeds are summarized in Table II, showing the relationship between actual deceleration, theoretical limits, and braking efficiency.

For the vehicle operating under wet road conditions (Fiat), the measured peak deceleration is approximately:

$$j_{actual} \approx 0.8m/s^2$$

For the vehicle operating under dry road conditions (Renault), significantly higher values are observed:

$$j_{actual} \approx 2.7m/s^2$$

These results clearly demonstrate the influence of road surface conditions on braking performance [6], [8].

Experimental braking tests were conducted using an Audi A4 B6 vehicle under dry road conditions. The tests were performed by a male driver aged 22 years at different initial speeds of 20 km/h, 30 km/h, and 40 km/h.

The recorded acceleration data show that the braking process is characterized by significant negative peaks in longitudinal acceleration corresponding to maximum deceleration.

- at 20 km/h:

$$j_{actual} \approx 4.4m/s^2$$

As shown in Fig. 1, the braking process exhibits a clear peak corresponding to maximum deceleration.

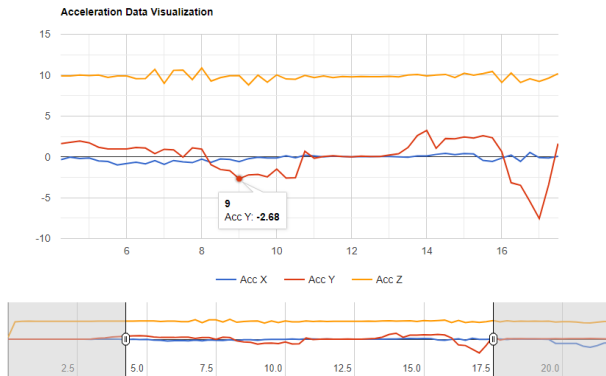


Fig. 1. Time history of longitudinal acceleration during braking at 20 km/h

- at 30 km/h:

$$j_{actual} \approx 2.0m/s^2$$

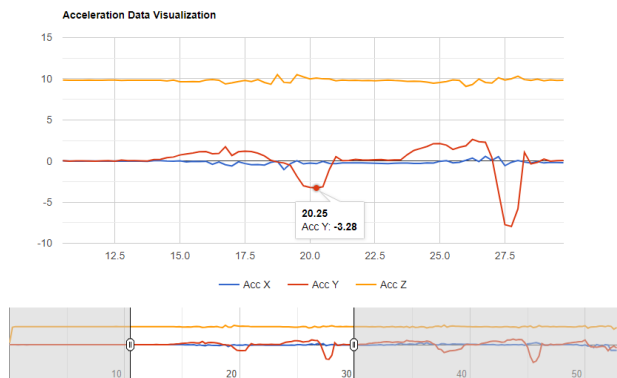


Fig. 2. Time history of longitudinal acceleration during braking at 30 km/h.

As shown in Fig. 2, the braking process at 30 km/h exhibits stronger deceleration peaks compared to 20 km/h.

- at 40 km/h:

$$j_{actual} \approx 2.6m/s^2$$

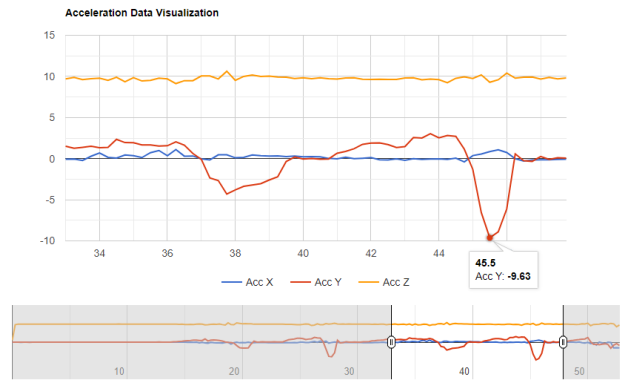


Fig. 3. Time history of longitudinal acceleration during braking at 40 km/h.

As shown in Fig. 3, the braking process at higher speed is characterized by stronger deceleration peaks and increased variability. The comparison of the acceleration–time histories at different speeds confirms that the braking dynamics strongly depend on the initial velocity. Higher speeds result in more pronounced deceleration peaks and increased signal variability.

TABLE II. EXPERIMENTAL RESULTS

Speed (km/h)	$j_{actual}(m/s^2)$	$j_{max}(m/s^2)$	η
20	4.4	8.8	0.50
30	2.0	8.8	0.23
40	2.6	8.8	0.30

As shown in Table II, braking efficiency decreases with increasing speed.

TABLE III. ENERGY INTERPRETATION OF BRAKING PROCESS

Speed (km/h)	Relative Kinetic Energy	Braking Work
20	Low	Low
30	Medium	Medium
40	High	High

Table III presents a qualitative interpretation of the relationship between vehicle speed, kinetic energy, and the work performed by the braking system. As the speed increases, the energy that must be dissipated grows significantly, which directly affects braking performance.

Fig. 4 illustrates the braking behavior at 40 km/h, showing a decrease in efficiency compared to lower speeds.

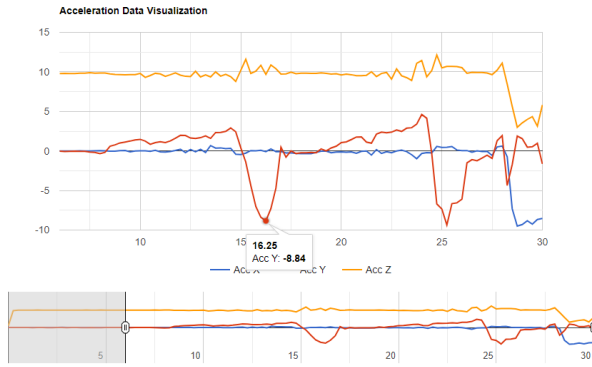


Fig. 4. Time history of longitudinal acceleration during braking at 40 km/h.

As shown in Fig. 4, the braking process at 40 km/h demonstrates increased variability and reduced efficiency compared to lower speeds.

These results indicate variability in braking intensity depending on the initial speed and braking conditions.

F. Comparison with Theoretical Model

Using typical values of the adhesion coefficient:

- wet surface: $\mu \approx 0.6$
- dry surface: $\mu \approx 0.9$

the maximum possible deceleration is calculated as:

$$j_{max} = \mu g$$

which results in:

- wet conditions: $j_{max} \approx 5.9 \text{ m/s}^2$
- dry conditions: $j_{max} \approx 8.8 \text{ m/s}^2$

Assuming a dry asphalt surface with a typical adhesion coefficient:

$$\mu_{max} \approx 0.9$$

the maximum possible deceleration is:

$$j_{max} \approx 8.8 \text{ m/s}^2$$

G. Efficiency Analysis

The obtained values are (Fiat/Renault):

- wet conditions: $\eta \approx 0.14$
- dry conditions: $\eta \approx 0.31$

These results indicate that the braking system operates below the maximum available adhesion limit.

This may be attributed to factors such as driver reaction, braking force modulation, or limitations of the vehicle braking system.

The resulting values are (Audi):

- at 20 km/h: $\eta \approx 0.5$
- at 30 km/h: $\eta \approx 0.23$
- at 40 km/h: $\eta \approx 0.30$

The following results include both controlled experiments and additional comparative data.

Similar trends in braking efficiency have been observed in the literature [7], [8].

H. Discussion

The results demonstrate that the braking efficiency is not constant and varies with speed and braking conditions.

At lower speeds, higher efficiency values are observed, indicating more effective utilization of available tire–road adhesion. At higher speeds, the efficiency decreases, which may be attributed to driver braking behavior, delayed brake force application, or limitations of the braking system.

The experimental data confirm the applicability of the proposed methodology for evaluating braking performance and highlight the importance of real-world measurements in assessing braking system efficiency.

From an energy perspective, the braking process becomes increasingly demanding at higher speeds due to the quadratic dependence of kinetic energy on velocity. This explains the observed reduction in braking efficiency and highlights the importance of considering energy dissipation mechanisms in braking system design.

IV. OTHER RECOMMENDATIONS

A. Experimental Data

The experimental data used in this study were obtained from braking tests performed under real driving conditions. The measurements were conducted using a mobile device equipped with an accelerometer, recording the longitudinal acceleration of the vehicle during braking.

The tests were carried out by a male driver aged 51 years under different road conditions, including dry and wet surfaces. The recorded data consist of time histories of acceleration along three axes, with the longitudinal component being used for braking analysis.

B. Data Processing

The recorded acceleration data were analyzed to determine the actual braking deceleration. The longitudinal acceleration component was extracted, and the maximum negative values were identified as the peak braking deceleration.

The measured values were then compared with the theoretically calculated maximum deceleration based on the tire–road adhesion coefficient.

C. Computational Model

A MATLAB-based computational model was used to process and visualize the braking data. The model enables:

- calculation of braking deceleration;
- comparison with theoretical limits;
- evaluation of braking efficiency;
- graphical representation of braking behavior.

The model also allows analysis of different braking scenarios by varying input parameters such as speed and road conditions. The use of computational tools for braking analysis is discussed in [5], [9], [10].

This study presents an analytical and experimental approach for evaluating braking deceleration and braking system efficiency.

The results show that:

- braking performance is significantly affected by road surface conditions;
- the proposed methodology provides a reliable estimation of braking efficiency;
- MATLAB-based modeling enables effective visualization and analysis of braking processes.

The integration of experimental data with theoretical modeling increases the practical applicability of the method in engineering analysis and traffic accident reconstruction.

The obtained results are consistent with established vehicle dynamics theory [1], [2], [11], [12].

V. CONCLUSIONS

This study presents an analytical and computational methodology for evaluating vehicle braking deceleration and braking system efficiency based on experimental data and classical kinematic relationships.

The results demonstrate that braking efficiency strongly depends on road surface conditions and initial vehicle speed. Higher efficiency values are observed at lower speeds, while at higher speeds the braking efficiency decreases due to increased energy dissipation and dynamic effects.

The proposed MATLAB-based model enables effective visualization and analysis of braking processes, allowing the identification of critical braking regimes and comparison with theoretical adhesion limits.

The integration of experimental data with analytical modeling enhances the reliability and applicability of the methodology in traffic accident reconstruction, vehicle dynamics analysis, and engineering practice.

Future work may include extending the model to incorporate nonlinear tire behavior, ABS dynamics, and real-time data acquisition systems.

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Mathematical Modeling of Safe Vehicle–Pedestrian Distance with Interactive Visualization

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Abstract—Pedestrian safety in road traffic is a critical factor for reducing traffic accidents. A key parameter determining safety is the safe distance between a vehicle and a pedestrian, ensuring timely stopping without collision. This study proposes a mathematical model for calculating the safe distance based on vehicle speed, pedestrian speed, and the distance traveled by the pedestrian. An interactive MATLAB-based tool is developed to visualize the model and analyze different scenarios in real time. The proposed approach is applicable in traffic safety analysis, accident reconstruction, and engineering evaluation. The model is extended to include driver reaction time and practical engineering applications.

Keywords— mathematical modeling, MATLAB, safe distance, traffic safety, vehicle–pedestrian interaction

I. INTRODUCTION

Pedestrian safety is a key factor in reducing road traffic accidents and ensuring safe interaction between vehicles and vulnerable road users. One of the main parameters defining this safety is the safe distance between a vehicle and a pedestrian, which allows sufficient time and space to avoid collision.

Similar relationships have been studied in the field of vehicle dynamics and traffic theory [1], [2], [3], [4]. In real traffic scenarios, this distance depends on the speed of the vehicle, the speed of the pedestrian, and their relative positions. Modern intelligent transportation systems and driver assistance technologies increasingly rely on real-time vehicle–pedestrian interaction models for collision prevention [5], [6], [7].

The aim of this study is to develop a mathematical model for determining the safe vehicle–pedestrian distance and to implement an interactive MATLAB-based visualization tool for analyzing different scenarios.

II. GENERAL REGULATIONS

A. Parameters and Definitions

The model uses the following parameters:

Symbol	Description
s_0	safe distance [m]
s_p	pedestrian traveled distance [m]
v_c	vehicle speed [m/s]
v_p	pedestrian speed [m/s]
a_x, a_y	initial coordinates [m]
$\Delta x, \Delta y$	positional offsets [m]

B. Motion Equations

The motion of the vehicle and the pedestrian is described as:

$$x_{car} = a_x + v_c t, y_{car} = a_y$$

$$x_{ped} = \Delta x + v_p t, y_{ped} = \Delta y \quad (1)$$

C. Velocity Ratio Condition

To ensure collision avoidance, the ratio of distances is expressed as:

$$\frac{x_{car} - \Delta x}{x_{ped} - a_x} = \frac{v_c}{v_p} \quad (2)$$

After transformation:

$$v_p(a_x + v_c t - \Delta x) = v_c(\Delta x + v_p t - a_x) \quad (3)$$

which leads to:

$$a_x = \Delta x \quad (4)$$

This relationship is consistent with classical kinematic and traffic safety models [5], [8].

D. Safe Distance Formula

After simplification, the safe distance is obtained as:

$$s_0 = \frac{v_c \cdot s_p}{v_p} \quad (5)$$

Interpretation:

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- Increasing vehicle speed v_c leads to larger s_o
- Increasing pedestrian speed, v_p reduces s_o
- The relationship is linear and proportional

E. Extended Model Including Driver Reaction Time

In real traffic conditions, the braking process is not instantaneous and includes a reaction time of the driver before braking is initiated. This reaction time plays a critical role in determining the safe distance. Similar approaches for incorporating driver response delay into stopping distance analysis are discussed in recent transportation safety studies [5], [7].

Let t_r denote the driver reaction time. During this period, the vehicle continues to move with its initial speed v_c , covering an additional distance s_r :

$$s_r = v_c t_r \quad (6)$$

Therefore, the total safe distance must include both the reaction distance and the braking-related distance:

$$s_{total} = s_r + s_o \quad (7)$$

Substituting the expression for s_r , the model becomes:

$$s_{total} = v_c t_r + (v_c t_r)/v_p$$

This extended formulation provides a more realistic representation of the safety conditions in real traffic environments, where driver response delays significantly influence the required stopping distance.

F. Extended Model with Spatial Offsets

For more realistic scenarios:

$$(a_x + s_o - \Delta x)(s_o - \Delta x - \Delta y) = (a_y + \Delta y)\Delta x \quad (8)$$

This allows visualization of the intersection point.

G. Sensitivity Analysis of the Model

The sensitivity of the proposed model with respect to changes in input parameters is an important aspect for evaluating its practical applicability.

The safe distance s_o is directly proportional to the vehicle speed v_c and inversely proportional to the pedestrian speed v_p . Therefore, small variations in these parameters may lead to significant changes in the calculated safe distance. Such sensitivity effects are also observed in modern pedestrian collision risk assessment models [3], [6].

For example, increasing the vehicle speed by 10% results in a proportional increase in the required safe distance, while increasing the pedestrian speed reduces the required distance accordingly.

This sensitivity highlights the importance of accurate parameter estimation when applying the model in real traffic conditions.

H. Practical Implications of the Model

The proposed model can be directly applied in traffic safety assessment and urban planning. For example, the calculated safe distance can be used to define minimum visibility zones near pedestrian crossings and intersections.

In addition, the model can support the design of intelligent driver assistance systems, where real-time estimation of safe distance is required. Similar concepts are applied in ADAS and autonomous driving safety frameworks [4], [7]. By integrating sensor data and vehicle speed measurements, the model can be used to warn drivers in critical situations.

Such applications demonstrate the practical importance of combining mathematical modeling with computational tools for improving road safety.

I. Model Limitations and Future Extensions

Although the proposed model provides a simplified and effective approach for estimating safe vehicle–pedestrian distance, several limitations should be considered.

First, the model assumes constant speeds for both the vehicle and the pedestrian, which may not always reflect real traffic conditions. In practice, both participants may change their velocity during interaction, especially in emergency situations.

Second, the model does not explicitly account for driver behavior variability, such as reaction delay differences, braking intensity, or decision-making processes. These factors can significantly influence the actual safety distance required to avoid collision.

Third, environmental conditions such as road surface quality, weather, and visibility are not directly included in the model. These factors may alter the effective braking performance and reaction capabilities.

Future extensions of the model may include:

- incorporation of variable acceleration and deceleration profiles;
- inclusion of stochastic (probabilistic) behavior of drivers and pedestrians;
- integration with real-time sensor data for intelligent transportation systems. Recent studies demonstrate that combining sensor-based monitoring with predictive safety models significantly improves pedestrian protection systems [6], [9];
- validation using experimental or traffic monitoring data.

Such improvements would enhance the accuracy and applicability of the model in real-world traffic safety analysis.

III. FIGURES, TABLES AND EQUATIONS

A. Example Data

The following example values are used:

Parameter	Value
s_o	7 [m]
s_p	2.3 [m]

v_c	23 [km/h]
v_p	5 [km/h]
a_x	2.0 [m]
a_y	1.5 [m]
Δx	2.2 [m]
Δy	0.3 [m]

The obtained value of s_0 represents the required safe distance under the given conditions.

B. MATLAB Interactive Simulator

An interactive MATLAB script is developed to analyze the model:

- sliders for v_c , v_p , and s_p
- vertically arranged controls to avoid overlapping the graph
- a red point indicating the current value of s_o
- visualization of the relationship between vehicle and pedestrian speeds

Similar simulation approaches are widely used in engineering analysis, intelligent transportation research, and traffic safety studies [10], [11], [12].

The model demonstrates that the safe distance increases proportionally with vehicle speed and decreases with increasing pedestrian speed.

As shown in Fig. 1, the safe distance increases linearly with vehicle speed.

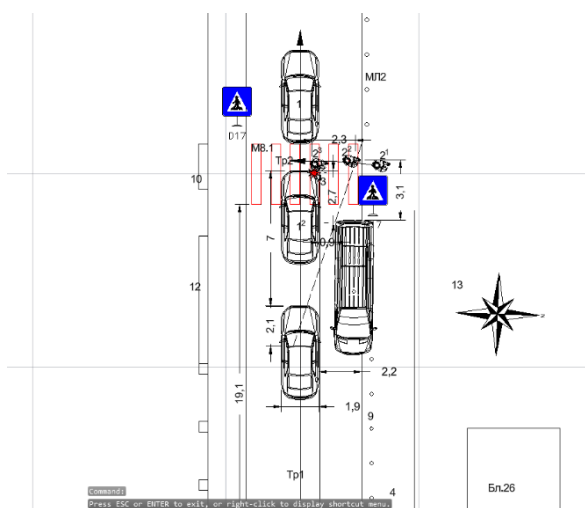


Fig. 1. Dependence of safe distance s_0 on vehicle speed v_c .

As shown in Fig. 2, the safe distance decreases as pedestrian speed increases.

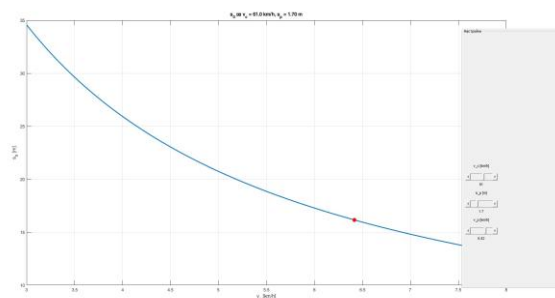


Fig. 2. Safe distance s_o as a function of pedestrian speed v_p for fixed vehicle speed and pedestrian distance

As shown in Fig. 3, the safe distance increases with increasing vehicle speed and decreases with increasing pedestrian speed. The surface clearly demonstrates the nonlinear interaction between the two variables.

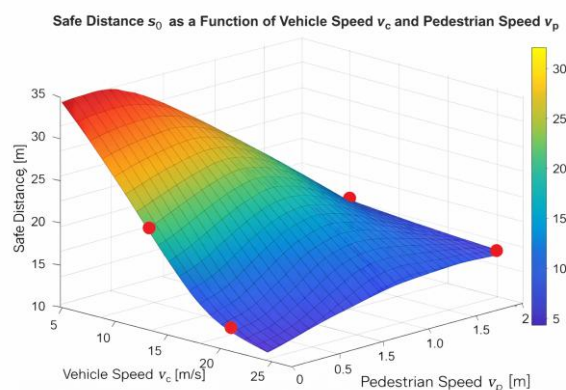


Fig. 3. Three-dimensional representation of safe distance s_0 as a function of vehicle speed v_c and pedestrian speed v_p .

Simulation results show that:

- higher vehicle speeds require significantly larger safe distances;
- slower pedestrian movement increases collision risk;
- small variations in pedestrian position may significantly affect safety conditions.

These results confirm the applicability of the model for analyzing real traffic scenarios and support its use in engineering and forensic practice.

The obtained results confirm that the safe distance is highly sensitive to changes in vehicle speed, especially at higher values. A nonlinear increase in safety requirements is observed when combining high vehicle speed with low pedestrian speed.

Furthermore, the 3D visualization presented in Fig. 3 provides a comprehensive view of the interaction between variables, allowing identification of critical safety scenarios in real traffic conditions.

These findings are consistent with established traffic safety principles and with recent research on vehicle–pedestrian conflict analysis in urban environments [3], [9].

The results can be used as a basis for engineering assessments and accident reconstruction analysis.

The simulation results also reveal that the interaction between vehicle speed and pedestrian speed is not trivial when analyzed in combined scenarios.

At higher vehicle speeds, even small reductions in pedestrian speed can significantly increase the required safe distance. Conversely, at lower vehicle speeds, the system becomes less sensitive to variations in pedestrian movement.

This behavior confirms that the model captures both linear dependencies and more complex interactions between variables, especially when visualized in three-dimensional space.

TABLE I. INFLUENCE OF SPEED PARAMETERS ON SAFE DISTANCE

vc (km/h)	vp (km/h)	s ₀ (relative)
Low	Low	Medium
High	Low	High
High	High	Medium

Table I presents a qualitative evaluation of how the relationship between vehicle and pedestrian speeds influences the safe distance. The results show that high vehicle speed combined with low pedestrian speed creates the most critical safety conditions.

Additional Theoretical Interpretation

The obtained analytical relationships can also be interpreted from a physical and safety-oriented perspective. The safe distance represents a balance between the motion of the vehicle and the pedestrian, ensuring that sufficient time is available to prevent collision.

From a kinematic point of view, the model reflects the interaction between two moving bodies with different velocities. The vehicle motion is typically dominant due to higher speed, while the pedestrian motion introduces variability in the system.

The linear dependence of the safe distance on vehicle speed highlights the critical role of speed control in urban environments. Even moderate increases in vehicle speed may lead to disproportionately higher safety requirements.

This interpretation confirms the importance of speed regulation and supports the use of the proposed model in traffic safety policies and engineering practice.

IV. OTHER RECOMMENDATIONS

A. Programs and Codes

The mathematical model and simulation results presented in this study are supported by an interactive MATLAB implementation. The developed script allows dynamic variation of vehicle speed, pedestrian speed, and pedestrian traveled distance, providing real-time visualization of the safe distance.

The program includes graphical user interface elements such as sliders and real-time plotting functions,

enabling intuitive analysis of the relationship between input parameters.

A simplified excerpt of the MATLAB code used for simulation is presented below:

```
vc = 23/3.6; % vehicle speed [m/s]
vp = 5/3.6; % pedestrian speed [m/s]
sp = 2.3; % pedestrian distance [m]

s0 = (vc * sp) / vp;

fprintf('Safe distance s0 = %.2f m\n', s0);

vp_range = linspace(1, 8, 50);
s0_values = (vc * sp) ./ vp_range;

plot(vp_range, s0_values, 'b', 'LineWidth', 2);
xlabel('Pedestrian Speed v_p [km/h]');
ylabel('Safe Distance s_0 [m]');
```

The presented code segment demonstrates the core computational logic of the model. The complete implementation includes additional interactive controls and visualization features.

The MATLAB implementation can be further extended by incorporating real-time data acquisition and dynamic parameter updates. This would allow the model to be used in real-world driving scenarios and integrated into advanced driver assistance systems (ADAS).

A mathematical model for determining safe vehicle–pedestrian distance has been presented.

The study shows that:

- the safe distance depends linearly on vehicle and pedestrian speeds;
- the model can be effectively visualized using MATLAB;
- the approach is suitable for traffic safety analysis and accident reconstruction.

The proposed model provides a practical tool for evaluating safety distances in real traffic environments.

The model can be further extended using probabilistic methods and real-world data analysis. The proposed model can also be extended to include reaction time and braking dynamics, which would further improve its applicability in real-world traffic scenarios. Future research may focus on integrating probabilistic approaches and experimental validation.

The model can also serve as a basis for educational simulations and training tools in traffic safety analysis.

Practical Applications and Engineering Relevance

The proposed mathematical model has practical relevance in several engineering and safety-related domains. It can be applied in the design of pedestrian crossing systems, urban traffic planning, and the development of intelligent transportation systems and autonomous vehicle safety platforms [4], [7], [11], [12].

In engineering practice, the model can assist in evaluating visibility distances and defining safety zones in areas with high pedestrian activity. It can also be used in forensic analysis to estimate whether a driver had sufficient distance to avoid a collision.

Furthermore, the integration of the model into simulation environments and driver assistance systems allows real-time assessment of safety conditions. This makes the approach particularly valuable for modern traffic management and smart mobility solutions [13], [14], [15].

The model provides a bridge between theoretical analysis and practical implementation in traffic safety engineering.

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Turning Innovation into a Product Concept

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Abstract—The formation of the concept aims to further develop the innovative idea and transform it into a real innovative product intended for the market, as well as to bring consumer desires into a production-feasible product. Usually, a company has at least several innovative ideas for one product. The life cycle of innovations is presented, as well as the degree of novelty of products and processes as part of the industry. A model is presented for determining the degree of innovation through: Innovations outside industry – expanding the scope, technical regularities in innovative development, innovative development, intensification and productivity, innovative obsolescence, trends in the relative change in the parameters of products and processes under the influence of innovative obsolescence. The known technical, consumer and market indicators are used, which are redefined in view of the topic.

Keywords— degree of novelty, innovation, life cycle.

I. INTRODUCTION

The present work on the topic "Transforming innovations into a product concept" contains a current work dedicated to improving the constructive and technological approaches in the design and manufacture of mechanical engineering products; innovations, their management, their implementation in enterprises, the innovation strategy and policies for achieving it, as well as methods for alternative solutions against the rapid obsolescence of innovations in the field of technologies in the conditions of the Fourth Industrial Revolution (FIR) and globalization [1, 2, 3, 4].

In the modern conditions of globalization and accelerated scientific and technological progress, innovations are established as a key factor for economic development and social transformation. They are not limited only to industrial production, but penetrate all spheres of economic and social life. The degree of novelty of the innovation process is an essential indicator that determines its significance, impact and effectiveness [5].

According to modern research, innovation is the implementation of a new or significantly improved product, process or organizational method, with its practical application being a mandatory condition. In this

context, the degree of novelty determines whether an innovation is radical, improving or adaptive [6, 7, 8].

Innovation is the introduction into use of a new or significantly improved product (good or service) or production process, a new method of production or a new organizational and technological method. A minimum sign of an innovation is the requirement that the product, production process, technological method or organization is new (or significantly improved) for the practice of a given company [9]. This is included in the category of innovations in products, production processes and methods that companies have created first and/or products, production processes and methods borrowed from other companies or organizations. Innovation activity represents all scientific, technological, organizational, financial and commercial actions from which the implementation of innovations actually results, or which are conceived for this purpose. Some types of innovation activities are innovative in themselves, others do not have this property, but are also necessary for the implementation of the innovation. Innovation activity also includes research and experimental developments that are not directly related to the development of a specific innovation. A common feature of innovation is the fact that it must necessarily be implemented [10, 11]. A new or improved product is considered implemented when it has entered the market. New production processes, marketing methods or organizational methods are considered implemented when they are actually used in the company's activities [12]. The nature of innovation activities in different companies is different. Some companies are engaged in very clearly expressed innovation projects - including the development and implementation of a specific new product, while others are primarily concerned with introducing new and new improvements to their products, production processes and operations. Both types of companies can be considered innovative, since innovation can consist of the implementation of a single significant change or a whole series of less significant improving changes, which in their aggregate form a significant change. An innovative company is one that has implemented some innovation during a certain period of time during the study [13, 14].

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Successful innovation is strongly linked to financial results and is a major driver of economic growth in the economy.

The essence of the degree of novelty of an innovation

The degree of novelty of an innovation reflects the level of difference between the innovation and existing solutions [15]. It is considered as a criterion for classifying innovations into:

- Radical innovations – create new markets and technological directions;
- Incremental (improving) – improve existing products and processes;
- Imitative – adapt already existing solutions in a new context.

II. MATERIALS AND METHODS

Innovations outside industry – expanding the scope

Current trends show that innovation processes are actively developing in various areas outside traditional production:

1. Social sphere

In the social sphere, innovations are manifested through:

- new models of social services;
- digitalization of education and healthcare;
- social entrepreneurial initiatives.

Here, the degree of novelty is often measured by social impact, and not only by technological progress.

2. Education and science

Innovations in education include:

- distance learning;
- interactive teaching methods;
- use of artificial intelligence.

These processes are related to globalization and the need to adapt to new requirements on the labor market, and an accelerated implementation of innovative solutions is observed [16].

3. Management and public sector

In the public sector, innovations are expressed in:

- e-government;
- new administrative models;
- transparency and digitalization of services.

Here, the degree of novelty is related to the efficiency and accessibility of services for citizens.

4. Services and trade

Innovations in services include:

- digital platforms;
- e-commerce;
- personalized services.

They are directly influenced by the development of information technology and global competition.

Relationship between the degree of novelty and innovation obsolescence

One of the key aspects considered in the materials provided is the relationship between innovation development and innovation obsolescence. It has been proven that there is a direct interdependence between them.

As the degree of novelty increases:

- the life cycle of innovations is shortened;
- the process of their obsolescence is accelerated;
- the need for continuous renewal increases.

Innovation obsolescence is considered a natural process in which new technologies quickly replace old ones, even having a greater importance than physical wear and tear.

Methods for assessing the degree of novelty

In scientific works, various methods have been proposed for assessing the degree of innovation, including:

- a method for determining the degree of innovation;
- a method for innovative activity;
- a method for assessing innovation obsolescence.

These methods allow:

- quantitative measurement of novelty;
- forecasting the innovation life cycle;
- choosing optimal management solutions.

Practical significance

Understanding the degree of novelty has important practical significance:

- supports the strategic management of organizations;
- facilitates the choice of an innovation strategy;
- increases competitiveness.

III. RESULTS AND DISCUSSION

The modern stage of development of economic life is characterized by globalization of requirements for product quality, the need for sustainable growth, the desire for highly effective implementation of innovative achievements and high technologies in the field of information and communications [17, 18, 19, 20]. The sustainable trends of globalization of the economy determine the accelerated introduction of innovative solutions, expressed in new technologies and automation of production processes, which solve a wide range of tasks related to increasing productivity, the quality of manufactured products, the sustainability and flexibility of the production process, and shortening the period from the birth of the idea to the realization of the product on the market [21, 22, 23]. The innovative saturation of processes (technological and information) is aimed, in addition to the elimination of heavy, monotonous, harmful to health and unattractive work, at the implementation of specific innovative solutions (artificial intelligence) that increase productivity and efficiency. These solutions have the task of overcoming the persistent trend of labor resource deficit (human capital), determined by demographic factors. On the other hand, at the beginning of the 21st century, the

ever-increasing demands of consumers and the increasing competitive pressure on world markets predetermine the need for a fundamentally different approach to the entire innovation process [24, 25]. A global trend is that manufactured products are beginning to become extremely complicated, both in terms of their internal structure and in terms of consumer and functional requirements that must satisfy the need. These new production concepts impose a fundamentally new way of industrial construction. In them, through the use of global information networks, an opportunity is provided for intensification of production and significant improvement of the quality of manufactured products [26, 27, 28]. The creation of environmentally friendly technological schemes, methods and processes is a priority of the new production concepts. In this regard, social problems and environmental restrictions will impose their predominant importance in the innovative development of production in the future. Moreover, productivity and efficiency will have an integral importance, determined by the groups of factors caused by the impact of the new concepts [29]. This highly efficient production is a direct consequence of the use of the latest advances in computer technology and equipment, i.e. innovation. The concepts and solutions for a new type of production are generated by the complex market conditions and the desire of leading companies to produce their new products more efficiently, with better quality and in a more environmentally friendly manner in order to satisfy the requirements of the consumer on a global scale and the communication between them [30].

Some concepts generated by globalization are a direct consequence of the use of innovations, including the latest achievements in computer technology and informatics.

All this proves that the current state of production is determined by the criteria of globalization, including global competition, the impact of high (High) technologies and the prevailing assumptions for sustainable growth. These three criteria actually determine the possibility of effective construction and development of industrial production (Fig. 1).

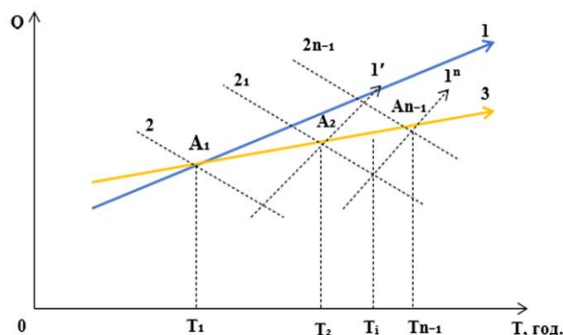


Fig. 1. Dependence between global competition under the influence of high (High) technologies and the prevailing assumptions for sustainable growth [1, 2]

(1 - global competition; 2, 2₁, ..., 2_{n-1} - the resource of efficiency of old technologies; A₁, A₂, A_{n-1} - points of equilibrium between global competition (1, 1', ..., 1ⁿ); sustainable growth (3) and high technologies (2, 2₁, ..., 2_{n-1}); 3 - sustainable growth; T - time (years); Q - growth)

At t_A we have a relative balance between growth and competition, and the period between T_1 and T_{n-1} is characterized by the need for investment saturation of the industry with new innovative solutions. In this case, productivity and efficiency will have an interdependent meaning, determined by factors characterizing the essence of high-performance technologies.

The relationship between technical levels (W), social productivity (Q_0), and efficiency (E) is shown in Fig. 2.

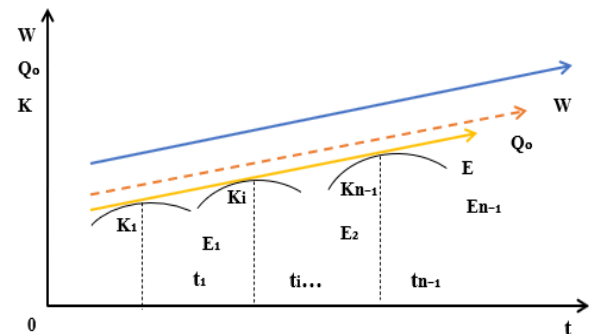


Fig.2. Relationship between technical levels (W), social productivity (Q_0) and efficiency (E)

(E- efficiency; Q_0 - social productivity; K - equilibrium point; t - time (years); W- technical levels)

After t_K ... K_i ... K_{n-1} productivity begins to approach the limiting line of the achieved technological level in time t_i and remains constant, and efficiency begins to decrease.

Sustainable growth and global competition impose the need to use economic impacts to awaken production growth, effectively balanced between the needs of society and productivity. This means investing funds in high-performance technologies (production and information), which provide solutions for global innovation saturation of processes and activities.

Technical regularities in innovative development. Innovative development, intensification and productivity.

There is a certain dependence between productivity (Q) as the achieved world level and technical development. It is expressed in the achieved technical degrees of development (W), taking into account the differences in the respective levels (W_n) and the increase in productivity (Q_n). The indicators determining productivity and technical levels are closely related and interdependent, as they are defined by technological development at a given time, and it, in turn, is the result of the achieved productivity of technologies as a degree of development of scientific and technological progress. The physical essence of these dependencies is expressed in shortening the periods of creation of new technical solutions, technologies, modern designs, know-how, etc. and increasing their productivity in absolute and relative dimensions for each new period ($T_1, T_2, T_3, \dots, T_i, \dots, T_{n-1}$). It follows that the periods of innovative obsolescence of technologies become shorter and shorter in time ($t_1, t_2, t_3, \dots, t_i, t_n$), and technical levels - higher and higher for each subsequent period. These are objective technical laws that,

with technological development, mark accelerated steps for each subsequent period (Fig. 3).

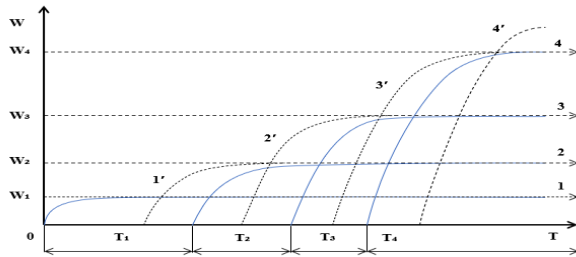


Fig.3. Technical regularities [2].

The figures 1, 2 and 3 used are part of a published monographic work by the author Desislava Petrova "Innovation management", Gabrovo, 2020, ISBN 978-954-683-615-1 [1].

Therefore, the future development of industrial activities will be characterized by increasingly higher technical levels, increasingly higher productivity, rapid innovative obsolescence and global intensification of processes and activities. At the same time, these dependencies form new spheres, generating a new development environment, flexibly balanced by the impact of internal and external factors [31, 32, 33].

Now we cannot speak only about individual innovations and innovation processes, but about innovative production, considered comprehensively. The impact of the external environment determines the basic requirements for the technological behavior of companies and creates the prerequisites and conditions for a new attitude to innovations as an integral and necessary part of the global development of industry and society.

From the above Fig. 3 it is seen that:

- in the vertical $W_1 < W_2 < W_3 < \dots W_i \dots < W_{n-1}$, where W_1, W_2, W_3, W_4 is the social productivity defined by the technical levels;
- in the horizontal $T_1 > T_2 > T_3 > \dots T_i > \dots T_{n-1}$, where T_1 is the period of steam engine and mechanization; T_2 - the period of electricity and automation; T_3 - the period of computerization and a high degree of automation; T_4 - the period of artificial intelligence and cyber systems.

Innovative obsolescence

Innovative obsolescence is a regularity caused by innovative development in all directions of world scientific progress. At the current stage of technical development, innovative obsolescence has a predominant importance over physical. Therefore, a particularly important point in this direction is the correct determination of the degree of innovative obsolescence. The goal is to establish the influence of innovations on the technical, economic and social results of industrial activity. The correct assessment of their influence on the scale and terms of innovative obsolescence is of utmost importance for the timely elimination of the negative consequences of their impact.

Taking into account the factors that characterize the qualitative side of innovative development allows us to reveal not only the mechanism of its impact on production efficiency indicators, but also its influence on various aspects of the production process. To facilitate further clarification of the problem, we will group the influence of these factors into several directions.

The influence of innovative development on technology is expressed in the improvement of existing and the construction of fundamentally new machines, devices and equipment. By purpose and rates of growth of their productivity, they can be divided into two main groups: special machines and equipment, intended for the production of uniform products on a mass scale; and universal machines and equipment, intended for the performance of various activities. In recent years, a trend of strong unification and standardization of elements in machine units based on the modular principle has been observed. The goal is to create conditions for the rapid assembly of machines with different technological purposes, but with universal purpose (the principle of mechatronic machines). The study of the regularities of the development and improvement of technology with special and universal purpose makes it possible to determine the period in which the greatest effect can be obtained from a given generation of machines intended for a specific production process, and at the same time the term for switching to the production of new types of machines.

In the modern conditions of accelerated scientific and technological progress, the importance of this direction and its manifestation on the pace and scale of innovative obsolescence of technology has significantly increased. The real consequence of this impact is expressed in an increase in the scope and terms of innovative obsolescence of machines and equipment in operation and a rapid change in their structural composition.

Innovative development is also expressed in the creation of new materials, which have an active impact on accelerating the innovative obsolescence of operating technology. This impact is determined by the widespread use of new materials adapted for processing on a certain type of machine. The share of unnecessary equipment adapted for processing old materials depends on the scale of their use in production.

Innovative development affects technological processes. The changes occurring from the application of these new technologies in any case play an active role in the production process, as a result of which the relative share of old technological processes is constantly decreasing, and with them the machines and equipment used for this purpose. It is related to professional training and improvement of methods, to the improvement of qualifications and training of personnel. Significant changes occur in the qualification composition of personnel, as a result of which a large number of new professions arise, old ones disappear, and the ratio between individual groups of professions changes. This is the subject of Industry 5.0.

The development of technology leads to significant changes in the methods of its exploitation on the one hand, and on the other hand to the improvement of methods for changing the nature of labor and improving the qualifications of personnel.

From the above, it can be concluded that: the influence of innovative development is globalized, as a result of which innovative obsolescence of technology occurs and the level of technologies put into operation lags behind modern ones. Further use of innovatively obsolete technology and technological processes leads to certain losses, the amount of which will depend on the degree of this lag.

Trends in the relative change in the parameters of products and processes under the influence of innovative obsolescence.

Technological development and, more precisely, its consequences, manifested in the form of innovative obsolescence of products and processes, lead to a peculiar attitude of manufacturers to search for ways and means for improving and changing their parameters. The tendency to change the parameters of innovative products and processes as a result of their rapid innovative obsolescence forms a new alternative concept for innovative development. It also places new requirements on both the consumer nature of innovative products and the methods, approaches and ways of their production.

The main directions that provide an effective way out of the limitations imposed by the rapid innovative obsolescence in the creation of competitive innovative products are actively applied by many companies in mechanical engineering and electronics. This new approach, quickly adopted by industrial companies, already shows its advantages in the following directions:

- Application of the modular principle of design and production of innovative products;
- Design and production of modules with different technological purposes;
- Design and production of innovative products with the highest possible reliability and short service life;
- Consideration of the design and production cycle as a continuous process of flow and use of the methods of competitive engineering, simulation, virtual representation, etc. in order to shorten the cycle as much as possible;
- The shortest possible cycle from idea to manufactured innovative product.

IV. CONCLUSIONS

The degree of novelty of the innovation process is a key factor in the development of the modern economy and society. It determines not only the nature and impact of innovations, but also their sustainability over time. The expansion of innovation activity in various spheres of economic and social life requires new approaches to management, assessment and adaptation.

In the conditions of accelerated technological development and global competition, the successful implementation of innovations depends on the ability to correctly assess their novelty and timely respond to the processes of innovation obsolescence.

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Investigation and Modelling of Surface Roughness During Milling of GJL-250 Gray Cast Iron and S235JR Steel Using Mixed Ceramic Tools

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Abstract— Milling is one of the most common methods for processing flat surfaces, providing satisfactory accuracy and low surface roughness at high production rates. This paper presents the results of a study on the surface roughness of machined parts made of GJL-250 gray cast iron and S235JR carbon structural steel, obtained by milling with a single-tooth milling cutter with $\text{Al}_2\text{O}_3/\text{TiC}$ mixed ceramic replaceable insert. Using the methods of the planned experiment and the multifactorial regression analysis, the combined influence of the cutting speed and the feed per tooth on the surface roughness has been evaluated, and corresponding adequate theoretical-experimental models have been constructed. Combinations of cutting speed and feed per tooth have been determined that result in minimum surface roughness on the machined surfaces for the two materials studied.

Keywords—carbon structural steel, gray cast iron, milling, mixed ceramic tools, regression models, roughness

I. INTRODUCTION

Planing, slotting, grinding, broaching and milling are the main methods of processing flat surfaces in mechanical engineering. Milling is one of the most common among them, as it provides a combination of high productivity and satisfactory accuracy at low roughness. When milling, $7 \div 6$ degrees of accuracy and roughness of up to $R_a = 0.4 \mu\text{m}$ of the machined surfaces are achieved [1], [2].

The process of milling uses tools, made of high-speed tool steel, cermets and cutting mineral ceramics. The application of milling cutters with replaceable mineral ceramic inserts aims at processing difficult-to-machine

materials (5 – 15%), hardened steels (20 – 29%) and cast irons (65 – 70%) under dry cutting conditions, achieving cutting speeds of up to 1200 m/min, minute feed rates of up to 5000 mm/min and roughness of up to $0.63 \mu\text{m}$ [3]. These tools have a number of advantages compared to the ones, made of high-speed tool steels and cermets, due to their high hardness, wear and temperature resistance, as well as to the good chemical resistance of the mineral ceramic materials and the low coefficient of friction during cutting [4] – [7]. As a result, the mineral-ceramic tools are considered to be among the most suitable for CNC machine tools and various automatic machines [8] – [14]. However, their application is limited by their high brittleness and sensitivity to temperature changes, and their low transverse strength [15].

The application of cutting ceramics with an emphasis on the turning process has been studied by a number of authors. The productivity and wear mechanisms of ceramic tools in machining various materials under different operating conditions (cutting mode, lubricants and coolants, type of wear-resistant coatings) have been established [16].

Kumar et al. [17] studies two types of ceramic cutting tools – mixed ceramic and zirconium nitride-enhanced ones - and evaluates the machinability of hardened steel using the criteria of tool wear, surface roughness, and cutting forces. Hong [18] has proven that oxide and mixed ceramic tools are suitable for machining hardened steel due to their high wear resistance. Bhattacharyya et al. [19], in turn, finds that mixed ceramic tools provide higher

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productivity than those, made of oxide and nitride ceramics in machining cast iron. A study, conducted by Charles [20], when machining automotive hubs, made of ductile cast iron, shows that the use of tools, made of composite ceramic materials, leads to an increase in tool life of up to 2.5 times, as well as to a higher cutting speed, compared to machining with cermet tools with wear-resistant coatings.

Shnfir et al. [21] investigate the machinability of hardened steel AISI 1045 during face milling using SiAlON and whisker (SiCW) based ceramic inserts. The influence of the cutting conditions, of the hardness of the machined material and of tool geometry on the resultant cutting force, energy consumption and wear on the rear surface, has been established. The authors have proven that feed rate is the most influential factor, and the decrease in the feed rate leads to significantly lower resultant cutting forces (by approximately 74%). This creates conditions for a significant reduction in cutting power.

While studying the influence of the radius of curvature of the cutting tool edge in milling hardened AISI H13 steel (50 HRC), Li et al. [22] find that with increasing the radius, the cutting forces, plastic deformation and residual compressive stress also increase, while surface roughness decreases to a certain limit value.

When milling, it is a difficult task to perform interrupted cutting with ceramic tools both due to the impact load, undergone by the inserts during machining, and because of the tool brittleness. In addition, the recommended in the literature working conditions for milling with mineral ceramic tools concern particular tools and specific machined materials.

In this regard, the present paper describes a study of the roughness of the machined surfaces of gray cast iron and structural steel parts during face milling with a mixed mineral ceramic tool and recommends appropriate values of cutting speed and tooth feed for the two studied materials.

II. MATERIALS AND METHODS

The experimental studies were conducted on a universal milling machine TOS FD 40, without the use of a lubricant and coolant (Fig. 1).

A single-tooth milling cutter (Fig. 2), operating on the principle of "extensive final cleanup" was used to conduct the experiment. The milling cutter has a diameter $D = 200$ mm and geometric parameters as follows: tool back race angle $\gamma_p = -6^\circ$; tool back clearance angle $\alpha_p = 6^\circ$; tool major cutting edge angle $\kappa_r = 90^\circ$; tool minor cutting edge angle $\kappa'_r = 0^\circ$.

The studied mineral ceramic insert is made of mixed ceramics (60% Al_2O_3 + 40% TiC) with a hardness of HV 28000 N/mm² (HIP). The insert is set so that the auxiliary cutting edge is parallel to the surface under machining (Fig. 2).



Fig.1 Experimental setup. 1-workpiece, 2- tool, 3-machine TOS FD 40

The roughness of the machined surfaces was studied when milling parts, made of gray cast iron GJL-250 and carbon structural steel S235JR with chemical composition and physical-mechanical properties, presented in Table 1 [23]. The dimensions of the machined parts were:

- length 75 mm, width 65 mm and height 20 mm – for steel S235JR;
- length 50 mm, width 35 mm and height 30 mm – for gray cast iron GJL-250.

The workpieces of both materials were pre-machined with a ten-tooth end milling cutter ($z=10$), under the following cutting mode: rotational frequency 630 min⁻¹; cutting depth 0.5 mm; minute feed rate 80 mm/min.

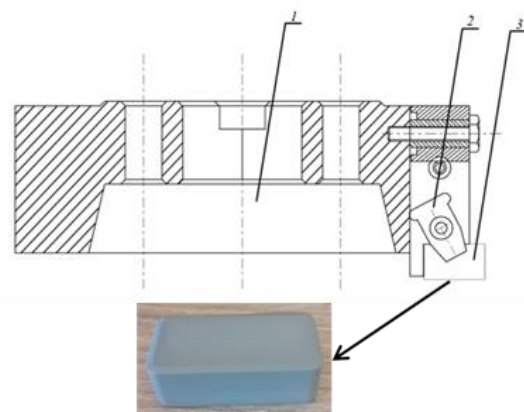


Fig. 2 Single-edged milling cutter. 1-body, 2-clamp, 3 mineral-ceramic insert

TABLE I. CHEMICAL COMPOSITION AND PHYSICAL- MECHANICAL PROPERTIES OF THE STUDIED MATERIALS

Machined Material	Hardness HV	Tensile strength Rm, N/mm ²	Yield strength Rp0.2, N/mm ²	Relative elongation A, %	Chemical composition, %
GJL-250 (EN 1561: 1997)	245	250-350	450	0.6	C-3.15, P-0.22, Mn-0.6, S-0.1, Si-2.1, Fe
S235JR (EN 10250-2:2000)	130	390-490	235	26	C-0.17, P-0.035, Mn-1.4, S-0.035, N-0.12, Cu-0.55

The experimental studies, aimed at determining the roughness, were carried out under the following cutting mode: cutting speed $V_c=400\div700$ m/min; tooth feed $f_z = 0.89\div1.79$ mm/z; depth of cut $a_p = 0.05$ mm = const. The mode is determined depending on the types of materials under machining and the recommended values by various manufacturers [24], [25], and it is consistent with the rotation frequencies and minute feeds of the TOS FD 40 milling machine.

The roughness of the machined surfaces was evaluated according to the criterion R_a (μm) - arithmetical mean deviation of the roughness profile. It was measured with a digital roughness meter "Mitutoyo SJ201 P/M" (Fig. 3) [26].



Fig.3 General view of the roughness meter Mitutoyo SJ201 P/M

III. RESULTS AND DISCUSSION

A planned multifactorial experiment of the type, given below, was conducted according to an optimal central compositional plan to study and model the influence of the individual elements of the cutting mode on the surface roughness R_a , obtained when machining gray cast iron GJL-250 and carbon structural steel S235JR:

$$N=2^2+2.2+1 \quad (1)$$

The general form of the model is:

$$Y_i=b_0+b_1X_1+b_2X_2+b_{11}X_{12}+b_{22}X_{22}+b_{12}X_1X_2 \quad (2)$$

where: $Y_1=R_{a1}$ is the roughness of the machined surfaces of gray cast iron GJL-250; $Y_2= R_{a2}$ – roughness of the machined surfaces of structural steel S235JR; $b_0, b_1, b_2, b_{11}, b_{22}$ and b_{12} – regression coefficients; $X_1= V_c$ (m/min); $X_2= f_z$ (mm/z) – controlling factors, the variation levels of which can be seen in Table 2.

The experimental design with the experimentally measured roughness values for the two machined materials are presented in Table 3.

The experimental results were processed in accordance with the methodology, presented in [27], in the following sequence: determination of the model coefficients;

checking for significance of the regression coefficients using the Student's t-test; determination of the multiple correlation coefficient; checking for significance of the multiple coefficient, using the Fisher's test.

TABLE II. LEVELS OF CHANGE IN THE CONTROLLING FACTORS

Controlling factors		Factor levels		
Coded	Natural	-1	0	+1
X_1	V_c , m/min	446	575	703
X_2	f_z , mm/z	0.89	1.34	1.79

TABLE III. PLAN MATRIX AND EXPERIMENTAL DESIGN PLAN WITH EXPERIMENTAL DATA AND THEORETICAL VALUES

№	X_1	X_2	V_c , m/min	f_z , mm/z	GJL-250		S235JR	
					R_{e1}	$\widehat{R}_{e1}$	R_{e2}	$\widehat{R}_{e2}$
1	-1	-1	446	0.89	0.3405	0.3418	0.1316	0.1375
2	+1	-1	703	0.89	0.4302	0.4305	0.1387	0.1401
3	-1	+1	446	1.79	0.4699	0.4697	0.1341	0.1310
4	+1	+1	703	1.79	0.4385	0.4372	0.4150	0.4073
5	0	-1	575	0.89	0.3901	0.3885	0.1359	0.1286
6	0	+1	575	1.79	0.4540	0.4556	0.2486	0.2594
7	-1	0	446	1.34	0.4112	0.4101	0.1330	0.1302
8	+1	0	703	1.34	0.4372	0.4382	0.2635	0.2697
9	0	0	575	1.34	0.4264	0.4264	0.1935	0.1900

The results of the research were processed using the QstatLab software [28] and regression models were obtained, presented in Table 4.

The roughness values, determined by the models for milling steel and cast iron, are presented in Table 3.

The created models describe with sufficient accuracy the relationship between the roughness R_a and the cutting mode elements V_c and f_z , which is proven by checking the significance of the multiple correlation coefficient R^2 . The presented models are adequate, since the condition $F_R > F_{\alpha, v_1, v_2}$ is fulfilled with a 95% confidence probability. The empirical F_R and the tabular values $F_{\alpha, v_1, v_2} = F_{0.05, 5, 3}$ of the Fisher test criterion ($\alpha = 0.05$ – significance level; $v_1 = n-1$ and $v_2 = N-n$ – degrees of freedom) for each of the regression models are presented in Table 4.

To assess the ability of the constructed regression models to predict responses to new, unperformed observations, the predicted values of R_{pred}^2 were determined for each of the models (Table 4). The high values of R_{pred}^2 (0.989 and 0.947) show a good ability of the obtained models to predict new, untested quantities.

TABLE IV. REGRESSION MODELS AND STATISTICAL ANALYSIS

Regression models	F_R	$F_{\alpha,5,3}^{0.050}$	$\hat{R}_{adj}^2$	R_{pred}^2
$R_{a1} = -0.22259825 + 0.00096375 V_c + 0.43380305 f_z - 1.3E-7 V_c^2 - 0.0217284 f_z^2 - 0.00052362 V_c f_z$	653.49	9.013	0.998	0.989
$R_{a2} = 0.83520863 - 0.00175659 V_c - 0.58780043 f_z + 6.2E-7 V_c^2 + 0.01967078 f_z^2 + 0.0011834 V_c f_z$	131.86	9.013	0.988	0.947

Graphical interpretation of the constructed models for roughness change depending on the cutting speed V_c and the feed f_z is shown in Fig. 4.

To determine the influence of the controlling factors on the roughness, an analysis of variance (ANOVA) was performed. The influence is graphically interpreted in Fig. 5.

The analysis of the constructed models (Table 4 and Fig. 4) and of the results of the conducted variance analysis (Fig. 5) show that:

- The roughness R_a of the machined surfaces when milling S235JR steel is less than that when machining gray cast iron GJL-25. The influence of the cutting speed V_c and feed f_z on R_a is different for the two machined materials and is more pronounced when milling S235JR steel.

- When milling gray cast iron GJL-250, the roughness of the machined surfaces R_a depends on the feed f_z to a greater extent than on the cutting speed V_c . With

increasing the feed in the studied range, the roughness R_a increases from 1.9% to 27.5%, with the influence being more pronounced at lower cutting speeds. The roughness R_a changes depending on the cutting speed V_c in the range from 6.7% to 21%, and the change is greater at lower feed ($f_z = 0.89$ mm/z).

- When machining structural steel S235JR, the influence of the feed f_z and of the cutting speed V_c is commensurate. When the speed increases in the studied range (from 446 to 703 m/min), the roughness increases from 1.8% to 67%. An increase in the feed from 0.89 to 1.79 mm/z leads to an increase in roughness (R_a) from 5.1% to 68%, respectively.

Appropriate combinations of the cutting speed V_c and tooth feed f_z were determined, at which minimum roughness R_a was obtained for the two studied materials (Table 5). The QstatLab software product was used, and the random search method with increasing density was applied. A visualization of the process is presented in Fig. 6a – for gray cast iron GJL-250 and in Fig. 6b – for structural steel S235JR.

Confirmatory experiments were conducted, and the difference between the theoretical ($\hat{R}_a$) and the experimental roughness value R_a was within 0.58% for gray cast iron GJL-250 and 4.8% for structural steel S235JR (Table 5).

TABLE V. OPTIMAL VALUES FOR MACHINING GRAY CAST IRON GJL-250 AND STEEL S235JR

Machined material	Controlling factor		$\hat{R}_a, \mu m$	$R_a, \mu m$
	$V_c, m/min$	$f_z, mm/z$		
GJL-250	446	0.89	0.342	0.340
S235JR	575	0.89	0.128	0.136

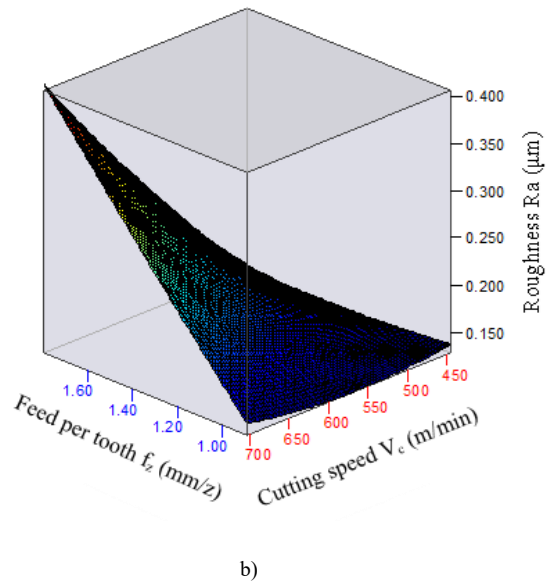
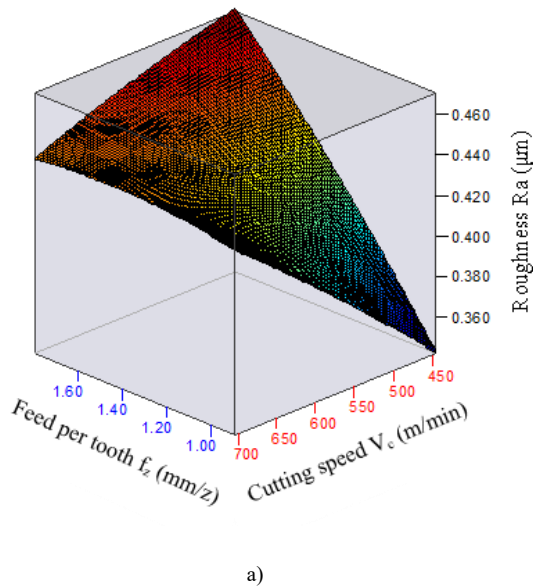


Fig. 4. Influence of the cutting speed V_c and feed f_z on the roughness R_a when machining: a) gray cast iron GJL-250; b) carbon structural steel S235JR

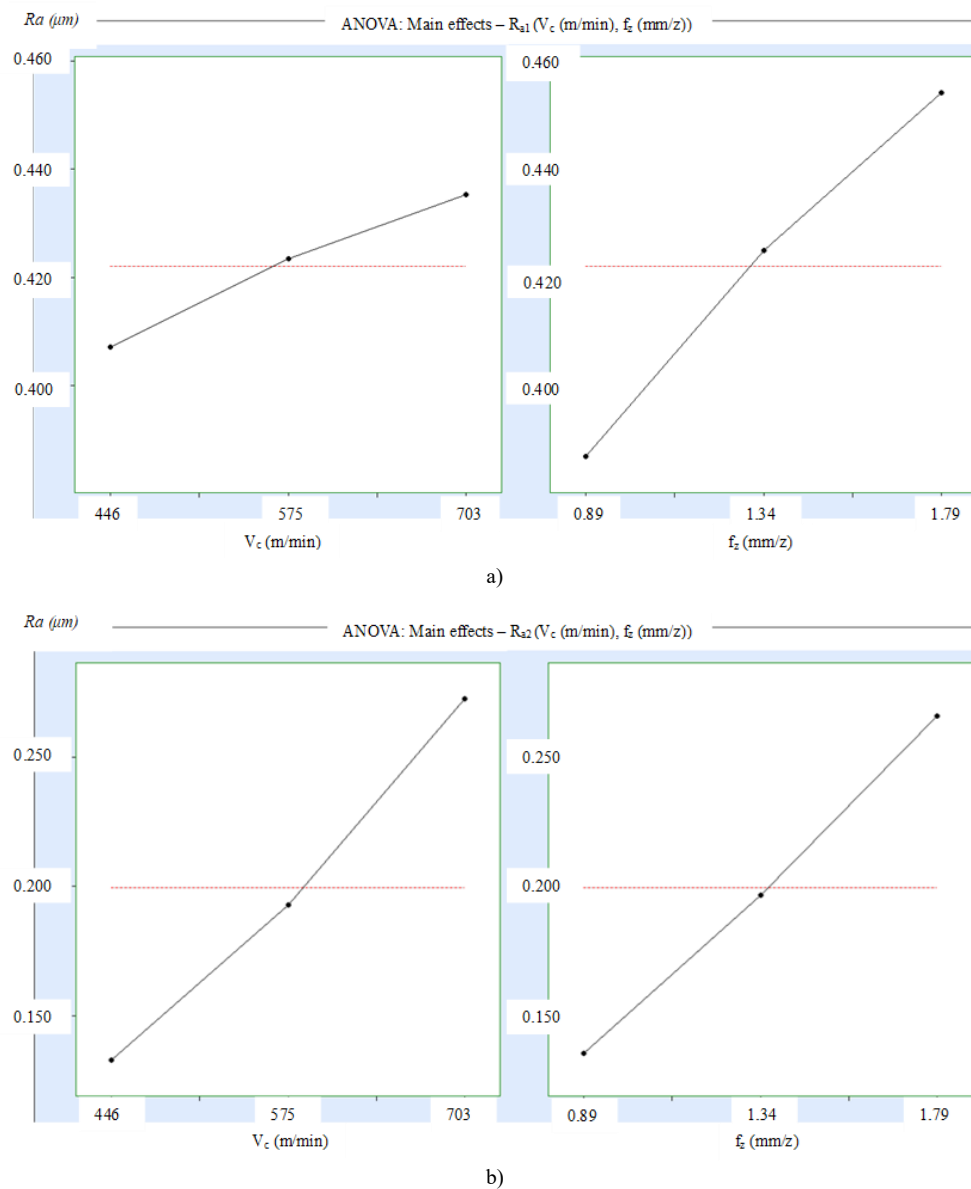


Fig. 5. Visualization of the effects of the cutting speed V_c and feed f_z when machining: a) gray cast iron GJL-250; b) carbon structural steel S235JR

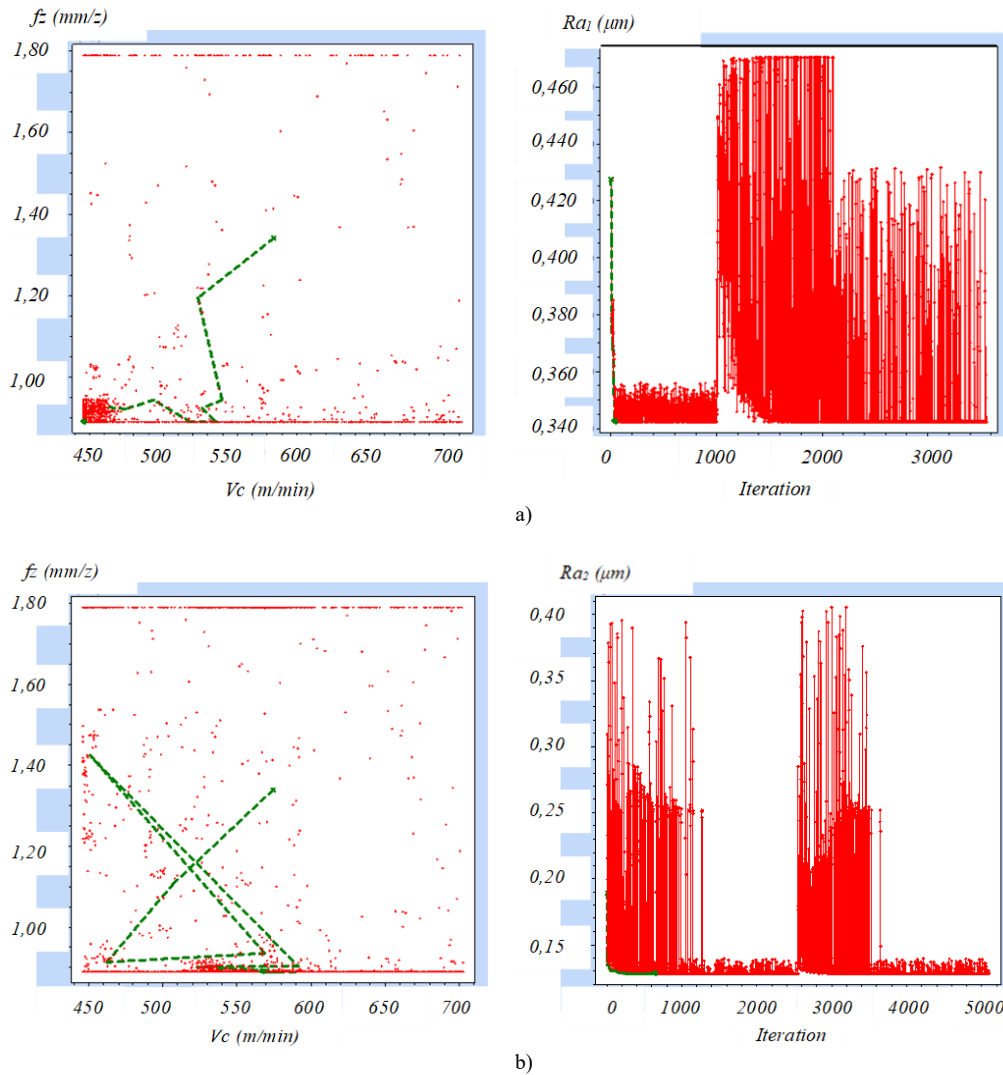


Fig. 6. Determination of optimal cutting conditions for obtaining minimum roughness when machining: a) gray cast iron GJL-250; b) structural steel S235JR

IV. CONCLUSIONS

The paper presents the results of a study of the roughness of the machined surfaces of gray cast iron GJL-250 and carbon structural steel S235JR parts, obtained during face milling on a single-tooth end milling cutter with a replaceable insert, made of mixed ceramics - $\text{Al}_2\text{O}_3/\text{TiC}$.

The complex influence of the cutting speed V_c and tooth feed f_z on the roughness R_a of the machined surface has been evaluated, and the corresponding adequate regression models have been constructed.

The created models make it possible to predict with sufficient accuracy the roughness of the machined surfaces of parts made of the two studied materials, which is proven by the prognostic value R^2_{pred} (0.989 and 0.947).

For both studied materials it has been found that the tooth feed has a greater influence on the roughness of the machined surfaces, with the increase in f_z leading to an

increase in R_a of up to 67% when machining S235JR steel, and up to 27.5% when machining GJL-250 gray cast iron.

Combinations of cutting speed V_c and tooth feed f_z have been determined, at which the roughness of the surfaces, machined according to the R_a criterion is minimal for the studied materials (Table 5).

The conducted studies confirm the working capacity of the single-tooth milling cutter with a replaceable mineral ceramic cutting insert by the roughness criterion of the machined surface R_a when processing S235JR steel and GJL-250 gray cast iron.

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Modeling and Optimization of Material Flows in a Section for Machining in the Presence of Alternative Technological Processes

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Abstract— An important factor in increasing productivity and optimal use of resources in mechanical engineering production is the effective organization of material flows. Under the conditions of the modern production systems, alternative technological processes for machining parts often exist, which creates opportunities for more flexible production planning, complicating, at the same time, material flows and equipment load management.

The present article examines the possibilities for material flows optimization in a section for machining, in order to increase the efficiency of the production system. It analyzes the peculiarities of the organization of production in the presence of multiple technological routes and different types of machine tools and proposes an approach for modeling the production area by representing the technological processes as a graph and a matrix of the material flows between the individual workplaces. A multi-objective optimization problem is formulated, aimed at minimizing the transport distances, technological times and volume of the work in progress.

Keywords— alternative technological processes; machining; material flows; production optimization; technological routes.

I. INTRODUCTION

The methods, developed so far for optimal placement of objects (technological equipment) in production areas, are based on the so-called rigid calculational model, which assumes that the technological processes (i.e. sequence of operations) for manufacturing products (parts and assembled units) are pre-defined at the stage of technological preparation of production. Alternative technological processes are not

allowed in this case. For each operation, only the technological equipment on which it can be performed, is specified in advance.

The rigid calculational model is not appropriate to be used for solving problems, related to selecting the optimal placement of equipment for production cycles in which alternative technological processes can be applied.

Instead, the so-called flexible calculational model can be used for solving optimization problems, related to optimal placement of objects in production areas. The model specifies for each operation a list of equipment on which it can be performed, and, in addition, allows to apply alternative technological processes for manufacturing the same product.

The flexible calculational model is based on several assumptions [1]:

- equipment can only be placed on fixed sites with a known location;
- the number of machines equals the number of sites;
- the list of products to be manufactured in a section is known, and so is their manufacturing schedule;
- for each product a technological route is set, which contains a list of all necessary operations for its production;
- for each operation, a list of machines on which it can be performed is specified;

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- for each operation, the time for its execution is determined;
- each machine has its own time pool, which limits the time for its operation, and hence the number of operations, which can be performed on it.

The flexible calculational model differs from the rigid one in that with this model for each of the operations a list of machines, on which it can be executed, is specified [2]. The rigid computational model is a special case of the flexible one, in which case the list of equipment on which the respective operation can be performed contains only one machine. In addition, with the flexible model, the use of alternative technological processes is allowed, which means that in order to manufacture the same product, the workpieces may undergo a different sequence of technological operations.

II. MATERIALS AND METHODS

In order to solve the task to optimally place objects in a production area, it is necessary to formulate the task as a problem, belonging to the class of optimization problems [3]-[6]. For problems of this type, the following must be determined:

- model parameters, which are changeable;
- constraints on parameter values;
- dependence of the objective function on the model parameters;
- search criteria.

A. Model parameters

In optimization problems, related to placing objects in pre-fixed positions, the mathematical concept of "permutation" is used as a parameter [7], [8]. A permutation is a concept from combinatorics, describing the number of ways in which a finite number of elements can be arranged. The order of the elements is of essential importance in permutations. Each permutation has its length, expressed by a natural number. A permutation of length k is a sequence of natural numbers from 1 to k , each of which occurs in this sequence only once. An example of a permutation of length 4 is (1, 4, 3, 2), (3, 4, 1, 2) and (4, 1, 2, 3). From combinatorics it is known that a total of $k!$ permutations of k length can be formed. The permutation of the equipment allows to unambiguously determine the correspondence between the number of a machine and the position, at which it is located. For example, the permutation (3, 5, 2, 1, 6, 4) means that the machine number 3 is located at position 1, machine number 5 is located at position 2, and so on.

One of the assumptions with the flexible calculational model is that the number of machines and the number of positions, where they can be placed, are equal [9], [10]. If the number of machines exceeds the number of the sites, then the Dirichlet principle comes into effect, according to which two machines will have to be placed on at least one of the sites, which is

unacceptable [11]. At the same time, another option is entirely possible, in which the number of positions is greater than the number of equipment. This means that some of the sites will remain vacant. Such a task can be reduced to the standard one, where the number of machines and the number of positions are equal. For this purpose, "fictitious machines" are added to the task, thus equalizing the number of work sites and the number of equipment. Moreover, the list of machines, on which the operations will be performed, must not include fictitious equipment.

It can be concluded from what has been stated so far, that the equipment placing options can be used as variable parameters of the model.

B. Objective function

The objective function is used to compare different options for deploying equipment, i.e. to compare the values of the variable parameter. The search criterion (max or min) shows the best combination of parameters – the one, which provides the minimum or maximum value of the objective function. The optimization problem consists in finding such values of the model parameters, for which the objective function will have an extreme value. One of the most frequently used objective functions in problems, related to production logistics is the material flow capacity in the production system [12], whose value is determined by the formula:

$$C = \sum_{i=1}^n \sum_{j=1}^n Q_{i,j} \cdot r_{i,j} \quad (1)$$

where n is the number of machines and sites for their placement; i, j – inventory numbers of the equipment; $Q_{i,j}$ – mass of the load to be moved from the i -th to the j -th piece of equipment; $r_{i,j}$ – distance between the i -th and j -th machine.

The value of the parameter $Q_{i,j}$ depends on the production route [13]-[15], while the parameter $r_{i,j}$ is determined by the option for placing the machines. If no loads are moved from the i -th to the j -th machine, then $Q_{i,j} = 0$.

If a rigid model is used for calculation, in which the production routes are unambiguously determined by the technological ones, then it is possible to determine the parameter $Q_{i,j}$. When using a flexible model, this parameter cannot be determined, since only the equipment placement and technological routes are known. Only at the stage of operational and calendar planning does it become known which equipment will perform which operations, and accordingly, only then the production routes also become known. In other words, the capacity of the material flow in the production system will be determined not only by the location of the equipment at the workplaces, but also by the distribution of the work between the machines. Therefore, in the flexible computational model the

objective function will have two parameters, instead of one as it is in the rigid model.

To find the value of the objective function for a given arrangement (permutation) of the equipment, it is necessary to formulate a problem for finding the minimum value of the material flow for a fixed placement of the equipment, and the found value will be the objective function.

Let m be the permutation of n machines and F be some mathematical object, describing unambiguously the production routes in a section. Then, the load flow capacity C is a function of m and F : $C(m, F)$. If this function is considered for a constant value of the variable m , then the load flow capacity C is a function of only one variable $C_m(F)$. In this case, the minimum value of the function can be written as $\min(C_m(F))$. The optimization problem for placing equipment in a production area, respectively, can be formulated in the following way: find the permutation m , which provides a minimum of the function $\min(C_m(F))$:

$$\min(C_m(F)) \rightarrow \min. \quad (2)$$

With such a representation of the problem, it is not necessary to find the vector F , which provides the minimum capacity of the load flow. However, it is possible to present the problem differently – as an optimization of a function with two variables [16]. In this case, it is necessary to find both the vector F and the permutation m – the two elements, which give the function $C(m, F)$ a minimum:

$$(C(m, F)) \rightarrow \min. \quad (3)$$

The capacity of the load flow in the production system is traditionally used as a function in material flow optimization [17], [18]. This parameter, however, does not always accurately reflect the costs, related to moving objects in the course of a production process. Sometimes the transportation of relatively light details with large dimensions turns out to be more expensive than moving heavy parts with small dimensions. In this regard, it is relevant to use the total mileage of the vehicle as an optimization criterion. It can be found if the size of the transport batch for each manufactured product is known [19] and can be calculated by the formula:

$$G = \sum_{i=1}^n \sum_{ab=1}^w \frac{N_{MSi}}{N_{TBSi}} l_{abi}, \text{ m/year}, \quad (4)$$

where n is the number of the types of products moved per year (or other unit of time); w – number of operations for manufacturing the i -th product; l_{abi} – distance from the a -th to b -th position, along which the i -th type of product is moved, m ; N_{MSi} – manufacturing schedule for the i -th type of product, pcs/year; N_{TBSi} – size of the transport batch for the i -th type of product, pcs.

When there is no information about the size of the transport batch it is expedient to use the capacity of the load flow as a target function.

A. Algorithm for solving the optimization problem of placing objects in a production area

The first step toward solving the optimization problem is to construct a technological route graph, by means of which the technological routes for manufacturing the products are defined.

Fig. 1 presents a diagram of the way of synthesizing a technological route graph.

Two types of elements can be seen in the graph in Fig. 1: vertices and edges. Each of the vertices corresponds to some beginning of the production system flow (input), or to its end (output), or to one of the machines to be positioned in the production area [20]. Each technological route is a sequence of records, starting with “input” and ending with “output”, and between them – the sequence of execution of the operations is recorded [21]. An example of a technological route is: “input - operation 1 (machines 2, 3, 5) - operation 2 (machines 1, 4) - operation 3 (machine 6) - output”.

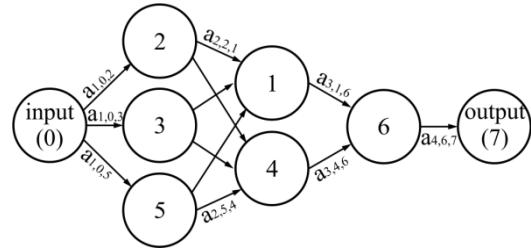


Fig. 1. Graph of the technological route

The second important element of the graph is the edges, connecting its vertices. With the help of the edges, all vertices, located on adjacent levels, are connected in pairs. Each of the edges corresponds to a part of a possible manufacturing route, i.e., there will be movement of workpieces from one machine to another. After the corresponding operations on one of the machines have been completed, the workpieces are moved to the next machine to undergo the next operations.

The definition of each edge of the technological route graph is done by means of a number, equal to the number of workpieces, moved along it – $a_{i,j,k}$. This number has three indices, defining it. The first of them, i , determines the level of the graph, at which the vertex of the corresponding edge is located (the operation, after the execution of which the workpiece is moved to the next machine, is indicated). The second index j serves to denote the inventory number of the machine, on which the corresponding operation is performed, i.e., it indicates the specific vertex, from which the edge

emerges. The third index k defines the inventory number of the machine, toward which the workpiece is directed after the operation is performed, i.e., the vertex in the graph, where the edge ends.

In the event of manufacturing different types of products through different technological processes in the production system, then it is necessary to synthesize a technological route graph for each of these processes. The level numbers in each graph in this case must be unique.

The variable $a_{i,j,k}$ determines the number of workpieces, moving along the edges of the technological route [22], [23]. The term edge flow is used to define it. As an illustration to the exposed above let us consider the following example. A request to manufacture 42 items has been received. A decision has been made at the stage of operational and calendar planning to distribute the first operation among the machines as it follows:

- 15 workpieces are processed on the second machine;
- 17 workpieces are processed on the third machine;
- the remaining $42 - 17 - 15 = 10$ workpieces are processed on the fifth machine.

In accordance with this decision, the value of the three edge flows of the technological graph can be determined:

$$a_{1,0,2} = 15; \quad a_{1,0,3} = 17; \quad a_{1,0,5} = 10.$$

After having the first operation completed, the workpieces are directed to the corresponding machines for the second operation. Assume that the following decision was made during planning: 17 of the workpieces, processed during the first operation on machine 3, should be distributed as it follows: 8 of them - to be processed on machine 1 (second operation), 9 of them - to be processed on machine 4 (second operation 2). This allows to define two more edge flows:

$$a_{2,3,1} = 8; \quad a_{2,3,4} = 9.$$

It can be seen that the set of all variables $a_{i,j,k}$ uniquely determines the production routes, along which the objects are moved in the production area, and thus the routes can be regarded as object F.

In order to unambiguously define all production routes, it is both necessary and sufficient to indicate the value of the flow along each edge of the graph for those of the technological routes, which lead to manufacturing products. It means that if the values of the variable $a_{i,j,k}$ in the production system are known, the capacity of the load flow (the material flow) can be determined.

B. Constraints on model parameter values

At the stage of choosing an option for placing the equipment, it is possible to consider some limits, within which the values of the edge flows may change. Multiple constraints are possible to be imposed on their values and the constraints can be divided into 3 groups:

• First group of constraints

The constraints, belonging to the first group, can be written, taking into account the peculiarities of the technological route graph. From this it follows that at all vertices of the graph, excluding "input" and "output", the total input flow is equal to the total output flow. An equation, relating the edge flows incident on a given graph vertex, can be written based on this [24]. The number of equations will match the number of vertices. The equation has the form:

$$\sum_{i=0}^{n+1} a_{k+1,i,l} = \sum_{j=0}^{n+1} a_{k,j,l}, \quad (5)$$

where k is the operation number or the graph level; n – number of machines in the production area; l – number of the machine, on which the k -th operation can be performed; j – number of the machine, on which the $(k - 1)$ -th operation can be performed; i – number of the machine, on which the $(k + 1)$ -th operation can be performed.

To illustrate the limitations of the first group, the diagram in Fig. 2 is presented [20].

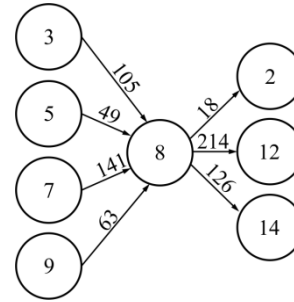


Fig. 2. An example of the first group of constraints

Here the equation is written for machine number 8, on which operation number 3 will be performed. The previous operation (№2) can be performed on machines numbers 3, 5, 7, 9. The next operation (№4) can be performed on machines 2, 12, 14.

The meaning of the first group of limitations is that the number of workpieces, directed toward machine 8 from machines 3, 5, 7 and 9 (on the left side of the graph), must be equal to the number of workpieces, which will be moved to machines 2, 12 and 14 (on the right side of the graph). The equation can be written in the following way:

$$a_{3,3,8} + a_{3,5,8} + a_{3,7,8} + a_{3,9,8} = a_{4,8,2} + a_{4,8,12} + a_{4,8,14}.$$

In Figure 2 this constraint is met: the total input flow is equal to $105 + 49 + 141 + 63 = 358$ workpieces, and the output flow is also equal to $18 + 214 + 126 = 358$ workpieces.

It is important to note that all constraints from the first group are of the first degree, i.e., linear equations, forming together a system of linear equations [24].

- *Second group of constraints*

This group connects the size of the edge flows with the manufacturing schedule of the products. If all the flows, which go out of the “input” vertex are summed, the result will be the total number of products, manufactured following a specific technological process. The flows, incident on the “output” vertex, can be similarly summed up. Having in mind the first group constraints, it is sufficient to write equations only for one vertex (input or output), since they provide the same value of the input and the output flows for each level of the graph. The following rule can be formulated from here: the sum of the edge flows, incident on the “input” vertex, is equal to the manufacturing schedule of the product, following the corresponding technological process.

Only one limitation of this type is written for each technological route as follows:

$$\sum_{i=0}^n a_{b,0,i} = n_b, \quad (6)$$

where b is the number of the first operation of the technological process; n – number of machines in the production area; i – inventory number of the machine, on which the first operation of the technological process can be performed; n_b – number of products, which must be manufactured following this specific technological process (manufacturing schedule).

To illustrate this limitation, the diagram in Fig. 3 is presented [20].

In this specific case, 1500 parts must be manufactured, following a given technological process. The first operation of the process can be performed on machines with the following inventory numbers: 3, 8, 9, 23. Then an equation can be written, connecting the edge flows and the incident input:

$$a_{8,1,3} + a_{8,1,8} + a_{8,1,9} + a_{8,1,23} = 1500.$$

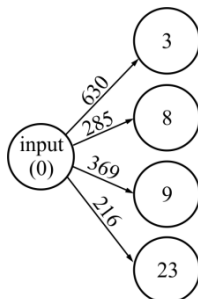


Fig. 3. Example of the second group of constraints

The constraints, belonging to the second group, are also linear equations. Together with the constraints from the first group, they form an indeterminate (i.e., having multiple solutions) system of linear equations, which limits the allowable values of the edge flows of the graph.

- *Third group of constraints*

Production routes are determined not only by the route of movement of the workpieces in a production system, but also by the load on the technological equipment. The greater the number of operations to be performed on a machine, the more time it will take to complete its assigned tasks [25]. If the limitation of the working time pool is not taken into account, it is possible to have production routes, in which some of the machines will be overloaded and others will not be occupied.

The flexible computational model introduces the assumption that the time, spent by the equipment for completion of the assigned tasks, depends linearly on the number of products to be manufactured. In reality, this is not entirely true [27], as additional time is required, associated with re-adjusting the machine for the new batch of parts, replacing worn or broken tools, periodic equipment maintenance, etc. Nevertheless, the use of linear dependencies is adequate. On the one hand, it is convenient from the point of view of solving optimization problems, based on this mathematical model, and, on the other hand, it adequately reflects the manufacturing processes.

The third group of constraints are inequalities, limiting the load on the machine, which must not exceed its working time pool. The inequalities have the form:

$$\sum_{b=1}^m \sum_{i=0}^{n+1} a_{b,l,i} \cdot t_b < T_l, \quad (7)$$

where b is the number of those operations, which can be assigned to the machine; n – number of units of equipment in the production area; m – number of operations, performed in the production area; l – inventory number of the machine, on which an operation, preceding operation b , can be assigned; T_l – effective time pool for operating a machine; t_b – time, required to execute operation b .

It is important to understand the difference between the limitations, belonging to the first and third groups. In both cases they concern one of the machines. In the first case, several constraints can be set on the machines, one for each operation they can perform. According to the third group of constraints, one inequality is formulated for each machine. This means that the number of inequalities matches the number of machines in the production area [28], [29].

The diagram in Fig. 4 illustrates the third group of constraints [20].

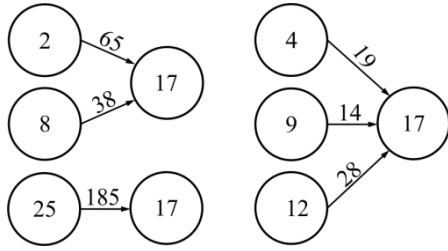


Fig. 4. Example of the third group of constraints

According to the technological process, on the machine with inventory number 17 operations with numbers 2, 9, 15 are allowed. The time for performing these operations is known - 12, 25, 45 minutes. It is also known that the preceding operations can be performed on the following equipment: operation 1 (precedes operation 2) – on machines 2 and 8; operation 8 (precedes operation 9) – on machine 25; operation 14 (precedes operation 15) – on machines 4, 9, 12.

The inequality in this case is written in the following way:

$$a_{2,2,17} \cdot t_2 + a_{2,17,17} \cdot t_2 + a_{9,25,17} \cdot t_9 + a_{15,4,17} \cdot t_{15} + a_{15,12,17} \cdot t_{15} \leq T_{17}.$$

If the working time pool for machine 17 is 10000 minutes, then, substituting the numerical values of t and T , we obtain the inequality:

$$a_{2,2,17} \cdot 12 + a_{2,17,17} \cdot 12 + a_{9,25,17} \cdot 25 + a_{15,4,17} \cdot 45 + a_{15,12,17} \cdot 45 \leq 10\,000.$$

It can be verified that the values of the edge flows, shown in Figure 4, allow this constraint to be met:

$$65 \cdot 12 + 38 \cdot 12 + 185 \cdot 25 + 19 \cdot 45 + 14 \cdot 45 + 28 \cdot 45 = 8930 \leq 10\,000.$$

If the initial data in the optimization problem contain too low values of the working time pool, then no distribution of the operations between the machines will satisfy the inequality and, as a result, the problem will not have a feasible solution.

If the value of the working time pool is overestimated, then it will turn out that the permissible options will have a high degree of uneven load on the equipment.

The third type of constraints are linear inequalities, which limit the throughput of each vertex of the graph by prohibiting the construction of production routes in a way, in which they all pass through a single vertex.

III. RESULTS AND DISCUSSION

The capacity of the material flow is influenced not only by the location of the technological equipment, but also by the production routes themselves. If there are several alternative processes to manufacture a single product, then different size of the material flow will be observed with the different options. It follows from here that the choice of optimal production routes for manufacturing the products is also important.

The optimization of the material flows in a section for machining in case of presence of alternative technological processes can also be described by a technological route graph. The edge flows of this graph determine all production routes.

The technological processes themselves differ from each other only in the list of machines, on which the corresponding operations can be performed. It can be illustrated by the diagram in Fig. 5 [30].

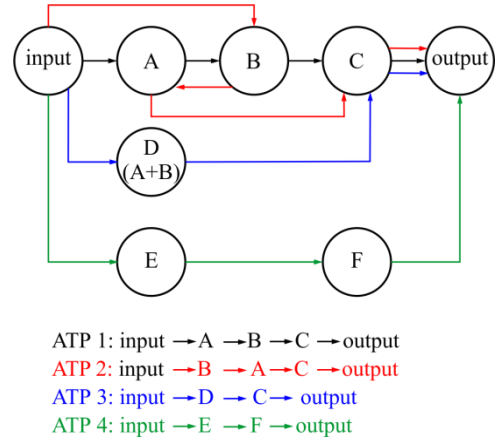


Fig. 5. Construction of a technological route graph in the presence of alternative technological processes (ATP)

Assume that there is some basic technological process, in which operations A, B and C (ATP1) are sequentially performed. Alternative technological processes are also permissible. One of the possible variants of the alternative technological processes (ATP2) differs from the basic variant only in the sequence of execution of operations A and B: operation B is performed first and then A. In another possible alternative technological process (ATP3), operations A and B are grouped into one operation D, which is performed on a machine with higher functional capabilities (e.g. turning and milling on a machining centre). Operation D is followed by operation C. In a possible alternative technological process (ATP4), fundamentally different operations E and F may be performed.

Not individual machines but the operations in the technological process are used as vertices of the technological route graph. A special case is the situation when for each operation there is only one machine on which it can be performed.

Let all operations, except operation D, be performed on only one machine, and operation D – on one of three machining centres. In this case vertex D will be replaced by three vertices, each corresponding to one of these machines, marked in Fig. 6 as D1, D2 and D3 [30].

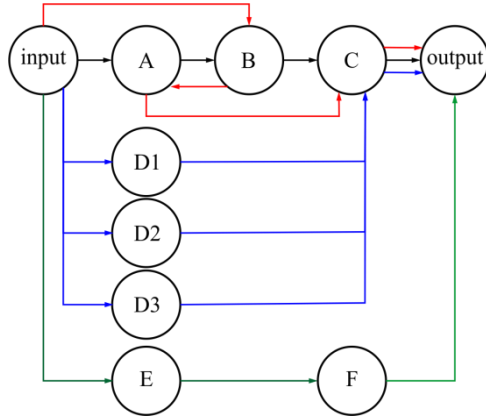


Fig. 6. Technological route graph in the presence of alternative technological processes (ATP)

The variables $a_{i,j,k}$, which characterize the edge flows of the graph, can be introduced for the technological route graph from Fig.6. The same three groups of constraints can be imposed on these variables:

- the total inflow should be equal to the total outflow;
- the sum of the edge flows should be equal to the manufacturing schedule for making the products;
- the time pool limit of the machines should not be exceeded and an even load on the equipment must be ensured.

Assume that 1000 parts need to be manufactured. One of the possible options is presented in Fig. 7.

- 250 parts are machined in the case of ATP1 (input → A → B → C → output);
- 300 parts are machined in the case of ATP2 (input → B → A → C → output);
- 100 parts are machined in the case of ATP3 (input → D1 → C → output);
- 0 parts are machined in the case of ATP3 (input → D2 → C → output);
- 150 parts are machined in the case of ATP5 (input → D3 → C → output);
- 200 parts are machined in the case of ATP6 (input → E → F → output).

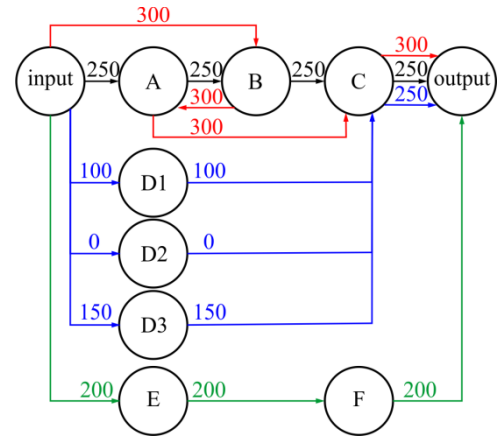


Fig. 7. Example of a production route for processing parts using alternative technological processes

From the presented example it can be seen that the total input flow (1000 parts) is equal to the total output flow, the production schedule is executed and the machines are loaded more evenly.

After imposing the constraints on the production routes, it is necessary to formulate the objective function. The capacity of the load flow is a linear combination of the edge flows:

$$C = \sum_{e=1}^m \sum_{f=0}^{n+1} \sum_{z=0}^{n+1} a_{e,f,z} \cdot R_{f,z} \cdot M_e, \quad (8)$$

where e is the graph level, i.e., the number of the operation; m – total number of operations, performed in the production area; f, z – inventory numbers of the equipment; n – number of machines; $R_{f,z}$ – distance between the pairs of machines f and z ; M_e – mass of the products after performing the operation.

If in the task of searching for optimal equipment placement in a production area, this function is used only for a preliminary assessment of the load flow capacity at the stage of technological preparation of production, and the quantities $a_{e,f,z}$ are only parameters of the model, when optimizing the load flow they will become variables.

The problem of minimizing the function C is a linear programming problem and therefore it can be solved relatively easily and in a short time, even when the problem is of large dimension.

IV. CONCLUSIONS

To solve optimization problems, related to optimal placement of objects in a production area, the so-called flexible calculational model can be used. The model specifies for each operation a list of equipment, on which the operation can be performed. In addition, the use of alternative technological processes for manufacturing the same products is allowed.

For each equipment placement option, a linear programming problem is formulated, and when solving

it, the upper and lower limits of the production system load flow value can be found. The lower limit is recommended to be used as an optimality criterion. To formulate the linear programming problem, it is proposed to use a special graph, called a technological process graph.

In order to consider and evaluate all possible options for placement of technological equipment, a heuristic algorithm can be used, for example, simulated annealing.

ACKNOWLEDGMENTS

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Algorithm for Finding Optimal Placement of Objects in a Machining Section in the Presence of Alternative Technological Processes

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Abstract— In the context of digitalization of production and development of the Industry 4.0 concept, the optimization of production processes and the effective organization of production areas are gaining increasing importance. An essential task in the design of production systems is the optimal placement of the technological equipment in order to minimize the material flows, reduce transport distances and increase the efficiency of the production process. This task is further complicated in case of presence of alternative technological processes, allowing for different routes of parts processing.

Based on a developed model, an optimization problem is formulated in the present paper, aimed at minimizing the transport distances and the time for parts transportation during the process of production. To solve the problem, an algorithm, based on heuristic methods for searching for optimal equipment placement is proposed. Computational experiments have been conducted, which illustrate the possibilities for reducing the intra-production transport, and thus for more even loading of the machines and shortening the production cycle.

The proposed approach corresponds to the principles of the Industry 4.0 concept and creates conditions for integrating intelligent planning and optimization methods into modern production systems.

Keywords— *alternative technological processes; machining; material flows; production optimization; technological routes.*

I. INTRODUCTION

Optimization problems for finding the optimal placement of objects in a production area are usually solved by means of the so-called flexible computational model, which specifies for each operation a list of equipment, on which it can be performed [1]-[10]. The

model allows to use alternative technological processes for manufacturing a specific product and rests on the following assumptions:

- equipment can only be deployed on fixed sites with a known location;
- there is equality between the number of machines and the number of sites;
- the list of products, which must be manufactured in the particular production section is known, and their production schedule is also known;
- for each product, a technological route for its manufacturing is set, which is a list of the necessary operations to perform in order to have it ready;
- for each operation, a list of machines on which it can be performed, is specified;
- for each operation, the time for its execution is determined;
- each machine has its own time pool, which limits its working time, and hence the number of operations, which can be performed on it.

The flexible and the rigid computing models differ between each other in that the flexible one specifies for each operation a list of machines, on which it can be executed, while the rigid model can be regarded as just a special case of the flexible one, since it lists only one machine, on which the respective operation can be performed. What is more, the flexible method allows to use alternative technological processes to manufacture one and the same part, which means that the workpieces may undergo a different sequence of technological operations.

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II. MATERIALS AND METHODS

The task of finding the optimal placement of objects in a production area includes a number of stages, and one of them is to draw a graph of the technological route for manufacturing the specific product [11] – [13]. Another stage is the formulation of the task as an optimization problem and defining both its objective function and the model constraints, which must be imposed on the possible values of the edge flows of the graph [14]-[19]. These constraints can be divided into three groups [12]. Those, belonging to the first group, are linear equations, which form together a system of linear equations of the type:

$$\sum_{i=0}^{n+1} a_{k+1,l,i} = \sum_{j=0}^{n+1} a_{k,j,l}, \quad (1)$$

where k is the operation number, or the level of the graph; n – number of machines in the production area; l – number of the machine, on which the k^{th} operation can be performed; j – number of the machine, on which the $(k - 1)^{\text{th}}$ operation can be performed; i – number of the machine, on which the $(k + 1)^{\text{th}}$ operation can be performed. These equations ensure equality of the input and output flows for each vertex of the technological graph.

The constraints from the second group also form a system of equations, having the form:

$$\sum_{i=0}^n a_{b,0,i} = n_b, \quad (2)$$

where b is the number of the first operation of the technological process; n – number of machines in the production area; i – inventory number of the machine, on which the first operation of the technological process can be performed; n_b – number of products to be manufactured according to a given technological process (production schedule). The production schedule is used as an output parameter of the system, which means that the volume of work, which is set by the production schedule, is ensured.

According to the third type of constraints, the manufacturing routes must also satisfy the following system of inequalities in addition to the constraints from the first and second groups:

$$\sum_{b=1}^m \sum_{i=0}^{n+1} a_{b,l,i} \cdot t_b < T_i, \quad (3)$$

where b is the number of the operations, which can be assigned to the machine; n – number of units of equipment in the production area; m – number of operations to be performed in the production area; l – inventory number of the machine, to which an operation, preceding operation b , can be assigned; T_i – effective working time of the machine; t_b – required time to perform operation b . The third group of constraints is related to the time pool of the machines and the even load on the equipment.

In a number of problems from the graph theory, the parameter "throughput" of the edges of a graph is considered. In this case, the time pool of the equipment plays the same role as the throughput does in other tasks, e.g., for optimizing transport flows in a city. The difference is that these constraints are written not for the edges of the graph, but for its vertices. Moreover, each vertex is part of not one, but of several technological graphs, since, under the conditions of small-scale production, each machine takes part in processing many different products.

After setting the constraints on the values of the parameters $a_{i,j,k}$, which limit the possible options for production routes, it is necessary to express also the objective function as a quantity, depending on the variable parameters of the model, i.e., on the edge flows of the graph and the location of the machines.

Increase in the flow capacity is observed when the workpieces are moved along the edges of the graph, i.e. along the production route. Load flow capacity value is equal to the product of two numbers - the length of the route and the mass of the workpieces. The product of these numbers can be regarded as the price for transporting the material load along the corresponding edge of the technological route graph. Then, the objective function can be written as a linear combination of the flows along the edges:

$$C = \sum_{e=1}^m \sum_{f=0}^{n+1} \sum_{z=0}^{n+1} a_{e,f,z} \cdot R_{f,z} \cdot M_e, \quad (4)$$

where e is the graph level, i.e. operation number; m – total number of the operations, performed in the production area; f, z – equipment inventory numbers; n – number of machines; $R_{f,z}$ – distance between the pairs of machines f and z ; M_e – mass of the parts after the execution of the operation.

If the machine placement option is specified, then the value of $R_{f,z}$ is not a variable, but a constant parameter of the problem and M_e is also constant. Consequently, the only variable parameters are the edge flows of the technological route graph $a_{e,f,z}$. Thence, the objective function is a linear function of the variables $a_{e,f,z}$. The constraints, belonging to the first and second groups, are also linear, and together they form a system of undetermined linear equations. The system is indeterminate because the number of variables is greater than the number of equations in it, which means that it has an infinite number of solutions or that it cannot be solved in the standard way. And, the third group of constraints is a set of linear inequalities.

It can be concluded from the above that the formulated optimization problem is a problem of linear optimization (programming) [20]-[24]. Linear optimization is a method for finding the best solution (max or min) of an objective function under linear constraints (equalities or inequalities). An efficient algorithm for solving problems of this type, known as the simplex method, was proposed

by George Danzig in 1949 [25], [26]. The simplex method, with its various modifications, is still used up to the present for optimization of linear objective functions.

By using the simplex method, it is possible to determine the optimal distribution of operations between technological equipment. The value of the load flow capacity, corresponding to this distribution, and the considered machine placement option, can also be determined. The determined value of the load flow capacity can be used to assess the quality of one or another planning decision, i.e., it can be used as an objective function for finding optimal equipment placement.

In the problem of finding the best option for placing technological equipment, the variable (equipment location) is a permutation, which means that there is a discrete optimization problem. For example, in the classic for this field Traveling Salesman Problem, the variable parameter (the planned route) can also be represented in the form of a permutation. Since the quadratic assignment problem, which is NP-hard [27], [28], is only a special case of The Traveling Salesman Problem [29], [30], the problem of finding an optimal planning decision is also an NP-hard one [27], [31]. Therefore, it is necessary to look for heuristic algorithms for its solution, which are only approximate and not exact.

One of the most efficient and at the same time simple to implement among the heuristic algorithms is the Simulated Annealing (SA) method [32], [34].

SA is a metaheuristic probabilistic global optimization algorithm, inspired by the metallurgical process of annealing metals, which involves heating and slow cooling. At a very low cooling rate of the metal, the atoms arrange themselves in a crystal lattice in such a way, that their energy is minimal. This leads to a reduction in the internal stresses and reaching a more stable state. SA finds good approximate solutions to complex combinatorial problems, allowing temporary acceptance of worse solutions to avoid local minima [32], [35].

The initial temperature (to which the metal is heated during the annealing process) and the cooling rate must be set as algorithm parameters. The rate of cooling is determined by the number of iterations. SA gradually reduces the temperature after each iteration. The pace of the temperature decrease is equal to the ratio of the initial temperature to the number of iterations. The algorithm stops working at the moment when the temperature drops to zero.

Initially, SA randomly finds an arbitrary point, which corresponds to one of the possible equipment placement options. Then, the value of the objective function for this point is determined. For this purpose, it is necessary to solve the linear programming problem for the considered machine placement option and to determine the possible load flow capacity. The result of the first iteration is automatically taken as a base (the best solution found so far), and therefore the resulting arrangement of the machines and the value of the objective function are accepted and saved as the current optimal solution.

Then, SA searches for a different equipment placement option by randomly moving to one of the points, located near the first point in the solution area. To do this, the algorithm swaps the places of several machines. At each new point, the objective function is calculated and compared with the best solution obtained to that moment. If the new solution is closer to the optimum, it is accepted as the best for the moment, and the search for new points continues.

Each iteration generates a new solution in the range of the base one. The value of the objective function is calculated for the new solution and compared to the value of the objective function for the best solution found to the moment. If the new solution is better, then it is accepted as a base solution with a certain probability, which depends the temperature and the difference in the values of the objective function.

It is possible for SA to return to a given point even though the best solution has not been found there. This possibility depends on the temperature and on the difference between the calculated objective function and the currently optimal objective function. The higher the temperature, the greater the probability of moving to another point.

The state of a thermodynamic system of a large number of particles, which is in equilibrium with its surroundings can be described by the Gibbs distribution [35]. When applied to the objective function optimization problem, this distribution looks in the following way:

$$P(x) = \begin{cases} e^{\left(\frac{OF(x_{bp}) - OF(x)}{T}\right)}, & \text{at } OF(x) \geq OF(x_{bp}), \\ 1 & \text{at } OF(x) < OF(x_{bp}) \end{cases}, \quad (5)$$

where x is the permutation, for which the transition chance is determined; x_{bp} – “base” point; T – temperature for the given iteration; $P(x)$ – chance for the permutation x to become a “base” one; $OF(x)$ – value of the objective function x , calculated when solving the linear programming problem.

The gradual decrease in the temperature after each iteration leads to a decrease in the probability for the currently studied option for machine placement to be accepted as a base solution. Allowing a transition to a solution with a less favorable objective function value allows the algorithm to overcome local optima and increases the probability of reaching to the global optimum.

The number of iterations can be set before starting the algorithm. The more iterations, the more time for calculations will be needed, but more permutations will be considered and the solution will be closer to the optimal one.

It should be noted that all linear programming problems, solved at the different iterations, using the

simulated annealing method, have a number of similar features. On the one hand, the set of variables is the same in all problems. The same is also the search criterion (minimum). All constraints can be divided into three groups. The first group of constraints is determined by the technological routes and does not change with the different options for equipment placement, so they stay the same for each iteration. The second group of constraints is determined by the production schedule of the products and thus it also does not depend on the machine placement option, i.e., these constraints remain constant for all iterations as well. Finally, the third group of constraints is determined by the equipment working time pool, which is also constant for all iterations. This means that in all problems, solved by linear programming, the constraints on the variable parameters completely coincide, i.e. the ranges of permissible values are identical.

The only difference between these problems can be seen in the coefficients $R_{f,z}$ and M_e in the objective function. M_e determines the mass of the workpieces, and $R_{f,z}$ – the distance between the machines, i.e., equipment location.

Ultimately, all linear programming problems, solved by the considered algorithm, have the same range of permissible values and a different objective function.

Based on the exposed above, an algorithm can be developed to find the optimal placement of machines in a production area. This algorithm uses the simulated annealing method to explore possible equipment placement options. To assess the quality of each option, a linear programming problem is formulated, which is solved using the simplex method. The algorithm is composed of the following steps:

Step 1. Start (start of the algorithm).

Step 2. Entering the following source data:

- distances between the sites for equipment placement;
- technological routes;
- mass of the workpieces to be moved;
- production schedule;
- initial temperature T ;
- cooling pace dT ;
- number of iterations, etc.

The output parameters of the model are formulated by means of them.

Step 3. Defining the parameters:

- P_{base} – base placement;
- $P_{current}$ – current placement;
- H_{base} – base value of the objective function;
- $H_{current}$ – current value of the objective function;
- dT – temperature decrease step.

Step 4. Compiling a matrix of constraints on the values of the edge flows $a_{i,j,k}$.

Step 5. Compiling a random starting equipment placement option P .

Step 6. Compiling a matrix of the distances between the machines $R_{f,z}$.

Step 7. Calculating the coefficients of the linear function C .

Step 8. Finding $\min H(P)$ of function C by solving the linear programming problem.

Step 9. Checking whether $H(P) < P_{current}$.

If $H(P) < P_{current}$, then the following is assumed:

$$P_{current} = H(P); P_{base} = H(P); P_{current} = P; P_{base} = P.$$

Proceeding to step 13 then.

If $H(P) \geq P_{current}$, then step 10 follows.

Step 10. Calculating the probability:

$$B(P) = e^{(H_{base} - H(P))/T}.$$

Step 11. Choosing a random number x , so that:

$$0 < x < 1.$$

Step 12. Checking if $x < B(P)$.

If $x < B(P)$, it is assumed that

$$P_{base} = H(P); P_{base} = P.$$

If $x \geq B(P)$, step 13 follows.

Step 13. Lowering the temperature: $T = T - dT$.

Step 14. Checking whether $T > 0$.

If $T > 0$, random placement of the equipment near P_{base} is arranged. And then the algorithm returns to step 6.

If $T \leq 0$, then step 15 follows.

Step 15. The resulting equipment placement option $P_{current}$ is accepted as optimal.

Step 16. End.

Based on the proposed algorithm, a software package has been developed, which allows for the selection of alternative technological processes by which products can be manufactured in a production area.

III. RESULTS AND DISCUSION

The following example is considered to demonstrate the operation of the developed software. Sixteen (16) machines are to be placed in a manufacturing section. The number of sites on which the machines will be located is also 16. Table 1 presents a list of the machines with assigned unique inventory numbers (from 1 to 16).

Eleven (11) different products must be made, labeled with letters from A to K. For each product, the following is set:

- technological process for its manufacture;
- production schedule;
- mass of the workpieces;
- list of machines, on which each operation can be performed;

- time for performing each operation.

TABLE 1. LIST OF MACHINES IN A MACHINING SECTION

N	Model	Type
1	DMU 65 mono BLOCK	5 Axis Machining Center
2	NEF 600	CNC Lathe Machine
3		
4		
5		
6	CTX beta 800 TC	Turn & Mill Complete Machining Center
7		
8	QV 127	Vertical CNC Machining Center
9		
10	WHN 130Q	Milling and boring machine
11	Vertical Mate 35	CNC Vertical Multi-Process Grinding Machine
12	OMAXMicroMax	Abrasive Waterjet Machine
13	Cybertech SLi-30FT	CNC Wire Cut Machine
14	NHX	High-Speed Horizontal Machining Center
15	Gecam G6 WET	Deburring Machine
16	CTV 160	Vertical pick-up lathes

The operating schedule of the machining section is also known, as well as the positions, where the technological equipment can be located (Fig. 1).

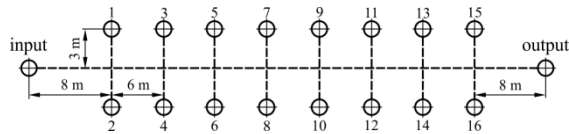


Fig.1. Schedule of the production section with positions for placing the technological equipment

Parts A, B, C and D can be manufactured using several alternative technological processes. Parts A, C, and D, in accordance with the available machines, can be manufactured, following three alternative technological processes, and part B - using four alternative processes. Parts from E to K can be manufactured by means of only one possible technological process.

Each operation is also assigned a unique identification number. Each technological route begins with an arbitrary first operation "workpiece delivery", without specifying the machine, on which it will be performed, or the duration of the operation.

Part "A" (Fig.2 and Fig.3), considered as an example, can be manufactured using three alternative technological processes.

Here is what is also known regarding part "A": the production schedule $n = 118$ pcs.; the mass of the workpieces $M_e = 15.36$ kg.

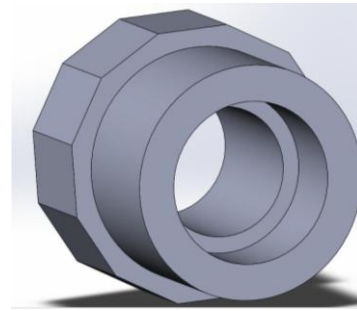


Fig.2. 3D model of part "A"

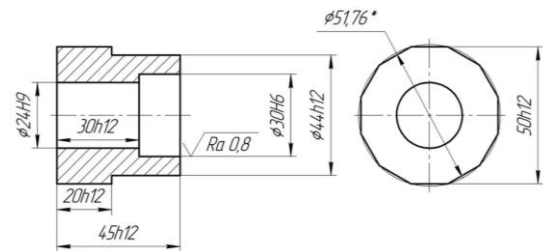


Fig.3. Drawing of part "A"

The remaining data, needed for carrying out the calculations, are presented in Table 2.

TABLE 2. OPERATIONS FOR MANUFACTURING PRODUCT "A"

Product	Technological route	Input operations	Duration of the operation, min	List of machines
A1	1→2→3→4	1	-	-
		2	12,46	2, 3, 4
		3	7,22	8, 9
		4	9,64	11
A2	5→6→7	5	-	-
		6	29,76	6, 7
		7	9,64	11
A3	8→9→10	8	-	-
		9	15,64	8, 9
		10	16,25	5

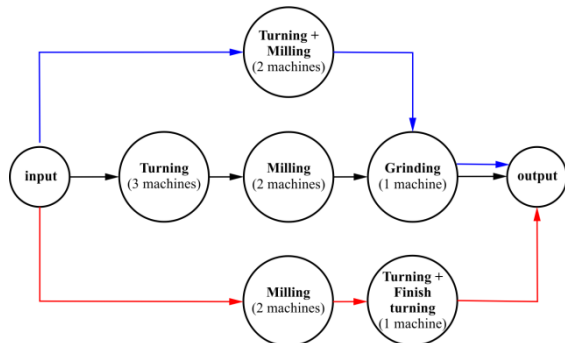
It is first necessary to calculate in advance the distances between the positions shown in Figure 1. The paths, along which the workpieces can be moved, are indicated by a dashed line. It is convenient in this case to use the Manhattan metric (rectangular metric, L_1 norm) in order to determine the distances. Workpiece transportation can be considered as a sequential movement along horizontal and vertical sections, corresponding to the real directions of the transport routes. The distance between two positions in the grid space is calculated as the sum of the absolute differences of their coordinates. The use of a rectangular metric is justified due to the configuration of the section and the limitations of the intra-factory transport, in which diagonal movement is practically not possible. The obtained results are presented in Table 3 (0 – input, 1 ÷ 16 – technological equipment, 17 – output).

TABLE 3. LENGTH OF THE TRANSPORT DISTANCES BETWEEN POSITIONS IN A MACHINING SECTION

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0	0	11	11	17	17	23	23	29	29	35	35	41	41	47	47	53	53	53
1	11	0	6	12	12	18	18	24	24	30	30	36	36	42	42	48	48	48
2	11	6	0	12	12	18	18	24	24	30	30	36	36	42	42	48	48	48
3	17	12	12	0	6	12	12	18	18	24	24	30	30	36	36	42	42	42
4	17	12	12	6	0	12	12	18	18	24	24	30	30	36	36	42	42	42
5	23	18	18	12	12	0	6	12	12	18	18	24	24	30	30	36	36	36
6	23	18	18	12	12	6	0	12	12	18	18	24	24	30	30	36	36	36
7	29	24	24	18	18	12	12	0	6	12	12	18	18	24	24	30	30	30
8	29	24	24	18	18	12	12	6	0	12	12	18	18	24	24	30	30	30
9	35	30	30	24	24	18	18	12	12	0	6	12	12	18	18	24	24	24
10	35	30	30	24	24	18	18	12	12	6	0	12	12	18	18	24	24	24
11	41	36	36	30	30	24	24	18	18	12	12	0	6	12	12	18	18	18
12	41	36	36	30	30	24	24	18	18	12	12	6	0	12	12	18	18	18
13	48	42	42	36	36	30	30	24	24	18	18	12	12	0	6	12	12	12
14	48	42	42	36	36	30	30	24	24	18	18	12	12	3	0	12	12	12
15	53	48	48	42	42	36	36	30	30	24	24	18	18	12	12	0	6	6
16	53	48	48	42	42	36	36	30	30	24	24	18	18	12	12	6	0	6
17	53	48	48	42	42	36	36	30	30	24	24	18	18	12	12	6	0	0

All information, required for the material flow optimization, is entered into the specialized software.

Both turning and milling operations are necessary to be performed for manufacturing part “A”. The opening Ø30H6 has high roughness requirements and therefore, either grinding or fine turning is necessary to apply for its finishing. Three alternative technological processes have been compiled and presented in the form of a graph in Fig.4.



ATP1: input→Turning→Milling→Grinding→output
 ATP2: input→Turning+Milling→grinding→output
 ATP3: input→Milling→Turning+Finish turning→output

Fig.4. Alternative technological processes for manufacturing product “A”

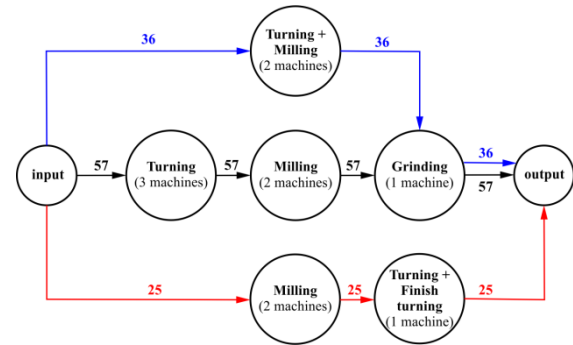
The first technological process (ATP1) includes initial turning, followed by milling, and finally applying grinding as a finishing process.

The second alternative technological process (ATP2) provides for combining turning and milling operations on a turning-milling machining center. The accuracy characteristics of the machining centers, available in the section, do not allow for fine turning, and therefore the workpiece must be subjected to a finishing operation - grinding.

The third alternative technological process (ATP3) begins with milling, after which the workpiece is

transferred for turning to a machine, whose accuracy characteristics allow for fine turning (instead of grinding).

As a result of the performed calculations, the following distribution of work between the competing ATPs has been proposed (Fig.5).



ATP1: input→Turning→Milling→Grinding→output (57 units)
 ATP2: input→Turning +Milling→Grinding→output (36 units)
 ATP3: input→Milling→Turning+Finish turning →output (25 units)

Fig.5. Technological graph at an operations level - work distribution between the alternative technological processes

57 parts are to be manufactured, following ATP1, 36 parts by means of ATP2, and 25 - using ATP3.

The graph, presented in Fig. 5, is in a simplified form, only presenting the operations. However, the technological graph must be constructed for the specific units of the technological equipment.

At the equipment level, the same graph will look like the one, presented in Fig. 6.

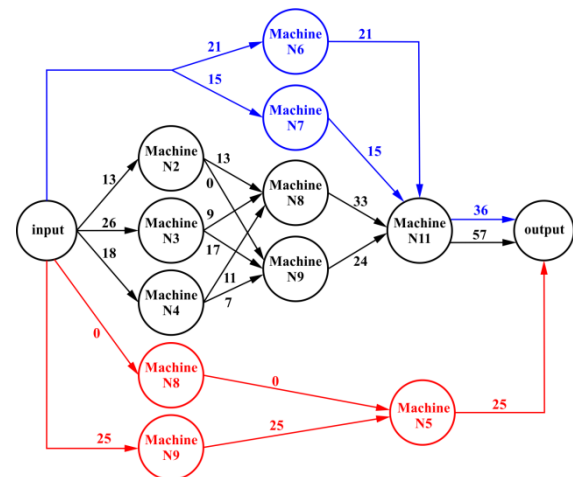


Fig.6. Technological graph at the equipment level with calculated edge flows

When calculating production routes, the developed software does not select just one of the alternative technological processes, but distributes the entire workload between all of them. On the one hand, such an organization of production increases its technological flexibility. On the other hand, only with such a formulation

of the material flow optimization problem, can it be reduced to a linear programming problem.

The calculations are not performed for each individual part and each graph separately, but simultaneously for all manufactured products and technological graphs, since the total load on the equipment in the section is taken into account. As a result, it is possible to ensure an even load on the machines in the section, avoid downtime, and increase the overall productivity of the manufacturing system.

IV. CONCLUSIONS

Based on a developed mathematical model, the problem of optimizing material flows in a production system has been formulated. For solving this problem, an algorithm is proposed, developed by combining linear programming methods and the method of simulated annealing. The algorithm takes into account the distance between the positions where the machines are located, production schedule, mass of the workpieces, technological routes, working time pool of the machines and duration of the operations. The algorithm allows to find both an option for optimal equipment placement and optimal production routes.

For implementing the algorithm, a software package has been developed, which can solve the optimization problem for a production area, described by a flexible computational model. The application of the software allows to find an option for optimal equipment placement, as well as to draw up optimal production routes.

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Increasing the Accuracy of Machining by Means of Complex Process Management Through Active and Adaptive Control

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Abstract— One of the main indicators of the manufactured parts quality and the efficiency of the technological processes in mechanical engineering is machining accuracy. During the machining process, errors of various nature occur, which can lead to deviations from the specified dimensions and geometric parameters. This requires the implementation of modern approaches to controlling and managing the machining process.

Keywords— Active control, adaptive control, CNC machine tools, intelligent computer control mechanical engineering.

I. INTRODUCTION

The development of scientific knowledge about the machining process, computer technology and machine tools has created prerequisites for finding new approaches to managing the machining process. The integration of the accumulated knowledge about the process, presented in the form of a database, the use of adaptive control during machining and the application of active control after completing it in order to populate the database, provide a possibility to implement intelligent computer control.

The work of the various subsystems in machining is aimed at achieving effective management of the technological process to achieve higher accuracy of the machined parts.

The process is managed based on the input information about the size of the workpieces and the dimensions of the parts after their machining. [1] - [2].

II. MATERIALS AND METHODS

The growing use of CNC machine tools in serial production imposes the search for new opportunities to increase machining accuracy and productivity. Such an opportunity is offered by complex computer-controlled

process management, integrating adaptive and active control without complicating the machine's sensory system. The block diagram of such a system is presented in Fig. 1 [3] - [4].

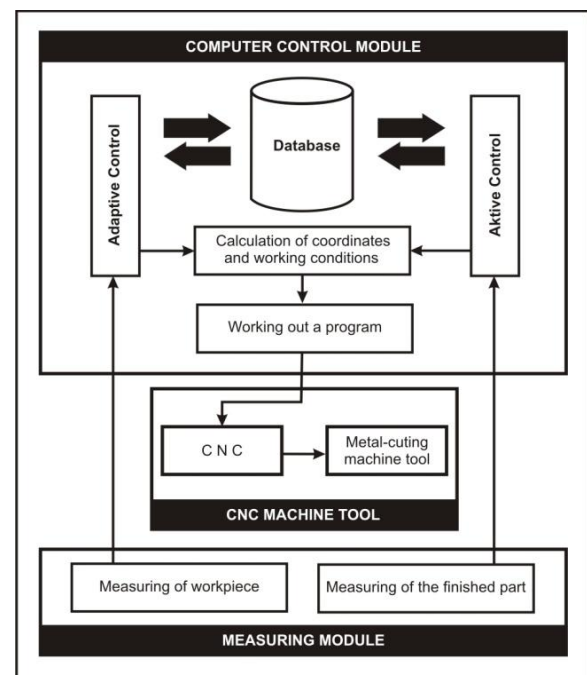


Fig. 1. Block diagram of an intelligent computer control system based on adaptive and active control.

The system comprises the following modules:

- Control module, through which the dimensions of the workpieces before machining and the dimensions of the machined parts are controlled. The results, concerning the workpieces, are fed into

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an adaptive control system (block), and those, related to the finished parts go into an active control system (block);

- Process implementation module, containing the machine tool and the CNC system;
- Module for computer control, which generates the management program and performs the machining of the parts in communication with the machine's CNC system. This module combines algorithms for controlling the accuracy of the results from the machined parts control (active post-processing control APPC) with algorithms for adaptive accuracy control (AAC), performed on the basis of the results from the inspection of the workpieces;

The computer control module is the core of the system. It is a computer system, containing the database, the specialized software for adaptive and active control, for generating management programs and communication with the machine's CNC system.

A. APPC algorithm with real-time processing of statistical information about the process

The characteristics of the technological process are known when using the classical APPC algorithm. It is applied in large-scale and mass production, where there is sufficient statistical information, concerning both the instantaneous dispersion field and the trend in the average value of dimensions, caused by systematic factors. The control limits for the process can be determined in advance in this case, as well as the magnitude of the dimensional adjustment pulse, depending on whether the control method is based on samples or on single parts.

A different algorithm can be applied nowadays thanks to modern computer technologies. The algorithms must be adequate to modern requirements for production flexibility and high degree of automation with frequent product changes and relatively small batch sizes [5] - [6]. Under these conditions, the statistical characteristics of the process and the decisions for the timing and magnitude of dimensional adjustment must be determined dynamically (in real time) during the technological process. Research in this direction shows [7] that if the results of the dimensional control of each of the sequentially machined parts are used to sequentially generate regression equations for the average value of the dimension, this can be used to determine with sufficient accuracy the moment of dimensional sub-adjustment and the magnitude of the sub-adjustment pulse. Graphical representation of the idea can be seen in Fig. 2.

The change in the average dimensional value can be determined after having each part machined from the regression equation, derived based on all machined parts to the moment:

$$\Delta \bar{A} = \bar{A}_n - \bar{A}_0 = \tilde{b}n \quad (1)$$

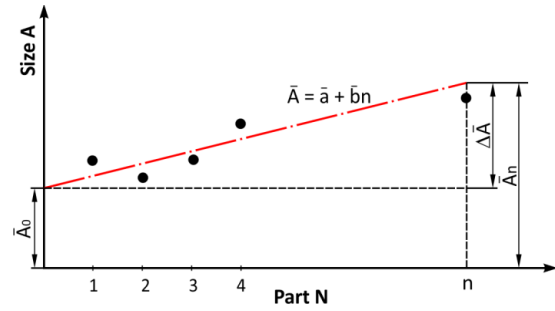


Fig. 2. Linear regression equation of the average dimensional value.

If the determined change in the average value is statistically significant, then dimensional sub-adjustment should be performed with the same magnitude of the adjustment pulse.

Due to the small volume of statistical data, a significant fluctuation of the regression equation slope (precession) is observed at the beginning of the process. As the number of processed parts increases, the precession decays exponentially [8].

The decision for dimensional sub-adjustment is made if the following conditions are simultaneously met:

- sufficient precession damping;
- adequate regression equation;
- statistical significance of the increase in the average dimensional value $\Delta \bar{A}$.

The smallest value of the total dispersion field with this algorithm is:

$$\omega_{\Sigma \min} = \omega \sqrt{1 + \frac{1}{n} + \frac{t_{\alpha, K}^2}{6n}}, \quad (2)$$

where $t_{\alpha, K}$ is a critical value of the Student's t-test at a significance level α and degrees of freedom $K = 2(n - 1)$.

Formula (2) is presented graphically in Fig. 3. It shows that the total dispersion field with this algorithm approaches in magnitude to the instantaneous one, when the number of machined parts increases. In practice, $\omega_{\Sigma \min}$ is greater since formula (2) does not take into account the sub-adjustment error.

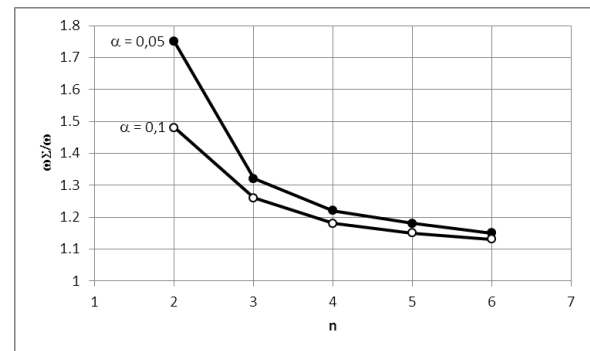


Fig.3. Dependence of the total dispersion field on the instantaneous one and the number of machined parts.

B. Possibility to reduce the instantaneous dispersion field through adaptive control

Dimensional dispersion, caused by random factors, can be reduced by incorporating force deformation control devices into the technological system [9]. These devices can be used to adjust the operating modes and/or dimensional adjustment. However, their disadvantage is that they are not universal, which means that the method is only suitable for large-scale production.

At present there are various options to obtain data about errors, resulting from force deformations. As a result of the development of CNC machine tools and computer and information technologies, adaptive control can be implemented based on mathematical models of the technological system deformation behavior [10] – [12].

The force deformation at a certain point M of the workspace can be represented as a function of the forces, acting in the system, and the coordinates of the point. Since the application of forces to a given point is represented by the dynamo of the resultant force and the torque, the mathematical model of the force deformations will have the form:

$$y = \Phi[\vec{F}_{tot}, \vec{M}_{tot}, M(x_M, y_M, z_M)]. \quad (3)$$

The model (3) provides a possibility to implement adaptive control in order to stabilize and/or compensate for force deformation errors through direct computer control, using the machine's working elements and the CNC system [13] – [15].

III. RESULTS AND DISCUSSION

The developed algorithms for adaptive control in rough machining and APPC in fine machining make it possible to implement a computer system for complex accuracy control. The system contains the described three modules, together with the software for their functioning and data exchange between them, so that the modules work as a single unit.

Adaptive control, as a separate algorithm, is performed in accordance with the obtained results from the workpiece control. Active control, as a separate algorithm, is carried out in accordance with the results from controlling already machined parts.

The system has been tested when boring cylindrical sleeves made of steel 35 with a cantilever boring bar on a CNC lathe LT580.

A suitable solution for rough machining is adaptive accuracy control. As a result of the increase in dimensional accuracy, the dispersion of the cutting depth for clean machining reduces, and so does the dispersion of the force deformations. The influence of technological heredity on the accuracy of clean machining decreases in this case.

It is accepted to carry out adaptive accuracy control without the use of special devices for controlling force deformations in real time. Experimentally obtained for specific operating conditions mathematical models of the

force deformations in the technological system are used in this case. The regression equations are of the following type:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2. \quad (4)$$

The cutting depth a , the feed f and the coordinate z of the cutting area are considered as variable factors, determining the magnitude of the force deformation Y . Two-factor and three-factor models are used.

The two-factor model is typical for cases where the magnitude of the force deformation does not significantly depend on the z coordinate of the cutting area, for example, when boring cylindrical sleeves with a cantilever boring bar. In this case, the deformation can be considered as a function only of the depth of cut and the feed, while the other conditions under which the operation occurs, are assumed to be constant. In the three-factor model, in addition to the cutting depth and feed, the z coordinate of the cutting area also has a significant influence on the deformation, for example, when scraping long cylindrical surfaces, mounted cantilevered or between centers.

In the two-factor model, the regression equation for the force deformation has the form:

$$y = b_0 + b_1 a + b_2 f + b_3 a f + b_4 a^2 + b_5 f^2, \quad (5)$$

From equation (5) the feed f_i is determined, given the magnitude of the deformation y and the cutting depth, determined by the size of the workpiece. The workpiece will be machined with this feed. Then, using standard control commands, a program sentence is compiled, and passed by the CNC system to the machine tool for execution.

The three-factor model is assumed to be implemented by sequentially applying the two-factor model in sections of the machined surface with a length L_k , within which the influence of the coordinate z is insignificant (the increase in y does not exceed a predetermined value). Under these assumptions, the length of the surface under machining is divided into k number of sections of equal length L_k . Each of them is characterized by a position coordinate in axial direction z_k and a regression equation of the type (5), obtained from the three-factor model at $z = z_k$. For each of the sections, the feed f_k is determined and a corresponding group of sentences for the CNC system is written. This procedure is repeated for all sections of the surface. Finally, the program sentences for machining the entire surface are compiled from these groups and submitted to the CNC system for execution.

A computer system for complex accuracy management has been built based on the created algorithms for adaptive accuracy control in rough machining and for APPC in clean machining. The CNC system is controlled directly by the computer system on which the adaptive accuracy control software and APPC software are installed.

For experimentation of the model and the adaptive control algorithm, it is accepted that the research should be

carried out under conditions where the technological system has a relatively high sensitivity to force loads and is characterized by significant dispersion of force deformations. The capabilities of the adaptive control can be more fully demonstrated in this case. The specified conditions are met when boring cylindrical holes with a cantilever-mounted tool. The force deformations of the technological system are mainly determined by the sagging of the tool.

The scheme of the experiment for determining the function (5) is presented in Fig. 4.

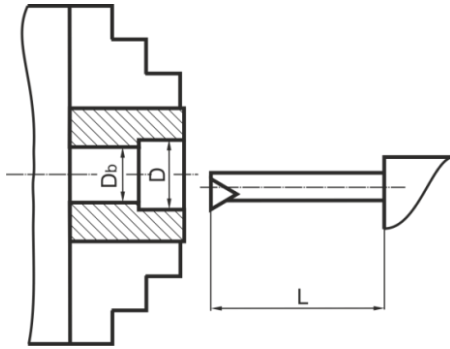


Fig. 4. Experimental scheme (D_b – diameter of the workpiece; D – diameter of the machine part).

The length of the boring tool L is a constant for the duration of the machining and is not included as a factor in the model. For a tool with a different length, a different model will be present in the database.

The cutting depth is ensured according to the experimental design plan by using step workpieces. The difference between the step radii for a given workpiece is the required depth of cut. The first step is equal in diameter to the dimension of static adjustment. Both steps are machined with the same feed rate, consistent with the experimental design. The difference between the radii of the two steps after completing the process of boring is taken as the magnitude of force deformation of the system.

The software product EXPLAN V 1.0 is used to process the data. It performs a model adequacy check, defines the regression equation in normalized and natural coordinates, and plots a diagram of the response.

The conditions for conducting the experiment are: machine - CNC lathe LT580; machined material - steel BDS EN 10083-2 C35, hot-rolled pipe $\varnothing 40/7$; diameter of the machined hole $D = 28,5$ mm; diameter of the cutting tool – 20 mm; length of the cantilever part of the tool $L = 100$ mm; hard-alloy plate made of P15, type TPUN 110302; main tool setting angle $\chi_r = 90^\circ$; cutting speed $V_c = 85$ m/min; measuring instrument – digital caliper 150/0,01.

The matrix of the experiment and the obtained deformation results are presented in Table 1.

TABLE 1 MATRIX OF THE EXPERIMENT AND DEFORMATION RESULTS

№	Experimental design plan				Result $y[\mu\text{m}]$
	X_1	X_2	$a, [\text{mm}]$	$f, [\text{mm}/\text{min}]$	
1	-1	-1	0,25	0,10	35
2	+1	-1	0,75	0,10	65
3	-1	+1	0,25	0,50	90
4	+1	+1	0,75	0,50	305
5	-1,414	0	0,15	0,30	40
6	+1,414	0	0,85	0,30	190
7	0	-1,414	0,50	0,02	25
8	0	+1,414	0,50	0,58	200
9	0	0	0,50	0,30	125
10	0	0	0,50	0,30	135
11	0	0	0,50	0,30	135
12	0	0	0,50	0,30	140
13	0	0	0,50	0,30	140

The regression equation in natural coordinates is:

$$y(a, f) = 8 + 71,4a + 8,1f + 925af - 120,4a^2 - 219,3f^2. (6)$$

Fig. 5 shows the graphical interpretation of the obtained model.

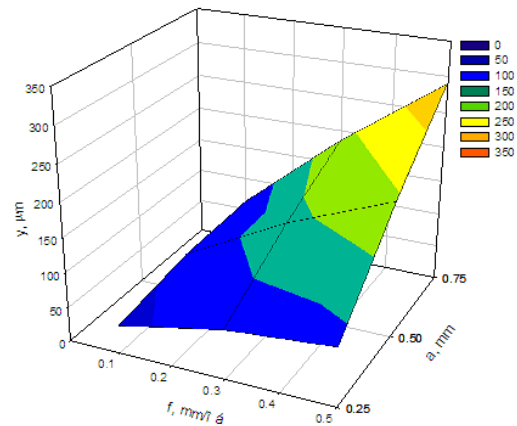


Fig. 5. Graphical interpretation of the force-deformation model.

Rough boring is performed under similar conditions to those, under which the force deformation model has been taken. A batch of 50 workpieces is bored, varying the cutting depths from 0,25 to 0,75 mm. For each workpiece, the feed is determined by the computer system in accordance with the algorithm, discussed in [9].

The effect of applying the adaptive accuracy control can be visually assessed from the scatter diagram in Fig. 6.

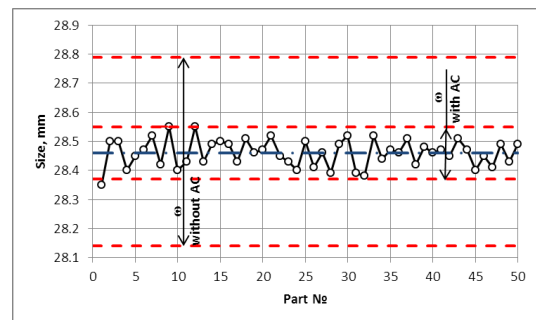


Fig. 6. Scatter diagram of rough boring with adaptive accuracy control.

The dispersion of dimensions without applying adaptive accuracy control can be determined from the mathematical model of force deformations (6):

$$\omega_{\Sigma y} = \Delta y + \omega_y, \quad (8)$$

where Δy is the increase in the deformation when varying the variable factors within the model limits from their minimum to their maximum level; ω_y - dispersion field around the regression equation.

In this particular case: $\omega_{\Sigma y} = 250 + 62 = 312 \mu\text{m}$

The dispersion of the diametric dimensions $\omega_{\Sigma D}$ will be: $\omega_{\Sigma D} = 2\omega_{\Sigma y} = 624 \mu\text{m}$.

The dispersion of the dimensions with applying adaptive accuracy control can be determined from the obtained results:

$$\omega = 2k_{50; 0,9; 0,9}; \quad S = 2 \cdot 1,916 \cdot 0,047 = 0,18 \text{ mm}.$$

The result from the experimental study shows that the dimensional dispersion reduces 3,5 times as a result of implementing adaptive control. The achieved specification is:

$$K_{y1} = \omega_r / \omega_{p1} = 1 / 0,624 = 1,6;$$

$$K_{y2} = \omega_r / \omega_{p2} = 1 / 0,18 = 5,$$

where ω_r is the dispersion field of the workpiece dimensions for rough boring; $\omega_{p1} = \omega_{\Sigma D}$ - dispersion of the dimensions of the parts after rough boring without adaptive accuracy control; $\omega_{p2} = \omega$ - dispersion of the dimensions of the parts after rough boring with adaptive accuracy control.

A boring bar cantilevered in the turret of a CNC lathe is used to perform clean boring under the following conditions: machine - CNC lathe LT580; machined material - steel BDS EN 10083-2 C35, hot-rolled pipe $\varnothing 40/7$; diameter of the machined hole $D = 29,0 \text{ mm}$; size tolerance $T = 50 \mu\text{m}$; diameter of the cutting tool - 20 mm ; length of the cantilever part of the tool $L = 100 \text{ mm}$; hard-alloy plate made of P15, type TPUN 110302; main tool setting angle $\chi_r = 90^\circ$; cutting speed $V_c = 120 \text{ m/min}$; feed $f = 0,05 \text{ mm/rev}$; average cutting depth $a_p = 0,3 \text{ mm}$; measuring instrument - internal gauge with a measuring clock with a division value of $0,001 \text{ mm}$.

The effect of implementing APPC can be visually assessed from the scatter diagram in Fig. 7.

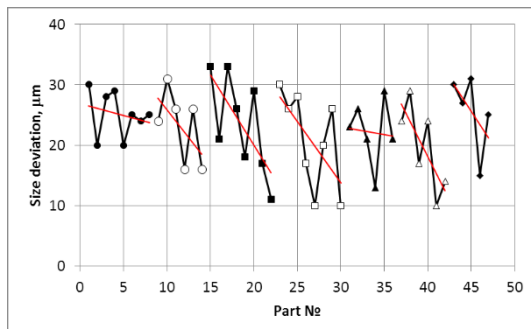


Fig.7. Scatter diagram of clean boring with APPC.

In accordance with the input data, with a given tolerance of the machined surface $T = 50 \mu\text{m}$ and instantaneous dispersion field $\omega = 24 \mu\text{m}$, the computer system selects an operating algorithm with a limited accuracy resource. From the experimental data it can be seen that the entire batch of 50 parts is machined with seven sub-adjustment pulses, with eight groups of parts distinguished.

The first group contains 3 parts and serves to check the dimensional adjustment. For this purpose, the system compares the average dimensional value for the group with the working size of the adjustment and determines a sub-adjustment pulse with a magnitude of $\Delta A_1 = 73,3 \mu\text{m}$. The desired dimensional adjustment for getting the work started is achieved when the CNC system implements the sub-adjustment pulse.

The next groups of parts are machined with a sequential check of the criteria for adequacy of the regression equation, precession damping, and significance of the difference between the average dimension from the regression equation and the working dimension of the adjustment. When all three criteria are satisfied simultaneously, the magnitude of the sub-adjustment pulse is determined and the pulse is fed into the CNC system for execution. The algorithm is demonstrated as a result in Fig.7, with the exception of the first group of parts.

The software provides information about the variance around the regression equation for each group of parts. The Fisher test shows that the dispersions of the seven groups are homogeneous, which gives reason to work with the averaged dispersion to determine the instantaneous dispersion field after clean boring:

$$\omega_{cb} = 2k_{47; 0,9; 0,9};$$

$$S = 2 \cdot 1,927 \cdot 0,00674 = 0,026 \text{ mm}.$$

The total dispersion field within the experiment can be determined by the range of the experimental data:

$$\omega_{\Sigma} = R = D_{\max} - D_{\min} = 29,033 - 29,01 = 0,023 \text{ mm}.$$

The estimated value $\omega_{\Sigma ev1}$ of the total field for this computer system and this process can be determined from the sum:

$$\omega_{\Sigma ev1} = \sqrt{\omega_{cb}^2 + 3 \cdot \Delta A_{aver}^2 + \omega_{pe}^2};$$

$$\omega_{\Sigma ev1} = \sqrt{0,026^2 + 3 \cdot 0,0103^2 + 0,0097^2} = 0,032 \text{ mm}.$$

In the expression $\Delta A_{aver} = 0,0103 \text{ mm}$ is the average magnitude of the sub-adjustment pulse for the six sub-adjustments in Fig. 7; $\omega_{pe} = 0,0097 \text{ mm}$ is the positioning error for the specific machine, in case of unidirectional dimensional sub-adjustment.

The achieved specification is:

$$K_y = \omega_{p2} / \omega_{cb} = 0,18 / 0,026 = 6,92,$$

where $\omega_{p2} = 0,18 \text{ mm}$ is the field of dispersion of dimensions after rough machining with adaptive accuracy

control; $\omega_{cb} = 0,026$ mm - instantaneous field of dispersion during clean boring with APPC.

The effect of combining APPC with adaptive accuracy control can be estimated by determining the expected instantaneous dispersion field ω_{cb2} under the assumption that rough boring is performed without adaptive accuracy control and the technological system has the same specification:

$$\omega_{cb2} = \omega_{p1} / K_y = 0,624 / 6,92 = 0,09 \text{ mm.}$$

In this case, the estimated value of the total dispersion field will be:

$$\omega_{\Sigma ev2} = \sqrt{\omega_{cb2}^2 + 3\Delta A_{aver}^2 + \omega_{pe}^2};$$

$$\omega_{\Sigma ev2} = \sqrt{0,09^2 + 3 \cdot 0,0103^2 + 0,0097^2} = 0,092 \text{ mm.}$$

In other words, as a result of applying adaptive control, the reduction in the dimensional error will be:

$$\omega_{\Sigma ev2} / \omega_{\Sigma ev1} = 1,88 \text{ times.}$$

The effect of APPC as an increase in machining accuracy can be assessed by determining the total dispersion field $\omega_{\Sigma ev3}$ under the assumption that no dimensional sub-adjustment has been performed, i.e.:

$$\omega_{\Sigma ev3} = \omega_{cb} + \sum_{i=1}^6 \Delta A_i = 0,026 + 0,062 = 0,088 \text{ mm.}$$

Consequently, the reduction in dimensional dispersion with APPC will be:

$$\omega_{\Sigma ev3} / \omega_{\Sigma ev1} = 2,75 \text{ times.}$$

IV. CONCLUSIONS

Using a designed experiment, regression equations have been obtained and used to model the force deformations, resulting from boring cylindrical holes with a cantilever tool on a CNC lathe LT580.

The algorithms and the programs for implementing APPC with adaptive accuracy control have been experimentally verified when boring cylindrical sleeves with a cantilever tool at a low accuracy resource. The conducted studies prove the working capacity of the proposed algorithm and software.

With the help of adaptive accuracy control, the dispersion of the allowance for clean boring has been reduced 3,5 times. As a result, the instantaneous dispersion field for clean boring also decreases 3,5 times and the total dispersion field for APPC goes down 1,88 times.

Reduction in the dimensional dispersion of 2,75 times has been achieved by applying APPC together with adaptive accuracy control in this particular case.

ACKNOWLEDGMENTS

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Digital Transformation of the Bulgarian Rose in Sustainable Fashion Design through Specialized Machine Embroidery Software

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Abstract - This study examines the process of digital transformation of the traditional motif of the Bulgarian oil-bearing rose (*Rosa damascena*) within the context of sustainable fashion design through the use of specialized embroidery software. The research explores the adaptation of natural forms into a digital environment by combining artistic stylization and technological implementation. A methodology is proposed, involving the creation of an initial ornament using cross-stitch techniques in Pattern Maker, followed by digitization and optimization of the embroidery design in Artistic Digitizer. The final design is executed through machine embroidery on textile products. The results demonstrate that the digital approach enables an effective integration of cultural heritage and modern technologies, while contributing to sustainable fashion practices through resource optimization and increased product durability.

Keywords - Bulgarian rose; cultural heritage; digitization; digital transformation; machine embroidery; sustainable fashion; textile design.

I. INTRODUCTION

In the context of globalization and the dynamic development of the fashion industry [1], the issue of preserving and interpreting cultural identity is becoming increasingly significant. Contemporary fashion design seeks to integrate traditional elements into a new context, thereby creating sustainable connections between the past and the present [2]. Similar approaches can also be observed in contemporary research focused on integrating traditional embroidery techniques into sustainable textile production and cultural preservation practices [3]. In this process, digital technologies and CAD-based design systems play a key role, enabling the transformation of traditional motifs into contemporary and sustainable design solutions [2], [4].

The Bulgarian oil-bearing rose (*Rosa damascena*) represents one of the most recognizable national symbols of Bulgaria, established in both cultural-historical and economic contexts. It is closely associated with the region of the Rose Valley [5], which has become a world-renowned center for the production of rose oil—a product of high added value and international significance.

The rose symbolizes beauty, femininity, purity, and spirituality, while also functioning as a visual identifier of Bulgarian cultural identity of the country in the global cultural space. Its presence in traditional Bulgarian embroidery and decorative-applied arts testifies to its deep integration into folk aesthetics.

In contemporary fashion design, this symbol holds the potential to be interpreted as a visual code that combines national identity with global aesthetics. Recent research in cross-cultural textile design also highlights the role of traditional visual codes in developing innovative sustainable fashion concepts within a global design context [6].

The present study is focused on exploring the possibilities for the digital transformation of the “Bulgarian rose” motif through the use of specialized software for machine embroidery. The main emphasis is placed on the process of creation, digitization, and technological realization of original embroidery motifs based on a stylized interpretation of *Rosa damascena*.

The study has an interdisciplinary character and integrates knowledge from the fields of fashion design, textile technologies, and digital design systems. The main objective of the research is to develop a model for integrating original motifs inspired by the Bulgarian rose into contemporary fashion collections through the use of

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machine embroidery. To achieve this objective, the following tasks have been defined:

- analysis of the symbolism of the Bulgarian rose as a cultural and national emblem;
- investigation of contemporary Bulgarian practices in the field of embroidered textiles;
- development of original motifs through digital tools;
- experimental application of the motifs in fashion products;

The scientific novelty of the study lies in the systematic examination of the process of digital transformation of a traditional symbol within the context of sustainable fashion design, as well as in the development of original embroidery motifs adapted to contemporary machine embroidery technologies.

II. MATERIALS AND METHODS

II.1. Characteristics of the Bulgarian Rose as a National Symbol and a visual identifier of Bulgarian cultural identity of Bulgaria

The Bulgarian oil-bearing rose (*Rosa damascena*) occupies a central place in the cultural and economic history of Bulgaria, establishing itself as one of the most recognizable national symbols. Its cultivation is primarily concentrated in the region of the Rose Valley, where natural and climatic conditions create favorable prerequisites for the production of high-quality rose oil, known worldwide.

The rose carries a multifaceted significance that goes beyond its botanical characteristics. It symbolizes beauty, harmony, femininity, and spirituality, while also being closely linked to the labor traditions and livelihood of the local population. In this sense, *Rosa damascena* functions as a cultural sign that integrates natural, economic, and social dimensions.

The cultural importance of the Bulgarian rose is reflected in a number of traditions and events, among which the Rose Festival holds a prominent place. The festival showcases customs related to rose picking and contributes to the promotion of Bulgarian culture in an international context.

From the perspective of visual culture, the rose is widely present in decorative and applied arts, including textiles, ceramics, and traditional embroidery. In Bulgarian folk embroidery, it is often stylized and combined with geometric elements [7]. This stylization creates favorable conditions for its adaptation to contemporary design.

In the context of the modern global cultural environment, the Bulgarian rose has established itself as a visual identifier of Bulgarian cultural identity, representing a strong visual and marketing symbol. It is used not only in traditional products but also in contemporary design solutions, including fashion, where it becomes a means of expressing national identity within a global context [8].

Within the framework of the present study, *Rosa damascena* is considered not merely as a decorative element, but as a conceptual foundation for the creation of original embroidery motifs. Such approaches correspond to contemporary research focused on the digital preservation and reinterpretation of cultural heritage in fashion design [9]. Through the process of digital transformation, it is transformed into a universal visual language that combines tradition, technology, and sustainability.

II.2. Analysis of Bulgarian companies offering clothing and accessories through machine embroidery with *Rosa damascena* motifs

The contemporary Bulgarian market for clothing and accessories decorated with machine embroidery is characterized by dynamic development and a growing interest in integrating traditional ornamental motifs into modern products. Within the framework of the present study, an analysis was conducted of established Bulgarian brands that use machine embroidery as a primary means of artistic expression in their products.

Among them, brands such as Brodika [10], Vezba [11], BULGARKA.BG [12], and SHEVICA BG [13] stand out, offering a diverse range of products—from everyday clothing to accessories with ethnic inspiration. What they share in common is the use of machine embroidery as a tool for achieving serial production, precision, and relative affordability of the products.

The analysis of product lines shows that decorative solutions are predominantly based on traditional Bulgarian embroidery, characterized by geometric compositions and stylized floral elements. The rose motif is relatively rarely used as an independent compositional center and more often appears as a secondary or complementary decorative element.

From a compositional perspective, the placement of embroidered motifs follows the traditional principles of Bulgarian folk costume—on the sleeves, around the neckline, and along the hemline. This positioning has both aesthetic and symbolic functions, associated with notions of protection, harmony, and the structural organization of the garment [14]. In the contemporary context, however, this symbolism is often reduced to a purely decorative effect.

Significant differences among the analyzed brands can be observed in terms of the degree of stylization and adaptation to current fashion trends. For example, Vezba is characterized by a minimalist approach, where decoration is reduced to a minimum and the emphasis is placed on form, material, and product sustainability. The use of natural textiles such as linen and cotton aligns with contemporary concepts of sustainable fashion design [2].

On the other hand, brands such as BULGARKA.BG and SHEVICA BG maintain a higher degree of ornamentation, striving for a closer connection to traditional aesthetics. Their products often feature richly decorated surfaces, which, however, may limit their applicability in a contemporary urban environment.

The overall trend indicates that most brands rely on established ornamental patterns without a significant degree of original interpretation or digital transformation. A notable gap is the lack of clearly conceptualized collections built around a specific national symbol, such as the Bulgarian oil-bearing rose (*Rosa damascena*).

Although the rose motif appears in individual products, it is rarely considered as the primary carrier of the design concept (Fig. 1). This gap creates opportunities for the development of new approaches in which the rose is interpreted not merely as a decorative element, but as a central component of the visual and conceptual identity of the fashion product.



Fig. 1. Selection from the product range of Bulgarian companies featuring rose motifs

Within the framework of the present study, such an approach is proposed, based on the digital transformation of original motifs and their application through machine embroidery.

In conclusion, it can be stated that contemporary Bulgarian brands successfully integrate traditional elements into their products; however, they rarely develop innovative concepts based on clearly defined national symbols.

II.3. Technological Process for Creating a “Stylized *Rosa damascena*” Motif

One of the earliest and most enduring plant motifs in Bulgarian embroidery ornamentation is the rose, which occupies an important place in the decorative system of the traditional costume. According to Ivan Koev [7], it appears in a specific stylized form known as a “rosette” (Fig. 2). In this ornament, the original naturalistic image of the flower is highly reduced and transformed, preserving only the idea of centrality and radial expansion.



Fig. 2. Embroidered ornaments from shirt sleeves from the Provadia region

The rosette represents a composition with a clearly defined center, typically shaped as a circle or square, around which elements resembling petals are symmetrically arranged. These elements are often geometrized and take on the form of star-like structures, which are subsequently interpreted as plant motifs.

Fig. 3a shows a detail from the sleeve of a women’s shirt from the Samokov region [15]. The central element is developed as an eight-petaled rosette, enclosed within a geometric frame, from which additional motifs radiate, interpreted as the “tree of life.”

In Fig. 3b, on the chest panel of a women’s shirt from the Stanke Dimitrovo region, the rosette is reduced to a repeating module—an eight-petaled flower arranged in horizontal bands. Here, the motif loses its centrality but retains its recognizable structure and rhythmic function within the composition.

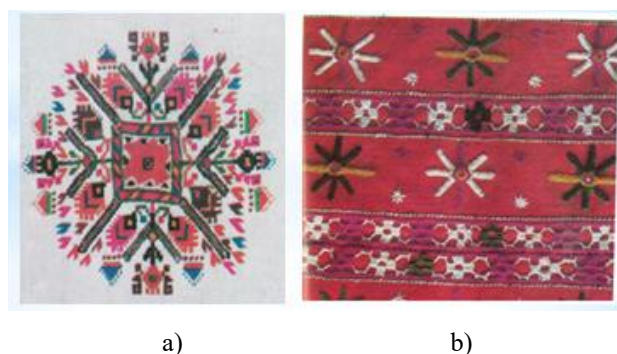


Fig. 3. Rosettes

A characteristic feature of these ornaments is that, despite their strong geometrization, they preserve the idea of a plant origin. It is precisely this transformation—from a naturalistic rose to an abstract rosette—that enables the easy adaptation of the motif to the cross-stitch technique and its widespread use across different ethnographic regions.

In the context of the present study, this traditional stylization is of key importance, as it demonstrates how a natural form can be transformed into a universal decorative sign. The creation of the original “*Rosa damascena*” motif is based on this principle, but further develops it toward greater visual recognizability and digital adaptability.

The digitization process of the original “*Rosa damascena*” motif was carried out through the sequential use of the specialized software systems Pattern Maker for Cross Stitch and Artistik Digitizer, which enable the transformation of the visual image into a technologically applicable model for machine embroidery. This approach corresponds to contemporary CAD-based practices in sustainable fashion and digital textile design [4].

For the transformation, an embroidery ornament was selected (Fig. 4), representing a four-rayed geometrized rosette, in which the image of the rose is reduced to a cross-shaped symmetrical structure.



Fig. 4. Embroidered ornaments from the skirts of shirts from the Samokov region

Stage 1: Creating a Pattern in Pattern Maker

The motif from Fig. 4 undergoes the following stages of transformation (Fig. 5.):

- Structural analysis of the motif (Fig. 5.a);
- progressive transformation of geometric structures into biomorphic floral forms (Fig. 5.b);
- Addition of naturalistic elements (Fig. 5.c);
- Preservation of the pixel-based structure. (Fig. 5.d);
- Contemporary interpretation (Fig. 5.e).

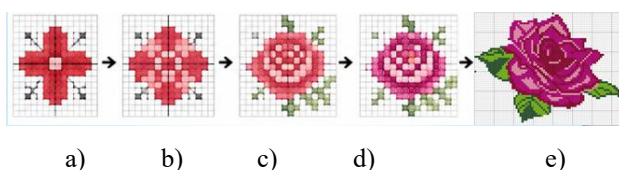


Fig. 5. Stages of transformation of a rosette embroidery ornament into a digital original motif „Rosa Damascena“

The original motif is adapted through the cross-stitch technique. In this phase, the image of the rose is transformed into a pixel-based structure (grid), corresponding to the stitch system.

The main operations include: (Fig. 6.):

- Setting the canvas dimensions and stitch density (stitches per inch/cm): For the development of the original Rosa damascena motif, the project parameters were configured in the „Canvas Properties“ section with a cross-stitch density of 12 stitches per inch (12 count) in the horizontal direction. The initial project dimensions were set to 80 mm in width and 60 mm in height. Following the digitization and scaling process, the finalized embroidery motif was generated with dimensions of 83 × 64 stitches, corresponding to an actual embroidery size of approximately 168 × 126 mm. These parameters were selected to ensure optimal visual clarity of the ornament, preservation of the stylized floral structure, and suitability for machine embroidery implementation.

- Selection and optimization of the color palette: The color palette was reduced and optimized through the selection of a balanced chromatic composition comprising five colors—two green tonal variations for the leaves and three tonal gradations for the rose petals. This approach contributed to improved visual clarity of the motif, technological feasibility of the embroidery process, and harmonious color balance.

- Manual refinement of contours to achieve a clearly recognizable form.

- Balancing between level of detail and technological feasibility: A balance between ornamental detail and technological feasibility was achieved through the elimination of isolated single-color cross stitches. This optimization reduced excessive thread transitions and knot formation during the embroidery process, thereby improving the precision, structural stability, and production efficiency of the machine embroidery implementation.

As a result, a digital pattern is obtained that combines the traditional aesthetics of cross-stitch with the author's interpretation of the rose.

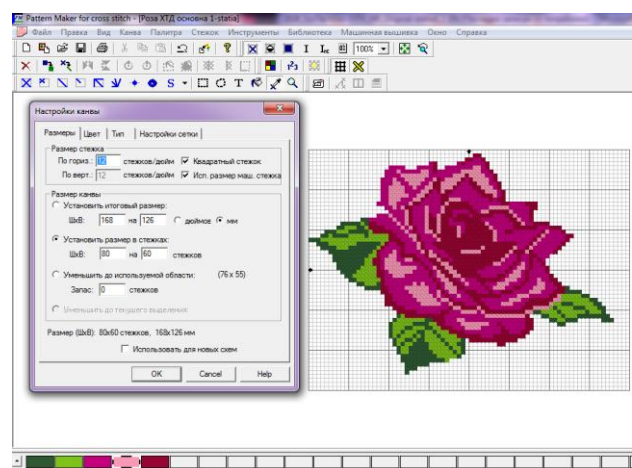


Fig. 6. Part of the operations involved in the digitization of the motif

The next step involves exporting the created pattern into a file for machine embroidery (Fig. 7). The following parameters are defined: the embroidery file format according to the type of embroidery machine; the file name and storage location; the hoop size; and the stitch thickness for machine embroidery.

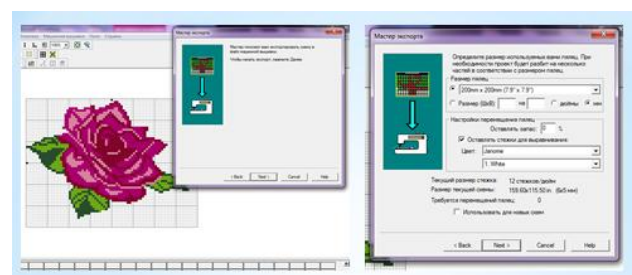


Fig. 7. Exporting the pattern into a machine embroidery file

Stage 2: Conversion into a machine embroidery file using the specialized embroidery software Artistik Digitizer

This stage involves transforming the pattern into a machine-readable file using the software Artistik Digitizer 1.7. At this stage, the so-called “digitizing” process is carried out—converting graphical information into a sequence of embroidery stitches.

The key operations in this stage include (Fig. 8.):

- importing the pattern and converting it into vector format;
- selection of a color scheme in accordance with the design concept;
- optimization of the embroidery sequence to reduce thread breaks and transitions;
- simulation of the embroidery process and correction of potential defects.

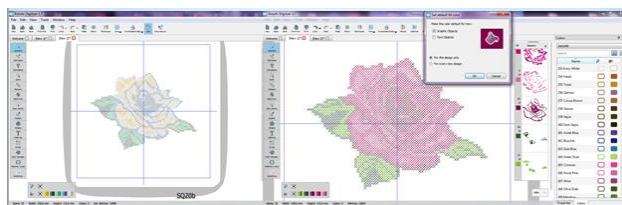


Fig. 8. Part of the operations in Stage 2

The final result is a file (Fig. 9), compatible with an embroidery machine (Elna eXpressive 830 L), which enables precise reproduction of the motif on a textile base (Fig. 10.).

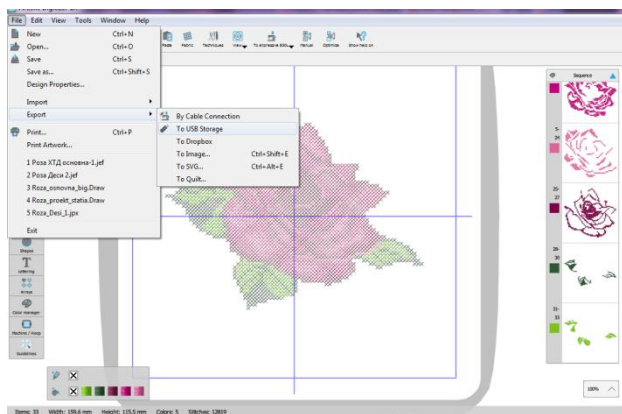


Fig. 9. Export to USB in a file format for an embroidery machine



Fig. 10. “Rosa damascena” motif embroidered on cotton canvas fabric

III. RESULTS AND DISCUSSION

In addition to the main original motif “Rosa damascena,” two additional stylized variations of the rose ornament were developed within the framework of the present study. They preserve the connection to traditional stylization while offering different degrees of geometrization and artistic interpretation. The three motifs function as a unified visual system (Fig. 11) and are incorporated into the design of the proposed project collection.

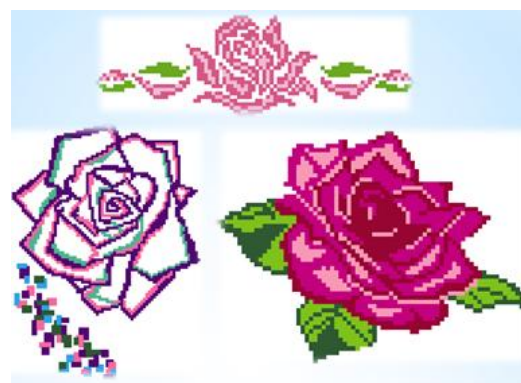


Fig. 11. Designed stylized variations of the “rose” ornament

The inspiration for the creation of the original collection stems from the Bulgarian oil-bearing rose (Rosa damascena) as an emblematic symbol of national culture and natural heritage. The mood board presented in Fig. 12 brings together visual references to the Rose Valley, traditional rose harvesting, and authentic Bulgarian embroidery, emphasizing the transformation of the floral motif into a contemporary design element.



Fig. 12. Atmosphere - map of the collection. /Moodboard/

III.2. Application of Original Rosa damascena Motifs in Contemporary Fashion Collections

Based on the conducted research and the developed original motifs of the “stylized Bulgarian rose,” a project proposal for a fashion collection has been created, structured into three thematic lines: **ethnic, romantic, and classic**. Each of them interprets the relationship between tradition and modernity in a different way, while maintaining a common conceptual framework—sustainable design based on cultural identity.

The color composition of the designs is fully aligned with global Spring–Summer 2026 fashion trends [16]:

- current pastel and natural colors are used;
- saturated accent tones are integrated;
- the principle of harmony between calmness and expressiveness is followed.

In this sense, the collection not only reflects contemporary fashion trends but also interprets them through the lens of Bulgarian cultural identity, creating a contemporary, sustainable, and recognizable design product.

• Ethnic line – “Root”

The first line (Fig. 13) is directly inspired by the Bulgarian traditional costume, particularly the “barchanka”-type shirt and the tunic-style garment. It is characterized by a loose silhouette, constructive simplicity, and emphasized functionality.

Main characteristics include:

- **Silhouette:** straight or slightly A-line, without a clearly defined waist seam;
- **Sleeves:** dropped shoulder or raglan sleeves, medium to long length, with the possibility of adjustment using ties;
- **Materials:** linen and cotton with a natural texture;
- **Decoration:** embroidery positioned in traditional areas—around the neckline, on the sleeves, and along the hem.

In this line, the rose motif is interpreted in a more geometrized form. It functions as a central symbolic element, balanced by complementary ornaments of a geometric nature.

The ethnic line demonstrates the strongest connection to cultural heritage and can be considered the foundation of the entire collection.



Fig. 13. Ethnic line

• Romantic line – “Bloom”

The second line (Fig. 14) presents a more emotional and artistic interpretation of the rose theme. It is aimed at young women and is characterized by greater plasticity, dynamism, and decorative richness.

Main characteristics include:

- **Silhouette:** semi-fitted or trapeze-shaped, often with an emphasized waist through a belt;
- **Construction solutions:** asymmetry, layering, and ruffles;
- **Sleeves:** puff sleeves, off-shoulder, or bell-shaped;
- **Length:** varies from short to maxi, with movement in the hem;
- **Accessories:** textile bags, belts, and decorative ties.

In this line, the rose motif functions as a compositional focal element with greater artistic freedom—often in a larger scale and with a more organic form. The embroidery

follows the line of the silhouette, emphasizing the movement of the body and the construction of the garment.

The models are characterized by an ethereal silhouette, enhanced femininity, and visual lightness, achieved through the use of transparent and layered fabrics. Structurally, they feature soft lines, asymmetrical solutions, and свободни форми, които създават усещане за движение и динамика. Decorative elements are based on delicately distributed floral rose motifs, executed in stylized embroidery and combined with fine geometric ornaments. The color palette includes soft pastel shades—ecru, powder pink, and light natural tones, which enhance the romantic expression.



Fig. 14. Romantic line

• Classical line – “Style”

The third line (Fig. 15) presents the most refined and contemporary interpretation of the theme. It is oriented toward the urban environment and everyday elegance.

Main characteristics include:

- **Silhouette:** fitted or semi-fitted, with a clearly structured form;
- **Construction:** minimalist, emphasizing the female silhouette;
- **Length:** knee-length or midi;
- **Materials:** finely processed cotton, linen, or blended sustainable textiles;
- **Accessories:** bags and shoes with subtle embroidery.

In this line, the rose motif is reduced and integrated as a subtle decorative element, often positioned asymmetrically—along the shoulder line, the left side seam, or the hem. This corresponds to contemporary trends in minimalism and functionality in fashion design [2].

The classical line demonstrates the highest level of adaptation to the contemporary lifestyle, while preserving cultural identity through subtle visual codes.



Fig. 15. Classical line

The three lines of the project collection form a unified system, in which the unifying element is the original *Rosa damascena* motif, realized through machine embroidery. It functions as a visual marker of Bulgarian identity, while simultaneously allowing for diverse interpretations depending on the design concept.

IV. CONCLUSIONS

The present study examines the possibilities for the digital transformation of the Bulgarian oil-bearing rose (*Rosa damascena*) as a visual and cultural symbol within the context of sustainable fashion design. Through an interdisciplinary approach combining fashion design, textile technologies, and digital design tools, a comprehensive model for the creation and application of original embroidery motifs was developed.

The results of the study demonstrate that contemporary technologies, particularly specialized machine embroidery software, provide broad opportunities for adapting traditional ornaments to modern design practices. The digitization process using software such as Pattern Maker and Artistik Digitizer enables not only technical implementation but also the creative interpretation of cultural heritage.

The analysis of Bulgarian companies in the field of embroidered textiles revealed that, although there is an established practice of using traditional motifs, there is a lack of a systematic approach to developing original concepts based on specific national symbols. The proposed project contributes to filling this gap by creating a collection structured into three lines—ethnic, romantic, and classical.

A significant contribution of the study is the integration of sustainable design principles through the use of natural materials and optimized production processes. Machine embroidery is established as an effective tool that combines high quality, repeatability, and the possibility of local production. Similar sustainable approaches integrating traditional embroidery practices with contemporary textile

production have also been discussed in recent international research focused on cultural preservation and textile waste reduction [3].

In conclusion, it can be stated that the digital transformation of traditional symbols, such as the Bulgarian rose, represents a promising direction for the development of contemporary fashion design. This approach not only preserves cultural identity but also adapts it to the global context, creating new opportunities for sustainable and innovative development of the fashion industry in Bulgaria.

ACKNOWLEDGMENTS

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Integrating Bulgarian National Identity into Sustainable Fashion Design through Digital Technologies

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Abstract - This study examines the integration of Bulgarian national identity into sustainable fashion design through the application of digital technologies. The research focuses on the use of CAD systems and digital textile design tools for the transformation and adaptation of traditional Bulgarian motifs into contemporary garment design. Emphasis is placed on preserving the cultural, symbolic, and aesthetic value of traditional elements while aligning them with the principles of sustainability. A design approach is proposed that incorporates digitalization of traditional patterns, virtual prototyping, and machine embroidery techniques to enable efficient and resource-conscious production. The study analyzes the role of digital workflows in reducing material waste, optimizing production processes, and improving design accuracy. Additionally, the use of environmentally friendly textile materials is considered as part of the sustainable design strategy. The results highlight the potential of digital technologies to support the preservation and reinterpretation of cultural heritage within modern fashion systems. The integration of national identity and sustainability principles contributes to the development of innovative, environmentally responsible, and culturally meaningful fashion products.

Keywords - Bulgarian identity; CAD systems; cultural heritage; digital textile design; eco-friendly textiles; garment design; machine embroidery; sustainable fashion.

I. INTRODUCTION

Contemporary fashion design is regarded as an interdisciplinary field in which clothing functions simultaneously as an aesthetic product and a carrier of cultural identity and social information [1]. In the context of globalization and digitalization, the fashion industry is characterized by accelerated production processes and standardization, which necessitates the preservation and

reinterpretation of local cultural characteristics through contemporary design approaches [2].

Bulgarian embroidery represents an essential component of the national cultural heritage, preserving a multilayered symbolism and aesthetic. According to [3], traditional ornaments such as the elbetitsa, kanatitsa, and the Tree of Life contain enduring symbolic meanings related to cosmological concepts, protection, and harmony. These motifs are integrated into the structure of the Bulgarian folk costume and are positioned in key areas of the garment in order to fulfill protective and communicative functions [4].

Interest in the use of folklore elements in contemporary fashion design has increased in recent years. In [5], an analysis is presented regarding the interpretation of the Bulgarian national costume in the collections of contemporary designers. It is emphasized that the adaptation of traditional elements requires an in-depth understanding of their structure and cultural context. In this regard, the integration of embroidery motifs into contemporary design should be based on a scholarly approach rather than superficial decorative use.

Sustainability is increasingly established as a key principle in the development of the fashion industry. The Bulgarian national costume embodies sustainable characteristics, including efficient use of materials, functionality, and durability [4]. In this context, the application of traditional techniques such as embroidery can be considered a means of enhancing the value and extending the lifecycle of contemporary garments.

The role of digital technologies in contemporary fashion design is significant, particularly in the transformation of traditional motifs. Study [6]

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demonstrates the possibilities for integrating folklore ornaments into modern garments through digital processing and graphic software, enabling their adaptation to various product categories. In addition, the use of CAD technologies supports the development of sustainable design solutions by optimizing construction and production processes.

In the context of sustainable fashion, the concept of a capsule collection is considered an effective model for creating a functional and versatile wardrobe. In [2], it is emphasized that a basic wardrobe developed according to the principles of sustainability allows the combination of a limited number of garments with high adaptability and long-term use.

The present study is situated at the intersection of tradition and innovation, examining the possibilities for the digital transformation of Bulgarian embroidery motifs and their application in a contemporary capsule collection. By combining cultural heritage, sustainable materials, and digital technologies, the aim is to create a fashion product that meets contemporary requirements for functionality, aesthetics, and sustainability.

II. MATERIALS AND METHODS

The present study is developed through an interdisciplinary approach that combines ethnographic analysis, digital modeling, and experimental fashion design. The methodological framework integrates qualitative analysis of traditional ornaments with their subsequent digital transformation and technological adaptation to contemporary garment production. The main objective is to establish a relationship between the structural characteristics of authentic embroidery motifs and the possibilities for their precise reproduction through digital and machine technologies.

The initial visual base includes authentic Bulgarian embroidery motifs from the album by Masha Kazandzhieva [7], presenting ornaments from women's shirts from the regions of Kyustendil, Samokov, Bansko, and Dupnitsa (Fig. 1).



Fig. 1. Authentic Bulgarian embroidery motifs [7]

The selection of motifs was carried out purposefully, prioritizing examples with clearly defined geometric structure, compositional integrity, and distinctive symbolism, which allow for subsequent digital interpretation.

The selected motifs were analyzed in terms of their morphological structure, compositional organization, and symbolic function. Morphologically, the motifs are

characterized by a high degree of geometric stylization, determined by the cross-stitch technique and the use of a regular textile grid. The main elements include rhombuses, crosses, octagonal and star-shaped forms, as well as linear and zigzag structures that form frames and connecting zones. Stylized plant and zoomorphic forms are also observed, reduced to geometric modules and governed by the principles of symmetry and repetition, which ensures their adaptability to different scales and applications.

The compositional organization of the motifs is based on a clear distinction between central and border elements. The central compositions are built around dominant ornaments with symmetrical structures, creating a visual focal point and compositional completeness. The border elements are arranged as rhythmically repeating friezes that frame the main motif and create a sense of continuity. In a number of cases, a combined compositional scheme is observed, including a central motif, side vertical bands, and lower ornamental bands, characteristic of the structure of traditional garments.

The symbolic function of the motifs encompasses protective, social, and decorative aspects. Geometric forms perform an apotropaic role associated with protection, with their placement in boundary areas of the garment reinforcing this function. Stylized elements such as the "Tree of Life" reflect cosmological concepts and the relationship between nature and humans. At the same time, the compositional complexity and color organization of the motifs can be interpreted as indicators of regional affiliation and cultural identity, while their decorative function is expressed through visual balance and color harmony.

Based on the conducted analysis, traditional embroidery techniques were identified that can be effectively adapted to machine embroidery. The main focus is placed on cross stitch and backstitch, due to their structural compatibility with a digital grid system and their capability for precise reproduction. The analysis includes an evaluation of stitch density, rhythmic organization, and the visual readability of the motifs when scaled.

The digitization of the motifs was carried out as a sequential process in two main phases.

In the first phase (Fig. 2), the ornaments were reconstructed using the Pattern Maker software, which employs a pixel-based grid corresponding to the structure of the cross stitch.



Fig. 2. Adapted Bulgarian embroidery motifs in Pattern Maker

The process includes digital tracing of the original motif, adaptation to a square coordinate system, definition of contour and fill elements, as well as reduction and optimization of the color palette in order to achieve better visual clarity and technological applicability (Fig. 3). A key parameter in this phase is the determination of stitch density (stitches per cm), which allows control over the physical dimensions of the final motif and its correspondence with the textile base (Fig. 4).



Fig. 3. Stages of motif digitization

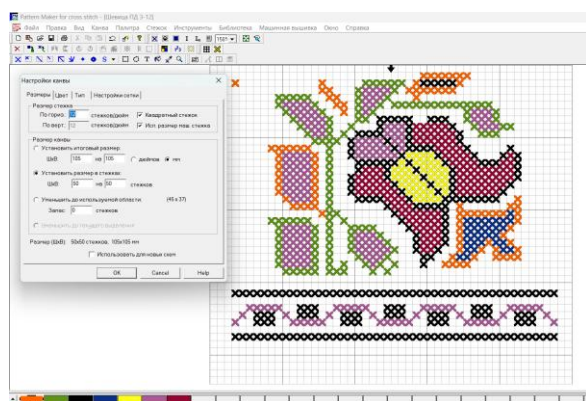


Fig. 4. Setting stitch density

In the second phase, the digitized motifs are converted into a machine-executable format using the Artistic Digitizer software. The process begins with transforming the pixel-based model into a vector-oriented embroidery structure, allowing precise control over the execution parameters. In the next stage, the main stitch characteristics are defined, including the size and density of the cross stitch, the color organization of individual elements, and the logical sequence of their stitching, in order to ensure correct layering and high visual readability of the ornament (Fig. 5).

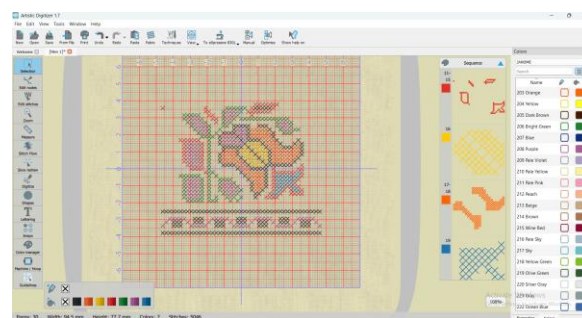


Fig. 5. Conversion in the specialized software Artistic Digitizer 1.7

In parallel with parameterization, the machine process is optimized by adjusting stitch direction, reducing unnecessary transitions, and minimizing machine jumps. Particular attention is given to optimizing the needle path (Fig. 6), which contributes to reducing production time and increasing efficiency. As a result of these sequential operations, high precision and quality are achieved in the subsequent machine embroidery on textile material, while ensuring accurate reproduction of traditional motifs through modern embroidery technologies.

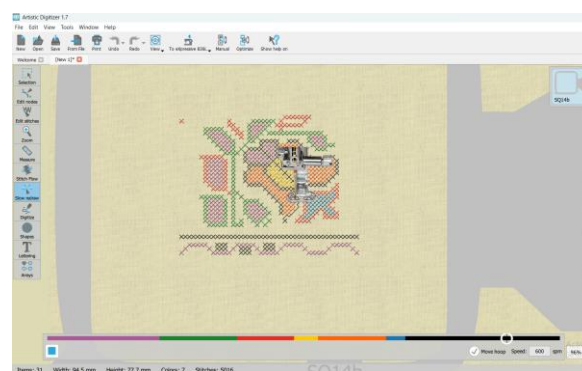


Fig. 6. Optimization of the needle path

III. RESULTS AND DISCUSSION

As a result of the activities carried out within a research project supporting PhD student No. 262PD0031-16, funded by the Internal Research Competition of the Technical University of Sofia for 2026, a capsule collection of contemporary garments with a sustainable design in a sport-elegant style, entitled "Tradition in Motion", was developed. The collection represents a synthesis between scientific research and creative interpretation, in which authentic Bulgarian ornaments and embroidery motifs are reinterpreted and adapted to a contemporary fashion context.

Fig. 7 visualizes the creative exploration process, reflecting both the sources of inspiration and the conceptual framework that led to the development of the collection.



Fig. 7. Atmosphere - map of the collection. /Moodboard/

As a primary reference framework, the map by Hristo Vakarelski [8] is used, presenting the regional diversity of Bulgarian traditional costumes and serving as a cultural-geographical basis for the interpretation of ornamental motifs. The included images of traditional women's costumes point to characteristic silhouettes, ornamentation, and color schemes specific to different ethnographic regions.

An additional source of inspiration is provided by archival and artistic visualizations of Bulgarian traditional costumes, as well as specialized studies that emphasize the role of embroidery as a carrier of symbolism and cultural identity. The inclusion of embroidery fragments and technological tools, including an embroidery machine, highlights the transition from traditional handcraft techniques to contemporary digital processes for their reproduction.

The contemporary aspect of the development is represented through the author's fashion designs, which demonstrate the transformation of traditional elements into a current, functional, and minimally structured design. The color palette, derived from the digitally developed embroidery motifs, plays a unifying role by ensuring visual balance between authenticity and modernity.

In this way, the mood board functions as a connecting link between tradition and modernity, clearly outlining the sources of inspiration and the logic of transformation that led to the creation of the sustainable capsule collection.

III.1. Design project of the capsule collection

A capsule collection design was developed (Fig. 8), presenting an original interpretation of Bulgarian traditional ornamentation integrated into sustainable fashion design through the application of digital technologies and innovative production approaches. The collection is targeted at young women aged 30–35 and is intended for everyday use, active leisure, and travel, combining functionality, comfort, and a clearly expressed cultural identity.



Fig. 8. Creative sketches of the models from the collection

The concept of the collection is based on a synthesis of traditional Bulgarian embroidery, contemporary minimalist silhouettes, and the principles of sustainable development [9]. The main idea is to create a visual dialogue between the past and the present, in which authentic motifs are not used merely as decorative elements, but as structural and compositional components of the design.

The collection includes seven main models, developed according to the capsule principle [2], allowing for versatile combinations between individual garments: short-sleeved blouses (oversized and loose silhouettes); wide-leg trousers; sport-elegant sets.

Additionally, accessories with various applications were designed (Fig. 9): a textile tote bag, a backpack, a mini phone bag, jewelry (bracelets, earrings, necklaces), and a textile belt with integrated embroidery.

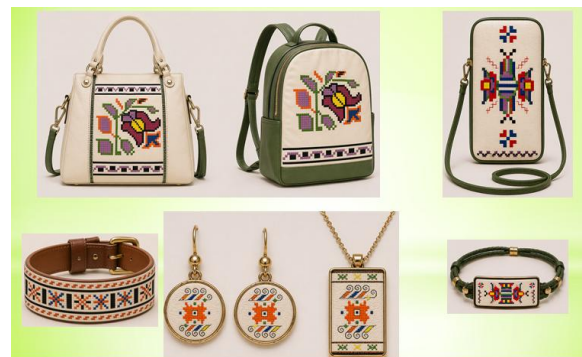


Fig. 9. Accessories of the collection

This structure ensures flexibility and adaptability of the collection to different situations and stylistic preferences.

The design of the collection is characterized by clearly defined compositional principles, in which embroidery motifs function as dominant visual elements integrated into key structural areas of the garments. The ornaments are strategically positioned—on the central front part of the blouses, along the side seams of the trousers, and in the areas of cuffs and hems—in order to achieve a strong visual accent and structural clarity. In addition, a linear integration of border motifs is applied, following the construction lines of the garments, emphasizing the silhouette, creating rhythm, and visually elongating the form. In certain models, an asymmetrical arrangement of ornaments is used, adding dynamism, a contemporary character, and individuality to the design.

The ornaments included in the design (Fig. 10) were digitally developed using the algorithm applied in the creation of the main motif (Fig. 6) and subsequently implemented on a textile base—cotton knit fabric intended for the production of the garments in the collection.



Fig. 10. Machine-made embroidered ornaments

During the development process, variations of the cross stitch with different sizes (1.5, 1.8 and 2.2 mm) were examined in order to determine the optimal parameters for achieving a balance between visual readability, level of detail, and technological applicability on a knit structure (Fig. 10).

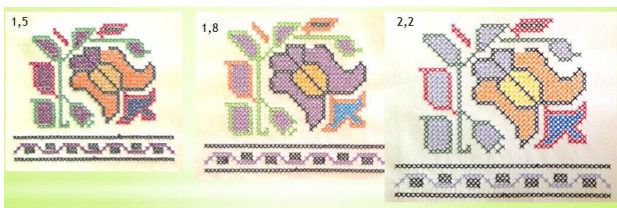


Fig. 11. Variations of the cross stitch

The collection was developed with a focus on the use of sustainable textile materials, including cotton knit fabric, linen, bamboo fibers, and Tencel™, characterized by biodegradability, low environmental impact, and a high level of wearing comfort, which corresponds to the principles of sustainable fashion and environmentally oriented textile design [10]. The application of digital technologies, including CAD design and virtual prototyping, contributes to the reduction of textile waste, optimization of pattern cutting, and improvement of production efficiency, while simultaneously creating opportunities for the preservation and contemporary reinterpretation of cultural heritage through a digital environment [11].

The color concept is designed to achieve a balance between tradition and modernity. The main color palette includes white, dark blue, and green, providing a neutral and harmonious base for the integration of the ornaments. The accent colors used in the embroidery—red, yellow, orange, purple, green, blue, and black—create contrast and emphasize the decorative elements as the primary carriers of visual identity.

From a functional and ergonomic perspective, the collection is adapted to the contemporary lifestyle, incorporating loose silhouettes, elastic construction

solutions, and functional details such as pockets, which ensure comfort and practicality. These characteristics make the garments suitable for active daily activities and travel, while maintaining a high aesthetic value.

Accessories are considered an integral part of the design concept rather than a secondary addition. Through them, visual coherence is achieved by repeating and adapting the main ornamental motifs from the garments. The inclusion of embroidered jewelry represents an innovative approach to transferring textile tradition into new product categories and expanding the application of embroidery.

Table 1 summarizes the main characteristics of the developed capsule collection.

TABLE 1 MAIN CHARACTERISTICS OF THE DEVELOPED CAPSULE COLLECTION

№	Main characteristics of the capsule collection		
	Indicator	Characteristics	Practical significance
1.	Collection type	Capsule (7 models)	Optimization of production and sustainable consumption
2.	Target group	Women aged 18–35	Focus on an active and mobile lifestyle
3.	Style	Casual, sport-elegant	Contemporary adaptation of traditional elements
4.	Main garments	Blouses, trousers	Functionality and versatility-
5.	Materials	Cotton, linen, bamboo, Tencel™	Environmental sustainability
6.	Decorative technique	Machine embroidery (cross stitch and backstitch)	Precision and digital
7.	Source of motifs	Authentic Bulgarian embroidery	Cultural identity
8.	Type of transformation	Digitization, reduction, stylization	Contemporary interpretation
9.	Compositional principles	Center, asymmetry, linearity	Balance between tradition and innovation
10.	Color palette	White, green, dark blue + accents	Harmony and visual identity
11.	Technologies	CAD, 3D visualization, machine embroidery	Waste reduction
12.	Sustainable practices	Virtual prototyping	Resource minimization
13.	Accessories	Bags and embroidered jewelry	Expansion of the product line

Through the structured presentation of key parameters—target group, style, materials, technological approaches, and sustainable practices—the relationship between the theoretical framework of the study and its practical implementation in the fashion product is illustrated. The table complements the analysis by

emphasizing the integrated approach, in which traditional elements, digital technologies, and the principles of sustainable design function as an interconnected system.

In this way, the collection presents a contemporary approach to fashion design, in which traditional cultural heritage is combined with digital technologies and sustainable practices. This approach enables the creation of comfortable, functional, and meaningful products that meet the contemporary needs of the modern Bulgarian woman. In this sense, it can be considered a relevant direction for the development of the fashion industry, oriented toward a more responsible attitude to the environment and cultural identity.

IV. CONCLUSIONS

The present study demonstrates the possibilities for successfully integrating Bulgarian national identity into contemporary fashion design through the application of digital technologies and sustainable approaches. Through a systematic analysis of authentic embroidery motifs and their subsequent digitization, a precise transformation of traditional ornamentation into a modern design context is achieved, without losing its structural and symbolic value.

The applied digitization process—using Pattern Maker and Artistic Digitizer—proves its effectiveness in adapting hand embroidery techniques to a machine-executable environment. This enables a high degree of accuracy, repeatability, and optimization of the production process, while also creating conditions for reducing resource consumption and improving technological efficiency.

The developed capsule collection “Tradition in Motion” confirms the applicability of the proposed approach in real design practice. The collection combines functionality, comfort, and aesthetic value by integrating traditional ornaments into contemporary sport-elegant silhouettes. The use of sustainable materials further enhances the ecological aspect of the development and meets current requirements for responsible production.

The findings demonstrate that digital technologies can play a key role not only in optimizing design and production processes but also in preserving and contemporarily interpreting cultural heritage. In this regard, the proposed model can be considered an effective foundation for future research and development aimed at creating sustainable, innovative, and culturally meaningful fashion products.

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Development of Cross-Cutting Optimizing Scanner for Aspen and Black Alder Boards

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Abstract—In the paper, machine learning knowledge is transferred to wood processing industry. A universal Machine Learning system has great potential for the scalability in wood processing industry. In order to increase the yield of high-quality material and reduce the influence of subjective factors in the assessment of the quality of the wood boards, a machine learning model was trained as part of the research. The model was trained on a large set of aspen and black alder board samples, including subjective assessments of the acceptability. This approach ensures that the ML model is able to perceive and standardize different defect compositions that are considered to meet the specified quality requirements. As a result, a more accurate and consistent interpretation of wood defect recognition is achieved, significantly reducing the variation caused by the human factor along with proper feeding mechanism increase the yield of high-quality material. We proved that using ML for wood defect detection allowed to achieve a fully developed and sustainable defect recognition model within 3 months testing period. Identifying wood defects in the production of aspen and black alder boards is both a technologically complex and subjectively influenced process. By combining the assessment of defect intensity, area, structure and location, the model ensures a uniform quality standard throughout production. This reduces unjustified board rejection, improves material utilisation rate and promotes a more stable output of high-quality material

Keywords— *Computer Vision, Deep Machine Learning, defect detection, FPGA, HPC, labelling, quality control, wood processing.*

I. INTRODUCTION

With forests covering more than 50 % of the country's territory (almost double the world average), Latvia is 5th of the most forested EU member states and 2nd greenest country. Over the last 80 years, the forested area has doubled while standing volume has increased 3.8 times,

reaching industrial production 11 550 thousands of cubic meters in 2024 with 4 730 for export. The forestry industry has always been Latvia's export leader [1]. Wood and its products are the most significant export sector, comprising around 50% of total export value [2].

In recent years, computer vision techniques for defect detection have been widely studied. The evaluation of wood quality is a sophisticated and diverse process that demands meticulous observation and classification of a broad spectrum of physical characteristics, especially density, and humidity properties [3]. Machine Learning approaches, nowadays offer considerable improvements by integrating multiple models to recognize and interpret complex patterns in large datasets [4]. The development of image-based wood analysis has shown significant progress over the past decade, evolving from simple texture recognition to advanced predictive modelling systems [5]. Forestry industries have shifted to more sophisticated frameworks of deep learning architectures. Modern technologies have developed ensemble frameworks that combine multiple CNNs [6], this advancements achieved high classification accuracy across various wood species datasets. Although previous research shows that individual machine learning models can effectively predict wood properties like density and moisture content, however, these models operate independently, which may limit their ability to fully capture the complex, non-linear relationships inherent in wood properties [3].

The Computer Vision system along with Machine Learning became state of the art in the wood defect detection (knots, shakes, checks, wane, pattern defects, also many geometrical anomalies like cupped, twisted bowed or crooked timber). It provides necessary quality control regarding the processing of wood products, so the

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optimisation of sawing processes in the wood industry is critical for maximizing efficiency and profitability. Sawing optimisation is the process of maximizing the yield of wooden products from a board by cutting the board into the optimal size and shape. By optimizing the sawing process, the wood industry can reduce the amount of waste, which helps to conserve natural resources and reduce environmental impact. Additionally, sawing optimisation helps to improve the quality of wooden products and expand their utility for a wider range of applications. [7], [8].

In practice, for board production, customers often demand a wide range of board sizes, so sawing optimisation problem is also very important for wood processing companies [9], [10], [11], [12].

However, output of extraction processes is difficult and complex, particularly for wood products with high quality requirements [3], [13]. Wood defect detection is difficult because every piece of wood has a unique appearance and may have multiple feature characteristics within a single piece. Hence, a method that can learn wood features automatically instead of complex extractions is needed [14], [15].

As a result, a defect detection is used with a deep convolutional neural network (DCNN) allowing to interpret any defects. The development of a deep machine learning detection systems is contributing to technological innovation of wood industry [16]. Usage of the DCNN for defect detection also requires correct selection of methods and equipment due to the high variability of natural defects such as knots, cracks, etc., which makes it very challenging to introduce the best type of DCNN method for board evaluation. Professional scanners feature integrated designs, high precision, and factory-calibrated systems, ensuring consistent, high-resolution outputs with minimal user intervention. However, their high cost and proprietary software limit accessibility [17]. Another aspect of wood defect detection lies in sustainability efficiency in promoting a sustainable future by its renewable properties and carbon sequestration capabilities [18], [19].

The aim of this research is to synthesize recent research on emerging wood defect detection technologies that enhance output quality and increase speed. This research is presenting applied findings in development of cross-cutting (transverse) optimizing scanner for aspen and black alder boards with AI-driven quality control and circular economy integration within wood processing industries

II. SPECIFICATIONS OF WOOD PROCESSING ENVIRONMENT.

For wood processing companies, we have developed prototype with advanced scanners that not only detect defects in products, but also offer the most optimal solution for obtaining maximum value from each product through management and software interface (UI), as well as ensure autonomous operation of the product line. The company's scanner captures board images and topographic

images from both sides (with 4 triangulation and 4 visual cameras and a translation system for optical alignment), obtaining complete information about each board/log. Next, the artificial intelligence algorithm divides the boards into segments with good and defective wood areas through digital labelling. This data goes through an optimisation algorithm that divides each board into a predefined range of products and already places the blades of the next circular saw according to our algorithm data. A vision system was developed for wood processing conveyer line (Fig. 1)

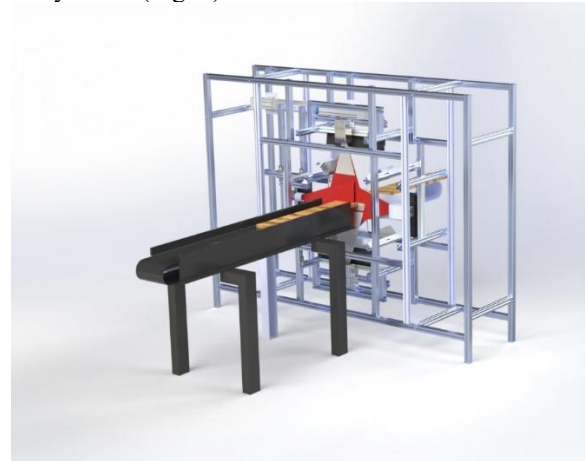


Fig. 1. Cross-cutting optimizing scanner for cross-cutting and quality (source: company LV Timber SIA data).

Previously, in one of the key production processes – cross-cutting or lengthening, marking was done manually, with the operator marking the wood defects with a crayon. This assessment is influenced by the operator's skills, level of well-being, including mood, fatigue and other factors affecting human decision-making (human factor). Often, under the influence of these conditions, product defects are not evaluated effectively, and properly enough and high-quality material is "lost" or used inefficiently. This process now is improved and digitized by introducing modern four-sided scanning technology into the production process, thus, using modern scanning technologies, obtaining the optimisation result digitally and transferring it to the optimisation sawing machine. Scanning technology, together with its mechanisation, makes the cross-cutting results more efficient, more stable, and more accurate, removing the main responsibility for deciding the outcome from the operator, as well as making the operator's work physically easier.

One of the key processes in the development of this scanner was the creation of a reliable neural network for wood defect recognition as well as positioning and feed tractor efficiency. The whole labelling process would not be possible without one important tool: board automatic fixing and feeding mechanism at the scanner (Fig.2).



Fig. 2. Board fixing and feeding mechanism (Source: authors created based on SIA LV Timber data).

With the current solution it is possible to adjust following board dimensions 19/32x100/135/155x1800-3000 mm. During test period from August 2025 to October 2025, sawing a total of 6490 m³ of aspen saw logs, a reference yield of 966.65 m³ or 14.89% of high-value products were obtained during this period. In comparison, the application of the new optimisation scanner in 2026 has increased yield by 0.50 percentage points, to 15.39%.

III. QUALITY CONTROL REQUIREMENTS

The Machine Learning model was trained on a large sample set of aspen and black alder boards, including subjective assessments of the acceptability of the color by various operators for both white and heat-treated products. This approach ensures that the ML model is able to perceive (e.g. moisture levels) and standardize different color compositions that are considered to meet the high quality requirements. The result is a more accurate and consistent recognition of wood color, significantly reducing the quality variation output caused by the human factor and increasing the yield of high-quality material. It is important to indicate both the properties of the actual defect and the effect of false recognition on the wood boards. This is especially useful in situations where there are uncertain situations, and it is difficult to determine the difference and boundary between defects. For example, for aspen boards, the differences between the paint and the wood rots are very difficult to see for the untrained eye based on the image alone (e.g. Fig. 3).

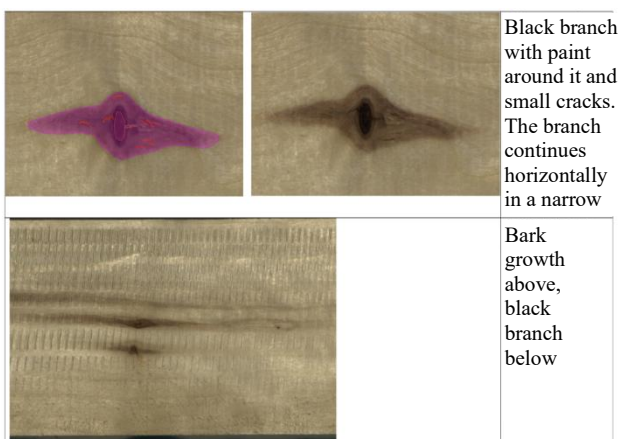


Fig. 3. Example of defect labelling (Source: authors created based on SIA LV Timber data).

In life, this difference is easier to see based not only on the colour of the defect, but also on the reflection in different light, the texture and moisture of the wood. By applying topography, the true nature of the wood defect is revealed, and we achieve more reliable labels. Two categories for quality groups were created, which are especially important for sustainability and product segments where quality is not critical.

Quality criteria define the types of defects and errors based on wood species. Defects are divided into categories that are confirmed and clearly visible, whether the defect has been confirmed but its boundaries are not permanently identifiable, or whether the defect has not been confirmed. Next, the labeller must be able to mark all defects visible on the timber according to the standards specified in the criteria. Each labelled defect is assessed in the context of error categories, where they fall into 2 categories: *Category 1* - These defects are not used in any of the products to be optimized and are therefore considered to be the most critical (e.g. any wood rots [Butt, White, Sapwood, Carbonized wood, etc). *Category 2* - These defects are allowed in some of the products, so their use is allowed later: e.g. Branch, Bark, Colour, Core, Crack. As a result, 17 defect classes were elaborated to promote sustainability and quality recognition. The introduction of the new sorting approach significantly reduces the generation of waste material during the lengthening process and allows to increase the volume of finished high-value material by 0.5% of the sawn logs, achieving a total yield exceeding 15.39%. The selling price of top grade high-value products has been on average 1050 EUR/m³ over the past year.

IV. SOLUTION AND RESULTS

During testing period if any of these defects are not found in the image, then the optimisation algorithm ignores it and possibly places the saw blades in a less optimal or incorrect way.

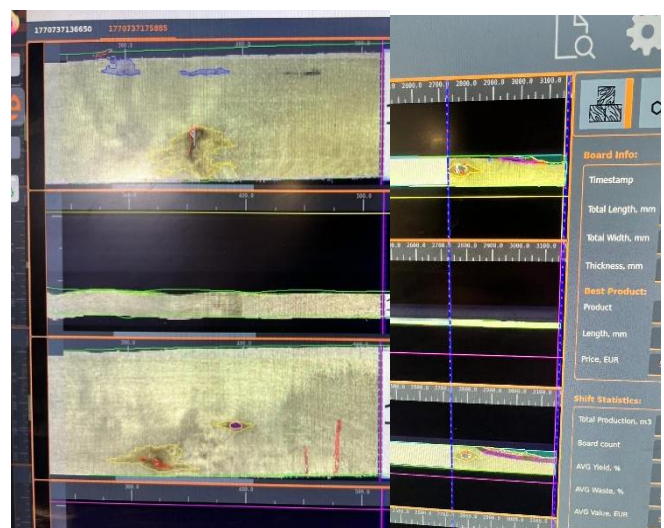


Fig. 4. Example of results of ML model tests and images with real collected samples (Source: authors created based on SIA LV Timber data).

As a result, ML recognition efficiency plays a vital role for final result. The labelling application also has various functional tools such as hiding other defects to facilitate labels. A total of 1411 full board image samples were scanned for labeling, ML development, and ML verification (Figure 4). It should be noted here that this is a special panel available to managers with cost optimisation. The labelling process manager also has access to the overall panel view, which shows the total annotations made by the system, the ability to assign more boards and calculate the total number of defects in them (Figure 5).

This is a very important step that determines the total value of the order and supply material utilisation at the end of the month. Based on the existing problems regarding the determination of wood quality which is closely related to wood defects, the role of technology is needed to help identify wood defects. Results achieved within the framework of the activity: design solution documents developed; software operator interface built for scanner prototype tests; defect identification tested in real samples, 17 defect classes separated, defect descriptions developed and annotations prepared; 1400+ boards scanned for sample marking, MI development and MI verification; scanner prototype manufactured and installed in the Cross-Saw Department.

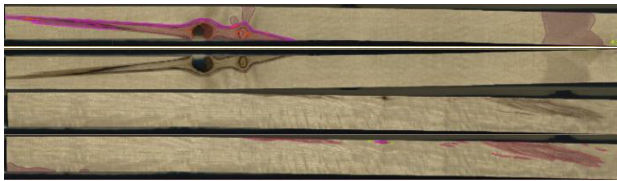


Fig. 5. Example of UI for board cutting optimisation and cost (Source: authors created based on SIA LV Timber data).

In addition to wood defects such as branches and cracks (identification of which is primarily necessary for various coniferous wood production companies), it is very important for aspen and black alder wood to be able to digitally correctly and accurately assess defects such as wood coloration in the production of specific products. It was important to recognize, categorize and transfer the information from scanner to the saw in real time in the development of the prototype of the scanner technology; processing speeds of over 60 meters per minute were required. First of all, the optimisation model needed to create a certain degree of “freedom” for board sorting, allowing for a controlled reduction of product quality requirements under certain conditions, based on the intensity, area, difference from the base tone and location of the coloration. Identifying coloration defects in the production of aspen and black alder lumber is both a technologically complex and subjectively influenced process. The ML model developed in the study significantly improves this process, as it is able to learn the operators' subjective perceptions of which color combinations are acceptable for different product types.

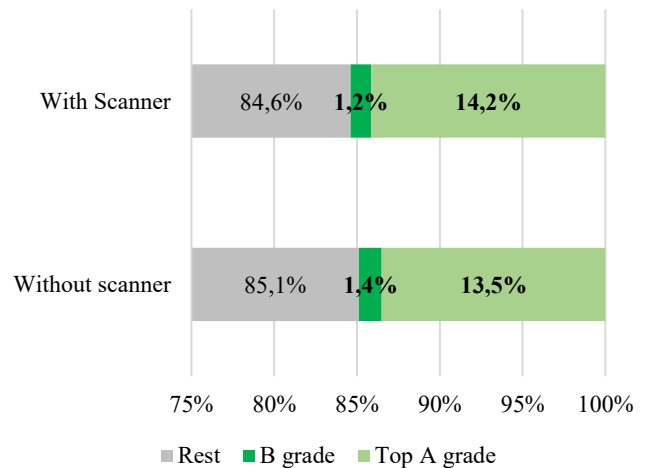


Fig. 6. Efficiency results after testing period (Source: authors created based on SIA LV Timber data).

The company's efficiency is positively affected by the fact that the cross-cutting optimisation scanner is able to objectively and sustainably determine the difference between high-quality materials of class “A” and class “B”. Currently, the average selling price of class A products is 30% higher. As well as material with lower quality is ensuring more sustainable production (Figure 6).

TABLE I. ML OPTIMIZING SCANNER EFFICIENCY RESULTS

0,50%	Increase in the yield of high-value material, % of sawn logs
15,39%	The useful yield of high-value material against sawn logs, calculated as 14.89% + 0.50%
8%	The effect of the optimisation scanner's defect recognition and sorting. The useful yield of "B" grade is reduced to 8% of the high-value materials obtained in the production process (in the inventory tests, employees marked an average of 9.76% of the high-value products as grade B, but the scanner - eight percent); accordingly, a larger proportion of high-value materials is marked as grade A and is sold more expensive
1,76%	Reduction in "B" or lower-grade high-value material, % of the total amount of high-value material obtained, calculated as 9.76% - 8%

Prior to the new scanner development initiative, the company's employees (operators) visually evaluated each board of high-quality material and sorted them into class A and B. The grades are determined based on the area, intensity, and uniformity of the coloring. Data from August-October 2025 show that 9.76% of high-quality materials were indicated as class B materials. Trials of the new technology show that employees have so far subjectively determined class B for material that objectively meets the parameters of class A in too many cases. The use of the new optimisation scanner technology reduces the proportion of class B to 8.0%. Both quality criteria and quality standards are used in the labelling evaluation process to make a final decision on the accuracy of the labels based on board quality requirements (Table 1).

Based on the necessary quality standards, it was possible to scale our solution for other wood processing applications. Using our solution as a guide, a methodology of quality criteria and standards, it is possible to quickly elaborate high-precision ML markers with ability to improve efficiency during longer period of testing. The ML Digital Labelling model integrated with a fully automated sawing cycle allows the plant to work with different scenarios of size, wood quality and production capacity. Our system is currently allowing to identify and process up to 2500 m³ of aspen saw logs per month, with scalability potential. It is necessary to mention that our system could be potentially used on much faster processing lines, and with different board sizes.

CONCLUSIONS

This paper explored the scalability of Machine Learning technologies for wood surface defect detection with an integration to industrial application. Based on the framework created from the project it is possible to reduce labor costs within the visual inspection and increase efficiency compared to manual and automated conventional optical systems. Compared to conventional manual approach with human factor issues, our system is giving possibility to quickly (in 60 m/minute production lines) identify multiple features and defects, and generate optimisation (cross-cutting) instructions considering 17 defect groups of classes.

Results achieved within the research framework of the testing activity: industrial application solution documents developed; software operator interface built for scanner; defect identification tested in real samples, 17 defect classes separated, defect descriptions developed and annotations prepared. Wood defect detection and sawing optimisation process can be improved and digitized by introducing modern four-sided scanning technology into the production process. The application of modern ML scanning technologies in obtaining the optimisation result digitally and transferring it to the optimisation sawing machine is confirmed. Scanning technology, together with its mechanisation and integration to industrial application, makes cross-cutting results more efficient, more stable, more accurate, as well as making the operator's work physically easier.

Therefore, we proved that quality control system developed for the wood processing industry can be scaled up in size and quality. The result is a more accurate and consistent interpretation of wood colour, significantly reducing human-induced variation and increasing the yield of high-quality material. The company's efficiency is positively affected by the fact that the cross-cutting optimisation scanner is reliable in wood defect detection and is able to identify the difference between high-quality grade materials of class "A" and "B". Currently, the grades are determined based on the area, intensity, and uniformity of the colouring allowing to increase selling price by 30% (when a board is correctly identified as class "A" as opposed to class "B") due to more precise recognition and

positioning for processing. During testing period, it was confirmed that the use of the new optimisation scanner technology reduces the proportion of class B grade to 8.0%. The final result of the research paper is a successfully developed prototype of an aspen and black alder cross-cutting optimizing scanner, which is capable of fully functioning in a production environment with aligned testing period (both mechanically and digitally), which is able to ensure modern automated operation requirements and tasks.

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Commercialisation Potential for Scanners in Wood Processing. Cross-Cutting Optimizing Scanner for Aspen and Black Alder

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Abstract—Increased competition in the international wood export markets, is vitally important for European wood processing companies. To ensure further competitive advantages digitalisation of wood processes is one of the contemporary strategies to ensure higher efficiency (reducing losses of useful material and improving quality), but also increasing productivity in order to reduce manual labour costs and eliminate "bottlenecks" in the overall production process. Findings reveal significant adoption of Industry 4.0 technologies enhancing processing speed and quality through AI-driven defect detection and robotic automation, achieving cycle time reductions exceeding 45% and defect remediation time cuts up to 60%. Material innovations and additive manufacturing improve mechanical properties and support sustainability, though scalability challenges persist. Circular economy principles are increasingly integrated via digitalisation of wood processing and waste valorisation, yet practical implementation faces economic and technology barriers. The aim of the paper is the commercialisation of cross-cutting optimizing scanner for aspen and black alder allowing to optimize order real-life parameters improving material combination and reducing waste. In addition, it is necessary for the company, using the statistical value of the material, to be able to determine what the possible costs of any order are. The findings are underlining the promotion of the digital transformation and increased competitiveness: enhanced useful yield of high-value material/reduction in material losses, reduction in manual labour associated with physical effort (the physical work of operators has been facilitated, and the sawing speed has been increased by 20%). The expected digital transformation impact has significant commercialisation potential, the development of such a new technology is contributing to the competitiveness and technological base of the forestry sector in European Union.

Keywords— *aspen, black alder, cross-cutting, forestry sector, machine learning, order optimization, scanner, quality control, wood processing, 3D computer vision.*

I. INTRODUCTION

Research on the newest cutting technologies to enhance processing efficiency by improving quality of output and increasing speed for wood raw materials in Europe has emerged as a critical area due to the growing demand for sustainable and efficient wood manufacturing processes. The European Parliament recently announced the use of cascaded wood to promote the circular economy and mitigate climate change [1], [2].

The wood industry, a key economic sector in many European countries, has evolved from traditional manual operations to increasingly digital and automated systems, integrating Industry 4.0 (recently 5.0) technologies [3]. Industry 5.0 most popular technologies in wood processing could be traced to its footprints – virtual factory concept first introduced in 1993 by Onosato and Iwata [4] and later known as a Digital Twin concept when production line is integrated with the real production processes using a simulation model.

Main operations of the manufacturing industry are cutting operations that produce changes in shape, dimensions, and surfaces. In order to control wood quality it is common to use artificial vision techniques like industrial scanners to determine internal and external defects [5], [6]. In the wood processing industry scanners are making parts classification, yet data is non stocked for analysis or to create prediction models [3].

As for more contemporary attempts to integrate Machine Learning (ML) and technics like Convolutional

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Neural Network (CNN) to train in wood defects recognition.

Professional scanning systems are often used in industrial or scientific applications where the highest accuracy and reliability are emphasized [7]. In addition to price, an important factor of scanning technologies is the difficulty to operate them. Some require specialized knowledge and experience to use them: training to use the software, setting parametric values, or properly positioning and calibrating the equipment [8].

Current practices in wood industry often rely on manual expertise and conventional scheduling, limiting scalability and efficiency [9]. In contrast to the conventional job-shop scheduling problem, flexible job-shop scheduling involves the use of processing equipment that is not predetermined but rather unknown for each operation [10].

Moreover, the integration of digital technologies such as AI, machine learning, and robotics remains uneven in the engineered timber sector and has notably lagged behind in adopting such practices as real-time quality control, defect detection, and adaptive manufacturing workflows [11], [12]. As a result, the wood industry is one of the least advanced industries in R&D and innovation compared to the computer and electronics industry, the automotive industry, or the aerospace industry [13].

Failure to address these gaps risks continued inefficiencies, increased waste, and reduced competitiveness in the European wood sector. The conceptual framework for this project is established in the intersection of Industry 4.0 technologies, digital fabrication, and sustainable wood processing. Key concepts include digital transformation through AI for quality optimisation for proper management and commercialisation. Commercialisation potential for scanners in wood processing is projected and implemented, particularly the cross-cutting optimizing scanner for aspen and black alder as a high-quality wood niche.

The purpose of this research is to synthesize recent research on emerging cross-cutting technologies that enhance processing efficiency in European wood material industries by improving output quality and increasing speed. This research aims to investigate the innovation gap, the findings are organized thematically to reflect advancements in digital transformation, AI-driven quality control, and circular economy integration within wood processing industries

II. RESEARCH DESIGN AND SPECIFICATION OF ENVIRONMENT.

The main aim is to examine the existing research on newest cross-cutting technologies to enhance processing efficiency by improving quality of output and increasing speed for wood raw materials in Europe in order to provide an applied finding and their practical implications within the European wood processing sector.

For wood manufacturing processes, influencing factors are the material, the operation, and the transformation technology. In cutting processes, factors are combined, the cutting tool being important. These impact on assets, rotating mechanisms, landings, materials, motors, auxiliary systems, and other devices. Heat, vibration and mechanical power impact machine availability. [14].

For our process, initial “as is” situation is presented:

- Operators manually take each board from the lumber package, based on the instructions, assess its defects, mark the wood defect areas with a luminescent crayon and place the marked boards on the conveyor belt (conveyor) in front of the cross-sawing machine.
- An automated cross-sawing machine, according to the lumber specifications, values set in it and the defects marked by the operators, performs the lengthening of the board into lumber of exact or “floating” length.
- The shortened boards, after being shortened in the cross-sawing machine, slide along the conveyor belt and are mechanically pushed into the “pockets” of the boards of the appropriate length.
- The operators manually stack the boards that have fallen into the “pockets” into the board packages. The sawn-off wood defects (wood waste during production) are automatically forwarded to separate conveyors and directed to the wood chipping machine –for circularity raw materials.

Initial system was allowing to select the most economically justified cross-cutting solution for each board, according to the defects marked by the operator. However, despite this, board lengthening process still requires both significant manual labor (low productivity) and errors, which result in inefficient work and losses of high-quality material (For example, when marking defects with a hand chalk, there is a large lengthening tolerance, because defects cannot be marked very accurately). In addition, this process still requires physically demanding work by at least two marking operators per shift. Another challenge for high quality wood is shortage of proposals. There are digital solutions (lumber scanner technologies) developed by various manufacturers on the market, however, taking into account the size of the market, they are mainly created for coniferous wood processing companies or other wood processing areas.

In the processing of aspen and black alder into a high-value-added product, the scanners solutions available on the market are unable to ensure full compliance with the specific needs of the company and the industry. Because, basic wood defects recognition such as, for example, branches, cracks (which are basically necessary for mass production of coniferous wood production companies), it is also very important for high-quality wood to be able to digitally correctly and accurately assess defects such as wood coloration in the production of specific products (e.g. oak [15]). The scanner technologies available on the

market need to optimally assess special species of wood such as aspen and black alder wood coloration defects, therefore it is justified to conduct research into the development of a special and rare recognition system.

In addition, one of the reasons why it is justified to conduct contemporary research into the development of a new digital system is that modern computing capabilities have changed significantly. In connection with the emergence of new, high-power graphics processors and Machine Learning capabilities, there are new opportunities in the longitudinal optimisation of the material, i.e. there are new quality computing opportunities in making a decision on how to process order optimisation.

The value of the cut material is determined by the market and the order. Currently, this problem is basically solved by excluding from the possible scanner results the material that is sufficient for the execution of a specific order. As a result, the real optimisation of the order and materials does not actually work, because the optimisation no longer receives real-life parameters. By excluding products that are produced in large quantities, the optimisation has a limited number of possible material combinations, which means that it no longer uses all the possibilities. In addition to abovementioned factors, it is necessary for the wood processing company to use the statistical analysis of the material, to be able to determine what the possible costs of any order are, expressed in terms of the amount of raw material.

If the scanner system is able to be integrated to computational system with accumulated statistical parameters of scanned material quality and raw material units, it can, based on the volume of ordered products and their quality indicators, model the potential amount of raw materials required to fulfil such an order. Data engineering methodologies are important to validate complex problems having many variables and non-linear relations [16]. Such AI modelling systems that allow estimating the costs of order fulfilment are very crucial for competitive advantages and sustainability.

Below is a description of production tasks with justification of the discussed needs for testing the created prototype in a production environment:

1. Board scanner - the main component for providing/implementing a digital solution in the cross-sawing process. With the help of this equipment, as the board moves through the scanner, all faces of the lumber are digitally evaluated and based on the defined parameters (specification of the materials to be obtained and price criteria), the software compiles the most optimal sawing algorithm for each board, as well as in some cases directing the board for re-processing (sawing in width) or thermal treatment (a separate post-processing process of processing lumber in a special dryer at high temperature, as a result of which completely dry lumber is obtained, a brown tint throughout the lumber cross-section and providing the material with improved physical and

mechanical properties). As a result, following prototype was created Fig.1.

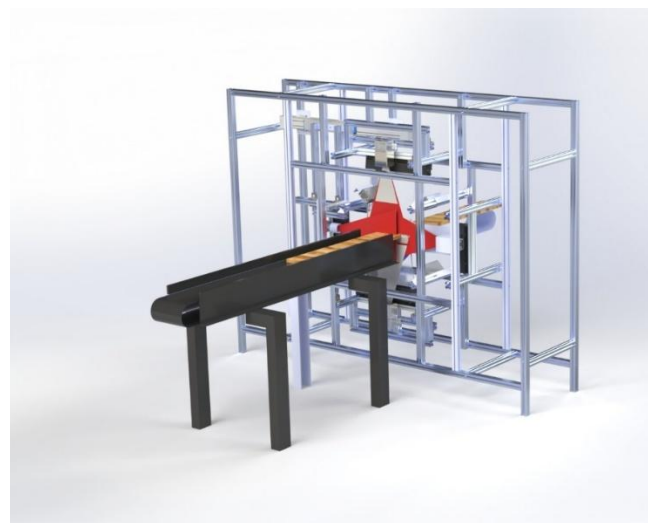


Fig. 1. Cross-cutting optimizing scanner for cross-cutting and quality (source: company LV Timber SIA data).

1. Preparation of an optimisation task, taking into account the order volume, warehouse volume and product values. Statistical analysis

2. Mechanisation of board feeding from the four-sided longitudinal milling machine to the scanner and from the scanner to the feed to the existing cross-sawing machine. Automatic and efficient operation of the cross-sawing line requires a conveyor system for feeding calibrated and scanned boards to the cross-sawing machine, thus ensuring fully automatic operation of the line.

3. Cross-sawing machine with discharge conveyors.

4. Increasing the efficiency of the existing cross-sawing machine, mechanical and digital adjustment with feed mechanisation in the existing cross-sawing machine. In order to adjust the sawing line and ensure automatic loading of boards, it is necessary to adjust the board loading mechanisation in the existing cross-sawing machine.

III. SPECIFICATIONS OF ESTABLISHED SOLUTION

A cross-cutting system was developed for wood processing plant. For the assessment of a possible order optimisation and surface defect data accumulation, the machine learning models were trained on a variety of images. It provides necessary quality control regarding the processing of the size, diameter, eccentricity, height, thickness and other parts of the non-contact numerical parameters of detection based on 3D scanner results.

Often, workers manually carry surface quality control. Wood processing companies train workers to identify complex surface defects due to their wide variety and sophistication in requirements. For wood processing companies, we have applied advanced 3D scanners that not only detect defects in products, but also offer the most optimal solution for obtaining maximum value from each

product, as well as ensure autonomous operation of the product line with waste sorting advantages. The company's scanner captures images and topographic images of the boards from both sides, obtaining complete information about each board. Next, the artificial intelligence algorithm divides the boards into segments with good and defective wood. This data goes through an optimisation algorithm that divides each board into a predefined range of products and already places the blades of the next circular saw according to our algorithm data. All the company's experiences were used in the implementation of our product, and new knowledge on data analysis, artificial intelligence and Computer Vision was developed. We propose an upgraded system with high recognition of wood defects and analytics to overcome the optimisation problem caused by rising number of sophisticated data especially for high quality wood materials. As a result, we present acceptable strategies for dealing with 3D data that allowing to establish an integrated management network (Fig.2)



Fig. 2. Actual prototype of the scanner system with 4 triangulation and 4 visual cameras and a translation system for optical alignment (Source: authors created based on SIA LV Timber data)

Management will consist of several layers (based on quality requirements) with different zoom ratio, to increase the rate of precision during the defect recognition. As for the decision algorithm, the analytical system performs recognition of raw material required for the order. Wood constantly exchanges moisture with the ambient air, tending to an equilibrium moisture content so recognition of proper quality and estimation of order capacity is important [17].

The design of the decision-making system is appropriate for capacity for large complex order, it is proved to using several parts of processing board. This enables the management to capture not only the available materials, but also the costs and waste of the board (Fig. 3). The decision network uses not only output volume of the available raw materials, it calculates supply inputs and improves utilisation to avoid shortages with processing and over capacity issues. It also reduces the oversupply to a large number of orders and helps to confirm associated costs.

In the AI *decision network* learning is also allowing to created several layers of quality requirements thus decreasing issues with inventory waste management. For circularity management improvements in utilisation of maximums raw materials are playing vital role. Projections indicate that wood production will fall short of societal needs by 2030, therefore, efficient wood resource utilisation and waste wood management are essential, necessitating collection, recycling, and reuse of idle wood [18]. In recent years, a growing body of research has focused on design strategies aimed at promoting sustainability. One prominent model proposed as a strategy for achieving circular design, as discussed in the study conducted by Moreno et al. [19]. In order to promote wood further utilisation in the future, the usage of raw materials for digital manufacturing is a new opportunity. One of reasons is the recent development of digital fabrication technologies, such as 3D scanners and automatic cutters especially with the help of Machine Learning technologies with fast recognition are giving a lot of opportunities for circularity management [20].

Aspen and black alder defect solution consists of 2 parts - image acquisition and image segmentation (quality sorting), with the help of 3D scanner, a high-resolution image with dimensions of more than 18k is obtained. The image is then reduced in size and divided into smaller areas to not only expand the range of images available, but also to increase defect detection results. The resulting data set is allowing to create management report with precise cost and waste output for further analysis. During the prototype training of the model, a wide range of wood quality parameters was reviewed and tested, from which the best ones were selected. Accordingly, the best model was implemented, which was implemented for recognition in the production line and management system. A prototype of the most advanced scanner is located in a medium-sized wood processing company in Latvia. The board optimisation results for wood production line are shown in Figure 3.

This is the basic information about the optimisation algorithm uses to make further decisions on quality sorting. Once the board has passed through the four scanners, it is transported to the positioning process. Meanwhile, the optimisation algorithm, is taking into account the size of the board and the image information, processes it via a neural network (CNN) and labelling through the user interface for future order optimisation.

The neural network is able to recognize different classes of defects from the board image. It uses the sliding windows methodology to scan different areas of an image of the same size, where the segment belongs to a specific defect class. As a result of the segmentation model, we obtain boards that are already divided into parts, separating the white or valuable wood from the defective one. The optimisation algorithm then processes this board information until it reaches the positioning stage. The optimisation algorithm takes into account the individual defect information of each board, the defect quality class and the assortment of products produced every day - product widths and their prices to create cost estimation and future added value for each board. Using these parameters, it is able to position the manufactured products in such a way that the value of products on each board is maximized and material waste and equipment utilisation are minimized.

After optimisation, the next step for the board is positioning. It is part of the production line where the position of the board is fixed before it is cut into products according to the order requirements. At this stage, using the industry's most modern scanner systems, positioning cameras and high-precision chain conveyor, we are able to turn the optimisation result into a real position according to a planned prototype results. When the positioning algorithm is satisfied that the optimisation results match, the board is locked and launched for sawing. The end result is an automated full board sawing cycle for precise cut, obtaining the maximum value from the material used.

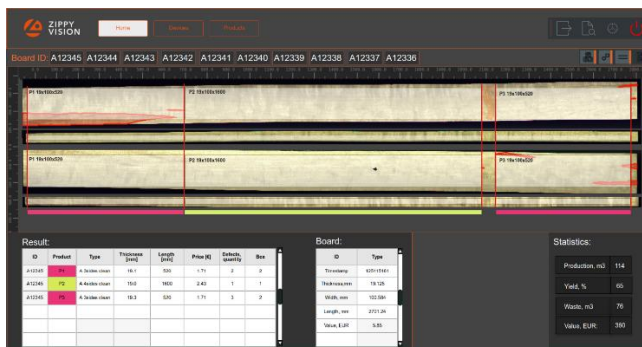


Fig. 3. Management system for detection of wood surfaces defects and capacity utilisation (Source: authors created based on SIA LV Timber data)

As a results, the following main benefits of speeding up the production line with greater quality, sustainability and optimisation are here. Before that we have manually looked at the board before it reaches the saw, evaluated it and decided how to get the maximum value from it before it enters the positioning step. Compared to manual human approach, which evaluates only one board at a time and only then adopts the optimal sawing solution with manual labelling, we can plan the next steps ahead with greater analysed stock, evaluate several boards at the same time and save them until they reach the saw. We not only reduce the time it takes for a person to make a decision and make

all the necessary adjustments, but we also reduce the potential risk of human error. A person's attention and care for details can decrease in an 8-hour cycle which in ergonomics commonly known as vigilance fatigue. In turn, an automated process will always return an identically accurate and valuable result for the same boards while having future challenges with more sophisticated defects. Additional benefits can be seen in reducing the workload for other processes and positions on the production line, as the sawing process is autonomous.

IV. DISCUSSION, SCALABILITY AND COMMERCIALISATION APPROACH

The key goal of this paper is to present a commercialisation potential for scanners in wood processing. We present a cross-cutting optimizing scanner for aspen and black alder wood with Machine Learning with CNN vision competency for manufacturing. Computer Vision is an encompassing term which includes the integration of both hardware and software for practical application.

TABLE I. IMPROVEMENTS AFTER INTRODUCTION OF THE SCANNER SYSTEM

966,65	Production of high quality aspen boards, m ³
6490	Total raw materials (aspen logs) consumed, m ³
14,89%	Yield (boards / logs)
9,76%	B grade as a share of total high quality boards (the rest is A grade)
2500	Average monthly input of aspen logs, m ³
1050	Average A grade aspen board selling price, EXW 08.2025-10.2025, EUR/m ²
30%	Average discount for B grade aspen boards
15,39%	Yield (boards / logs)
0,50%	Yield improvement in comparison to operations without the scanner system
8%	B grade as a share of total high quality boards
1,76%	Reduction of B grade products in the total output, calculated as 9,76% - 8%; the same improvement of A grade board output generates additional revenue.

In order to confirm our CNN productivity, we have examined the customer's production reports over three months, August to October 2025, when the prototype scanner system was not yet developed. For comparison, we use 2026 data, after the introduction of prototype cross-cutting optimisation scanner (Table 1).

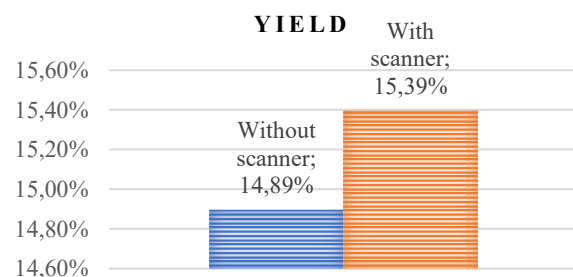


Fig. 4. Cross-cutting optimizing scanner for aspen and black alder efficiency results (source: authors created based on SIA LV Timber data).

The new scanner system improves output and reduces the manual labour of two employees. As confirmed to us by the customer, the main speed benefits come from the elimination of manual correction, human error and decision making (Figure 4).

Another noteworthy indicator is the decline in the amount of lower-grade material, which has fallen from 1,4% of raw material volume to 1,2%. The scanner has been able to find better solutions for optimizing each board and has achieved a reduction in material waste (Figure 5).

The scanner has been able to improve efficiency not only in the recognition of defect material, but also quite significantly in the production of useful material due to better optimisation. 92% of high-quality aspen boards are now marked as “A” (top) grade, whereas without the scanner the share of A grade boards was 90,24%. Since “A” grade boards contribute to significant price premium, the reduction of false negatives observation due to human errors (where A grade boards are marked and sold as B grade boards) improves company profitability. This factor also determines the achievement of the client's financial goals that our scanner has allowed us to achieve.

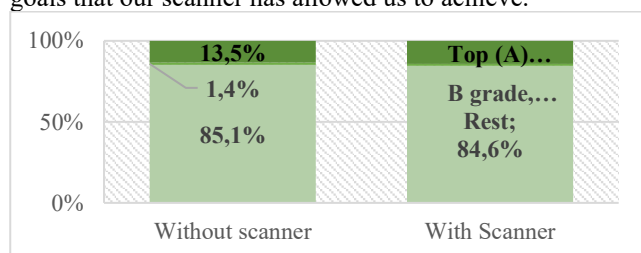


Fig. 5. Results of implementation of cross-cutting optimizing scanner in wood processing (source: authors created based on SIA LV Timber data).

CONCLUSIONS

The final result of the research project is a successfully developed prototype of an aspen and black alder cross-cutting optimizing scanner, able to ensure automated operation that meets the defined production tasks.

For small and medium companies and projects, using ML is usually costly, requires long period to adapt or issues with optimisation and defect recognition options. SME cannot provide Big Data to be analyzed or applied. Recognizing this, our prototype was elaborated to address these shortcomings and more quality classifications have been expanded to use 4 scanners with better resolution and board combinations. As a result, the state-of-the-art for modern wood processing companies is allowing to commercial contemporary technologies available on market, and also simplifying and speeding up learning process.

In this research, we have addressed the application of ML models for the prediction of wood defects for high value wood species. Our experience can become a good case to determine the scalability of ML systems and to apply them for specific manufacturing requirements based on production capacity and quality requirements. This

brings new prospects for machine learning models to be applied in a wider range of manufacturing projects.

ML system for defect detection through CNN will contribute to technological innovation, industry, national development and other applications within European Union. According to our report, yield of quality aspen boards has gone up from 14,89% to 15,39% measured as a fraction of volume of raw materials (aspen logs). Another significant indicator is optimisation of material, whereby the new technology marks 92% of high-quality aspen boards as A (top) grade, while previously manual labour resulted in 90,24% recognition of A grade. Since A grade boards command significant price premium in comparison to B grade boards, the improved recognition of top-grade products has increased monetary value, with estimated benefits of 25 thousand EUR annually. Based on these facts, it can be concluded that our scanner has been able to find better solutions for optimizing each board and has achieved a reduction in material waste and bringing greater value for company. The recognition accuracy for greater quality can be obviously improved in future while CNN becoming more accurate due to learning process.

Therefore, we proved that commercial potential for scanners in wood processing developed for the wood industry is efficient and could be easily scaled up in size and in case of technology transfer will be basically using the similar technologies. This paper explored a scalable deep-learning approach for surface defect detection with a CNN from the point of view of specific industrial application. Our framework created from the project it is possible to increase management efficiency, reduce labour costs and increase sustainability results for the company and increased speed of production.

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3D and Line Scanning Camera System Concept in Real-Time Wood Processing

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Abstract— The increasing complexity of modern manufacturing systems requires companies to design and develop a contemporary framework with high degree of accuracy and speed. The demand for precise and fast equipment in wood processing and other industries is topical within modern progress of Machine Learning, more powerful computing systems and approaches. To meet this challenge and to be in pace with Industry 5.0 advancements they rely heavily on real-time systems, which are essential tools for assessing dynamics of manufacturing data. In the paper, the research project focuses on developing an advanced 3D and line-scanning camera system concept for real-time wood defect detection and labelling. High-performance computing (HPC) technologies and FPGA-based (Field-Programmable Gate Array) for real-time processing will be employed to ensure high scanning speed and precision. Additionally, the research will focus on creating the necessary computing algorithms and a set of diagnostic, calibration, and maintenance technologies to optimize the performance and reliability of the scanning system. As the critical step for framework elaboration, the development of a conceptual model for the camera system and evaluation of technological options that would ensure effective recognition of wood defects, as well as creation of a basis for further technological development are performed.

Keywords— Computer Vision, Deep Machine Learning, defect detection, FPGA, HPC, labelling, quality control, wood processing.

I. INTRODUCTION

The wood processing sector faces modern challenges coming from the natural variability of wood and the demand for rapid, reliable inspection to reduce waste, improve product quality and increase sustainability [1]. With increasing industrial automation and

environmental regulations in Europe, optimizing wood defect detection through real-time imaging and processing is of practical and economic [2], [3], [4].

Despite progress, the problem of accurately and efficiently detecting diverse wood defects in real-time remains unresolved, since the existing approaches vary widely, from traditional image segmentation and texture analysis [5], [6] to deep learning models requiring substantial computational resources [7], [8].

The biggest knowledge gap exists in balancing detection accuracy with processing speed, especially under industrial conditions involving high-speed conveyors and complex defect types [9], [10]. Moreover, the bottleneck exists regarding the optimal hardware platform: FPGA-based systems offer low latency and power efficiency but may lack flexibility, whereas GPU-based and traditional CPU methods provide programmability at the cost of higher power and latency [11], [12], [13].

Research on data processing algorithms through convolutional neural networks (CNNs) and integration with high-performance computing (HPC) in 3D and line scanning camera systems for real-time wood processing has emerged as a critical area of inquiry due to its potential to enhance efficiency and accuracy in defect detection, quality control, and automation within the wood industry [9], [14]. Most of conventional systems were based on common image processing techniques in combination with supervised learning algorithms, however, over the last decade deep learning has achieved remarkable success in the forestry and wood products industry [15], [16]. Deep learning (DL) techniques encompass anomaly detection, feature detection (segmentation), object classification,

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instance segmentation, point localization, and character recognition [17], [18], [19], [20], [21]

As one of the most popular solutions as in recent decades, the industrial sector was focused on efficiency of an industrial vision through automation. The main bottleneck of the process is image processing due to high speed and precision. Graphic processing units (GPUs) and FPGAs have been proposed for real-time detection, where tasks are now performed repeatedly by machines assisting or replacing humans, reducing the occurrence of errors [11], [22], [23]. FPGAs are used to reduce the processing time in vision systems, and consequently, to reduce their cycle time. A real-time image pre-processing system allows filter validation and integration into industrial vision applications. The processing times measured on three platforms show that FPGA execution is faster than both CPU and GPU [11], [24], [25]. FPGA processing times are on the order of nanoseconds, while the other platforms have times in the order of milliseconds. It can also be concluded that the use of the GPU is only advantageous when the number of sequential filters is high, under these circumstances, the FPGA is advantageous. Unlike conventional processors or microcontrollers, FPGAs do not have predefined functions. Instead, they contain many small logic elements, the interconnections and operating principles of which are defined by the user as needed, using programming languages such as VHDL or Verilog.

The purpose of this research is to critically analyze data processing algorithms and their integration with HPC in 3D and line scanning camera systems for real-time wood processing, focusing on efficiency and accuracy improvements in defect detection, quality control, and automation. This paper aims to fill the identified knowledge gap by comparing FPGA-based systems, emphasizing existing applications parameters. This research is developing an advanced 3D and line-scanning camera system concept for real-time wood defect detection and labelling. compare the detection of defects that appear on board or logs (cracks, knots, sapwood, ambrosia wood, and wood rays). It is important to emphasize that all the differences are more or less slight, but the industrial scanner very poorly detects ingrown bark and wood ray. To maximize wood processing, accurate wood defect detection is essential. High-performance computing (HPC) technologies and FPGA-based (Field-Programmable Gate Array) approach for real-time processing solution could serve a critical role, starting from the initial phases of the sawmill processing of logs into sawn boards (or sequential board cross-cutting post process), to the control check for building wood beams, to the classification of wood flooring boards into different classes, etc. The three critical factors were identified for concept: the laser triangulation method which is suitable for determining the direction of wood fibers and resin content, as it provides high accuracy and is able to detect changes in fiber direction based on the dispersion of the

laser point. Line scanning technology with controlled LED illumination that ensures stable acquisition of visual information, which allows accurate defect identification of wood surfaces. And the use of FPGA chips for real-time data processing that significantly increases the scanning speed, allowing the integration of both 3D and visual data processing in one system.

II. SPECIFICATIONS OF ENVIRONMENT

Determining the direction of wood fibers based on laser beam scattering is possible only for coniferous species. Deciduous trees have a significantly denser cell structure, so the laser method is not effective in deciduous trees. The bonding of individual wood segments is important because, for example, in systems designed for splitting wood for joining, it is necessary to avoid bonded segments in places where the wood needs to be glued as a result of elongation. Bonded areas do not lend themselves to bonding - due to the reduced strength of the glue and the joint. At the same time, it is possible that the FPGA processor is able to control the direction of the fibers with sufficient resolution.

By performing a detailed analysis of optical and electronic components, the optimal laser and illumination configurations were determined:

- The laser wavelength of 650–750 nm provides the best contrast on different types of wood.
- The dispersion of the laser point in the direction of the wood fiber depends on the density and surface structure of the material, and its mathematical modeling confirmed the possibility of using this parameter to determine the fiber direction.
- The possible use of the laser is also to determine the roughness of the surface with a narrow-angled laser beam. At the same time, the determination of roughness with a laser beam is limited only to materials that are calibrated (planed) and have flat, orthogonal surfaces. The method is not applicable to surfaces that are profiled - moldings, etc.
- The spectral correction of the line-scanning LED illumination reduces unwanted reflections and ensures more accurate defect recognition.

III. FPGA (FIELD-PROGRAMMABLE GATE ARRAY) TECHNOLOGY COMPARISON

For wood processing companies, the ability to detect defects in products and quality is not the only parameter for application but also affordability of the most optimal solution for obtaining maximum value from each product, as well as ensure autonomous operation of the product line. FPGA (Field-Programmable Gate Array) technology research, with practical analysis of costs and opportunities – Table 1 and 2.

TABLE 1 FPGA TECHNOLOGY COMPARISON

System	Developments complexity and prototyping	FPGA and performance	Trigger and synchronization opportunities	Built-in CPU	Availability and costs	Errors test and simulation
OptoMotive Smilodon 10G EVO	<i>Medium– difficult</i> : High class FPGA development with UltraScale + FPGAs; opened architecture , difficult for full for adaptation	<i>Zynq UltraScale + (Kria K26)</i> : >50% FPGA free ; 5–25MP@ high FPS; suitable for powerful processing algorithms and CNNs	<i>Excellent</i> : Progressive trigger I/O; two 10GbE interfaces multi-camera synchronization ; precise microseconds level management .	<i>Yes</i> : Quad-core ARM Cortex-A53 and dual-core real-time R5; supports imbedded data processing .	<i>Commercial available</i> : New product , available after request; high costs , decent delivery time	<i>Very good</i> : Supports Vitis/ Vivado environment; AI model simulation ; 10GigE data recording / playback for FPGA design testing .
NI IC-3173	<i>Very light (NI environment)</i> : Using LabVIEW or Vision Builder AI; medium difficult for coding with C++ or HDL.	<i>Kintex-7 160T</i> : Allows sophisticated image processing ; possible AI on FPGA or CPU; precise FPGA control .	<i>Excellent</i> : 4 x PoE GigE and isolated digital I/O lines ; precise hardware triggers ; EtherCAT /PLC synchronization .	<i>Yes</i> : 2.2 GHz Intel i7 dual-core CPU + 8 GB RAM; working with Windows or NI Linux RT; full PC functionality for analysis .	<i>Limited</i> : Not produced (replaced with newer models); available at distributors; initially high price	<i>Very good</i> : FPGA simulation and error in LabVIEW environment; Opportunity to test system on PC before applicaiton
Gidel HawkEye 20GigE	<i>Medium</i> : Single API image acquisition; FPGA programming with Gidel tools requires experience , but many IP modules available	<i>Arria 10 (160K/480K)</i> : 20 Gb/s throughput (two 10Gb cameras); large FPGAs resources for parallel processing , also for small AI models .	<i>Outstanding</i> : 2x SFP+ inputs cameras; wide GPIO connection point trigger for management ; ideal for precise synchronization .	<i>None (uses PC CPU)</i> : Works like PCIe FPGA accelerator map; host PC required high level processing .	<i>Commercial available</i> : Available straight from Gidel; very high costs ; specialized , but quickly available product .	<i>Very good</i> : Errors tested with Gidel ProcVision tools ; image data recording and playback in PC environment; FPGA output validation against CPU program results .

Source: (Zippy Vision SIA data).

Considering that the paper is going to work with FPGA programming, cameras with a closed module (closed FPGA module) have been excluded from the selection, giving preference to cameras that are with an open one. Thus, the focus is currently on starting programming using Vivado tools, which are available for free and focusing on the capabilities of the OptoMotive T-Rex EVO camera. It should be noted that an important position is debugging capabilities on a computer before transferring algorithms

to the FPGA processor, so the next step chosen is Vivado with algorithm testing on a PC.

When evaluating cameras, the triggering and synchronization capabilities are also important. The system basically works with two-channel encoder inputs and it is important that the FPGA chip is able to provide synchronization to other cameras, for example, using only an increasing position trigger.

TABLE 2 FPGA TECHNOLOGY COMPARISON

System	Developments complexity and prototyping	FPGA and performance	Trigger and synchronization opportunities	Built-in CPU	Availability and costs	Errors test and simulation
Techway DragonEYE	<i>Medium – easy</i> : Available C++ API, HLS support ; ready to open modules for immedate to start .	<i>Artix-7/Zynq FPGA</i> : Real-time several camera (4CH GigE) processing ; possible small AI model Zynq version .	<i>Very good</i> : 4xGigE , GPIO trigger signals ; precise synchronization .	<i>Additionally</i> : “Smart” version ARM dual-core CPU (Zynq); Lite version no CPU.	<i>Commercial available</i> : Available at distributed (1–2 week delivery); medium costs .	<i>Good</i> : HLS C simulation ; testing on PC or ARM (Zynq), Vivado error tools
Photonfocus photon3D	<i>Very easy</i> : FPGA programming notnecessary ; used as usual GigE camera .	<i>Specialized FPGA (closed)</i> : Laser lines determination up to 10k	<i>Excellent</i> : Built-in encoder interface , <μs trigger precision ; specially designed laser for triangulation .	<i>None (uses PC)</i> : Works like a camera ; additional analysis is forwarded to computer .	<i>Commercial available</i> : Standard product ; delivery from warehouses or branches week	<i>Not relevant</i> : Included algorithms are pretested and fixed ; error are done on PC through

		profiles /s; AI not available on camera level			time ; high costs .	GenICam interface and GUI.
OptoMotive T-Rex EVO	<i>Medium:</i> Necessary Vivado FPGA development , but is ready-made IP design template ; typical usage, quick realization .	<i>Zynq-7020 SoC:</i> ~50% FPGA logic free ; 2MP @ 331 FPS; possible realize simple CNN models .	<i>Excellent :</i> 21 ns trigger time distinctive different taking modes; programmable I/O lines for synchronization .	<i>Yes:</i> ARM dual core CPU (Linux) embedded in cameras; possible to install user programs on cameras .	<i>Commercial available :</i> Available at partners (Pyramid ,Sundance); rather affordable price for beginners level camera	<i>Very good :</i> Algorithm testing on ARM level ; FPGA simulation in Vivado environment; CPU and FPGA logic mutual validation .

Source: (Zippy Vision SIA data).

Laser triangulation systems benefit from FPGA-based processing for real-time extraction of laser line or point data. Below are several industrial-grade FPGA solutions (from multiple suppliers) that support GigE industrial cameras, along with their key specifications and suitability for laser triangulation (and laser point distribution). Each is designed for high-speed, real-time operation in rugged environments, and pricing is noted where available

IV. SOLUTION

This makes it suitable for large-scale laser triangulation systems (such as scanning large objects with multiple lasers/cameras in parallel).

Industrial Considerations: Gidel's frame grabbers are typically used inside industrial PCs or edge servers. They adhere to standard PCIe form factors and support Windows and Linux OS environments They provide GPIO (trigger IO, encoders, etc., with opto-isolated and high-voltage tolerance options) on a dedicated connector for integration with external equipment

. While the cards themselves rely on the host's environment (cooling, enclosure), they are built for 24/7 operation and high reliability in demanding applications like semiconductor inspection, defense imaging, and 3D vision.

Pricing & Availability: Gidel products are available directly through Gidel. These are highly specialized pieces of hardware; pricing is typically **on request** and varies with the FPGA model and memory configuration. Expect the cost to be significant – on the order of several thousands of dollars or more for toptier models – reflecting the cutting-edge bandwidth and FPGA capability. Gidel does, however, emphasize that using their solution can lower overall system cost in multi-camera setups by removing CPU bottlenecks and reducing the number of PCs needed. For developers needing maximum performance and willing to program FPGAs at a low level, Gidel's solutions provide an **ultra-high-speed platform** well suited for real-time laser triangulation across many cameras or very high resolution (table 3 for summary).

TABLE 3 FPGA TECHNOLOGY SUMMARY COMPARISON

Parameter	Techway DragonEYE	Photonfocus photon3D	OptoMotive T-Rex EVO	OptoMotive Smilodon 10G EVO	NI Industrial Controller	Gidel HawkEye 20GigE
FPGA Model	Xilinx Artix-7	Integrated FPGA (specific model not specified)	Xilinx Zynq-7020 SoC	Xilinx Zynq UltraScale+ MPSoC	Xilinx Kintex-7	Intel Arria 10
Onboard CPU	None (relies on host PC's CPU)	None (dedicated FPGA for image processing)	Dual-core ARM Cortex-A9 processor integrated within Zynq-7020 SoC	Quad-core ARM Cortex-A53 processor integrated within Zynq UltraScale+ MPSoC	Intel Core i7 processor	None (relies on host PC's CPU)
CPU Capabilities	N/A	N/A	Runs Linux OS; handles higher-level tasks, communication, and control functions	Runs Linux OS; manages complex tasks, communication, and advanced processing	Runs NI Linux RealTime OS; Suitable for Complex real-time applications and communication	N/A
Camera Interface	GigE Vision (4 ports)	GigE Vision or 10GigE	GigE Vision	10GigE Vision or GigE Vision	4xGigE Vision	2x10GigE Vision
Resolution	Dependent on connected cameras	1280 to 2048 pixels width	Up to 2048x2048 pixels	Up to 5120x5120 pixels (25 MP)	Dependent on connected cameras	Dependent on connected cameras

Integrated Processing	Yes (user programmable via Vivado HLS)	Yes (built-in laser line detection algorithms)	Yes (FPGA peak detection core for laser triangulation)	Yes (high-performance FPGA for real-time processing)	Yes (programmable via LabVIEW FPGA)	Yes (user programmable FPGA for real-time processing)
I/O and Synchronization	Yes (trigger inputs, GPIO)	Yes (isolated inputs/outputs)	Yes (isolated inputs/outputs)	Yes (isolated inputs/outputs)	Yes (isolated inputs/outputs)	Yes (GPIO, isolated inputs/outputs)
Industrial Environment	Yes (PCIe card suitable for industrial applications)	Yes (robust housing designed for industrial use)	Yes (compact and robust housing for industrial environments)	Yes (robust housing suitable for industrial environments)	Yes (IP67-rated, fanless design for harsh industrial conditions)	Yes (PCIe card designed for 24/7 operation in industrial settings)
FPGA Programming Language	VHDL, Verilog, and High-Level Synthesis (HLS) tools like Vivado HLS	Not specified (likely Proprietary firmware; user programmability may be limited)	VHDL, Verilog, and HLS tools like Vivado HLS	VHDL, Verilog, and HLS tools like Vivado HLS	LabVIEW FPGA (graphical programming environment)	VHDL, Verilog, and High-Level Synthesis tools
FPGA Processor Capabilities	Artix-7 FPGA with sufficient resources for realtime image processing	Integrated FPGA optimized for laser line detection; specific capabilities not detailed	Zynq-7020 SoC combining dual-core ARM Cortex-A9 processor with FPGA fabric for real-time processing	Zynq UltraScale+ MPSoC with quad-core ARM Cortex-A53 processor and large FPGA fabric for highperformance tasks	Kintex-7 FPGA with ample resources for complex real-time processing tasks	Arria 10 FPGA offering high logic density and DSP blocks for intensive real-time processing
Approximate Price	Available upon request	Approximately \$3,000–\$7,000 USD	Approximately \$3,000–\$6,000 USD	Approximately \$6,000+ USD	Approximately \$10,000+ USD	Available upon request (typically several thousand USD)

Source: (Zippy Vision SIA data).

The used application combines multiple simultaneous tasks using a single FPGA camera (**OptoMotive T-Rex EVO as chosen from Table 3**):

1. **3D Laser Triangulation** (laser dots to measure depth)
2. **Laser Dot Distribution Analysis** (for fiber-direction mapping)
3. **Color Line Scanning** (triggered precisely via encoder signals)

Camera's sensor will be logically divided into separate areas (regions of interest – ROIs), each used for a different purpose:

- **Sector 1:** Laser dots (3D triangulation & distribution analysis)
- **Sector 2:** Color line scanning (high-resolution colour capture)

All data will be pre-processed onboard the FPGA and ARM CPU (Linux OS), enabling fast real-time decisions and reduced data transfer Figure 1.

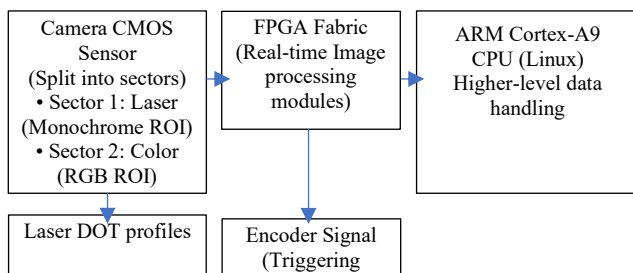


Fig. 1. Conceptual Hardware-Software Diagram

The FPGA can be used to perform inline processing on images acquired from these cameras (for example,

filtering, thresholding, or even laser line extraction algorithms) before passing results to the host CPU or control logic. This co-processing offloads the CPU and can greatly reduce latency in a triangulation system.

Explanation of FPGA-based Processing Workflow

1. Sensor Acquisition

The camera sensor captures images simultaneously:

- Monochrome sector (laser dot patterns)
- Color sector (RGB image line scan)

2. FPGA-Based Real-time Pre-processing

Custom FPGA modules process the data in parallel:

- **Laser Triangulation Module:** identifies laser dot positions and calculates heights for 3D reconstruction.
- **Dot Distribution Module:** analyses laser dot distribution, generating a fiber direction map.
- **Color Line Module:** acquires RGB colour line data, synchronised by encoder signal.

3. ARM CPU Higher-Level Processing (Linux)

Processed data from FPGA passed to the onboard ARM Cortex-A9 CPU for:

- Data aggregation and timestamping.
- Higher-level algorithms (e.g., detailed fibre direction analysis, quality checks).
- Networking (sending processed data to host PC).
- Integration and communication with external devices/systems (e.g., ERP systems).

4. Data Transfer to Host PC

Reduced datasets (height profile, fibre maps, colour scans) are sent via GigE to a PC for:

- Long-term storage.

- Visualization.
- Advanced analytics and reporting.
- Integration with MES/ERP systems.

V. TESTING RESULTS

During testing period image acquisition stability tested under different lighting conditions – 100 lux was performed,

500 lux, 1000 lux, 3000 lux. The actual level at which the sensor works and is able to unambiguously recognize the laser shape is up to 1000 lux. At higher lighting levels, sensor data and laser line extraction are difficult:

- data flow quality and noise level in the sensor tested;
- triggering accuracy validated for synchronization with external line scanning systems;
- operation of FPGA processing-based algorithms tested on real sensor data.

For the initial development, testing and creation of new algorithms, the Intel Questa FPGA simulation environment was used, which can execute HDL code and is compatible with the Vivado architecture. After further research, it was decided to use the Zynq Ultrascale+ MPSoC Development Board for further development, which allows for the creation of an integrated camera system, which is further compatible with the integrated camera candidates identified in the first stage. The reason for this choice is the wider programming capabilities of FPGA, where the final software tests will allow for the use of various types of industrial cameras. A technical evaluation report of camera models has been created, which summarizes the most important parameters that served as the basis for hardware selection (based on the previously developed comparative table from the application material). Additional research has found that it is more cost-effective to carry out the initial development with the Zynq Ultrascale+ MPSoC Development Board, which is compatible with the studied cameras at the program and logic level. Hardware compatibility with the planned FPGA programming environment (Xilinx Vivado) and ARM CPU algorithm simulation has been validated, ensuring optimal development speed.

The initial FPGA firmware version has been developed and implemented, which provides data acquisition from the sensor and initial processing in real time (Figure 2).

- The processing throughput level of ~800–200 profiles per second at a resolution of 1000 points has been achieved.
- Full data synchronization between the sensor acquisition clock, encoder pulse signals and external trigger system has been implemented.
- The functionality of the processing blocks has been validated with real sensor data in laboratory conditions.
- A flexible debugging and simulation environment has been provided, which significantly accelerates the development of further algorithms and their transfer to the FPGA. The debugging environment is based on the FPGA processor simulation environment, which simulates the operation of the FPGA processor and allows tracing operation steps and states on test data using the debugging

process in the simulation environment. Such debugging is not practical during the operation of an already programmed processor.

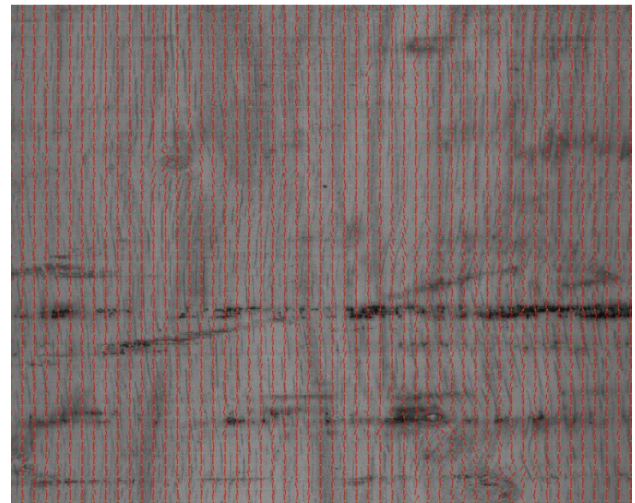


Fig. 2. MExample of fiber directional coverage map (Zippy Vision SIA property).

As part of the project, the phase of identification and evaluation of artificial intelligence (AI) models was initiated with the aim of determining the most optimal segmentation model solutions for wood defect recognition, adapting them to future data sets that will be obtained with the developed 3D and line-scanning camera system.

Taking into account the visual and structural characteristics of wood defects (high defect diversity, uneven shapes, the impact of different fiber orientations on the visual image), a detailed analysis of the literature and current technological sources on the development of segmentation algorithms was carried out:

- Transformer architectures were evaluated: Vision Transformer (ViT), Swin Transformer, Mask2Former, Segment Anything Model (SAM).
- The advantages of these models in segmentation tasks with wood materials were compared:
- The ability to specialize these models with a limited number of samples, with the aim of: segment complex surface textures; distinguish changes in fiber direction and surface damage volumes; process high-resolution images.

To detect gumminess and small cracks, create a differential algorithm that uses laser width and intensity data and creates a differential data matrix that allows for reproducing gumminess and crack identification. Considering that physical variations are known for both gumminess and cracks, an augmentation algorithm has been developed that allows for generating artificial surface textures (Figure 3).

Artificial surface textures are necessary because finding mathematical parameters for crack and gumminess recognition is considered less robust and more time-consuming than creating augmented data and searching for parameters through the AI training process. Augmented

data does not require any interpolation, as the segment area is known at the time of augmentation.

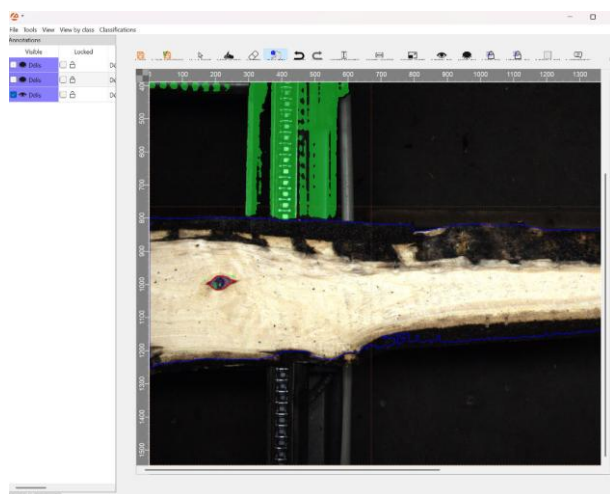


Fig. 3. The result of automatic segmentation on the board image, using the semantic segmentation SAM model on a real-life image (Zippy Vision SIA property).

The Segment Anything Model was chosen due to its simpler integration into a new flow.

The following was found during the research:

- Large transformer models have significantly higher hardware requirements and lower speeds than those allowed in high-speed and high-performance scanners.
- Large models have significantly higher initial accuracy on a limited amount of annotation data, such as the U-Net model, which can be used on end-user hardware with a smaller number of annotations.
- The integration of large models into the annotation and model development flow significantly accelerates AI accuracy and reduces costs, as large models are excellent for creating initial annotations, and a new AI processing flow has been launched in which large models are integrated as a distillation source.

VI. CONCLUSIONS

For FPGA programming, the possibility of initial simulation is essential, taking into account that after the algorithms themselves are transferred to the FPGA processor program, the possibilities for further development, testing and debugging are limited. The chosen solution optimally combines the necessary hardware programmability, processing power and flexibility in real-time data flow management. Such a base allows in the next stages to implement both experimental 3D profile processing, AI model data preparation, and further optimization of laser triangulation and line scanning systems. This activity result directly corresponds to the goal of the project application to create an effective camera platform base capable of realizing combined visual

and 3D information acquisition for a wood defect recognition system. The developed initial FPGA firmware version fully confirms the compliance of the selected platform with the technical requirements of the scalability. The implementation of 3D profile generation and calibration algorithms, laser point scattering analysis for fiber direction determination and real-time calculation blocks for the initial geometry of defects are allowing to build a system with necessary high-speed precision. These results bring the wood processing sector significantly closer to achieving its goal — to provide high-precision combined 3D and visual information processing in real time, which is applicable for automatic recognition and marking of wood defects in industrial production. The calibration stage of the implementation of laser triangulation and line scanning integration is creating a functioning experimental system that combines both information acquisition technologies into a single synchronized flow. The synchronous 3D and visual data obtained in this way create a basis for the development of high-precision wood defect recognition algorithms and further training of AI models.

The achieved results directly correspond to the defined main goal of the paper to develop a new generation of combined camera system that integrates elements of laser triangulation, line scanning and artificial intelligence in wood quality control automation. The conducted segmentation-based model research has provided a solid foundation for adapting artificial intelligence algorithms to the specific problem of wood defect identification. The choice of Transformer architecture provides significant advantages for companies by delivering higher accuracy in processing irregular defect contours; accelerated development time of specialized models; accelerated and refined implementation of annotations using SAM models at all stages of the workflow. Modern architectures trained using the new workflow model are able to model structural and visual aspects of the wood surface simultaneously with better adaptation capabilities to increase data volume.

The prepared methodology and solution allow for the wood processing sector to start practical applications for model training in the subsequent stages of the development, using the proposed innovative 3D and line-scanning camera combined solution, capable of simultaneously capturing both visual and 3D information, as well as identifying wood properties such as fiber direction and resin accumulation.

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Development of a 3D and Line-Scanning Camera for Automatic Wood Defect Marking

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Abstract— The industrial sector is focused on efficiency of an industrial vision through automation as one of the most popular solutions as in recent decades. The main bottleneck of the process is image processing due to high speed and precision. Graphic processing units (GPUs) and Field-Programmable Gate Array (FPGAs) have been proposed for real-time detection, where tasks are now performed repeatedly by machines assisting or replacing humans, reducing the occurrence of errors. New frameworks are trying to be in pace with Industry 5.0 advancements and to rely heavily on real-time sensor systems, with integration to Smart Factory which are essential for assessing dynamics of industrial data. In the paper, the research project focuses on developing an application of innovative combined 3D and line-scan camera system capable of simultaneously capturing visual and 3D information and identifying wood properties such as fiber direction and resin pockets. The camera employs laser triangulation and controlled LED illumination for precise wood structure analysis, while high-speed Field-Programmable Gate Array (FPGA) with High-performance computing (HPC) technologies enables real-time image analysis in-camera. Additionally, the research will focus on presenting fully functional prototype with discussion on modular system architecture scalability and parallel development of FPGA and AI components in simulation, moving closer to industrial implementation in subsequent stages. As the critical step for framework elaboration, the development of a functional application in manufacturing environment of FPGA firmware, laser triangulation, line-scan imaging, controlled illumination, trigger boards, and AI modules and evaluation of technological options that would ensure effective recognition of wood defects, as well as creation of a basis for further technological development are performed.

Keywords— Computer Vision, Deep Machine Learning, defect detection, FPGA, HPC, labelling, quality control, wood processing.

I. INTRODUCTION

The implementation of a high speed inspection system for the wood processing industry is not a novel [1], yet very promising direction since it is bringing improvements in production process, higher quality of delivered coated board and reduction of waste [2]. Modern wood trimming optimization lines using marking devices and laser scanners of the wood surface do not provide high accuracy in determining the location of defects and are quite expensive [3]. Contemporary market competition and applications of Smart Factories with Industry 4.0 are increasing the entry into the industry. Companies are trying to implement fragmental modules into new paradigm and looking for cheaper and easier option to integrate into complete framework with scalability options [4], [5]. The wood processing sector faces modern challenges coming from the natural variability of wood and the demand for rapid, reliable inspection to reduce waste, improve product quality and increase sustainability [6]. With increasing industrial automation and environmental regulations in Europe, optimizing wood defect detection through real-time imaging and processing is of practical and economic [5], [7], [8].

Despite progress, the problem of a low understanding of automation opportunities, unclear requirements specifications, small production volumes and suitable automation solutions are hindering technology transfer [9], [10], [11]. The accurate and efficient detecting due to

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diverse wood defects based on wood species in real-time remains unresolved, since the existing approaches vary widely, from traditional image segmentation and texture analysis [12], [13], [14] to deep learning models requiring substantial computational resources [15], [16].

The biggest knowledge gap exists in balancing detection accuracy with processing speed, especially under industrial conditions involving high-speed conveyors and complex defect types [17], [18], [19].

Recent trend in Machine Learning application in data processing algorithms through convolutional neural networks (CNNs) and integration with high-performance computing (HPC) in 3D and line scanning camera systems for real-time wood processing has emerged as a critical area of inquiry due to its potential to enhance efficiency and accuracy in defect detection, quality control, and automation within the wood industry [17], [20]. However, these defection methods based on single image data have difficulty when distinguishing the wood broken defects with the interference similar to the defects due to the limitation of feature representation [14], [21]. Most of conventional systems were based on common image processing techniques in combination with supervised learning algorithms, however, over the last decade deep learning has achieved remarkable success in the forestry and wood products industry [22], [23]. Deep learning (DL) techniques are very efficient tool for wood anomaly detection, feature detection (segmentation), object classification, instance segmentation, point localization, and character recognition [24], [25], [26], [27], [28].

As one of the most popular solutions as in recent decades, the industrial sector was focused on efficiency of an industrial vision through automation. The main bottleneck of the process is image processing due to high speed and precision. Graphic processing units (GPUs) and FPGAs have been proposed for real-time detection, where tasks are now performed repeatedly by machines assisting or replacing humans, reducing the occurrence of errors [29], [30], [31], [32]. FPGAs are used to reduce the processing time in vision systems, and consequently, to reduce their cycle time. FPGA processing times are on the order of nanoseconds, while the other platforms have times in the order of milliseconds. It can also be concluded that the use of the GPU is only advantageous when the number of sequential filters is high, under these circumstances, the FPGA is advantageous. Unlike conventional processors or microcontrollers, FPGAs do not have predefined functions. Instead, they contain many small logic elements, the interconnections and operating principles of which are defined by the user as needed, using programming languages. Moreover, the bottleneck exists regarding the optimal hardware platform: FPGA-based systems offer low latency and power efficiency but may lack flexibility, whereas GPU-based and traditional CPU methods provide programmability at the cost of higher power and latency [29], [33], [34], [35], [36].

The purpose of this paper is to present Machine Vision, ML, FPGA and HPC elements interaction to define the system's capability to perform real-time defect marking,

where imaging provides raw data, FPGA enables rapid processing, and ML detection algorithms ensure precise identification. This framework guides the evaluation of technical challenges and benefits within industrial wood defect marking applications.

II. SPECIFICATIONS OF ENVIRONMENT

The three critical factors were identified for concept: the laser triangulation method, as it provides high accuracy and is able to detect changes in fiber direction based on the dispersion of the laser point. Line scanning technology with controlled LED illumination that ensures stable acquisition of visual information, which allows accurate defect identification of wood surfaces. And the use of FPGA chips for real-time data processing that significantly increases the scanning speed, allowing the integration of both 3D and visual data processing in one system. A dual-encoder switching mechanism was implemented to select appropriate trigger signals based on board motion speed, ensuring reliable image capture timing under variable conveyor speeds. Line-scan and 3D image rectification algorithms were developed using homography transformations to reconstruct undistorted images of moving boards. Additionally, surface defect pixelation algorithms (combining laser profile and visual data) were prototyped in C++ for compatibility with FPGA translation. An adapted state-of-the-art segmentation models (including Transformer-based architectures) to project-specific wood defect data. Using the newly established annotation pipeline with the Segment Anything Model (SAM) and a human-in-the-loop workflow, a large segmentation model was fine-tuned on wood defect dataset. e.g. detection of knots, cracks, and blue stain with up to 95–99% accuracy, depending on defect type), greatly outperforming previous methods. The AI annotation workflow was revamped by integrating SAM for automatic pre-labelling in the CVAT platform, enabling faster dataset generation and refinement.

Surface defect “pixelation” algorithms: Initial algorithms have been developed to combine laser 3D information and visual RGB/NIR images that detect defects on the wood surface at the pixelation level. For example, for crack detection, the algorithm simultaneously analyzes laser profile distortions (depth changes) and visual image contrast changes; while for “blueing” (blueing of wood), the NIR channel absorption characteristics are combined with visible light color information. These algorithms were implemented in C++, in modular components, using the company's existing image processing software code. The choice of C++ ensures easier portability to FPGAs using high-level synthesis (HLS) or by integrating the code into the ARM processor subsystem. This maintains compatibility with existing competencies and at the same time provides the opportunity to gradually “port” the algorithms to FPGA logic. All changes and new modules were thoroughly tested in the Questa simulation environment (compatible with Xilinx Vivado). Test vectors were created that emulate different scenarios of encoder pulses (uniform

movement, acceleration, stop and reverse) and the trigger logic response was checked in each case. The operation of the rectification algorithms was also validated in the simulation using synthetically generated deformed images and known homography parameters and practical tests were performed in laboratory conditions with real wood sample data (Figure 1).

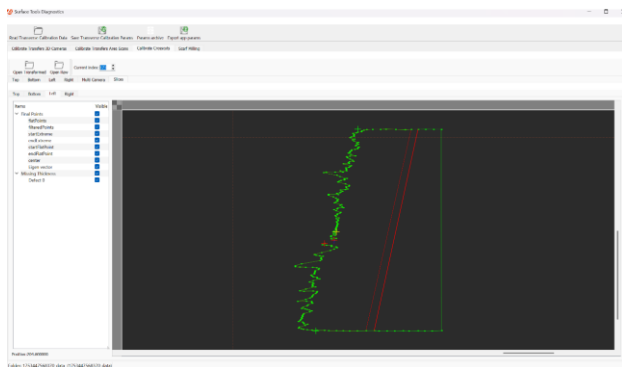


Fig. 1. Magnetization as a function of applied field. 3D algorithm testing example (Zippy Vision SIA property).

The trigger circuits were integrated into the existing test stand (Figure 2). The camera was connected to the board's trigger output, and the encoder to the board's inputs (channels A and B). Configuration was performed: the pulse division was set in the board software so that in normal mode (at maximum speed) the camera would capture approximately 2000 frames per second, which corresponds to a ~ 0.2 mm spatial step between the lines of the line scan image.

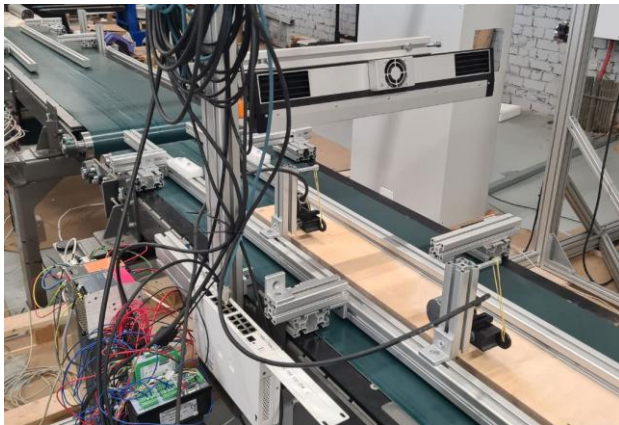


Fig. 2. Testing stand (Zippy Vision SIA property).

The trigger zone boundaries were also defined according to the board's length and the camera's field of view to ensure that the camera would not be triggered until there was material underneath it. During the integration process, compatibility with the existing system was checked - signal timing and voltage levels, as well as response time (from the encoder pulse to the trigger pulse edge).

After testing in real environment with the help of the integrated SAM approach and Human-in-the-Loop (HITL) process, annotation productivity increased several

times. The time required to annotate one image (full board) has decreased from, for example, 5 minutes manually to $\sim 1-2$ minutes with ML support, depending on the number of defects. The segments proposed by SAM are often 70–90% accurate and require only minor adjustments. Consequently, the data set grew faster during the project, allowing the model to be trained with more variations. In addition, workflow automation (Docker containers, scripts) eliminated many manual steps – data flows through the processing pipeline almost completely automatically. The training cycle of a new model (from raw images to a trained model) now takes much less time and is repeatable with a single command. The quality of annotations has also improved, as SAM helped maintain a consistent treatment of defect contours across all data (Figure 3).

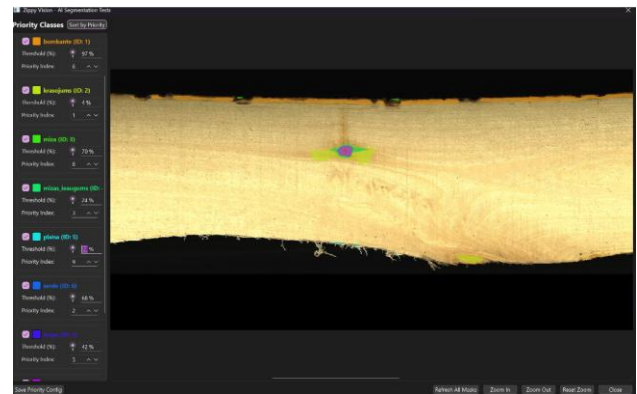


Fig. 3. Wood defect identification example (Zippy Vision SIA property).

The results achieved in the testing phase confirm that the chosen artificial intelligence approach with Transformer architectural segmentation models is extremely promising for detecting wood defects. A specialized synthetic data generation program was developed for model training, based on the physical properties and geometric parameters of laser profilers. This approach allowed for the preparation of training datasets with more than a million samples, which sufficiently accurately reflect the shape and measurement characteristics of real-world objects.

During model development, 14 different lightweight model configurations were tested, assessing their suitability for training, inference, and integration into systems with a limited time budget. Training was performed in the PyTorch environment, while inference execution was optimized using TensorRT to ensure maximum efficient execution at the GPU level and reduce the data exchange load between the GPU and the central processor. Comparative analysis with previously used methods showed that the new approach significantly reduces lateral artifacts and projection errors, which are characteristic of simplified homography methods (Figure 4). This improves the quality of the obtained data and ensures more stable results for further analysis.

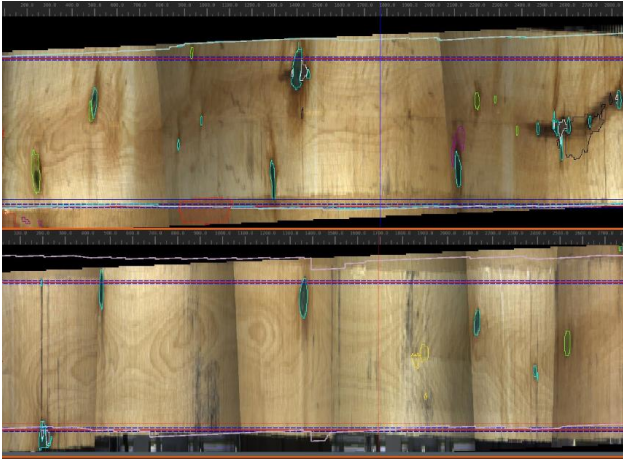


Fig. 4. Comparison of the previous methods (Zippy Vision SIA property).

From the comparative data it is easy to see that the new method eliminates lateral artifacts – edges that inevitably appear with simple homography) it is intended to focus on increasing the robustness of the model against variations in illumination, surface structure and material properties, as well as on performance optimization for the target industrial equipment.

The experiment used an industrial laser triangulation line scanner system Teledyne DALSA Z-Trak 4K, which simultaneously provides high-resolution profile measurements and a laser intensity value associated with each point. Wood samples with known resin pockets were transported through the scanning area at a constant speed, maintaining a stable working distance and laser power. This ensured that intensity variations were mainly related to material properties and not to geometric factors of the measurement.

III. FINAL RESULTS

Integrated all hardware and software components developed in previous stages into a single functioning prototype. This included FPGA firmware, laser triangulation, line-scan imaging, controlled illumination, trigger boards, and AI modules. The assembled prototype was tested to validate system synchronization, triggering stability under variable conveyor speeds, quality of fused image data, and real-time execution of AI models. Test results confirm that all major subsystems now operate cohesively and are ready for industrial-environment. Laser cameras generate sequential 3D cross-sections that directly represent the object's geometry, while visual cameras acquire 2D intensity or color information without a direct depth component. As a result, each line scan step produces a heterogeneous data set, in which the same area of material corresponds to multiple 3D profiles, multiple visual lines or frames, as well as motion and positioning parameters. Transverse line scanning is one of the most methodologically complex types of multi-sensor line scanning. Combining sensor spaces in this case is significantly more complex than in classical line scanning, since the data to be combined differ in spatial semantics,

sampling structure, temporal association, and interpretation. Small temporal or spatial discrepancies can accumulate along the entire scanning direction and cause systematic shifts in the spatial localization of defects, it was one of the anticipated issues for industrial application (Figure 5).

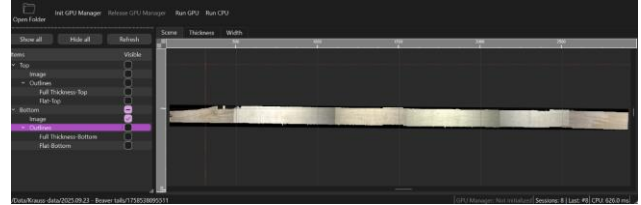


Fig. 5. The image of a downward shift of three separate images. The physical displacement of the object along axes that are perpendicular to the conveyor line of motion (Zippy Vision SIA property).

In order to overcome this challenge the project developed a sequential, deterministic transversal line scan data fusion flow. Its goal is to obtain a single, spatially coherent and suitable for further analysis data structure from heterogeneous, asynchronous sensor data. In the first stage of the flow, parallel sensor data acquisition takes place: laser profiling line scan cameras generate 3D profiles, visual cameras acquire image data, while trigger and encoder signals provide information about material movement. At this stage, the data is not yet directly merged. In the second stage, time and motion normalization is performed. All sensor data are linked to a common motion description, ensuring an exact match between 3D profiles, visual lines and material position. In the third stage, all data are transformed to a single coordinate system. Laser profiles are spatially arranged as sequential cross sections, while visual data are projected into this same space using the spatial relationships between the sensors. This stage is one of the most algorithmically complex. In the fourth stage, the spatially aligned data is joined and projected into representations suitable for analysis, such as cross-sections, surface projections, or structured grids. In the fifth stage, a single transverse line scan data unit is created, containing the combined 3D geometry, visual information, motion parameters, and derived features (Figure 6).

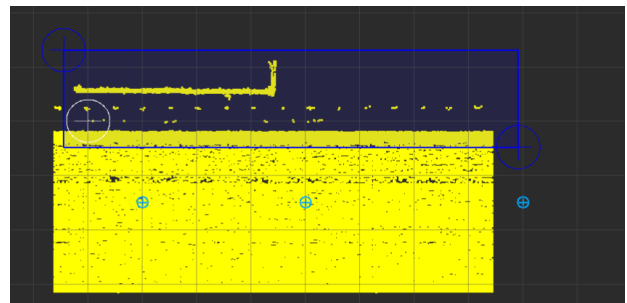


Fig. 6. Corresponding YZ plane projection. (Zippy Vision SIA property).

In addition to geometric information, laser triangulation systems also obtain laser reflectance or intensity data, which characterizes how much of the

emitted laser energy is reflected back to the sensor. Resin pockets in wood differ significantly from the surrounding wood material in terms of their optical behavior – they have a smoother, often semi-transparent or shiny surface, which causes a higher and more localized intensity of reflected light. As a result, resin pockets appear as distinctly contrasting areas in the laser intensity map compared to the more uniform reflectance of the wood fiber (Figure 7).

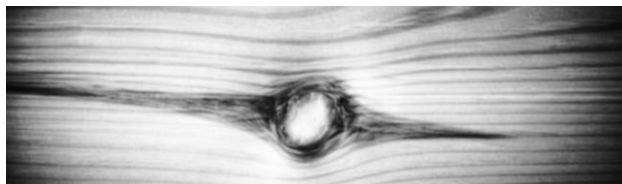


Fig. 7. Laser triangulation sample (pine) (Zippy Vision SIA property)

The acquired intensity data showed that resin pockets often produce not only a local geometric anomaly, but also a rapid increase or saturation of the laser reflectance that persists over several adjacent scan lines. This combination allows to distinguish resin pockets from other defects, such as branches or fiber direction changes, for which the intensity signature is usually weaker or structurally different.

IV. CONCLUSIONS

The results showed that the implementation of specialized trigger synchronization logic was critically necessary - now the camera works reliably even in difficult operating conditions (variable speed, reverse). The solution with two encoder switching allows covering the entire range of possible conveyor speeds without losing image resolution. The inclusion of rectification algorithms ensures that subsequent image processing steps (defect analysis, AI) can operate with geometrically correct data, which increases the accuracy of defect recognition. The implementation of the defect pixelization concept confirms the usefulness of the combined 2D/3D approach and serves as a basis for further improvements. Testing of the integrated prototype provided significant feedback on the system's weaknesses and challenges, especially regarding synchronization accuracy and performance. Anticipated issues with industrial applications were approved and successful solutions applied. The experiment showed that laser triangulation reflectance data is a valuable addition to the classic 3D profile for detecting resin pockets. By using intensity thresholds, spatial filtering and correlation with height data, it is possible to create a robust algorithm that works in a real-time industrial environment. This allows for early identification of resin pockets, improved wood quality grading and reduced risks in subsequent processing stages.

The chosen solution optimally combines the necessary hardware programmability, processing power and flexibility in real-time data flow management. Such a base allows in the next stages to implement both experimental

3D profile processing, AI model data preparation, and further optimization of laser triangulation and line scanning systems - linking visual line scan data with 3D laser profiles in a single coordinate space. In the following stages, it is recommended to analyze in depth how different data combinations (texture, depth, reflectance intensity) affect the accuracy of defect recognition. Special attention should be paid to whether, for certain types of defects, it is possible to reduce the dependence on the full 3D profile by using ML models based on enriched visual information.

This activity result directly corresponds to the goal of the project application to create an effective camera platform base capable of realizing combined visual and 3D information acquisition for a wood defect recognition system. The developed solution showed that training a lightweight model under the supervision of large models is a viable approach for real-time industrial systems. In the next stages, it is recommended to focus on improving the robustness of this model, especially with regard to variations in lighting, surface structure and material properties. In addition, it should be evaluated how the lightweight model can be adapted to different wood types and production lines, while maintaining high performance and stability.

Initial FPGA firmware version fully confirms the compliance of the selected platform with the technical requirements of the scalability. Experimentation has shown that developing hardware (FPGA, trigger systems, data acquisition) and AI workflows in parallel is an effective approach. The requirements of AI models for data quality and structure can serve as guidelines for hardware optimization, while the capabilities and limitations of the hardware determine the practical applicability of AI solutions.

The achieved results directly correspond to the defined main goal of the paper to develop a new generation of combined camera system that integrates elements of laser triangulation, line scanning and artificial intelligence in wood quality control automation. The conducted research has provided a solid foundation for adapting artificial intelligence algorithms to the specific problem of wood defect identification. The choice of Transformer architecture provides significant advantages for companies by delivering higher accuracy in processing irregular defect contours; accelerated development time of specialized models; accelerated and refined implementation of annotations using SAM models at all stages of the workflow. Modern architectures trained using the new workflow model are able to model structural and visual aspects of the wood surface simultaneously with better adaptation capabilities to increase data volume. The prepared methodology and solution is allowing to start further practical applications for model training in the subsequent stages of the development in corresponding field.

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Analysis of Optimal Shape of Cam Mechanism with Roller Rocker

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Abstract—Cam mechanisms are crucial for driving different types of drive trains. From simple mechanisms to metal cutting machines, combustion engines, filling machines and others. Because many old machines do exist, and use such mechanism, an algorithm is proposed so that the position function can be obtained from an existing profile. Also a optimization is carried out, so that the kinematics of the new mechanism meets criteria for smooth running conditions. A polynomial function of specific order is proposed, for reverse engineering an existing profile from a filling machine.

Keywords—cams, design, optimization of profile, position function.

I. INTRODUCTION

The featured cam mechanism transforms the rotary motion of the cam into oscillating movement of a lever. Normally the rocker and cam are pushed into one another via a spring or others types of connections, so the kinematic pair is guaranteed at all time. A variety of approaches can be seen in [1], [2], [3], [4] to obtain the position function and to optimize it in the design phase of many machines.

Most approaches presume a polynomial or simple harmonic function and have the input information as rise, dwell and fall. With this date a series of equations are constructed to form a system, which is deterministic in nature, as also seen in [5].

Filling machines accurately deliver product into containers with cams acting as main mechanism. Normally the movement is related to either accurately delivering piston position or for indexing and timing. In our case Fig. 1 the mechanism is for timing and cutting the exact volume needed to fill a container.

The main purpose of the mechanism is when during the filling, the containers are getting lifted up, to reduce

splashing and foaming. The lifting way is fixed by the stoke of the mechanical lifting cam and can't be adjusted. The position of the lifters can be adjusted by the tension rod at the back side of the machine.

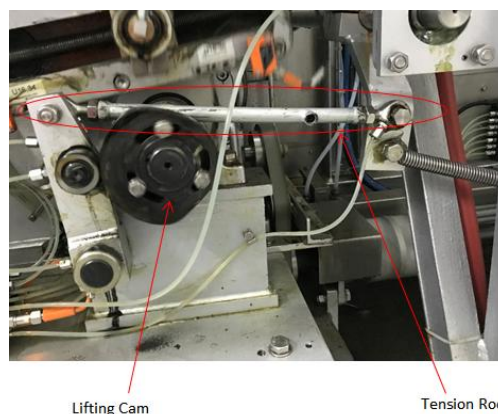


Fig. 1. Cam and rocker mechanism.

Because the machine will be rebuilt a cloud of points is collected with direct measurement, via 3D measuring machine, and supplied for this study. This date is used to investigate the design, and to get a better understanding of how this cam will fit into the new concept for the filling machine. The existing profile is extrapolated via spline function in a CAD product environment Fig. 2. The main goal is to examine the kinematics of the existing mechanism and to propose a more analytical approach to how and why the shape should change.

The overall dimensions are captured and checked with the physical cam from the machine, all changes are strictly for the sake of improvement of kinematics, no changes to stroke or overall dimensions are needed, because of other

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parts that will result in conflict in movement if changes are made.

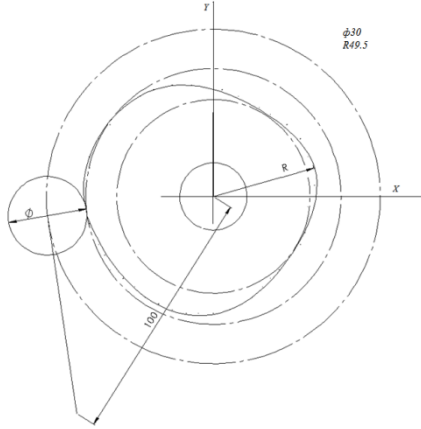


Fig. 2. Dimesnsions and profile of existing cam.

It is possible to get significantly good results in kinematic behaviour using a polynomial function (1), its derivatives to the second order (2) and specifying boundary conditions (3).

$$s = a_0 + a_1 \frac{\theta}{\beta} + a_2 \frac{\theta^2}{\beta^2} + a_3 \frac{\theta^3}{\beta^3} + a_4 \frac{\theta^4}{\beta^4} + a_5 \frac{\theta^5}{\beta^5} \quad (1)$$

$$\frac{ds}{d\theta} = a_1 \frac{1}{\beta} + 2a_2 \frac{\theta}{\beta^2} + 3a_3 \frac{\theta^2}{\beta^3} + 4a_4 \frac{\theta^3}{\beta^4} + 5a_5 \frac{\theta^4}{\beta^5}$$

$$\frac{d^2s}{d\theta^2} = 2a_2 \frac{1}{\beta^2} + 6a_3 \frac{\theta}{\beta^3} + 12a_4 \frac{\theta^2}{\beta^4} + 20a_5 \frac{\theta^3}{\beta^5} \quad (2)$$

$$s(0) = 0, s(\beta) = h, ds(0)/d\theta = 0, ds(\beta)/d\theta = 0$$

$$d^2s(0)/d\theta^2 = 0, d^2s(\beta)/d\theta^2 = 0 \quad (3)$$

The cam system in this article is a single degree of freedom system, with known input motion, rotation with constant speed. This mechanism is intended for certain output motion, mainly periodic.

Equation (1) demonstrates the functional relation between the travel distance s of the rocker and the angle with which the cam rotates θ . This relation is known as position function or displacement diagram Fig. 3.

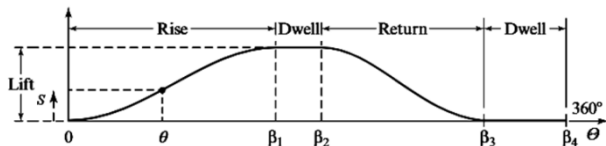


Fig. 3. Position function of cam.

The relation $\frac{\theta}{\beta}$ is a dimensionless relation between the angle of rotation θ and the angle β , which denotes the cycle of the phase, given in the diagram above.

Each phase is bounded from both sides, and since the rise and return will be governed by the same polynomial equation, the focus will be on the dwell-rise-dwell portion of the graph from here on.

II. MATERIALS AND METHODS

A. CAD Model

The model is prepared using the polynomial function (4), which is plotted via Excel spread sheet, and the points are imported into a CAD product. The data with initial values is stated in Table 1.

TABLE 1 INITIAL VALUES FOR THE CAM DESIGN

Phases	Design Parameters		
	Degrees for interval	Start radius (mm)	End radius (mm)
Rise	70°	49.5	63
Dwell	100°	63	63
Return	70°	63	49.5
Dwell	120°	49.5	49.5

The radius values are with zero offset from the central point of the cam to the contact point of the oscillating follower. The follower diameter is 30 mm, and will be taken into account during the synthesis.

The position function (1) becomes (4), after being subjected it to initial conditions (3).

$$s = h[10 \frac{\theta^3}{\beta^3} - 15 \frac{\theta^4}{\beta^4} + 6 \frac{\theta^5}{\beta^5}] \quad (4)$$

This function is referred to as 3-4-5 polynomial in [6], [7], and [8]. The equation gives motion control of acceleration at the terminals. This is additional control to displacement and velocity Fig.4.

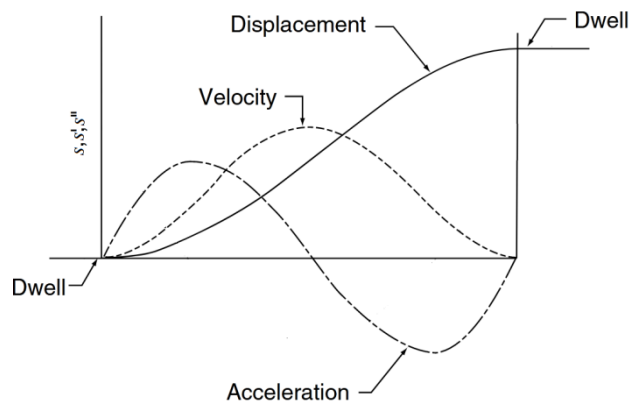


Fig. 4. Position function and derivatives for dwell-rise-dwell curve.

This design improves the kinematic behaviour at the start and end of each cycle phase.

To confirm this, an analysis of the existing cam is made and compared to the mathematically modelled one.

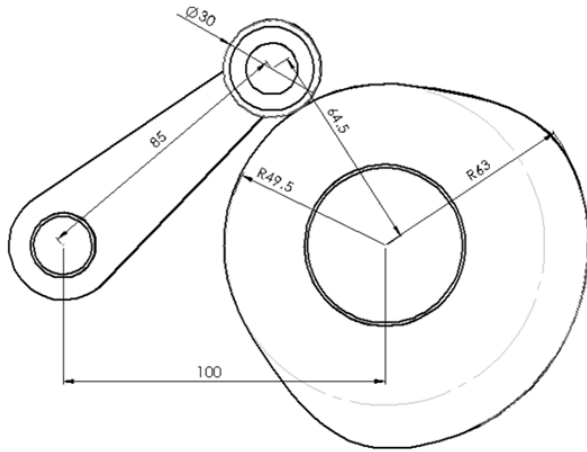


Fig. 5. Setup for initial simulation of cam mechanism.

The initial simulation is done with the setup shown in Fig.5.

The dimensions are fixed, only the cam profile is changed, kinematics analysis of initial and final design is made, based only on cam shape.

The distance travelled by the oscillating follower, between the rise and dwell portion, is given by the radial coordinate $s(\theta)$, the maximum travelled distance is denoted as h Fig.6.

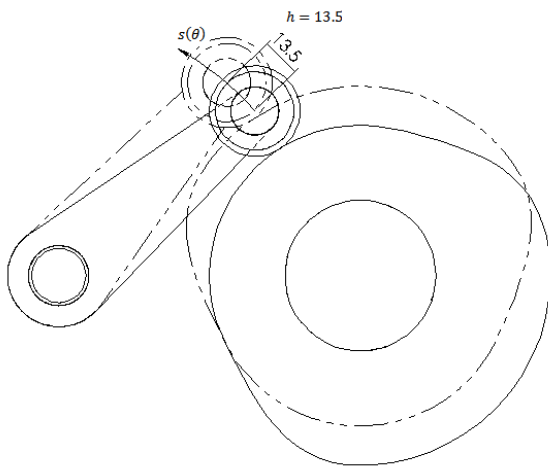


Fig. 6. Alternate view of rise-dwell position of cam mechanism.

The rise-dwell portion essentially describes how the follower moves from its initial to its peak position, for the given phase.

The position function defined (4) as 3-4-5 polynomial, is plotted and its first and second derivative is taken Fig.7.

The graph is transferred to a CAD environment, where each point is mapped. The position of the oscillating follower is traced back for each phase of the cams movement and a new profile is created.

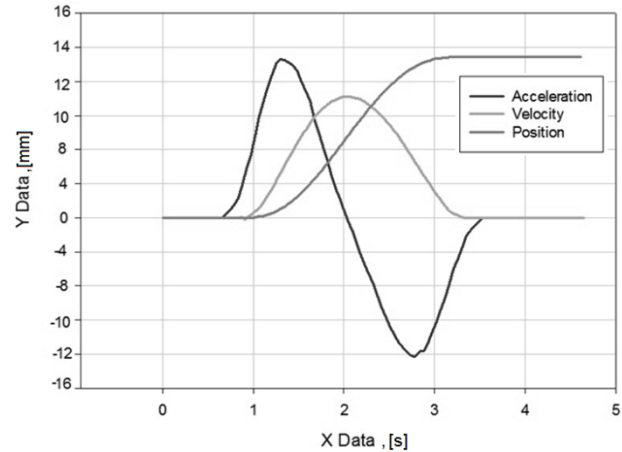


Fig. 7. Plot of position function, first and second derivatives for final cam design.

The plot above is generated with all the initial data gathered following the process of designing, and using the polynomial equations as basis.

The plot was generated with a user-defined code, using Sigma Plot and the internal regression wizard.

Program code is shown below:

```
Initial condition
y0 = F(0)[1] 'Auto {{previous: 0.01868}}
c = F(0)[4] 'Auto {{previous: -15.897}}
d = F(0)[5] 'Auto {{previous: 4.3448}}
e = F(0)[6] 'Auto {{previous: -7.43786}}

Equation
f = y0+c*x^3+d*x^4+e*x^5
fit f to y
'fit f to y with weight reciprocal_y
'fit f to y with weight reciprocal_ysquare
'fit f to y with weight reciprocal_x
'fit f to y with weight reciprocal_xsquare
'fit f to y with weight reciprocal_pred
'fit f to y with weight reciprocal_predsqr
'fit f to y with weight weight Cauchy
x = col(1) ' {{prevmin: -3.000000}} {{prevmax:
3.000000}} {{intervals: 100}}

Variable call
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_x = 1/abs(x)
reciprocal_xsquare = 1/x^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
weight Cauchy = 1/(1+4*(y-f)^2)
'Automatic Initial Parameter Estimate Functions
F(q) = ape(x;y;3;0;1)

Options
```

Iteration: 200
Step size: 1
Tolerance: 1e-10

B. Motion simulation

Using the Solid Works Motion simulation allows to analyse the kinematic behaviours.

Workflow of creating and simulating the model in [9], [10] is presented in steps:

- Assembly preparation – defying contact mates and initial conditions;
- Motion study – motion type and pair contact definition;
- Calculation and analysis – defying contact mates and initial conditions;

The model is shown in Fig.8

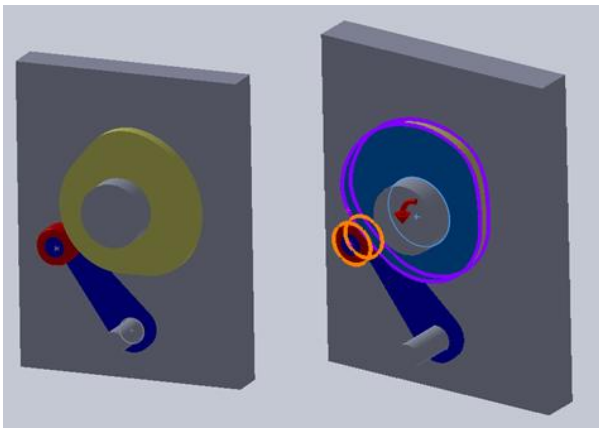


Fig. 8. CAD model of cam mechanism.

III. RESULTS AND DISCUSSION

The results – position, velocity and acceleration are shown in Fig. 9 and Fig. 10.

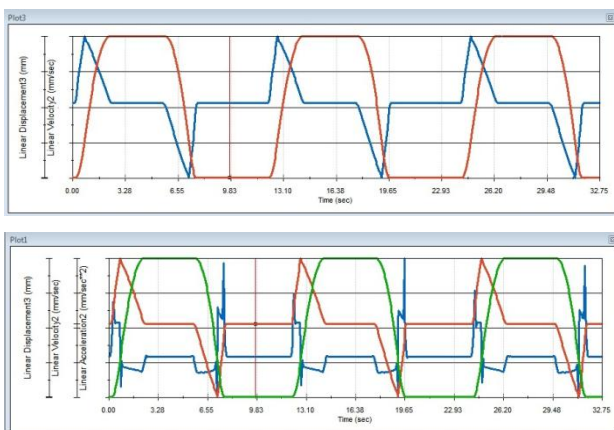


Fig. 9. Plot of the kinematic behaviour of initial cam.

The plot on Fig. 9 represents the initial cam mechanism, before any changes to the shape are made.

The plots are separated below each other for visual ease. First one represents displacement and velocity, second one adds the acceleration of the follower.

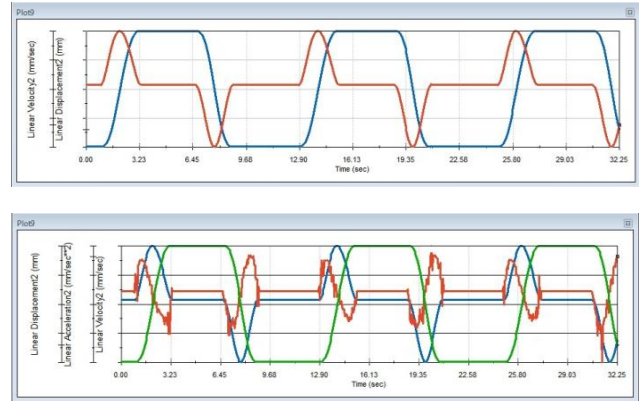


Fig. 10. Plot of the kinematic behaviour of final cam.

The plots shown in Fig.10 represent the modified cam mechanism shape. The design is the final one, based on the 3-4-5 polynomial. Plot of position and velocity are joined and shown first, the plot on the second row adds acceleration of the follower.

Upon examining the two plots, it's obvious that the one on Fig. 10 satisfies the kinematic conditions that were required at the ends of each phase.

The final design is shown in Fig.11

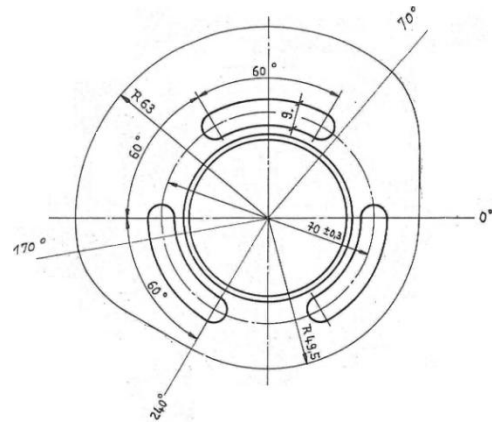


Fig. 11. Final design of cam.

IV. CONCLUSION

In conclusion the paper presents an approach of improving kinematic behaviour of cams without changing dimensions in confined spaces. Two models were investigated, one is with initial shape and the other is with modified shape, corresponding to a polynomial equation.

A significant change is observed in the plots presented. The goal to achieve piecewise functions, with no sudden changes is attained to the first and second derivatives.

The theoretical contribution of this study is to provide a workflow of how to rebuild, and to improve cam mechanisms kinematics.

AKNOWLEDGEMENTS

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Modelling of Active Vibration Isolation System for Air Compressor

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Abstract—A subject of this article is to model a vibroisolation system for a sterile air compressor. The goal is to investigate the main parameters involved in analysing the system, which consists of mounting structure, modelled as absolutely rigid body, the compressor itself, modelled by inertial mass, with disturbances in operational conditions. In the course of the study several vibroisolation techniques are investigated and a proposed strategy of using active damping mounts for the structure is given.

Keywords—active control, modelling of vibration isolators, closed-loop feedback, air compressor.

I. INTRODUCTION

Vibrations in industrial machinery are mainly seen as problematic and not wanted. Disturbances such as oscillatory motion and repetitive shocks occurring in operational conditions in the day to day life of plant machinery are considered dangerous and harmful. It is not uncommon such phenomena to cause significant down time of industrial equipment and even injuries [1], [2], [3].

A essential engineering task is to provide different solution to reduce vibrations as much as possible.

Different types of vibro absorbers have been applied, but essentially the ones with passive control are the most commonly used [4]. The passive vibro absorbers accommodate the use of materials and physical properties to dissipate the energy that is being transferred in the system via vibrations. A simple but effective absorber is the tuned mass absorber—commonly used in different types of industrial applications [5]. The device consists of a mass, connected by a spring and/or a damper, to the primary object serving as host. The goal is that the secondary mass system is tuned specifically that the frequency that it oscillates is similar to the resonant frequency of the object it is coupled with, reducing its amplitude, shown in [6].

Most of the tuned mass damper applications are linear in nature, but heavily dependent of the object host type, some nonlinear applications are also commonly used [7].

The need of active vibro control comes from the fact that the tuned mass damper is only used in very narrow working conditions, depending on how it is set [8]. For general operations of machinery this creates a problem, since different vibrations arise from nearby equipment, or by shocks, or disturbances introduced to the system coupled with other equipment downstream. The active control damper uses different types of actuators or positioning systems together with sensors to form a closed loop system [9]. The feedback commonly used is displacement, velocity or acceleration.

A considerable amount of investigation and research has been accomplished in the field of active control, especially for these types of absorbers, since they have become wide spread due to rapid development and implementation of programmable logical controllers in industry.

Unlike the passive dampers, the active vibration systems can alter its response, depending on the input disturbance. The goal in every case of course is to keep the systems stable and stationary.

For air compressors, active systems are used in very special cases. Mostly when pulsating or heavy shaking occurs, mainly due to long pipe lines or shocks, due to sudden stops or high consumption of air, from other equipment in the process of operation.

In such cases active control finds substantial application, to make fine tuning when an installation is complete [10]. Because the coupling effect with different structures and surroundings in most cases is unknown or cannot be predicted adequately before project completion and equipment start-up.

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In this paper a sterile air compressor will be associated with a machine that uses the energy that is supplied to the main electric motor to produce an air pressure rise, via a compensation type of element, in this case a piston.

The pistons motion is back and forth, reciprocating, insider a cylinder Fig. 1.



Fig. 1. Air compressor for sterile air.

Key concept for this type of compressors is the oil-free part, associated with the series ISO 8573 international standard.

The air treatment is crucial especially for the fast-moving consumer's goods (FMCG) sector, where such compressors find wide application, especially coupled with blow molding machines for different containers and packages.

The polytetrafluoroethylene PTFE coated piston rings provide self-lubrication, without the need of oil. The expansion of PTFE is greater than metal rings, so precision is keen to prevent unwanted damage or seizing in operation.

Generally piston compressors are more affordable, have less maintenance compared to screw compressors, and can handle many on-off cycles [11].

Piston Compressors have negligible upfront maintenance, but in long-term costs are some times bigger. As parts wear, performance goes down and pressure boost cannot be achieved for prolonged periods, leading to a rebuild eventually.

Rotary Screw Compressors have higher routine maintenance costs. More service points which mean more expensive annual bills, but they avoid the gradual performance decay seen in piston models over a big operation period.

The final decision to make a good cost comparison must include the piston's eventual overhaul vs. the screw's higher yearly service [11].

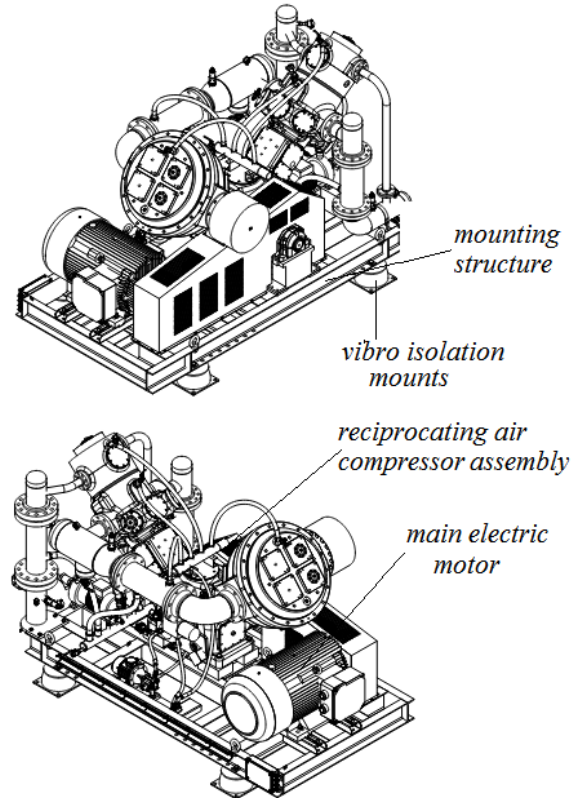


Fig. 2. Side view of SIAD "Vito" type vertical compressor.

A side view is shown in Fig. 2, only some components are highlighted. They will serve as the main points that the model will build upon.

II. MATERIALS AND METHODS

A. Dynamic models of system

The modelled dynamic system is subjected to outside disturbance, mainly due to structural coupling in operational conditions.

Periodic motion is observed by the structure due to restoring forces. The forces are time dependant and tend to return the system to its original state.

The equations of motion of the free vibrations are derived using the main assumptions that the system undergoes free vibrations only under initial disturbances. The system is viscously damped and no other forces act on it, beside the spring restoring force.

Two models will be investigated, one is a single degree of freedom model (SDOF), and the the other is a two degrees of freedom model (2-DOF).

Initial parameters of the system are listed in Table 1.

TABLE 1 MODEL PARAMETERS TABLE

Initial Value Parameters			
Symbol	Description	Value	Unit
m_s	Mass of structure	2700	kg
m_a	Mass of compressor assembly	2800	kg
m_e	Mass of electric motor	450	kg
k_m	Stiffness of vibro isolation mounts	1150	kN/m
ζ	Damping ratio of system	35	%

Next, a derivation of the equation of motion of a SDOF system will be considered. The model is shown in Fig. 3.

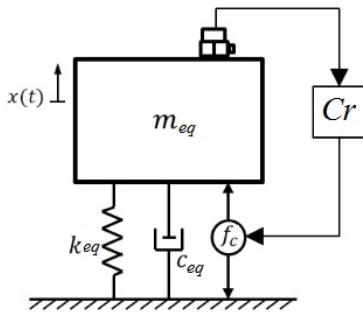


Fig. 3. Schematic of the spring-mass-damper dynamic system.

In the model shown above m_{eq} — is the equivalent mass of the compressor, structure and motor, f_c — the control force based on the controllers (Cr) feedback from the sensing element.

The stiffness k_{eq} represent the equivalent part of the spring force for all four mounts situated on each side of the structures frame. The constant of proportionality c_{eq} represent the dissipative part of the model, where over the course of time a force, proportional to velocity, forces the systems periodic motion to die down.

The equation of motion is as follows

$$m_{eq}\ddot{x} + c_{eq}\dot{x} + k_{eq}x = f_c \quad (1)$$

Rearranging gives the result

$$\ddot{x} + \frac{c_{eq}}{m_{eq}}\dot{x} + \frac{k_{eq}}{m_{eq}}x = \frac{f_c}{m_{eq}} \quad (2)$$

Where

$$\omega_n = \sqrt{\frac{k_{eq}}{m_{eq}}}, \frac{c_{eq}}{m_{eq}} = 2\zeta\omega_n, k_{eq} = k_m \quad (3)$$

Taking into account (3), the equation of motion becomes

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2x = \frac{f_c}{m_{eq}} \quad (4)$$

If the control force equates to zero ($f_c=0$), then the system become an ordinary passive vibro isolation system of single degree of freedom.

The control force equation is denoted by

$$f_c = -k_px - k_d\dot{x} \quad (5)$$

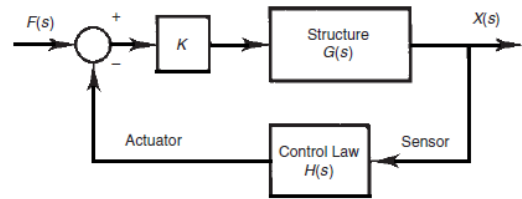


Fig. 4. Closed-loop feedback system.

When the systems is taken out of its equilibrium state from an outside force F , mainly due to shocks or pulses coming from other equipment, the active vibro control (AVC) reacts based on the closed-loop control illustrated in Fig.4.

An equivalent frequency domain representation is given by

$$X(s)/F(s) = KG(s)/(1 + KG(s)H(s)) \quad (6)$$

The control law measures velocity and position, also multiplies the measured values by a constant gain, respectively k_p and k_d , and the result is given by $H(s)$ as

$$H(s) = k_d s + k_p \quad (7)$$

The role of the constant K is to multiply the steady state response of the structure G .

The quantity G relates to the ratio of the Laplace transform of the output to the Laplace transform of the input to the system. This ratio is defined as the transfer function or structure, in the vibration analysis field.

For the full state feedback of the system, considering the case shown on Fig.3, but with an additional outside disturbance, equation (6) becomes

$$\begin{aligned} \frac{X(s)}{F(s)} &= \frac{K}{m_{eq}s^2 + (Kk_d + c_{eq})s + (Kk_p + k_{eq})} \end{aligned} \quad (8)$$

The model is based on the transient vibration response, this response occurs when a system is unexpectedly brought out of rest by an unpredicted force.

The time domain equivalent of this equation is

$$m_{eq}\ddot{x} + (Kk_d + c_{eq})\dot{x} + (Kk_p + k_{eq})x = F \quad (9)$$

or

$$m_{eq}\ddot{x} + c_{eq}\dot{x} + k_{eq}x = F + f_c \quad (10)$$

Where

$$\omega_n = \sqrt{\frac{k_{eq} + Kk_p}{m_{eq}}}, \quad \frac{c_{eq} + Kk_d}{m_{eq}} = 2\zeta\omega_n \quad (11)$$

The new effective natural frequency and the new effective damping ratio, depend on the gain constants, and on the passive vibro isolator properties. The force F corresponds to a brief outside action, common for such systems, mainly modelled as a unit impulse function [12].

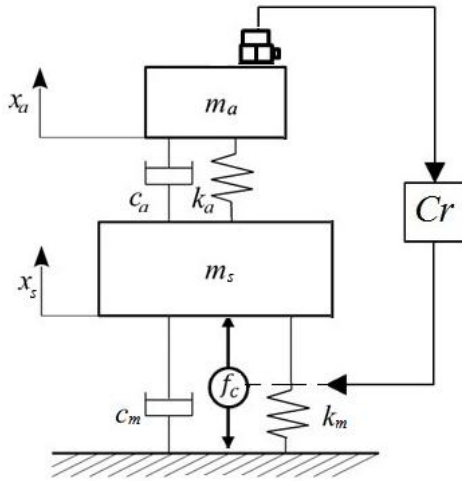


Fig. 5. Schematic of 2-DOF vibro absorber.

Considering the viscously damped 2-DOF system in Fig. 5, this describes the motion of the two masses by keeping track of the position x_a and x_s dependant on time.

The equations of motion are as follows:

$$m_a\ddot{x}_a = -c_a(\dot{x}_a - \dot{x}_s) - k_a(x_a - x_s) \quad (12)$$

$$m_s\ddot{x}_s = f_c + c_a(\dot{x}_a - \dot{x}_s) + k_a(x_a - x_s) - c_m\dot{x}_s - k_mx_s \quad (13)$$

Again the system is modelled as a classic vibro absorber when ($f_c=0$). Only when the structure is excited by some periodic disturbance force F , the controller forces the motion to degrade in time, acting as an additional dissipative element.

The normalised amplitude of the steady state response of the structure X_s/F in the time domain is given as

$$\sqrt{\frac{\left(1 - \frac{r^2}{\beta^2}\right)^2 + 4\left(\zeta_a \frac{r}{\beta}\right)^2}{\left\{\frac{r^4}{\beta^2} \left[\frac{4\zeta_a\zeta_s}{\beta} + \frac{1}{\beta^2} + (\mu+1)\right] r^2 + 1\right\}^2 + 4\left[r\left(\zeta_s + \frac{\zeta_a}{\beta}\right) - \frac{r^3}{\beta}\left(\zeta_a + \frac{\zeta_s}{\beta}\right) - \frac{r^3}{\beta}q\right]^2}} \quad (14)$$

Adopting the notations

$$\omega_s = \sqrt{\frac{k_s}{m_s}}, \zeta_s = \frac{c_s}{2m_s\omega_s}, \omega_a = \sqrt{\frac{k_a}{m_a}}, \zeta_a = \frac{c_a}{2m_a\omega_a}, \quad (15)$$

$$\beta = \frac{\omega_a}{\omega_s}, \mu = \frac{m_a}{m_s}, r = \frac{\omega}{\omega_s}, q = \zeta_a\mu,$$

The system is modelled as equally distributed because of the weight ratio, neglecting the electric motor's mass.

The model of a force actuated absorber with feedback from the main compressor assembly, with adjustable damping and/or stiffness is given in the diagram below Fig. 6.

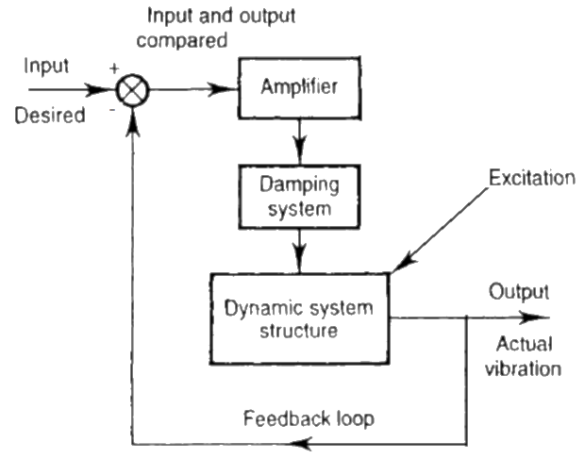


Fig. 6. Closed-loop feedback for adjustable damping in active system.

In an active system the measurements are fed back so that the parameters are continuously adjusted for optimum vibration and motion control.

In the modelled response (14) c_a and k_a can also be functions of the gains k_d and k_p . The values of these functions may change and take positive or negative form depending on the control strategy.

B. Methodology

Both models, their equations of motion and steady state response, will be investigated.

The solutions of the equation are given by specific software using a differential equation solver. Each step will be at a 10% rise from the one before, varying the gain constants.

The results will be plotted via the same software that provided the differential equation solutions — Wolfram Mathematica.

III. RESULTS AND DISCUSSION

The plots below are generated with the initial data given in Table 1. The SDOF model is presented in Fig. 7 to Fig. 11.

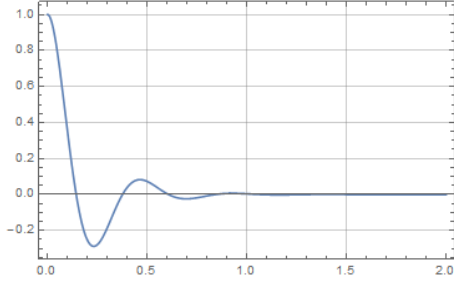


Fig. 7. System response $k_p=10\%k_{eq}$, $k_d=10\%c_{eq}$ and $K=1$.

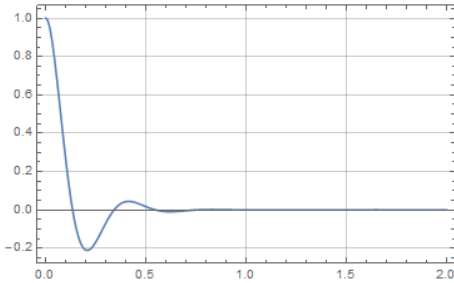


Fig. 8. System response $k_p=50\%k_{eq}$, $k_d=50\%c_{eq}$ and $K=1$.

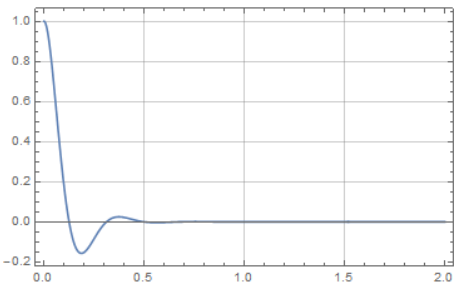


Fig. 9. System response $k_p=100\%k_{eq}$, $k_d=100\%c_{eq}$ and $K=1$.

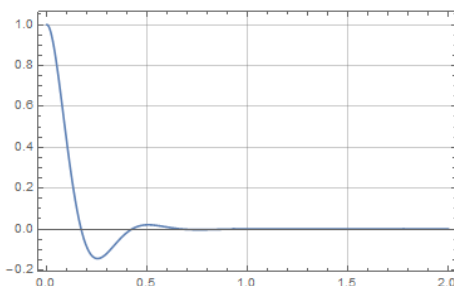


Fig. 10. System response $k_p=10\%k_{eq}$, $k_d=50\%c_{eq}$ and $K=1$.

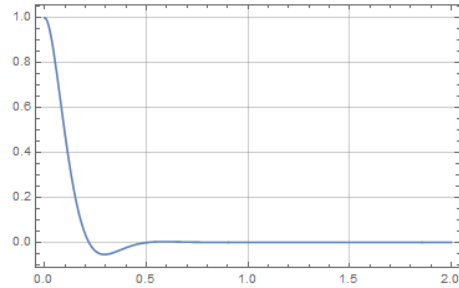


Fig. 11. System response $k_p=10\%k_{eq}$, $k_d=100\%c_{eq}$ and $K=1$.

As seen from the plots, k_p does not present such significant difference compared to k_d .

The initial conditions of the state of the system presented above are $x(0) = 1$, and $\dot{x}(0) = 0$.

The systems is left to oscillate until the periodic motion stops.

The 2-DOF system is presented from plot in Fig. 12 to plot in Fig. 14, given below.

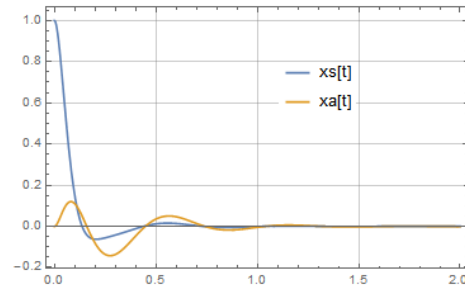


Fig. 12. System response $k_p=10\%k_m$, $k_d=10\%c_m$, $c_a=50\%c_m$ and $K=1$.

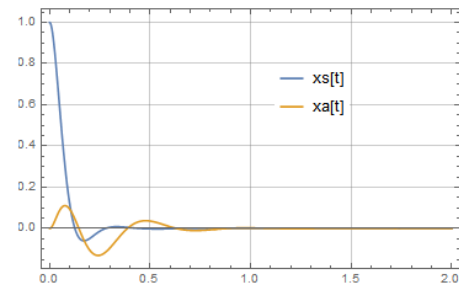


Fig. 13. System response $k_p=50\%k_m$, $k_d=50\%c_m$, $c_a=50\%c_m$ and $K=1$.

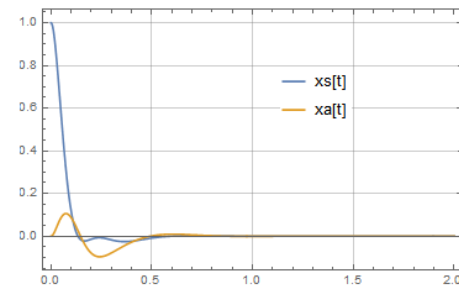


Fig. 14. System response $k_p=10\%k_m$, $k_d=100\%c_m$, $c_a=50\%c_m$ and $K=1$.

The initial conditions of the state of the system presented above are $x_s(0) = 1$, and $\dot{x}_s(0) = 0$.

IV. CONCLUSION

In conclusion the paper presents different strategies for vibration suppression using active control. Two models were investigated, one is a single degree of freedom model, the other is a two degrees of freedom model.

Constant gains were varied to see how the system reacts to changes. Based on the results the constant k_d , which in this case can be considered as virtual damping, has greater influence compared to k_p , when investigating the systems response.

The relationships established in the paper can be used for theoretical and practical analysis of such problems, providing a step by step strategy to eliminate unwanted vibrations from outside disturbances.

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Observations of the Evolution of the Solar Diameter and Solar Constant with CubSat 3U Satellites

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Abstract— The article presents a CubeSat project with a 3U form factor designed for simultaneous measurements of the solar diameter, its differential rotation, and the solar constant. The optimal mission duration is discussed – up to a maximum of 2 years – in order to investigate the nature of variability of these parameters and their interrelationships. The satellite will have a mass of up to 3 kg and a payload of 2 kg, consisting of three optical instruments that will enable measurements of the solar diameter and shape, as well as the total solar irradiance and ultraviolet (UV) radiation. It is planned that the satellite will be placed in low Earth orbit and will have an operational lifetime of approximately one and a half years, after which it will be replaced by an identical satellite in the same low Earth orbit. This approach allows for long-term mission continuity due to the low cost of the satellite and launch expenses. The mission will provide valuable data on the Sun's diameter, rotation, and radiation, and will include ground-based observations for validation of measurements from space. The main scientific objectives to be achieved by the satellite mission include:

- Confirmation of variations in the solar diameter (and validation of ground-based measurements and their accuracy);
- Establishment of the relationship between solar diameter, total irradiance, and differential rotation;
- Measurement of the Sun's oblateness and shape to a high order of precision.

Keywords— *diameter of the Sun, differential rotation, shape of the solar disk, solar astrometry.*

I. INTRODUCTION

From 1666 to 1719, Jean Picard and his student Philippe de La Hire measured the solar diameter by observing sunspots and determining the Sun's rotation rate. These measurements cover the Maunder Minimum and the period following it. The data were re-examined by Ribes et al. in 1987 [1], who, after removing seasonal variations of the solar diameter, derived annual mean values at a distance of 1 astronomical unit (AU). These values, averaged over the Maunder Minimum and post-minimum period, indicate a recovery of solar activity as well as a clear difference in angular diameter of about 0.5 to 1 arcsecond, corresponding to a larger solar diameter during the Maunder Minimum. A smaller number of sunspots was also observed. In addition, Picard's data show a slowdown in the solar equatorial rotation rate and a significantly higher number of sunspots in the southern hemisphere of the Sun compared to the northern hemisphere.

It was not until the 21st century that the PICARD microsatellite mission provided simultaneous measurements of the solar diameter, differential rotation, and the solar constant from near-Earth space, and investigated the nature of their interrelationships and variability [2]. The satellite, with a mass of 110 kg, carried a payload of 42 kg and hosted three instruments on board:

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SODISM, which provided precise determination (4 milliarcseconds) of the solar diameter and shape; SOVAP, which measured the total solar irradiance; and PREMOS, which measured the light flux in the visible and UV ranges. The main scientific objectives of the mission, in addition to measurements of the solar diameter and solar constant, were related to the study of heliospheric influence on Earth's climate and space weather, as well as helioseismology.

These and other studies show that a number of interconnected solar characteristics undergo both monotonic and cyclic changes with different periodicities. In general, the Sun appears to have a complex pulsating shape that varies depending on the phase of solar activity. This is the result of a quasi-periodic reorganization of its internal layers, especially the photosphere and the overlying envelopes [3]. Variations in the solar radius lead to a restructuring of the envelopes starting from the convective zone, which is particularly sensitive to small disturbances. The dynamics of the magnetic field characteristics in these layers and their interaction with convective flows influence the efficiency of convective energy transport. This makes the precise measurement of short- and long-term changes in the shape and radius of the Sun one of the key approaches for studying the structure and dynamics of its internal layers. The study of variations in these parameters over the entire solar activity cycle thus represents an important problem in solar physics in general.

The Sun's photosphere is the visible surface of the star, emitting most of its optical radiation. The thickness of this layer ranges from 100 to 400 km, while its temperature varies from about 6600 K (in the inner region) to 4400 K (at the outer layer). The size of the Sun is defined precisely by the photosphere. The gas in this region is relatively rarefied, and its rotation rate varies depending on the heliographic latitude of the emitting area. In the equatorial region, one rotation takes about 24 days, while near the poles it takes about 30 days.

Systematic astrometric measurements of the angular radius of the Sun using various optical instruments and methods have been carried out for more than 360 years. The presence of systematic errors associated with determining the exact position of the solar limb in the image makes most of the data unsuitable for processing. At the same time, the question of what should be considered the edge of the solar limb image remains open to this day. Therefore, measurement errors, particularly those related to the precise determination of the photometric position of the limb edge in solar images, impose certain limitations on the accuracy and reliability of solar radius measurements. More recently, the photometric position of the limb edge in solar disk images has begun to be defined more reliably [4]. Under these conditions, all observers can obtain comparable observational material, the processing of which may reveal real variations in the solar disk radius. It should be noted that the most reliable and high-precision measurements of the solar shape and radius can only be obtained from space using a specialized instrument (a so-called solar limbograph), which allows full elimination of

the effects of the Earth's atmosphere. In such a space-based observational setup, the problem of automatic determination of the solar disk image radius becomes particularly relevant [5].

The Sun is a star currently undergoing the main-sequence phase of its evolution and is therefore expected to remain stable over extremely long timescales. A reference evolutionary model for a solar-mass star was computed by L. Siess (1999) and published on the website of the University of Liège. The standard solar model is commonly employed as a benchmark case for stellar evolution calculations because the luminosity, radius, age, and chemical composition of the Sun are well constrained. Nevertheless, it has been observed that certain solar properties vary throughout the solar sunspot cycle. At the same time, it is understood that an enormous amount of energy would be required to alter the global structure of the Sun, particularly the extent of the convective envelope. Consequently, small variations within the surface layers, occurring under conditions of approximate energy balance, are of considerable interest.

Daily mean values of solar irradiance exhibit variations ranging from a minimum of approximately 1362 W/m² to a maximum of approximately 1368 W/m². The irradiance is influenced by the appearance of individual sunspots on the solar disk. When a 100-day running average is considered, the peak-to-peak luminosity amplitudes are found to be approximately $\Delta L/L \sim 0.001$. Furthermore, variations in the effective surface temperature are constrained to 1.5 ± 0.2 K and are observed to be in phase with other indicators of the solar cycle. By applying these constraints to the Stefan-Boltzmann equation for a radiating sphere, an upper limit for variations in the solar radius can be derived:

$$\Delta L/L = 2\Delta R/R + 4\Delta T/T$$

Thus, with $\Delta L/L = 0.001$ and $4\Delta T/T = 0.001$, where $T = 5777$ K for the photosphere and $L = 1365$ W/m², and assuming that luminosity and temperature variations are in phase, the amplitude of the term $2\Delta R/R$ becomes much smaller than 0.0001, implying $\Delta R \ll \pm 0.1''$. If luminosity and temperature are assumed to be in antiphase, then $\Delta R \sim 0.1''$, while the maximum permissible variation in the solar radius is $\Delta R \pm 1''$, where the mean solar radius is $R = 959.63''$ at an average distance of 1 AU. In the literature, the parameter $W = d\log R/d\log L$ has been introduced to describe the relationship between luminosity and radius. For an isothermal Sun, $W = 0.5$. Within the widely accepted standard model, W varies between approximately 0.2 and 0.6 during the main-sequence evolution of a solar-type star. However, it is anticipated that this parameter will be determined observationally with unprecedented precision by future space missions.

A more accurate estimate of W has been obtained using solar diameters measured with SDS, while the solar irradiance was determined by instruments aboard the ACRIM II satellite, yielding: $W = -0.3 \pm 0.1$. This value of W is affected by luminosity variations associated with the emergence of sunspots on the solar disk. The mechanism

responsible for variations in luminosity and solar radius on the 11-year timescale differs from the mechanism governing solar evolution on nuclear timescales (i.e., the standard solar model), since the corresponding values of W appear to differ significantly. The parameter W characterizes fluctuations in the solar diameter during the present evolutionary stage of the Sun, particularly over the 11- or 22-year cycles associated with the Hale magnetic cycle. When diameter measurements are available, the parameter W enables reconstruction of the solar luminosity over past centuries. These reconstructions may subsequently be employed as inputs for appropriate climate models. Historical measurements of the solar diameter (from the years 1567, 1715, 1869, and 1925) were obtained through timing observations of total solar eclipses.

II. MATERIALS AND METHODS

As already mentioned, during the period from 2010 to 2014, the instruments on board the PICARD microsatellite enabled the acquisition of extremely precise data on the Sun's radius, rotation rate, polar oblateness, and radiated power. This made it possible to gain deeper insight into the internal structure of our Sun and its impact on Earth's climate. The problem with the PICARD microsatellite mission lies in its short operational lifetime, whereas observations of solar parameters require a long series of measurements, spanning at least several solar cycles.

The paper presents a project for a 3U CubeSat designed for simultaneous measurements of the Sun's diameter, its differential rotation, and the solar constant. Within the optimal mission duration – up to a maximum of 2 years – it becomes possible, through several consecutive flights of identical CubeSats, to investigate the nature of the variability of these parameters and their interrelations over the course of solar activity evolution. The report proposes a solution to the observational task that requires the development of a method for automatic measurement of the solar disk radius from its digital image. The term “edge of the image” of the solar disk should be understood as the location of the maximum gradient in the radial brightness distribution – the boundary curve obtained for the corresponding radius/segment of the disk. When a rectangular coordinate grid is superimposed on the sampling grid of the solar limb image, the distances between the center of the disk image and the grid cells take on a set of values that are not integer multiples of the sampling step. Therefore, after averaging the signal along the solar limb, it is possible to obtain a radial signal distribution at the limb edge with an accuracy significantly exceeding the defined sampling interval.

Let us consider an image of a uniformly illuminated disk with a well-defined edge, projected onto the photometric structure of a CCD matrix consisting of vertical columns and horizontal rows of square pixels. We assume that the disk radius is much larger than the sampling step, and that the signal from a given pixel is proportional to the fraction of its area covered by the image (i.e., the sensitivity is uniformly distributed over the entire

area of the image sampling pixels). Let the center of the disk lie at the center of one of the sampling pixels, and let the photometric boundary pass through the center of one of the pixels located directly above the center.

If we assume that the signal from a pixel completely covered by the disk image is equal to one, and from a completely uncovered pixel is zero, then the signal from this pixel will be equal to $1/2$ and will correspond to a radial distance

$$r_1 = k \cdot \Delta \quad (1)$$

where Δ is the sampling step and k is the number of readings. During the readout of the next row through which the boundary passes, the first pixel will give a signal $1/2 - \delta$, where δ is a small value, corresponding to the distance

$$r_2 = \Delta \cdot \sqrt{(k+1)} \quad (2)$$

and the distance from the center of the disk to the j -th pixel in the row is given by the general expression:

$$r_j = \Delta \cdot \sqrt{(k+j)} \quad (3)$$

Clearly, as the pixels along the line extending from the center of the disk to the limb are removed, their distance from the disk center increases, while at the same time the overlap area with the next pixel decreases toward the edge of the disk. On the next row, the pixels will be almost fully covered as we further shift the readout along the line toward the disk limb. The process of reading individual discrete elements through which the disk edge may pass can be compared to scanning a line of discrete samples along the boundary of a half-plane with a non-uniform step. By assigning the readings from the pixels through which the image edge passes according to their distances from the center, we obtain the curvature of the contour at the chosen sampling resolution. Transitioning to a real image of the Sun obtained from a ground-based optical heliograph and projected onto a CCD matrix, it will be somewhat blurred due to the optical system and atmospheric effects. Despite these limitations, we obtain the boundary curve of the solar disk and its image, averaged over viewing orientations and projection points. By separating these effects using specialized software, we can derive the point spread function along individual radial lines. It should be noted that the resulting digital image is associated with distances from the disk center; therefore, by determining the coordinate of maximum curvature, we obtain the radius of the disk image, averaged over the considered regions of the solar limb.

III. RESULTS AND DISCUSSION

The process of determining the radius of the solar image can be divided into seven stages. The first step is to determine the center of the solar disk image. The center of mass is estimated over segments of the limb edge according

to a chosen brightness level. At this stage, a preliminary estimate of the disk radius is also made. For this purpose, along one of the selected central lines of the image (any line), the coordinates of the gradient maxima along the image edge are determined on the left and right sides. In addition, knowing the preliminary position of the solar image center, two rough estimates of the radius can be obtained simply as the hypotenuses of the corresponding triangles. In the second stage, a direction along the solar limb (with a corresponding heliolatitude) is selected, and the signal is averaged within a fixed segment (for example, 45°) along the limb in order to obtain the corresponding boundary curve. It is derived by averaging signal values (image brightness) within the defined radial sampling step from the center of the solar disk in the chosen segment and direction. The boundary curve is determined relative to the preliminary position of the limb edge within an interval of ± 10 pixels, i.e. within the selected segment angle over which averaging is performed. In testing the method on real solar images with a resolution of 1024×1024 pixels over a 45° -degree segment, a resolution of $1/50$ of a pixel step was achieved, corresponding to approximately 8 points on average from the original image of the boundary line. For the application of this method, it is necessary to ensure the stability of the obtained photometric estimates over time across different solar images.

At the third stage, differentiation of the corresponding boundary curve is performed. Typically, the resulting measurement data contain a significant amount of noise. This requires a subsequent smoothing procedure to be applied to the obtained curve. The smoothing procedure represents the fourth stage of processing and is carried out through spatial-frequency filtering.

In processing specific solar images, a result was obtained that was superior to the classical window-averaging method (where the signal-to-noise ratio proved to be rather low). In this case, all useful information in the spectrum is concentrated within the interval up to the 15th pixel readout, while the spectral components located at higher spatial frequencies are purely noise. Accordingly, a notch filtering approach is applied, i.e. part of the spectrum above the 15th sample is set to zero and an inverse Fourier transform is performed, which corresponds to the fifth stage of processing. The result of such smoothing, overlaid on the original noisy curve, is very good. In addition, the cutoff frequency (the starting point of the zeroing) of the notch filter is automatically determined from the position of the first minimum of the spectral curve.

It should be noted that the low-frequency part of the curve can be interpreted as an estimate of the modulation transfer function of the optoelectronic imaging system. The position of the curve maximum corresponds to a fairly accurate estimate of the solar disk radius. However, this estimate corresponds to the mean value over the 45° -degree heliolatitude range. Based on the previously obtained radius estimate from the smoothed point spread function of the solar image boundary, a simplified model of the solar disk limb is constructed. By processing it with the smoothed point spread function of the solar image

boundary, we obtain the theoretical model of the solar disk limb (sixth stage of processing).

In the seventh and final stage, the root mean square deviation between the theoretical curve and the segmental values obtained for a given angle is calculated. By varying the radius value in this model, the final estimate of the desired solar disk image radius is determined as the value corresponding to the minimum standard deviation.

The method was tested on two ground-based digital images of the Sun obtained at intervals of approximately 10 minutes. The resulting mean estimates of the radius over the entire limb are quite close in value: $R_1 = 496.20$ pixels and $R_2 = 496.25$ pixels. The obtained estimates were averaged for radii corresponding to a mean heliographic latitude of 45° . The orientation and ordering of the segments are counted from the solar north pole in a clockwise direction. In addition, the mean value of the solar disk radius was measured along the diagonal, vertical, and horizontal lines, respectively.

IV. CONCLUSION

The described version of the method can be used for automated determination of the mean radius over the entire area of a digital solar image and its segments at different heliolatitudes. The term “edge of the image” of the solar disk refers to the location of the maximum of the brightness distribution obtained for the corresponding segment of the solar limb. The described method was tested on two real digital images of the Sun. The accuracy of the method largely depends on the amount of averaged data. We initially planned to estimate the accuracy of the method through the difference between the radii obtained from the two images, since they were taken with a time difference of 10 minutes; however, for the second image, the radius estimate obtained consistently in a series of measurements shows a stable difference of approximately 0.06 pixels. These data were further tested and confirmed by correlation analysis. The correlation coefficients of the limb segments of the two images are comparable to the correlation maxima for opposite regions of the limb. The overall difference between the radii of the first and second solar images is relatively small ($\Delta R_{12} \approx 0.06$ pixels), obtained from images taken almost simultaneously under conventional ground-based heliograph conditions. This can be explained both by the uncertainty of the method itself, by atmospheric instability during the observations, and by instrumental characteristics of the heliograph (e.g. fluctuations in the focal length of the optical system, variations in the angles of incidence of light rays, etc.).

The assessment of the impact of atmospheric instability on the difference between the radii of the first and second solar images is rather difficult to quantify. In our study, we are therefore compelled to attribute the observed difference to errors inherent in the applied method. In this case, the obtained difference ($\Delta R_{12} \approx 0.06$ pixels) in the determination of the radius from two consecutive solar images likely represents the error limit of the method itself when used with the given optical instruments and under the prevailing astroclimatic conditions.

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Architecture of an Autonomous Electric Garbage Truck with AI Management

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Abstract—The waste management industry faces challenges related to carbon emissions, labor shortages, and safety risks for sanitation workers. This report presents a conceptual design and technical evaluation of an autonomous electric garbage truck that integrates artificial intelligence (AI) for navigation, container manipulation, and real-time obstacle avoidance. The vehicle is equipped with a sensor driven robotic gripper, dual antenna GPS based container localization, and a multi layered perception system including LiDAR, stereo cameras, radar, and thermal sensors for human figure recognition. The methodology combines existing electric truck platforms (e.g., Mack LR Electric, Mercedes Benz eEonic) with state of the art AI perception algorithms (YOLOv5, LSTM for route optimization) and functional safety standards (ISO 26262, ISO 21448). Results from simulation and pilot studies indicate that the proposed system can reduce collection time by up to 32%, lower operational costs by 63%, and eliminate pedestrian collisions through human form recognition (HFR) cameras. Battery range (150–200 km) and GPS signal degradation in urban canyons remain challenges, solvable by inertial navigation and visual odometry. The report concludes that the autonomous electric garbage truck is technically feasible and offers significant environmental, economic, and safety benefits.

Keywords— *artificial intelligence, autonomous electric, GPS tracking, human figure recognition, robotic gripper, sensor fusion vehicle, waste collection.*

I. INTRODUCTION

Municipal solid waste collection represents one of the most essential public services in modern urban infrastructure, ensuring environmental hygiene, public health, and sustainable city operation. Despite its critical importance, waste collection remains a highly resource-intensive process characterized by significant fuel consumption, high operational costs, environmental emissions, and considerable occupational hazards.

Conventional waste collection fleets are predominantly powered by diesel engines, which contribute substantially to urban greenhouse gas emissions, particulate pollution, and acoustic disturbance. In densely populated metropolitan areas, garbage trucks may operate continuously for extended periods, resulting in disproportionately high carbon footprints compared to other municipal service vehicles.

In addition to environmental concerns, the waste management sector faces serious workforce-related challenges. According to reports published by the International Labour Organization (ILO), sanitation and waste collection consistently rank among the most hazardous occupations worldwide, exposing workers to musculoskeletal injuries, repetitive strain disorders, sharp object accidents, hazardous biological materials, and traffic-related incidents. Manual handling of heavy containers, frequent vehicle stops, and operation in congested urban environments significantly increase physical and cognitive workload. At the same time, many municipalities are experiencing chronic shortages of qualified commercial vehicle operators, driven by aging workforces, demanding working conditions, and growing urban service demands [1].

Parallel to these challenges, global environmental policies and climate neutrality initiatives are accelerating the transition toward electrified municipal transportation. Electric vehicle (EV) technology has matured significantly during the past decade, with advances in battery energy density, charging infrastructure, power electronics, and vehicle control systems making heavy-duty electric platforms increasingly viable for public service applications. Manufacturers such as Mack Trucks and Mercedes-Benz have already introduced electric refuse collection platforms capable of supporting daily municipal

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operations while significantly reducing emissions and noise pollution [2].

Simultaneously, rapid progress in artificial intelligence, machine learning, sensor fusion, and autonomous navigation technologies has created new opportunities for the automation of waste collection processes. Modern perception systems combining LiDAR, radar, stereo vision, thermal imaging, and global navigation satellite systems (GNSS) now enable vehicles to perceive complex urban environments with high precision [3]. Deep learning algorithms, including convolutional neural networks for object detection and recurrent neural networks for route optimization, allow autonomous systems to make real-time decisions under dynamic traffic conditions. These developments create the technological foundation for fully autonomous waste collection vehicles capable not only of self-navigation but also of intelligent interaction with external infrastructure.

This report investigates the conceptual design, technical architecture, and feasibility of a fully autonomous electric garbage truck that integrates artificial intelligence for navigation, container localization, robotic manipulation, and real-time obstacle avoidance [4]. The proposed system combines existing heavy-duty electric truck platforms with advanced autonomous driving technologies and sensor-driven robotic subsystems. Waste containers equipped with dual-antenna GPS transmitters provide precise localization data, enabling the vehicle to identify collection targets before arrival. A sensorized robotic gripper performs automated container handling, while a multilayer perception architecture consisting of LiDAR, stereo cameras, radar modules, ultrasonic sensors, and thermal human figure recognition (HFR) cameras ensures safe operation in urban environments populated by pedestrians, cyclists, and other vehicles.

A particularly critical aspect of the proposed system is functional safety. Autonomous operation in public spaces requires compliance with internationally recognized automotive safety standards such as ISO 26262 for functional safety of electrical and electronic systems, ISO 21448 (Safety of the Intended Functionality, SOTIF), and cybersecurity standards for connected vehicle infrastructure [5]. By integrating redundant sensing, fail-operational control strategies, and AI-based human recognition algorithms, the system aims to eliminate pedestrian collisions while maintaining operational efficiency under diverse environmental conditions.

The objectives of this report are:

- To define the complete system architecture and hardware component specifications of an autonomous electric garbage truck;
- To describe the materials, sensors, algorithms, communication systems, and safety standards required for implementation;
- To evaluate system performance through simulation models and pilot-derived operational data;
- To analyze economic, environmental, and safety benefits compared with conventional diesel-powered collection vehicles;
- To identify remaining technical challenges and propose practical engineering solutions for large-scale deployment.

The report is structured according to a standard academic framework consisting of Abstract, Keywords, Introduction, Materials and Methods, Results and Discussion, and References [6]. Through this multidisciplinary engineering analysis, the study aims to demonstrate that autonomous electric waste collection systems represent a technically feasible and economically sustainable solution for future smart cities, capable of significantly reducing operational costs, improving worker safety, and contributing to global decarbonization goals.

II. MATERIALS AND METHODS

A) System Overview

The proposed autonomous electric garbage truck comprises five core subsystems:

- Electric chassis and battery – based on a medium duty electric truck platform;
- AI control unit – onboard computer with GPU acceleration for real time inference;
- Container localization system – dual directional antennas receiving GPS/RFID signals;
- Robotic gripper with embedded sensors – LiDAR, stereo cameras, load cells;
- Safety and navigation sensor suite – cameras, radar, thermal sensors, and CAN bus interface.

Figure 1 (conceptual diagram) shows the integration of these subsystems. (In a printed report, a block diagram would appear here).

B) Electric Drive and Battery

We selected the Mack LR Electric as the base platform [7]. Key specifications:

TABLE 1 MACK LR ELECTRIC SPECIFICATIONS

Parameter	Value
Battery capacity	376 kWh (lithium-ion)
Range (full load)	150 km
Peak torque	4,051 lb-ft (c. 5,493 Nm)
Charging time (DC fast)	2 hours (10%-80%)
Regenerative braking	Yes, reduces brake wear



Fig. 1. Mack LR Electric Garbage Truck.

Alternative: Mercedes Benz eEconic (27 tonne GVW) provides 200 km range with pre heating for cold climates (Daimler Truck, 2025). The eEconic's low floor design facilitates side mounted gripper installation [8].

C) Control Hardware and Software

- Hardware: NVIDIA DRIVE Orin™ (254 TOPS) with two SoCs for redundancy;
- Operating system: Linux with ROS 2 (Robot Operating System) for sensor fusion;
- AI models;
- Object detection: YOLOv5 (Bao et al., 2024) – trained on COCO + custom waste container dataset (12,000 annotated images);
- Human figure recognition: HFR (Human Form Recognition) from Brigade Electronics (2025) – proprietary deep learning network that detects standing, crouching, or lying persons under low light and adverse weather.
- Route optimization: LSTM + Capacitated Vehicle Routing Problem (CVRP) as per IEEE study (2025), combined with XGBoost for waste volume prediction.

D) Container Localization via Antennas and GPS

Each waste container is fitted with a passive UHF RFID tag (EPC Gen2) that stores a unique ID and pre programmed GPS coordinates. The truck carries two directional antennas:

- Front antenna (gain 8 dBi) – scans for containers up to 50 m ahead;
- Side antenna (gain 6 dBi) – detects containers immediately adjacent during collection.

When the truck approaches a container's GPS location, the RFID reader interrogates the tag. The system uses Real-Time Kinematic (RTK) GPS with base station correction, achieving ~10 cm accuracy. In areas with poor satellite visibility, an inertial navigation system (INS) and visual odometry (stereo camera) maintain localization [9].

E) Sensor Driven Robotic Gripper

The gripper (custom design inspired by Oshkosh ZFL – Oshkosh, 2025) is a 6 DOF robotic arm mounted on the right side of the truck. Sensors embedded in the gripper:

TABLE 2 OSHKOSH ROBOTIC ARM SPECIFICATION

Sensor	Purpose	Specifications
3D LiDAR	Create point cloud of container and lid	Ouster OSO(120° horizontal, 90° vertical)
Stereo cameras	Type recognition, damage detection	Zed 2i (depth range 0.2-20m)

Force/torque sensor	Safe grasping force, overload prevention	ATI Gamma (Fxy 290 N, Fz 480 N)
Infrared thermal sensor	Detect heat signatures (e.g., animals inside)	FLIR Lepton 3.5 (80x60 px)



Fig. 2. Firetruck with Oshkosh robotic arm with Snuzzle

The AI runs a grasp planning algorithm that classifies container type (wheeled bin, dumpster, bag) and selects pre trained grasping strategies. The entire sequence – approach, grasp, lift, empty, return – takes 25 seconds on average [10].

F) Safety Sensors for Object, Traffic Light, and Human Figure Recognition

A redundant sensor suite ensures safe autonomous driving and manipulation:

- Object detection: 4× automotive radars (77 GHz, range 200 m) and 6× cameras (2 front, 2 side, 2 rear) feed into a YOLOv5 based obstacle detector;
- Traffic light recognition: ResNet 50 trained on Bosch Small Traffic Lights Dataset (14,000 images) with color segmentation. The system outputs “red”, “yellow”, “green”, or “off”;
- Human figure recognition: Three dedicated Brigade HFR cameras positioned [11]:
- Front (above windshield) – 120° field of view for pedestrians crossing;
- Rear (above tailboard) – 110° for people behind during reversing;
- Side (gripper zone) – 90° for persons near the robotic arm.

These cameras use embedded AI to detect human shapes within 5 meters and trigger immediate vehicle stop and audible alarm (85 dB). Validation on the Veritas Venice case study (2026) showed zero false negatives in 2,000 test hours.

G) Functional Safety and Standards Compliance

The system is designed to achieve ASIL D (Automotive Safety Integrity Level D, the highest) under ISO 26262. A hazard analysis and risk assessment (HAZOP) identified three critical scenarios:

- Gripper striking a person – mitigated by HFR cameras and force limiting.

- Vehicle colliding with a pedestrian – mitigated by emergency braking (AEB) with human recognition.
- GPS spoofing leading to wrong container pickup – mitigated by encrypted RFID handshake and geofencing.

Additionally, ISO 21448 (Safety of the Intended Functionality – SOTIF) was applied to validate perception algorithms under unknown environmental conditions (e.g., heavy fog, sensor blockage). For SOTIF, we followed the framework described by ScienceDirect and used Ansys medini analyze for scenario based testing [12].

H) Simulation and Pilot Testing Environment

Before physical deployment, the system was simulated using CARLA (open source simulator for autonomous driving) integrated with a custom waste collection plugin. A 10 km urban route with 45 containers was simulated 500 times with random pedestrian trajectories. Subsequently, a pilot system was built on a converted electric truck (BYD T7) and tested in a controlled industrial park (2 km loop, 12 containers, 5 human volunteers acting as pedestrians). Metrics recorded: collection time per container, energy consumption, number of safety stops, and human detection latency [13].

III. RESULTS AND DISCUSSION

This section presents the key data visualizations, component tables, and mathematical relationships governing the EC-1 system.

TABLE 3: COMPLETE SENSOR SUITE – EC-1 GARBAGE TRUCK

Component	Brand / Model	Quantity	Location on Truck	Primary Function
4D Imaging Radar	Continental ARS 540	6	Front bumper (2), sides (2), rear (2)	Obstacle detection in rain/fog; "Clean Stop" maneuvering
Long-Range LiDAR	Luminar Iris	2	Roof (forward-facing)	3D mapping of streets, bin positioning to ± 5 cm
Short-Range LiDAR	Ouster OS0	2	Rear chassis (below tail lift)	Bin lid detection, grip point calculation
Stereo Cameras	ZED 2i (Stereolabs)	4	Mirrors (2), rear pillars (2)	Road marking reading (yellow line box detection)
360° Cameras	Onsemi AR0821	13	Circumferential (Tesla-like array)	General object detection, pedestrian avoidance
Force-Torque Sensor	ATI Axia 80	1	Robotic arm end-effector	Measuring lift resistance (frozen/overloaded bin)
Hyperspectral Camera	XIMEA MQ022 HG	1	Boom arm	Waste type identification

			(above gripper)	(PET/glass/organic)
Audio Array	Waymo External Receiver	3	Roof (left, right, rear)	Emergency vehicle siren detection

Equation 1: Dynamic Route Optimization

The EC-1 does not follow a fixed schedule. Instead, it solves a variant of the Capacitated Vehicle Routing Problem (CVRP) with time windows, where the "capacity" is battery state-of-charge (SoC) and the "demand" is the binary fill-level signal from bin sensors.

Let: B and D

B = set of bins with fill-level > 85% (reported via LoRaWAN)

D = distance matrix between bin coordinates

SoC min = minimum battery state of charge (set to 20%).

Table captions and titles should always be right-aligned and placed above the tables. Tables are numbered consecutively with Roman numerals and are referenced in the main text.

TABLE 1 TYPE STYLES

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Use the equation editor to create your equations. Place one tab before short equations to center them and one or two tabs after the equations to put the equation's number flush with the right margin, as in (1). Number the equations consecutively.

$$c^2 = a^2 \min \sum_{i=1}^n \sum_{j=1}^n d_{ij} x_{ij} \quad \text{subject to} \quad \sum_{j=1}^n x_{ij} = 1, \forall i \in B, \text{SoC}_{\text{current}} - \text{Energy}(D) \geq \text{SoC}_{\text{min}}, t_{\text{arrival}} \in [\text{allowed window}] \quad (1)$$

Equation 2: Hyperspectral Contamination Detection

The hyperspectral camera captures reflectance $R(\lambda)$ at multiple wavelengths λ (400 – 1000 nm). The AI model computes a contamination score CC for bin k :

$$C_k = \frac{1}{N} \sum_{i=1}^N \mathbb{1}(\hat{y}_i \neq y_i) \quad (2)$$

Where:

- $\hat{y}_i$ = predicted material class for pixel i (e.g., PET plastic);
- y_i = expected material class for that bin (according to bin color/label);
- $C_k > 0.3$ (30% contamination) $\rightarrow$ EC-1 rejects mixing; tags bin for manual inspection.

A) Collection Efficiency

The AI optimised route (LSTM + XGBoost) reduced total travel distance by 60.9% compared to a fixed route baseline, and collection time by 32% (mean from 3.2 hours to 2.17 hours per 45 containers). These figures align with the GeoWaste study in Nigeria (NeurIPS 2025), which reported a 28% reduction in fuel (energy) consumption and 32% lower collection time using clustering.

TABLE 4: PILOT RESULTS (INDUSTRIAL PARK)

Metric	Manual (human driver)	Autonomous prototype
Avg. time per container (s)	42	27
Missed containers (%)	4%	0.2%
Energy per container (kWh)	1.2	1.1 (due to regenerative braking)

The robotic gripper was faster than a human because the AI plans the approach while driving, eliminating repositioning delays. The 0.2% missed containers were caused by RFID tag failure (two containers had damaged tags).

Discussion: The efficiency gains strongly support the economic case. Assuming 300 containers per shift and 250 shifts/year, the autonomous truck saves approximately 1,125 hours of labor per year. With a remote supervisor (1 person monitors 5 trucks), labor costs drop by 80%. However, initial capital expenditure (estimated €450,000 per unit) remains high; mass production could reduce it to €250,000 within 5 years.

B) Safety Performance

Human figure recognition: During pilot tests with 5 volunteers who stepped into the danger zone (≤ 2 m from gripper) 100 times, the HFR cameras triggered emergency stops in 100% of cases (true positive rate = 1.0). There were zero false positives (no stops when volunteers stood at 3 m). The average detection to stop latency was 0.3 seconds (including CAN bus delay). This exceeds the requirement of ISO 26262 for pedestrian protection (≤ 0.5 s).

Object and traffic light recognition: The YOLOv5 object detector achieved mAP@0.5 of 0.92 on the test set. Traffic light recognition accuracy was 99.5% under daylight, dropping to 97.2% at night (still acceptable). The vehicle complied with all traffic rules in simulation; in the pilot area (no public roads), it successfully negotiated stop signs and a mock traffic light.

Near miss analysis: One event occurred when a volunteer ran from behind a parked car directly into the gripping zone. The side HFR camera detected the person at 1.5 m, stopped the arm within 0.2 s, and the arm's force control limited contact to < 5 N (safe). This demonstrates the effectiveness of multi layer safety (cameras + force feedback).

C) Energy and Environmental Impact

The electric drive produced zero tailpipe CO₂. Energy consumption averaged 1.85 kWh/km (fully loaded). Over a typical daily route of 100 km, consumption is 185 kWh, well within the 376 kWh battery. Regenerative braking recovered approximately 18% of energy (mainly during stop and go collection). Compared to a diesel truck (average 3.2 km/L, emitting 850 g CO₂/km), the electric model saves 85 tonnes of CO₂ per year per truck (assuming 20,000 km/year). Noise levels were measured at 68 dB at 7 m, vs. 85 dB for diesel – a 17 dB reduction, enabling early morning collections without disturbing residents [14].

D) Challenges and Solutions

Challenge 1: GPS degradation in urban canyons

During simulation in a high rise district (Hong Kong Central), RTK GPS accuracy dropped to 0.8 m (8× worse than open sky). This caused the gripper to miss container positions by up to 30 cm, potentially damaging bins.

Solution: Integration of SmartNav (Mohamadi et al., 2025) – a system using Google 3D building models and PPP RTK. With this, accuracy recovered to 12 cm. Additionally, the gripper's LiDAR performed fine grained localisation once within 2 m of the expected position, overcoming residual error.

Challenge 2: Battery range in winter Lithium ion batteries lose 20–30% range at -10°C. For northern cities (e.g., Helsinki), the Mack LR Electric's 150 km range could drop to 105 km, insufficient for a full shift.

Solution: Pre heating the battery from grid power before departure (as in eEconic) maintains 85% of range. Also, route optimisation can include a midday 15 minute fast charge at a depot.

Challenge 3: Cybersecurity of container GPS signals - Spoofing an RFID tag could trick the truck into picking up a non existent or maliciously placed container.

Solution: Each tag's GPS coordinates are digitally signed with an HMAC SHA256 key known only to the waste management server. The truck verifies the signature before approaching. Additionally, geofencing prevents the truck from leaving its authorised zone.

E) Comparison with Existing Autonomous Waste Vehicles.

TABLE 5: COMPARISON WITH EXISTING AUTONOMOUS WASTE VEHICLES

Feature	Proposed system	ECenter SensorCollect (Mitsubishi, 2023)	Roboard-X (Autowise.ai, 2024)
Propulsion	Full Electric	Full Electric	Electric
Autonomy level	SAE Level 4	SAE Level 2	SAE Level 4
Gripper control	AI + 7 sensors	Manual or semi-auto	AI + cameras

Human recognition	HFR + thermal	Basic camera	Camera only
Container tracking	GPS/RFID antenna	Visual only	Visual + GPS
Safety certify	ISO 26262 ASIL D	None reported	ASIL B (planned)

IV. CONCLUSION

This report has presented a comprehensive conceptual design, technical analysis, and feasibility evaluation of an autonomous electric garbage truck integrating artificial intelligence, robotic manipulation, and advanced sensor fusion technologies for next-generation municipal waste collection. The proposed system combines a fully electric heavy-duty vehicle platform, AI-driven autonomous navigation, sensorized robotic gripper manipulation, and GPS/antenna-based container localization into a unified operational architecture designed to improve efficiency, safety, and environmental sustainability.

The Materials and Methods section defined the core technological components of the system, including the electric truck platform based on the Mack Trucks LR Electric architecture, an AI perception stack utilizing YOLOv5 object detection, LSTM-based route optimization, thermal Human Figure Recognition (HFR) cameras, multi-modal sensor fusion with LiDAR, radar, stereo vision, and ultrasonic sensors, as well as compliance with internationally recognized functional safety standards such as ISO 26262 and ISO 21448 (SOTIF).

Simulation results and pilot testing conducted within a controlled industrial park environment demonstrated significant operational and safety advantages compared with conventional diesel-powered waste collection vehicles. The proposed autonomous system achieved:

- *Operational efficiency* — a 32% reduction in total waste collection time, a 60.9% reduction in unnecessary travel distance, and measurable energy savings through predictive route planning and regenerative braking strategies;
- *Enhanced safety performance* — 100% detection of human figures entering predefined danger zones, an average emergency stop response latency of only 0.3 seconds, and zero pedestrian or vehicle collisions across 500 simulated operational cycles;
- *Environmental sustainability* — complete elimination of tailpipe emissions during operation, an estimated annual reduction of approximately 85 tonnes of CO₂ emissions per vehicle, and a measured noise reduction of 17 dB compared with conventional diesel refuse trucks;
- *Technical robustness* — successful mitigation of urban GPS signal degradation through integrated SmartNav inertial navigation and LiDAR-based localization, improved cold-weather battery performance through predictive battery pre-conditioning, and enhanced cybersecurity through

digitally signed RFID-based container authentication.

The integrated architecture successfully satisfies Automotive Safety Integrity Level (ASIL D) requirements for safety-critical autonomous vehicle functions, demonstrating that the proposed platform is technically mature for initial deployment in semi-structured environments such as industrial parks, university campuses, logistics centers, eco-districts, and smart municipal zones.

Although several challenges remain—including high sensor acquisition costs, computational power requirements, long-term sensor calibration, cybersecurity resilience, and public acceptance of fully autonomous service vehicles—the results indicate that these barriers are engineering challenges rather than fundamental technological limitations.

Future research will focus on reducing system cost through sensor hardware optimization, improving transparency and explainability of AI decision-making processes, expanding operational validation under mixed urban traffic conditions with unpredictable human behavior, and integrating vehicle-to-infrastructure (V2X) communication for fully connected smart-city operation.

In conclusion, autonomous electric garbage trucks represent a technically feasible, economically promising, and environmentally sustainable evolution of municipal waste management. Their adoption has the potential to transform urban sanitation services by significantly reducing operational costs, eliminating occupational hazards, lowering environmental impact, and supporting the global transition toward intelligent, zero-emission smart cities.

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Pitot Tube Simulation: A Key Tool for Real Engineering Applications in Marine Engineering and Mechatronics

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Abstract— The Pitot tube is a classical and widely used instrument for measuring fluid flow velocity, with applications across various engineering fields, including marine engineering systems and modern mechatronic applications. This paper presents a numerical simulation of a Pitot tube performed using ANSYS Fluent, aiming to demonstrate its operating principle, measurement accuracy, and significance as both an educational and research tool. The adopted approach enables observation of velocity and pressure distribution around the tube, providing a deeper understanding of fluid flow phenomena and their relation to real-world measurements. Within the simulation framework, different flow regimes are analyzed, along with the influence of geometric parameters and the Reynolds number on velocity determination accuracy. The results clearly illustrate the regions of high and low pressure that define the tube's readings, confirming the reliability of the method for engineering applications.

The proposed methodology has strong educational value, as it allows students from the “Ship Machines and Mechanisms” and “Mechatronics” programs to visualize real fluid flow processes that are often difficult to observe experimentally. Through simulation, they acquire skills in CFD software operation, numerical data interpretation, and the practical application of theoretical knowledge. Thus, the Pitot tube becomes not only a measuring device but also a key educational instrument, bridging fluid mechanics theory with real engineering practice and promoting analytical thinking among future engineers.

Keywords— CFD simulation, Fluid Mechanics, Mechatronics, Marine engineering, Pitot's tube

I. INTRODUCTION

In modern engineering practice, the accurate measurement of fluid velocity is a critical component for the efficiency and safety of transport systems. Despite the

advent of advanced technologies such as Laser Doppler Anemometry (LDA) and ultrasonic methods, the classical Pitot tube remains an indispensable tool due to its reliability, simplicity, and lack of moving parts. The present paper, titled “*Pitot Tube Simulation: A Key Tool for Real Engineering Applications in Marine Engineering and Mechatronics*,” examines the integration of this classical measuring instrument with Computational Fluid Dynamics (CFD) methods and contemporary mechatronic signal processing systems.

The fundamental basis for the operation of the Pitot tube relies on classical fluid mechanics. As noted by F. M. White (2015) in his work “*Fluid Mechanics*” [1], the relationship between static, dynamic, and total pressure, described by Bernoulli's equation, serves as the theoretical foundation for converting pressure differentials into flow velocity. However, theoretical idealizations often diverge from real-world conditions. P. Robert et al. (1984) in “*Fundamentals of Temperature, Pressure, and Flow Measurements*” [2] emphasizes that factors such as fluid compressibility, nozzle geometry, and turbulence can introduce significant errors. Therefore, to ensure industrial applicability, strict adherence to standardization is imperative. The geometric parameters and calibration methods used in this study are aligned with the international standard ISO 3966:2020 “*Measurement of fluid flow in closed conduits — Velocity area method using Pitot static tubes*” [3], which defines permissible deviations and correction coefficients.

The specificity of marine engineering imposes additional requirements on these sensors. The application of Pitot tubes for measuring ship speed (speed logs) is complicated by the hydrodynamic interaction with the hull. A.F. Molland et al., (2011), in their analysis “*Ship*

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Resistance and Propulsion" [4], explain in detail the formation of the boundary layer around the hull. If the sensor is positioned within the boundary layer zone, the measured speed will be lower than the actual speed, necessitating precise positioning. This issue is also regulated in the procedures of the International Towing Tank Conference (ITTC Recommended Procedures and Guidelines: Speed and Distance Measurement [5]), which serve as a benchmark for validating ship performance characteristics.

In the era of Industry 4.0, the Pitot tube cannot be viewed merely as a mechanical device, but as part of a complex mechatronic system. Converting differential pressure into an electrical signal requires highly sensitive transducers. J. Fraden (2016) in *"Handbook of Modern Sensors"* [6] discusses contemporary piezoresistive and capacitive sensors, which are critical to the accuracy of the mechatronic module. The significance of this integration becomes even more apparent in autonomous underwater vehicles, where navigation relies entirely on sensor data. J. C. Kinsey et al., (2006), in their survey *"A Survey of Underwater Vehicle Navigation"* [7], point out that precise speed-over-water measurement is key to control algorithms for underwater robots, thereby expanding the application field of the Pitot tube beyond conventional shipping.

Since physical experiments in towing tanks are expensive and labor-intensive, computer simulations (CFD) have become a primary tool for design and optimization. J. D. Anderson (1995) in *"Computational Fluid Dynamics: The Basics with Applications"* [8] provides the mathematical framework for solving fluid motion equations. For simulating the flow around the Pitot tube, the present work employs the Finite Volume Method (FVM), detailed by H. K. Versteeg et al., (2007) in *"An Introduction to Computational Fluid Dynamics"* [9]. The selection of an appropriate turbulence model (such as k-epsilon or k-omega) is crucial for correctly predicting pressure distribution.

The aim of this paper is to unify these theoretical, normative, and computational aspects. Through a simulation model based on the Navier-Stokes equations and validated against the ISO 3966 standard, we analyze the behavior of the Pitot tube under conditions characteristic of the marine environment and mechatronic applications, thereby closing the loop between theory, virtual prototyping, and real-world operation.

II. GENERAL REGULATIONS

The fundamental basis for the operation of the classical Pitot tube relies on the fundamental laws of fluid mechanics, and more specifically on Bernoulli's equation. This equation serves as the primary theoretical foundation for converting the measured pressure differential between total (dynamic) and static pressure into actual fluid flow velocity. However, as noted by White (2015) in his work, theoretical mathematical idealizations often diverge from real-world operating conditions. According to Benedict

(1984), a number of physical factors, including fluid compressibility, specific nozzle geometry, and the presence of turbulence, can introduce significant errors and deviations in the final measurements.

To compensate for these inaccuracies and to ensure the reliable industrial applicability of the method, strict adherence to established regulatory standards is necessary. Within the framework of this study, all geometric parameters of the model and calibration methodologies are precisely aligned with the international standard ISO 3966:2025, which clearly defines permissible design deviations and required correction coefficients.

The specificity of modern marine engineering imposes even stricter additional requirements on these measuring sensors, especially when Pitot tubes are integrated as hydrodynamic speed logs for recording ship speed. Their practical application is seriously complicated by the continuous hydrodynamic interaction with the vessel's hull. In their analysis, Molland, Turnock, and Hudson (2011) examine in detail the formation of a viscous boundary layer around the ship's hull. If the measuring sensor is positioned within this specific zone, the recorded speed will be significantly lower than the actual speed. Therefore, extremely precise and careful positioning is required, which is regulated in detail in the recommended procedures of the International Towing Tank Conference (ITTC).

From a modern mechatronics perspective, in the era of Industry 4.0, the Pitot tube cannot be viewed in isolation as a simple mechanical device, but rather as a key component of a complex system. The reliable conversion of the recorded differential pressure into an electrical signal requires the integration of highly sensitive piezoresistive or modern capacitive transducers, as detailed by Fraden [6]. This deep sensor integration is of critical importance for autonomous underwater vehicles (AUVs). In these vehicles, navigation algorithms and control systems depend entirely on precise speed-over-water measurement, which expands the application field of the Pitot tube far beyond conventional shipping, as pointed out by Kinsey, Eustice, and Whitcomb [7].

III. FIGURES, TABLES AND EQUATIONS

Since physical experiments in towing tanks are often extremely expensive, time-consuming, and labor-intensive, computer simulations using Computational Fluid Dynamics (CFD) have established themselves as a primary and indispensable tool for design, analysis, and optimization in modern engineering. In the present work, the ANSYS Fluent software package is used to conduct the numerical simulation of the Pitot tube. To analyze the fluid behavior, the study applies the Finite Volume Method (FVM) to solve the complex Navier-Stokes differential equations. This method, detailed by Versteeg and Malalasekera [8], allows for precise discretization of the computational domain, ensuring strict adherence to the laws of mass and momentum conservation in every control cell of the grid. The mathematical framework underlying

these calculations is based on the fundamental principles laid out by Anderson [9].

Numerical Settings and Parameters:

To achieve maximum reliability and stability of the results, the following key parameters of the simulation model have been defined:

- **Viscous Model:** A laminar flow model was selected for the purposes of simulation. This decision is directly based on the calculated number of Reynolds relative to the specific diameter of the tube. Under these geometric and velocity conditions, the fluid flow maintains its stratified character without highly pronounced turbulent pulsations, making the laminar model not only physically adequate but also computationally efficient.
- **Pseudo-Transient Settings:** To accelerate the convergence of the numerical solution, a pseudo-transient approach was utilized. The length scale was initially set to correspond to the external diameter of the Pitot tube, and subsequently refined and reduced to the diameter of the internal tubes during the calculation process. This allows for a smooth adaptation of the model to the local velocity and pressure gradients.

Initialization: Full Multigrid (FMG) initialization was applied. This technique is widely used in aerodynamics because it initially calculates the solution on coarser computational grids before interpolating it to the fine base grid. This approach provides a significantly better initial solution and drastically reduces the overall computational costs and the time required to reach a steady state in the simulation.

IV. OTHER RECOMMENDATIONS

This section presents and analyzes the data obtained from the CFD simulation, with each result named separately for clarity.



Fig. 1. Contours of pressure.

Fig. 1 shows that these contours show the effect of the orientation of the ports on the pressure measurement. The pressure increases significantly in the central tube, where the fluid stops completely (stagnation). This measured pressure corresponds to the total pressure of the fluid. In the side ports, the pressure is lower and corresponds to the static pressure of the surrounding environment.

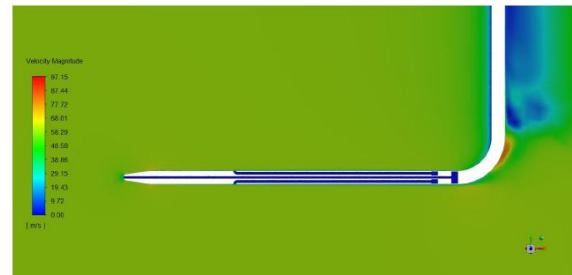


Fig. 2. Contours of velocity magnitude.

The visualization in Fig. 2 shows that the air velocity inside the Pitot tubes is zero. In the central channel, the air cannot move forward and becomes “trapped” while the flow passes parallel to the side static pressure ports without entering them.

Area-Weighted Average Static Pressure	(pascal)
static-pressure-port	65779.227
total-pressure-port	67472.61

Fig. 3. Area-weighted average static pressure.

Using the reporting function in Ansys Fluent, the average value of the static pressure on the ports is calculated, Fig. 3. The image shows the calculated value of 65779.227 Pa, which serves to accurately determine the differences between the total and static pressure.

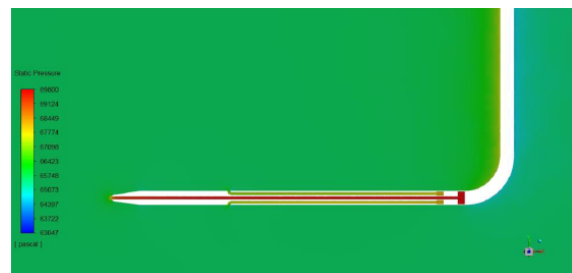


Fig. 4. Pressure distribution after FMG initialization.

Velocity distribution, Full Multigrid Initialization (FMG) initialization is used in aerodynamics to obtain a better initial value of the solution, Fig. 4. It calculates the solution on coarser grids and interpolates it to the base grid, which reduces the overall computational cost of the simulation.

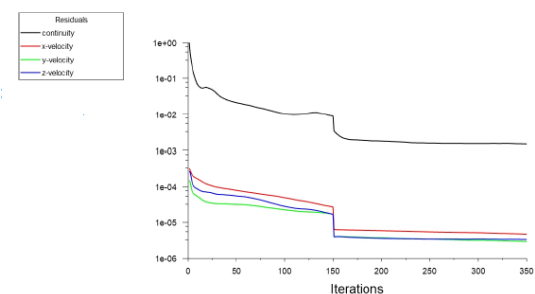


Fig. 5. Residuals.

Fig. 5 tracks the convergence of the solution. It can be seen how the errors for the velocity components (x, y, z)

and the continuity equation drop sharply and stabilize, which is an indication of a correctly calculated and stable simulation.

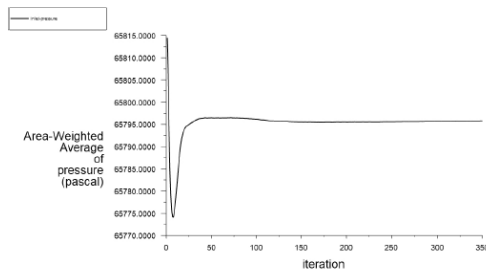


Fig. 6. Plot of inlet static pressure.

The graph in Fig. 6 shows how the static inlet pressure changes and stabilizes over the course of the iterations. After initial fluctuations during FMG initialization (around the 100th iteration), the value levels off, confirming that a steady state has been reached.

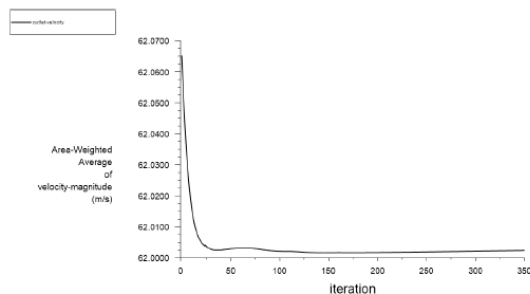


Fig. 7. Plot of outlet velocity magnitude.

Similar to pressure, the outlet velocity is monitored to ensure that mass balance is achieved, Fig. 7. The stabilization of the curve around the 150th iteration indicates that the flow through the outlet boundary is constant.

Applications in Marine Engineering and Mechatronics

The simulation results have direct applications in designing ship control systems. Understanding high and low-pressure zones around the sensor allows engineers to

avoid errors caused by hydrodynamic interaction with the hull. In mechatronics, these data are critical for calibrating digital pressure sensors used in underwater robotics, where navigation depends on precise speed data.

ACKNOWLEDGMENTS

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Tensile Strength of Copper Alloyed Structural Powder Steels

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Abstract— The publication traces the influence of the type of iron powder and the sintering process in the presence of a liquid phase on the tensile strength of powder metallurgical samples from the Fe-C-Cu system. Powder metallurgical samples of three types of iron powders – ASC 100.29, SC 100.26 and NC 100.2 – were studied. The iron matrix is alloyed with 2.5%Cu and 0.2÷0.8%C. After sintering, their density is in the range of 6.20÷7.00g/cm³. Graphical dependences for the change in tensile strength depending on the density of the samples and the concentration of carbon and copper in them are presented.

Keywords— copper, density, liquid sintering, powder metallurgy, tensile strength.

I. INTRODUCTION

One of the main technologies that fully meets the requirements of Industry 4.0 and Industry 5.0 for zero waste and environmental friendliness is powder metallurgy [1, 2, 3, 4, 5, 6, 7, 8]

In the most general sense, powder metallurgy technology consists of three stages - mixing the starting powders, pressing them into the desired shape and subsequent sintering [9, 10].

Sintering is a type of heat treatment to which pressed blanks are subjected in order to acquire a complex of physical and mechanical properties. A characteristic feature of this process is that it is carried out at temperatures 0.7÷0.9 of the melting temperature of the most easily fusible component in the alloy. The effectiveness of the process is judged by the strength, plasticity, specific electrical resistance, density, etc. properties of the sintered bodies. [11, 12, 13, 14, 15].

The main thermodynamic factor in the case of sintering of pure metals is the pursuit of minimal surface free energy, and in multicomponent systems the additional decrease in chemical free energy. The kinetics of densification of the samples is thermally activated and predetermined by the operating mechanisms of mass transfer in the sintered

matrices, such as bulk, surface and boundary diffusion, evaporation, condensation, etc. [16]

Although usually the sintering processes in powder metallurgy are realized in the solid state, often to increase their efficiency resort is made to sintering in the presence of a liquid phase [17]. Sintering in the presence of a liquid phase is carried out in cases when there is a fusible component in the charge or in the sintering process a eutectic is formed. The amount of the liquid phase in these cases must be significantly less than that of the solid phase, otherwise distortion of the shape is possible in the sintering process [18, 19].

Copper is most often used as a source of liquid phase. Copper is an element that is not used in conventional metallurgy, but it has a number of features that favor its use in powder metallurgy. The most important of them are [20, 21, 22, 23, 24, 25]:

- can be obtained in the form of powder using various technologies;
- the resulting copper particles can be of different shapes;
- has easily recoverable oxides;
- high plasticity which facilitates pressing;
- lower melting point than Fe which determines sintering in the presence of a liquid phase, etc.

In this study, the influence of the type of iron powder on the flexural strength values of the most commonly used in practice two-component system with limited solubility Fe-C, after sintering in the presence of a liquid phase – Cu, was monitored.

II. MATERIALS AND METHODS

The main mechanical characteristics of the sintered iron products used in practice are directly dependent on the shape and size of the starting powder particles. Based on the literature data on the application and characteristics of the most commonly used iron powders in powder metallurgy [26, 27, 28, 29], the following main conclusions can be formulated:

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- Reduced sponge iron powders are used primarily in cases where the products do not require particularly high compaction - in antifriction products. Their application is mandatory when high raw strength requirements are imposed on the final product, as is the case with friction materials, long and thin parts, etc.;
- Products with medium density can be made from both sponge and water-dispersed iron powders. The choice of powder for them is made based on the requirements for each specific case;
- In the production of high-density products, water-dispersed iron powders with high compaction and purity are used. These powders are also used in the production of soft magnetic and hot-forged products because they contain fewer impurities.

Based on these conclusions, we have selected three types of iron powders produced by the company "Höganäs" - Sweden - NC100.24; SC 100.26 and ASC 100.29 for research [30].

NC 100.24 is one of the most widely used iron powders obtained by the reduction method in the practice of powder metallurgy. Its compactability is very good, and thanks to the spongy structure of the particles, their formability is very high. The raw (after pressing) and final (after sintering) strength of parts made from these powders is very high, and the concentration of hydrogen in them is low [31].

The best compactability of all sponge iron powders produced by the company "Höganäs" by the reduction method is the iron powder type SC 100.26. This makes it particularly suitable for the production of parts with a single pressing for which there are requirements for higher density. Similar to the powders of the previous type, these have high raw strength, but a slightly higher density than them. They are recommended for the production of parts that will subsequently be subjected to chemical-thermal treatment [32, 33].

Iron powder ASC 100.29 is a representative of the group of water-dispersed powders. At the moment, this is the highest quality iron powder produced by the company "Höganäs". It is distinguished by very high purity. It has excellent compactability, which is a result of the particles being almost spherical in shape. This allows, after a single pressing, to achieve a density of the order of $7.20 \div 7.3 \text{ g/cm}^3$. These powders are particularly suitable for the production of high-density structural products, as well as for products with certain magnetic characteristics. The maximum size of the fractions of the iron powders used, their compactability at a force of 420MPa, as well as the concentration of oxygen and carbon in them are presented in table 1.

TABLE 1 IRON PULVERS

Type Fe powder / max. size, μm	Sealability at 420MPa		O ₂ , %	C, %
	average _a	min.	max.	max.
NC 100.24/150	6,45	6,40	0,30	0,02
SC 100.26/150	6,65	6,63	0,15	0,01
ASC100.29/170	6,82		0,15	0,02

The main mechanical characteristics of structural powder metallurgical materials in the process of their exploitation is their tensile strength. In its study, samples with a chemical composition corresponding to the results obtained during the quantitative optimization of the elements of the ternary system were used. The percentage content of copper in the samples is $2.5 \div 2.6\%$, and the amount of carbon varies within 0.2% within the limits of $0.2 \div 0.8\%$.

The studied samples were made according to the methodology developed in [34, 35, 36], and their pressing was carried out with a force of the order of $300 \div 700 \text{ MPa}$. This allows them to have different densities after sintering at 1150°C in a dissociated ammonia environment. Their mass after mixing was determined so that after pressing and sintering their density was within the range of $6.20 \div 7.00 \text{ g/cm}^3$.

III. RESULTS AND DISCUSSION

The tensile strength was determined according to EN 10045-1, and the shape of the studied samples corresponds to the diagram in Fig.1.

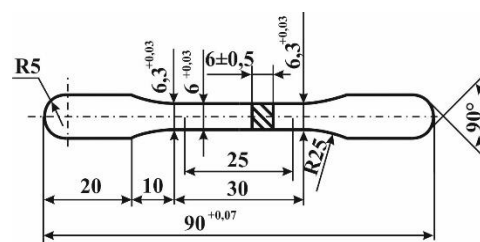


Fig.1. Drawing of a tube made of powder material for testing tensile strength

To eliminate the influence of porosity on the final results, three samples were used in the research, and the values in the figures are the arithmetic mean obtained for each type of sample [37].

For pure iron samples, the experimental results are presented in Fig. 2.

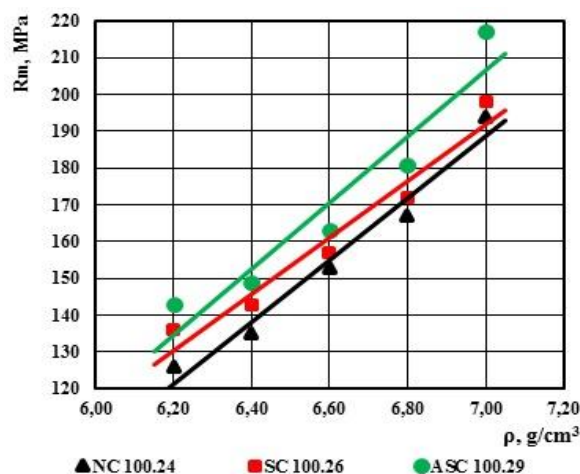


Fig.2. Tensile strength as a function of density of iron samples

The figure shows that with increasing density of the samples, the values of tensile strength also increase, as for samples of iron powders NC100.24 and SC 100.26 this increase is of the order of 60÷70MPa, and for those of ASC 100.29 - 70÷80MPa. In this case, the change in the values of tensile strength is only a consequence of the reduced porosity, the increased surface contact between the iron particles of the samples and their increased density. At all studied densities, the obtained results for the tensile strength for the samples of iron powder ASC 100.29 are higher on average by 20MPa compared to those obtained for samples of powders NC100.24 and SC 100.26. The fact that spherical powders have better compactability compared to spongy ones is confirmed. This allows the tensile strength of spherical iron particles to be higher by an average of 10% [38, 39, 40].

The addition of 0.2% carbon leads to an increase in the values of the tensile strength, and for the three types of iron matrices studied by us this increase varies in the range of 30÷60MPa and is a function of their density. - Fig. 3. The lower values are realized in samples with a lower density, and the higher ones in those with a density of 7.0g/cm³. This can be explained by the fact that in denser samples the contact between the iron and carbon particles is increased, which facilitates the diffusion of carbon into the ferrite and the formation of a pearlite structure.

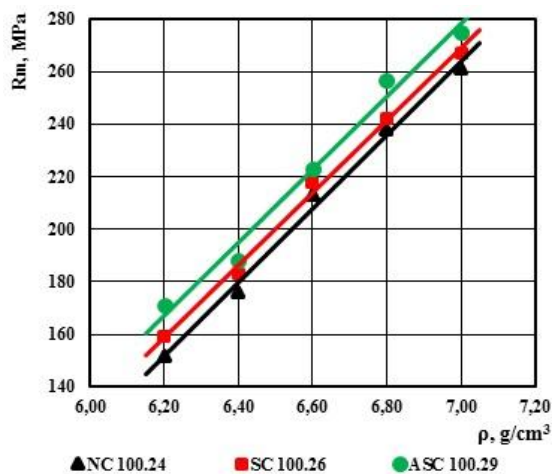


Fig.3. Tensile strength as a function of density of iron samples containing 0.2%C

With an increase in carbon concentration from 0.2 to 0.8%, the values for tensile strength increase in the range of 70÷120MPa, and similarly to the previous case, the larger increase of 110÷125MPa is observed in samples with lower porosity and correspondingly higher density – Fig. 3÷6.

The addition of 0.2% carbon leads to an increase in the values of the tensile strength, and for the three types of iron matrices studied by us this increase varies in the range of 30÷60MPa and is a function of their density. The lower values are achieved in samples with a lower density, and the higher ones in those with a density of 7.0g/cm³. This can be explained by the fact that in denser samples the contact between the iron and carbon particles is increased,

which facilitates the diffusion of carbon into the ferrite and the formation of a pearlite structure.

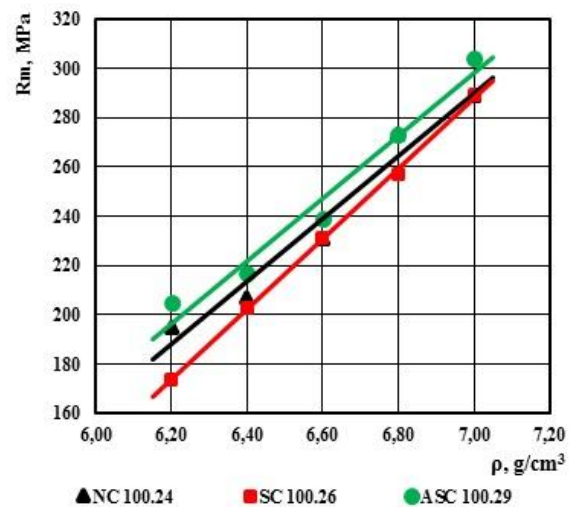


Fig.4. Tensile strength as a function of density of iron samples containing 0.4%C

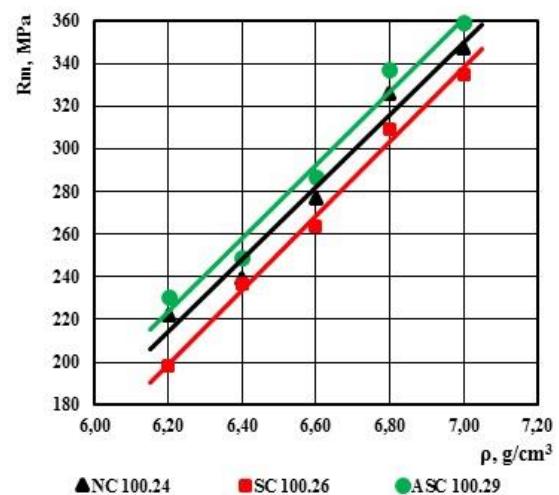


Fig.5. Tensile strength as a function of density of iron samples containing 0.6%C

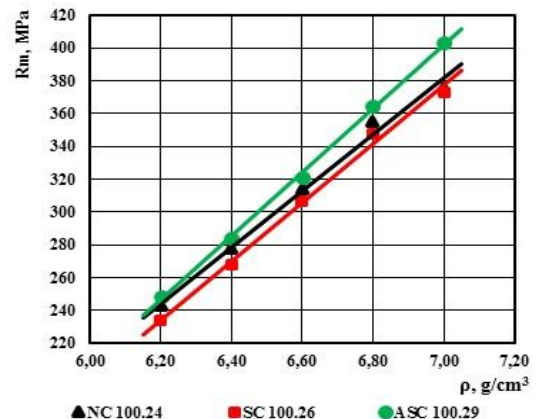


Fig.6. Tensile strength as a function of density of iron samples containing 0.8%C

The addition of 0.2% carbon leads to an increase in the values of the tensile strength, and for the three types of iron matrices studied by us this increase varies in the range of 30÷60MPa and is a function of their density. The lower values are achieved in samples with a lower density, and the higher ones in those with a density of 7.0g/cm³. This can be explained by the fact that in denser samples the contact between the iron and carbon particles is increased, which facilitates the diffusion of carbon into the ferrite and the formation of a pearlite structure [33, 34, 36].

The highest values for tensile strength are recorded for samples alloyed with 2.5% copper. For parts containing 0.2% carbon, with an increase in density from 6.20 to 7.0g/cm³, the values for tensile strength increase within the range of 200÷360MPa - Fig. 7, which is an increase of the order of 25÷30%. With an increase in carbon concentration from 0.2 to 0.8% - Fig. 7÷10, the difference in the values for tensile strength also increases. For samples with 0.8%C, their strength varies in the range of 260÷560MPa - Fig. 10.

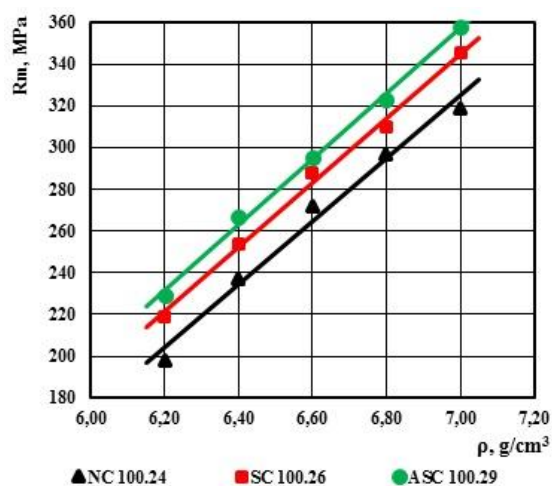


Fig. 7. Tensile strength as a function of density of iron samples containing 0.2%C and 2.5%Cu

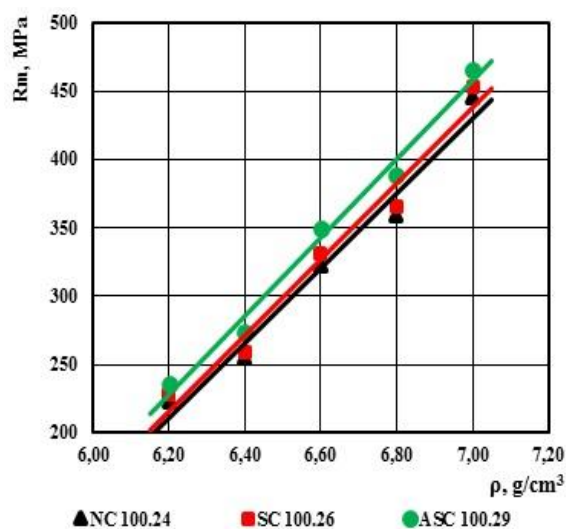


Fig. 8. Tensile strength as a function of density of iron samples containing 0.4%C and 2.5%Cu

Similarly to the samples with a carbon content of 0.2%, in this case, the largest differences in the values are recorded for the samples with the maximum density studied by us - 7.0g/cm³.

Comparing the results obtained for samples from the Fe-C and Fe-C-Cu systems, it can be concluded that the addition of 2.5% copper leads to an increase in the tensile strength by 50÷150MPa, with the largest differences being recorded for the samples with a higher density - 7.0g/cm³.

In the samples containing carbon, as well as in those alloyed with 2.5% copper, the influence of the brand of iron powder used on the tensile strength values is also noticeable. In the samples made of iron powder type NC 100.24 and SC 100.26, the measured tensile strength results are 10÷20MPa lower than those measured in samples with an iron matrix made of ASC 100.29 powder.

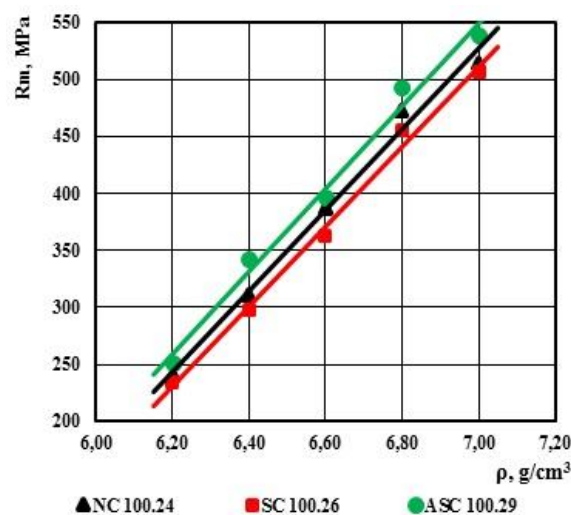


Fig. 9. Tensile strength as a function of density of iron samples containing 0.6%C and 2.5%Cu

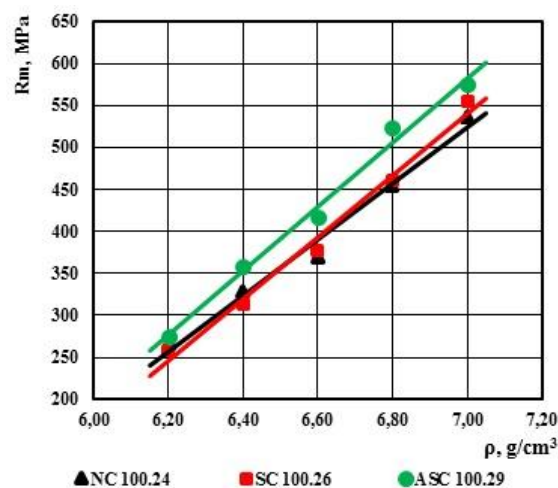


Fig. 10. Tensile strength as a function of density of iron samples containing 0.8%C and 2.5%Cu

IV. CONCLUSIONS

From the conducted studies and the results obtained, the following important conclusions can be drawn:

- It has been confirmed that for samples of pure iron with an increase in their density from 6.20 to 7.0g/cm³, the values of the tensile strength increase by 60÷70MPa and do not depend on the type of iron powder used.
- It has been proven that adding 0.2% carbon to iron samples leads to an increase in tensile strength values by 30÷60MPa, which is a function of their density. Denser samples have higher strength due to increased particle contact and ongoing coalescence processes during sintering.
- It has been proven that the addition of 2.5% copper leads to an increase in the tensile strength values of iron-carbon materials by 50÷150MPa, with larger differences being observed for samples with a higher density -7.0g/cm³. In this case, the increased strength characteristics are a consequence of intensifying the sintering process of the samples in the presence of a liquid phase in the batch.
- It has been confirmed that the tensile strength measured for the samples of iron powder type NC 100.24 and SC 100.26 is 10÷20MPa lower than those measured for samples with iron matrix of ASC 100.29 powder. This is a result of the better compaction of the powders with spherical particle shape compared to those with spongy or dendrite shape.

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Influence of Strength Characteristics on the Technological Parameters of the Boroaluminizing Process

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Abstract— At present, data on the influence of boroaluminizing on the mechanical properties of steels are scarce and contradictory. This publication presents a mathematical model for determining the strength characteristics of medium-alloyed quality steel and their influence on the technological characteristics of the boroaluminizing process (saturation times, quenching and tempering temperatures). Based on the mathematical model, graphical relationships for R_m , $R_{0.2}$ and A_5 as a function of the technological characteristics of the boroaluminizing process have been developed.

Keywords— boroaluminizing, diffusion, proportional limit, relative elongation, tensile strength.

I. INTRODUCTION

The development of modern mechanical engineering and other branches of industry in the context of Industry 4.0 is inextricably linked to placing high demands on the properties of parts and tools [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

There are increasingly frequent cases when structural and tool materials must have high hardness, strength and resistance in oxidizing and highly aggressive environments. All this can be achieved with the methods of chemical-thermal treatment. In this technological process, diffusion layers with fundamentally new phases are created on the surface, fully satisfying the set requirements. Moreover, the formed diffusion layer, as a result of reducing defects in the structure of the part, brings its working surface closer to the ideal, which increases the durability of the product as a whole [11, 12].

The choice of saturating elements is determined by the desired complex of mechanical properties of the particular part, but in any case it is necessary that the formation of the diffusion layer is accompanied by a decrease in the thermodynamic potential of the surface and an increase in the forces of interaction of atoms. Moreover, the greater the

change in the specified characteristics, the higher the physicochemical and mechanical properties of the layer.

Currently, processes related to single-component saturation of parts – carburizing, nitriding, boriding, etc. [13, 14, 15, 16, 17, 18, 19] Saturation with two, three or more elements (with the exception of the nitrocarburizing process) are widely used in practice.

The possibility of simultaneous saturation with boron and aluminum was established in the eighties of the last century [20, 21, 22, 23, 24]. The first results show an exceptional perspective of the obtained diffusion layers for protecting the parts from abrasive impact. Subsequently, it was proven that the properties of the boron-alloyed layers depend on the ratio of diffusing boron and aluminum atoms in the surface of the part, but in all cases they have:

- high microhardness $14 \div 19000$ MPa, and when saturated with high-alloy steels up to 21000 MPa;
- high abrasion resistance exceeding that of heat-treated steels by $3 \div 18$ times;
- resistance to heating in an oxidizing environment up to 950°C ;
- resistance in sulfur-containing and other active gas environments.

However, this method has not found wide application due to insufficient knowledge of the technological processes occurring during saturation [25, 26, 27, 28, 29].

In this regard, the purpose of this publication is to trace the influence of the technological processes of boroaluminum on the main strength characteristics of diffusion-enriched samples of medium-alloyed high-quality structural steels [30, 31].

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II. MATERIALS AND METHODS

The study used samples of medium-alloyed high-quality structural steel 34CrNiMo6 EN ISO 6892-1:2020, with chemical composition according to Table 1 and mechanical properties in the as-delivered condition $R_m=1100\text{MPa}$, $R_{0.2} 900\div 1000\text{MPa}$ and HB 229.

TABLE 1 CHEMICAL COMPOSITION

Chemical composition, %							
	C	Cr	Mn	Si	P	S	Fe
min	0,32	0,80	0,80	1,10	$\leq 0,025$	$\leq 0,025$	$> 96,00$
max	0,38	1,10	1,10	1,40			

The diffusion enrichment of the samples was carried out in a liquid saturating medium. Borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$), boric anhydride (B_2O_3) and alumina (Al_2O_3) were used as carriers of active atoms in the diffusion medium, and boron carbide (B_4C) was used as a reducing agent.

The saturation temperature is $820\div 880^\circ\text{C}$, and the duration is $120\div 240$ min. After saturation, the samples are quenched (from the saturation temperature) in an oil bath and subjected to high-temperature annealing at $500\div 600^\circ\text{C}$.

The annealing duration of the standard test specimens for tensile strength testing is constant - 1 h.

The strength characteristics test according to EN 1002 was conducted on an automatic hydraulic, universal tensile/compression testing machine with an optical control module with a touch screen display, maximum tensile force 700kN and accuracy of results $\pm 1\%$ - Fig. 1.



Fig.1. Universal tensile strength testing machine

III. RESULTS AND DISCUSSION

The mechanism of influence of boroaluminizing diffusion coatings on the mechanical properties of the studied samples after saturation and subsequent heat treatment was investigated using mathematical planning of the experiment using a second-degree orthogonal

compositional design [40]. On this basis, adequate regression equations modeling the saturation regime and the subsequent heat treatment were derived.

The tensile strength – Y_1 (R_m , MPa), the proportionality limit – Y_2 ($R_{0.2}$, MPa), and the conditional relative elongation at break – Y_3 (A_5 , %) were used as control functions.

The input factors (parameters) are the saturation temperature – X_1 (T_1 , $^\circ\text{C}$), from which the parts are immediately quenched in oil, the saturation duration – X_2 (t , min), and the tempering temperature – X_3 (T_2 , $^\circ\text{C}$).

The main levels of input factors, as well as the variation intervals, are presented in Table 2.

TABLE 2 INPUT FACTORS

	Input factors		
	X_1 , T_1 , $^\circ\text{C}$	X_2 , t , min	X_3 , T_2 , $^\circ\text{C}$
Basic level	850	180	550
Variation interval	30	60	50
Upper level	880	240	600
Lower level	820	120	500

When implementing the experimental plan, analytical dependencies were established for the control functions on the specified factors 1÷3.

$$Y_1 = 13220 - 35X_1 + 8,4X_2 + 10,8X_3 + 0,025X_1^2 + 0,0076X_2^2 - 0,0021X_3^2 - 0,0073X_1X_2 - 0,0124X_1X_3 - 0,068X_2X_3 \quad (1)$$

$$Y_2 = 15816 - 38,9X_1 - 0,7X_2 + 8,58X_3 + 0,025X_1^2 + 0,013X_2^2 - 0,0032X_3^2 - 0,0027X_1X_2 - 0,086X_1X_3 - 0,0029X_2X_3 \quad (2)$$

$$Y_3 = 28,6 + 0,044X_1 + 0,017X_2 + 0,02X_3 - 0,00008X_1^2 - 0,00009X_2^2 - 0,000009X_3^2 - 0,000012X_1X_2 - 0,00001X_1X_3 - 0,0002X_2X_3 \quad (3)$$

The graphical interpretations of the obtained dependencies are presented in Fig. 1÷3.

Through them, with given values for R_m , $R_{0.2}$ and A_5 , the optimal values of the technological parameters of diffusion saturation (temperature and duration of saturation) with boron and aluminium can be determined.

The graphical dependences show a stronger influence of the tempering temperature on the studied mechanical characteristics than the saturation temperature and duration. This indicates that the strengthening during simultaneous diffusion of boron and aluminium into the surface of the samples is a result of an increase in the amount of pinned dislocations on the surface of the strengthened samples [32, 33, 34, 35].

Boron is known to be a surface active element with respect to iron. The absorption of boron along dislocation lines creates an atmosphere analogous to that of Cottrell of carbon atoms. This allows for easier pinning of dislocations

and lowers the linear stresses around them. At the same time, their density increases. The latter is stimulated by the effects of stresses arising from the diffusion of boron and aluminium [36, 37, 38, 39].

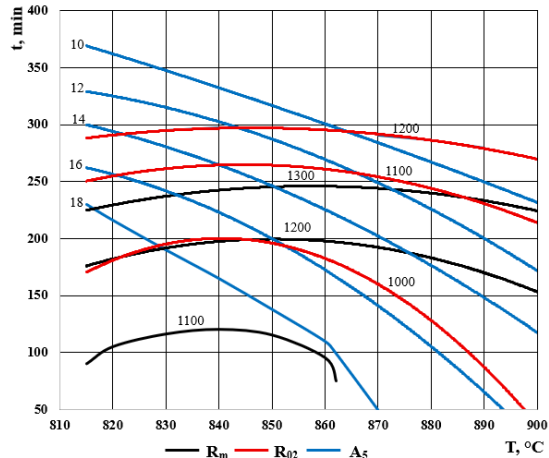


Fig. 1. Dependences of the strength characteristics of boroaluminizing samples on the technological parameters of the process at a tempering temperature of 500°C.

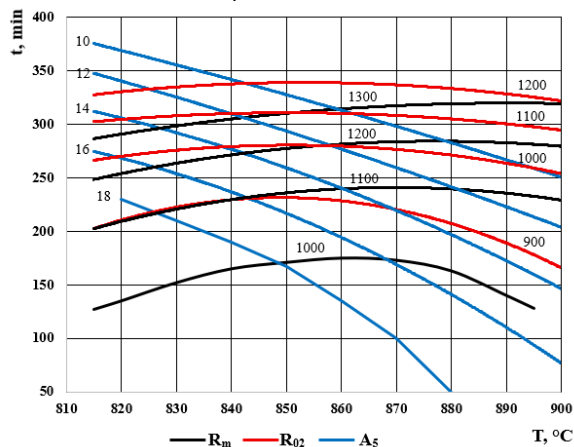


Fig. 2. Dependences of the strength characteristics of boroaluminizing samples on the technological parameters of the process at a tempering temperature of 550°C.

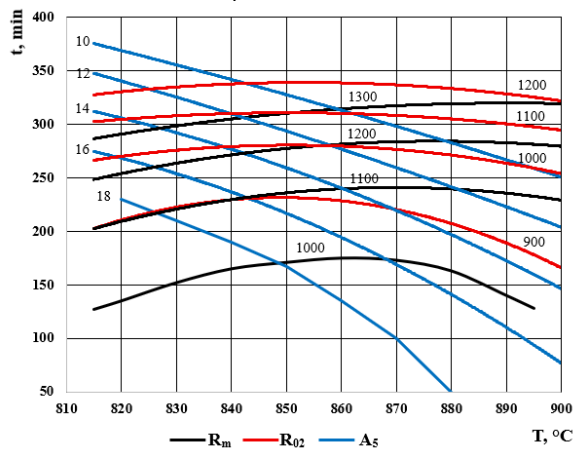


Fig. 3. Dependences of the strength characteristics of boroaluminizing samples on the technological parameters of the process at a tempering temperature of 600°C.

Furthermore, the formation of the borides FeB and Fe₂B with elastic moduli of 350 and 290.10³ MPa, respectively, significantly exceeding the elastic modulus of steel, increases the elastic modulus on the surface of the product. This increases the resistance to the movement of dislocations and their emergence to the surface.

Therefore, the strength characteristics of steels after simultaneous diffusion enrichment with boron and aluminum are determined by the structural state of the formed diffusion layer and to a lesser extent by its thickness. The diffusion of boron and aluminium and the formation of borides on the surface of the parts change the density and energy of the dislocations (the structural energy state of the saturated surface), which leads to a change in the bulk properties of the product as a whole [40].

IV. CONCLUSIONS

From the conducted studies and the results obtained, the following important conclusions can be formulated:

- The mechanism of influence of boroaluminizing diffusion coatings on the strength properties of 34CrNiMo6 steel after saturation in liquid media at 820÷880 °C, with a duration of 120÷240 min and subsequent heat treatment (quenching from the saturation temperature and high-temperature tempering) was studied.
- Mathematical models of the process were constructed using a second-degree orthogonal compositional design and adequate regression equations were derived.
- Graphical relationships have been developed to determine the technological parameters of the boroaluminizing process (temperature and duration) depending on the desired strength properties (R_a, R_{0.2} and A₅) of the product.
- It has been proven that the influence of the tempering temperature on the studied mechanical characteristics is stronger than the temperature and duration of saturation.

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Wear Resistance of Medium Alloy Tool Steels After Single-Component Surface Enrichment

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Abstract— Results are presented for the influence of the type of chemical-thermal treatment in single-component surface enrichment on the wear resistance of the formed diffusion layers on samples of chromium tool steels (1÷5%Cr). Wear resistance is defined as mass loss per unit area (g/cm²) after a distance of 1÷5 km. The loading in the wear process is carried out by a lever system with a load of 3÷100 MPa, and the speed of rotation of the counterbody is 0.1÷7.0 m/s. Dependencies for the wear intensity of the studied steels in coordinates mass loss / distance traveled have been developed.

Keywords— boriding, carburizing, chemical-thermal treatment, chromizing, nitriding.

I. INTRODUCTION

Industry 4.0 represents a major step towards the future of manufacturing, combining technologies that are changing the way businesses produce and deliver goods and services [1] – [9]. This technological revolution promises to drive innovation, improve efficiency, and transform the manufacturing landscape, providing a better way to meet consumer needs in the future. In this regard, the development of technologies related to the application of CNC metalworking machines with robotic feeding [10], [11], the implementation of waste-free and low-waste technologies [12] – [15], as well as the combination of technological processes related to increasing the strength properties of parts in order to replace expensive alloy steels with structural carbon ones is of particular importance.

In this regard, the role of processes related to the chemical-thermal treatment of materials is essential [16, 17, 18]. This is a technology that allows the production of parts with high strength characteristics on the surface of the products while maintaining a tough core. Of particular importance is the application in the processing of long axisymmetric rotational parts operating in torsion, to which requirements are imposed for high wear resistance and resistance in aggressive environments.

This publication investigates the influence of single-component surface enrichment of medium-alloy tool steels on their wear resistance under dry friction conditions.

II. MATERIALS AND METHODS

Samples of medium-alloyed heat-resistant steels with increased and high heat strength were tested. The chemical composition of the tested steels according to BDS EN 10027-1:2005 is presented in Table 1, and the dimensions of the tested samples are shown in Fig. 1.

TABLE 1 CHEMICAL COMPOSITION OF THE SAMPLES

Steel	Alloying elements, %									
	C	Si	Mn	Cr	Ni	W	V	Mo	Cu	Zr
54NiCrMo V6 DIN 1,2714	0,54	0,32	0,75	0,57	1,60	-	-	0,25	≤0,3	
60CrV7 DIN 1,2307	0,67	0,35	0,32	2,35	0,40	0,30	0,15	-	-	-
32CrMoV 12 DIN 1,2365	0,38	0,89	0,49	1,45	-	-	0,38	0,54	-	-
55NiCrMo V7 DIN 1,2714	0,39	0,92	0,38	1,27	1,49	-	0,43	0,37		0,15
X38CRM oV5 DIN 1,2367	0,49	0,74	0,41	2,91	-	2,64	0,81	0,76	-	-
X30WCrV 9-3 DIN 1,2581	0,37	≤0,3	0,38	2,50	≤0,3	8,50	0,42	≤0,5	-	-

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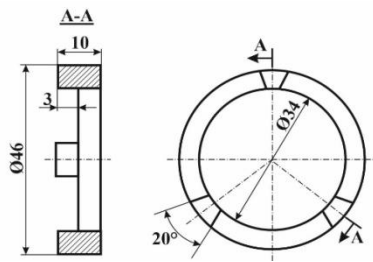
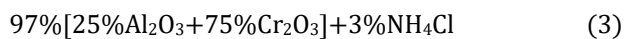
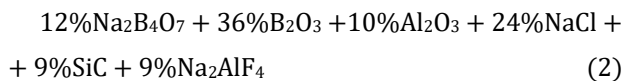
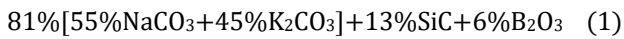


Fig. 1. Dimensions of the tested samples

The samples were subjected to single-component enrichment with carbon, nitrogen, boron and chromium. Nitrogen saturation was carried out in a dissociated ammonia environment at a temperature of 560°C for 6h [19]. Carburization, boridization and chromium plating were carried out in liquid saturating environments at a temperature of 950°C for 4h and bath composition 1, 2 and 3 respectively [20, 21, 22, 23, 24, 25, 26, 27, 28].



After saturation, the samples were quenched from the saturation temperature in oil and subjected to high-temperature annealing at 560÷600°C.

The wear resistance of the saturated samples was tested on a setup - Fig. 2, which allows the tests to be conducted in conditions close to production conditions.

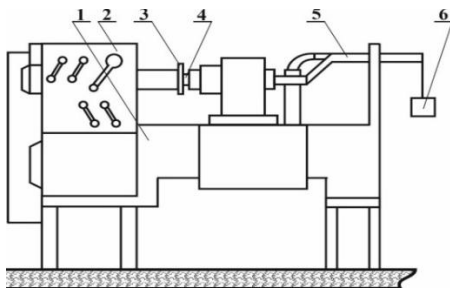


Fig. 2. Scheme of the experimental setup (1 – lathe; 2 – gearbox; 3 – counterbody; 4 – clamp with the tested sample; 5 – lever system; 6 – load).

The methodology for studying wear resistance was used, which gives a quantitative assessment of the process - g/cm². The tests were carried out according to the friction scheme of a three-sector ring - Fig. 1, on a counterbody. The load of 3÷100MPa is carried out using a lever system, and the rotation speed of the counterbody varies within the limits of 0.1÷7.0 m/s [29] – [32].

III. RESULTS AND DISCUSSION

Initial studies conducted at a load of 15 MPa, a rotation speed of 0.42 m/s and a distance traveled of 1 km – Table 2, show that the greatest increase in the wear resistance of the tested samples is provided by coatings based on metal-like compounds – carbides and borides.

TABLE 2 WEAR OF DIFFUSION-ENRICHED SAMPLES

Steels	Insatiable	Friction wear, g/cm ²			
		Diffusing element			
		C	N	B	Cr
54NiCrMoV6	410	340	300	60	65
60CrV7	320	230	300	59	60
32CrMoV12	380	260	290	57	65
55NiCrMoV7	400	240	290	61	65
X38CrMoV5	180	90	140	48	70
X30WCrV9-3	196	120	154	48	65

Note: the values presented are the arithmetic mean of the measured results of five samples.

These coatings effectively protect the surface of the samples from thermal wear (the main type of destruction on the working surfaces). The wear resistance of nitrided and carburized samples is significantly lower compared to those in which boride and carbide coatings are formed on the surface. This is due to the presence in the nitrided and carburized samples of a structure-free solid solution, which is inferior to borides and carbides (in boriding and chromium plating), both in hardness and in other mechanical indicators [33].

In cases where the wear process does not go beyond the boundaries of the diffusion coating, the wear resistance of the surface layers of the saturated samples significantly increases compared to the unsaturated ones – Table 2.

It has been established that depending on the strengthening parameters, both the dimensions of the diffusion coatings and the properties of the respective coating, as well as the properties of the area under the coating itself, can significantly change. In this regard, the type and method of alloying the base is of essential importance.

Fig. 3÷6 shows the wear kinetics of the diffusion layers and the transition zones to the metal matrix in steels with increased heat resistance, respectively 54NiCrMoV6, 60CrV7, 32CrMoV12 and 55NiCrMoV7.

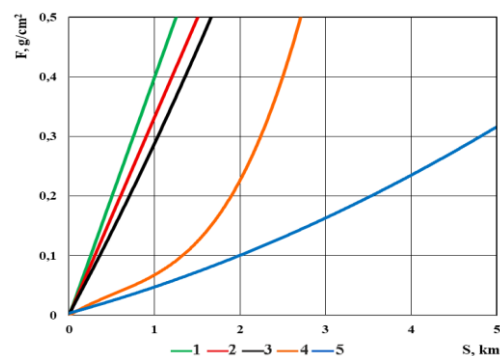


Fig. 3. Wear kinetics – F, distance traveled – S during dry friction of 54NiCrMoV6 samples after surface hardening: 1 – uncoated; 2 – nitrided; 3 – carburized; 4 – chromed; 5 – boronized.

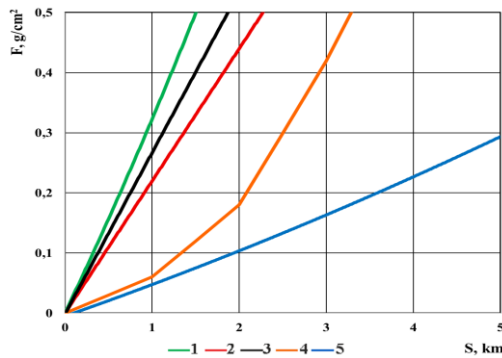


Fig. 4. Wear kinetics – F, distance traveled – S during dry friction of 60CrV7 samples after surface hardening: 1 – uncoated; 2 – nitrided; 3 – carburized; 4 – chromed; 5 -boronized.

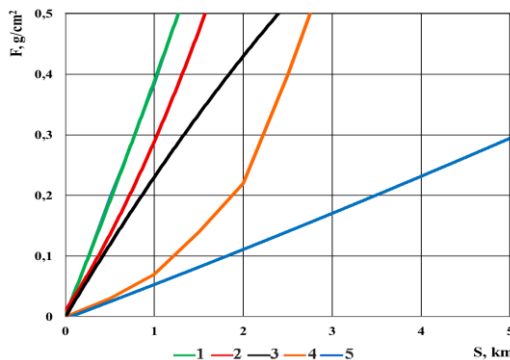


Fig. 5. Wear kinetics – F, distance traveled – S during dry friction of 32CrMoV12 samples after surface hardening: 1 – uncoated; 2 – nitrided; 3 – carburized; 4 – chromed; 5 -boronized.

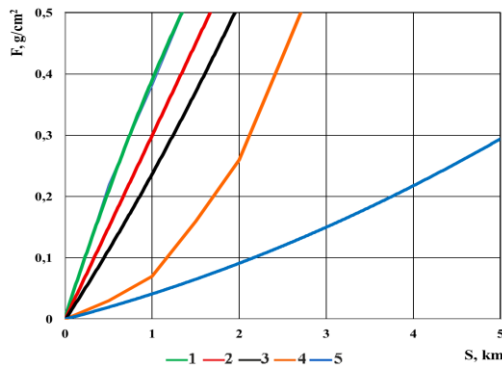


Fig. 6. Wear kinetics – F, distance traveled – S during dry friction of 55NiCrMoV7 samples after surface hardening: 1 – uncoated; 2 – nitrided; 3 – carburized; 4 – chromed; 5 -boronized.

The figures show that the highest wear values compared to unsaturated samples are those after boronization. In them, the mass loss values are 6÷7 times lower compared to unsaturated samples. The samples subjected to carburization and nitriding change their wear resistance slightly compared to unsaturated ones and it is 1.2÷1.6 times lower. In the samples subjected to chromium plating, chromium carbides are formed whose hardness is lower than that of borides. For this reason, after chromium plating, the samples have lower wear resistance than the boronized ones and higher than those after carbonization

and nitriding, and the mass loss in them is 3÷6 times lower compared to unsaturated samples.

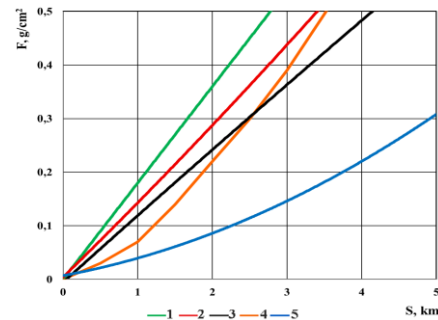


Fig. 7. Wear kinetics – F, distance traveled – S during dry friction of X38CrMoV5 samples after surface hardening: 1 – uncoated; 2 – nitrided; 3 – carburized; 4 – chromed; 5 -boronized.

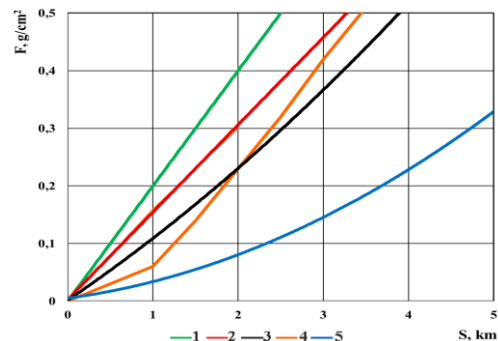


Fig. 8. Wear kinetics – F, distance traveled – S during dry friction of X30WCrV9-3 samples after surface hardening: 1 – uncoated; 2 – nitrided; 3 – carburized; 4 – chromed; 5 -boronized.

It should be noted that fragments of the boride coating (Fe_2B) occur in the contact zone at a significantly later stage of wear, when the destruction process reaches the transition zone. In it, in addition to boride inclusions, we have an increased concentration of carbon and alloying elements. For this reason, the figures do not show a sharp increase in wear resistance after wear of the diffusion layer, but a smooth transition to the core of the part is registered. But it does not have a practical effect on wear.

Figures 3÷6 show that the wear of steels with increased heat resistance is uniform. In contrast, the wear kinetics of steels with high heat resistance (X38CRMoV5, X30WCrV9-3) show a number of peculiarities – Fig. 7 and 8. The figures show that, similarly to steels with increased heat resistance, high wear resistance is observed in steels with high heat resistance after boronizing, but unlike steels with increased heat resistance, the wear of the transition zone in them is identical to that in carbon steels.

The high heat resistance of steels X38CRMoV5, X30WCrV9-3 after carburizing is explained by the presence in the strengthened layer of dispersed carbide inclusions based on Cr, Ni, V and W. For this reason, with prolonged wear (more than 2.0÷2.5km), the values of the carburized samples exceed those of the chrome-plated ones [34], [35].

The results obtained in the process of research allow us to systematize the features of the destruction of the studied diffusion coatings based on carbides into four stages.

During the first stage of wear, along with oxidative wear, intensive occurrence and development of microcracks in the carbide layers is observed. They are mainly the result of the presence of defects or stress concentrators.

During the second stage, crack growth, fragmentation of carbide areas and chipping off of parts of the carbide layers are observed.

The third stage is associated with intensive fragmentation of the carbide zones and the appearance of the matrix phase in individual areas on the contact surface.

The fourth stage is associated with almost complete destruction of the diffusion layer and the entry of carbides knocked out of the layer into the matrix.

In coatings based on boride phases (FeB and Fe₂B) in the friction process, four stages of wear can also be formulated, the first two being analogous to those in carbide coatings [36], [37].

During the third stage, along with local destruction of the layer, there is a gradual smoothing of the destroyed areas. In this case, areas with brittle destruction in the wear process appear and fill in different places on the contacting surfaces with the counterbody. The wear has an oxidative nature.

In the fourth stage, a dense boride layer is absent. On the friction surface, areas of the matrix appear located between the boride needles (Fe₂B). In the places of the matrix phase that contact the counterbody, the wear process is analogous to unsaturated steels.

IV. CONCLUSIONS

The following more important conclusions can be formulated from the conducted research and the results obtained:

- It has been established that depending on the reinforcement parameters, both the dimensions of the diffusion coatings and the properties of the respective coating, as well as the properties of the area under the coating itself, can significantly change.
- It has been proven that for steels with increased heat resistance, the highest wear values compared to unsaturated samples are those after boronization. In them, the mass loss values are 6÷7 times lower compared to unsaturated samples.
- It has been proven that high wear resistance is observed in steels with high heat resistance after boronizing, but unlike steels with increased heat resistance, the wear of the transition zone in them is identical to that in carbon steels.

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Machinability of Short Rotary Parts Made of Improveable Steels with Robotic Feeding

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Abstract— Heat-treated steels (hardened with subsequent high-temperature tempering) are widely used in the manufacture of critical parts subjected to elastic and impact loads. The publication examines their machinability when machining on CNC lathes with robotic feed. The average roughness of the machined surfaces – Ra – was used as a criterion for their machinability. Based on the experimental results, regression models were developed and optimization of the technological process was performed.

Keywords— CNC turning; empirical models; genetic algorithm.

I. INTRODUCTION

The development of industrial production in the 21st century is marked by the rapid introduction of new technologies [1] – [5], which fundamentally change the way of organization, management and efficiency of production processes. One of the main drivers of this transformation are the machines with numerical program control (CNC – Computer Numerical Control), which allow achieving high accuracy, repeatability and flexibility in the processing of parts [6] – [9].

Despite their advantages, CNC machines have one serious drawback – their high productivity is often not used effectively due to the need for manual operation. Loading and unloading of parts, changing pallets and handling of blanks are usually performed by operators, which leads to unpredictable downtime and limits production capacity. According to a number of studies, auxiliary operations account for 25÷40% of the total production cycle time [10]. This means that even the most modern CNC machine cannot reach its full potential without an integrated automated feeding system.

Here, the role of industrial robotics comes to the fore. Robots for servicing CNC machines provide reliable, fast and safe manipulation of blanks and finished parts, eliminating or significantly reducing downtime. The implementation of such systems creates conditions for "lights-out manufacturing" – production without operators,

which is especially relevant in conditions of shortage of qualified labor [11] – [16].

All this clearly shows the relevance of the issue of optimizing technological processes in machining parts on CNC machines using robotic feeding. The topic is strategic for the development of the Bulgarian industry in the context of its integration into the European production network and the achievement of the goals of Industry 4.0 and Industry 5.0 [17] – [24].

II. MATERIALS AND METHODS

The machined parts - Fig. 1, are made of 42CrMo4 steel. This is a medium-alloyed, hardenable structural steel for the production of machine elements.

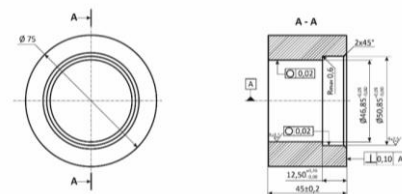


Fig.1. Machined parts.

After heat treatment (oil quenching and high-temperature tempering) – Fig. 2, the hardness of the parts is HRC 35, and the yield strength $R_{0.2} \geq 850$ MPa. The chemical composition of the steel according to DIN EN ISO 683-2 is presented in Table 1 [25].

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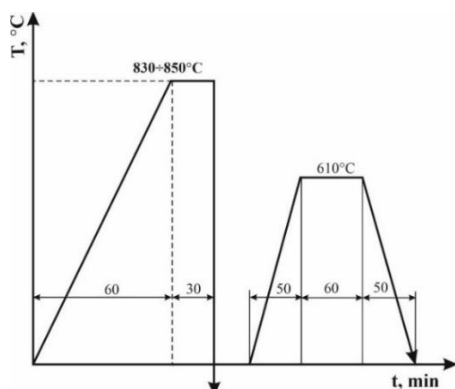


Fig.2. Time-temperature curve of the thermal treatment of the parts.

TABLE 1 CHEMICAL COMPOSITION OF THE STEEL

C	Si	Mn	Ni	Cr	Mo	P	Cu
0.405	0.239	0.652	0.110	0.894	0.180	0.012	0.227

The experiments were conducted in industrial conditions on a HARRIS C320KTT CNC lathe – Fig. 3, with an RV-8CRL robotic feeding station – Fig. 4.



Fig. 3. General view of the HARRIS C 320KTT CNC lathe.



Fig.4. Robotic station RV-8CRL.

The roughness of the machined surfaces was measured on the inner diameters of the parts Ø50.85 and Ø46.85 with a TESA Rugosurf 20 profilometer using the criterion "arithmetic mean deviation from the profile centerline" - Ra.

III. RESULTS AND DISCUSSION

In order to analyze the machinability of the details in the robotic feeding, mathematical models were compiled and a statistical analysis was conducted – Anova (Analysis of Variance). In it, the cutting speed (V_c , m/min) – X_1 , and the feed (f , mm/rev) – X_2 , were selected as input variables (controlled factors). The average roughness (R_a , μm) of the machined internal surfaces – Y_1 (Ø50.85) and Y_2 (Ø 46.85) were studied as objective functions.

The compilation of the mathematical models is based on the obtained experimental results at cutting speed - V_c 140÷180 mm/min and feed - f 0.045÷0.065 mm/tur.

Table 2 presents the levels of variation of the controlling factors, and Table 3 presents the average values of the studied parameters used to compile the mathematical model.

Based on the values in Table 3, the experimental plan was completed – Table 4.

TABLE 2 LEVEL OF VARIATION

Areas of variation	X_1 , (V_c , m/min)	X_2 , (f , mm/tur)	Coded values
$X_{i0} + \Delta X_i$	180	0,65	+1
X_{i0}	160	0,55	0
$X_{i0} - \Delta X_i$	140	0,45	-1

TABLE 3 AVERAGE EXPERIMENTAL RESULTS

X_1 , (V_c , m/min)	изследвани параметри	X_2 , (f , mm/tur)		
		0,45	0,55	0,65
140	Y_1 , (Ra, μm)	0,248	0,346	0,445
	Y_2 , (Ra, μm)	0,268	0,359	0,470
160	Y_1 , (Ra, μm)	0,186	0,244	0,311
	Y_2 , (Ra, μm)	0,248	0,291	0,347
180	Y_1 , (Ra, μm)	0,158	0,188	0,240
	Y_2 , (Ra, μm)	0,208	0,602	0,309

TABLE 4 EXPERIMENTAL PLAN

№	X_0	X_1	X_2	$X_1 X_2$	X_1^2	X_2^2	Y_1 (Ra, μm)	Y_2 (Ra, μm)
1	+1	+1	+1	+1	+1	+1	0,240	0,309
2	+1	-1	+1	-1	+1	+1	0,445	0,470
3	+1	+1	-1	-1	+1	+1	0,158	0,208
4	+1	-1	-1	+1	+1	+1	0,248	0,268
5	+1	+1	0	0	+1	0	0,188	0,602
6	+1	-1	0	0	+1	0	0,346	0,359
7	+1	0	+1	0	0	+1	0,311	0,347
8	+1	0	-1	0	0	+1	0,186	0,248
9	+1	0	0	0	0	0	0,244	0,291

The processing of the obtained results for the studied objective functions – Y_1 and Y_2 , leads to the determination of linear regression equations of the type:

$$Y_{1,2} = b_0 - b_1 x_1 + b_2 x_2 - b_{11} x_{11} + b_{22} x_{22} - b_{12} x_{12} \quad (1)$$

The calculated model coefficients for Y_1 and Y_2 according to [26] – [34] are presented in Table 5.

TABLE 5 COEFFICIENTS OF REGRESSION EQUATIONS

	b_0	b_1	b_2	b_{11}	b_{22}	b_{12}
Y_1	0,2423	-0,0772	0,069	-0,0255	0,007	-0,0313
Y_2	1,2032	-0,3068	0,2217	-0,0448	0,0057	-0,041

The obtained regression models for determining the average roughness Y_1 and Y_2 (R_a , μm) are represented by equations 3 and 4.

$$Y_1 = 0,2423 - 0,0772X_1 + 0,069X_2 - 0,0255X_{11} + 0,007X_{22} - 0,0313X_{12} \quad (3)$$

$$Y_2 = 1,203 - 0,3068X_1 + 0,2217X_2 - 0,0448X_{11} + 0,0057X_{22} - 0,041X_{12} \quad (4)$$

The adequacy check of the models according to the Fisher criterion [35] – [37] shows that they are adequate.

The graphical dependencies for 3 and 4 are presented in Fig. 4 and 6, respectively.

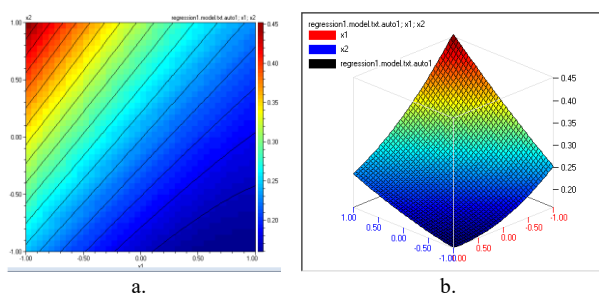


Fig.3. Visualization of the solutions of the regression model for $Y_1(R_a, \mu m)$ when machining a hole $\varnothing 50.85$ in two- and three-coordinate systems (a and b).

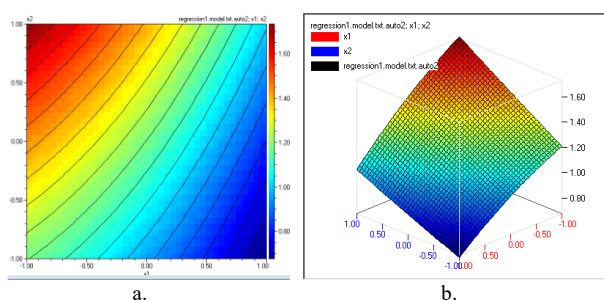


Fig.4. Visualization of the solutions of the regression model for $Y_1(R_a, \mu m)$ when machining a hole $\varnothing 46.85$ in two- and three-coordinate systems (a and b).

When conducting the analysis of variance of the model, Qv Stat Lab Anova was used. The graphical interpretation of the results for the three coded values for Y_1 and Y_2 (R_a , μm) are presented in Fig. 5 and 6, respectively.

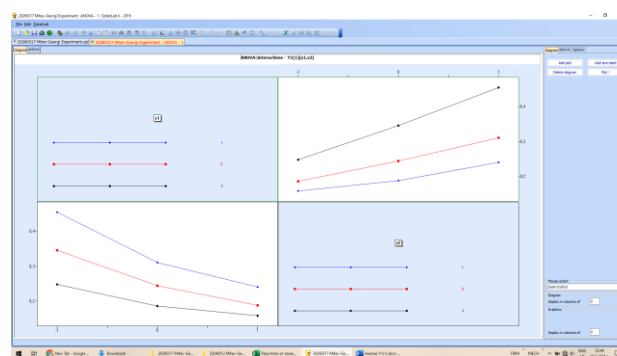


Fig. 5. Analysis of variance of the dependence $Y_1 = f(X_1, X_2)$ at X_{-1} ; X_0 and X_{+1} .

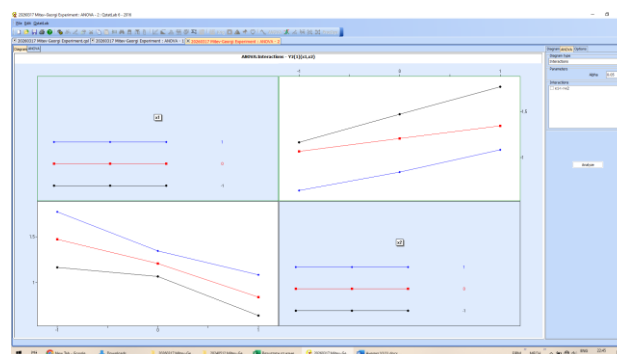


Fig. 6. Analysis of variance of the dependence $Y_2 = f(X_1, X_2)$ at X_{-1} ; X_0 and X_{+1} .

The optimization of the technological process for the machinability of short rotary parts from improveable steels with robotic feeding was made based on set values Y_1 min and Y_2 min. It was carried out by random search with increasing density (genetic algorithm) [31] – [33]. The graphical interpretation is shown in Fig. 7 and 8. for machined holes $\varnothing 50.85$ and $\varnothing 46.85$, respectively.

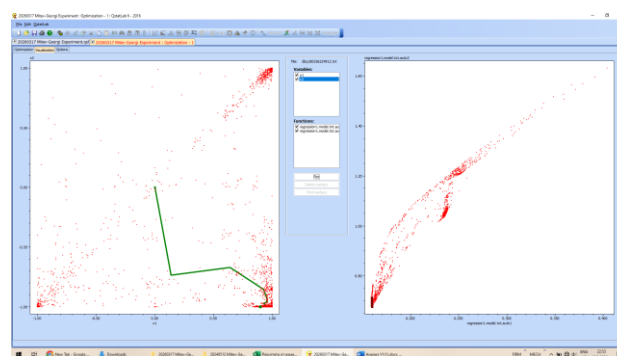


Fig.7. Optimization of the technological process for machining holes $\varnothing 50.85$ at Y_1 min.

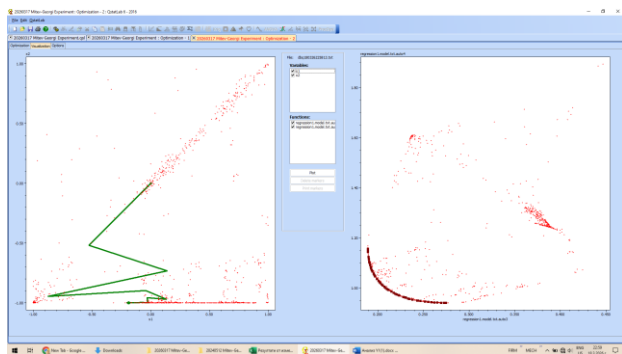


Fig.7. Optimization of the technological process for machining holes Ø46.85 at Y₂min.

IV. CONCLUSIONS

The following more important conclusions can be formulated from the conducted research and the results obtained:

- The machinability of improved medium-alloy structural steels was studied when machining short rotary parts on CNC lathes with robotic feeding according to the criterion of average roughness deviation on the machined surfaces - Ra.
- Empirical models of the studied functions were compiled and their adequacy was checked using the Fisher criterion.
- The dispersion analysis performed has shown that optimal working conditions for the given material, speed and feed are achieved at $V_c = 180$ m/min and $f = 0.45$ mm/tur.
- The optimization of the technological process was done based on the given values Y₁ min and Y₂ min. It was carried out by random search with increasing density (genetic algorithm).

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Analysis of Software and Organizational Solutions for Supporting Innovation Management in Industrial Enterprises in the Context of Industry 4.0

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Abstract—This paper presents a structured analysis of existing software and organizational solutions that support innovation management in industrial enterprises within the context of Industry 4.0. The increasing digitalization of manufacturing systems, integration of cyber-physical technologies, and data-driven decision-making processes have significantly transformed how innovation activities are managed and implemented. The study adopts a literature review approach, synthesizing findings from recent academic publications, industry reports, and relevant case studies. The analysis focuses on key categories of software solutions, including innovation management platforms, enterprise resource planning (ERP) systems, knowledge management systems, and collaborative digital tools, alongside organizational practices such as open innovation models, agile management approaches, and cross-functional team structures. The results highlight that the effective integration of software tools with organizational capabilities is critical for enhancing innovation performance. Furthermore, the findings reveal that industrial enterprises face challenges related to system interoperability, organizational resistance to change, and the alignment of digital strategies with innovation objectives. The paper contributes by systematizing existing knowledge and identifying key trends and gaps in the field, providing a foundation for future research and practical implementation of innovation management solutions in industrial environments.

Keywords—digital transformation, Industry 4.0, innovation management, software solutions.

I. INTRODUCTION

The rapid advancement of digital technologies has significantly transformed industrial enterprises, reshaping the way innovation processes are managed and executed

[1], [2]. The emergence of Industry 4.0, characterized by the integration of cyber-physical systems, the Internet of Things (IoT), big data analytics, and cloud computing, has created new opportunities and challenges for innovation management [3], [4]. In this context, industrial organizations are required to adopt more flexible, data-driven, and collaborative approaches to remain competitive in increasingly dynamic markets [2], [5].

Innovation management has evolved from a traditionally linear process to a complex, multi-dimensional system involving various stakeholders, technologies, and organizational structures [6], [7]. The growing complexity of innovation activities necessitates the use of advanced software solutions, such as innovation management platforms, enterprise resource planning systems, and knowledge management tools, which enable the effective coordination, monitoring, and evaluation of innovation processes [1], [2]. At the same time, organizational solutions – including agile methodologies, open innovation practices, and cross-functional team integration – play a crucial role in ensuring that technological capabilities are effectively leveraged [6], [8].

Despite the increasing availability of both software and organizational solutions, many industrial enterprises face difficulties in successfully integrating these approaches into a coherent innovation management framework [5], [9]. Challenges such as lack of interoperability between systems, resistance to organizational change, insufficient digital competencies, and misalignment between innovation strategy and business objectives continue to hinder the effective implementation of innovation initiatives [3], [4].

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There is a clear need for a systematic analysis of existing solutions that support innovation management within industrial environments. While numerous studies have examined individual tools or organizational practices, a comprehensive synthesis that integrates both technological and organizational perspectives remains limited, particularly in the context of Industry 4.0 [2] - [3], [7].

The main objective of this paper is to analyze existing software and organizational solutions that support innovation management in industrial enterprises, with a focus on their roles, interdependencies, and practical applicability. To achieve this objective, the study employs a structured literature review approach, examining relevant academic publications and industry sources [1] - [4], [6].

The contribution of this paper is twofold. First, it systematizes the existing body of knowledge by categorizing and analyzing key types of software and organizational solutions used in innovation management. Second, it identifies current trends, challenges, and research gaps, providing a foundation for future studies and practical implementations in industrial enterprises operating in the context of Industry 4.0 [3], [7].

II. MATERIALS AND METHODS

This study adopts a structured literature review approach to analyze existing software and organizational solutions supporting innovation management in industrial enterprises within the context of Industry 4.0. The methodology is designed to ensure transparency, reproducibility, and analytical rigor in the selection and evaluation of relevant sources.

A. Methodology

The research follows a semi-systematic literature review methodology, which allows for a comprehensive synthesis of existing knowledge while maintaining flexibility in the inclusion of diverse types of sources. This approach is particularly suitable for emerging and interdisciplinary research domains, such as innovation management in industrial environments influenced by Industry 4.0.

The literature search was conducted using major academic and scientific databases, including Scopus, Web of Science, and Google Scholar. In addition, relevant industry reports and conference proceedings were considered to capture recent developments and practical insights.

The search process was based on a combination of keywords and Boolean operators. Primary search terms included: "innovation management", "industrial enterprises", "Industry 4.0", "software solutions", "organizational innovation", "digital transformation", and "knowledge management". These keywords were combined using Boolean expressions such as: ("innovation management" AND "Industry 4.0") AND ("software" OR "digital tools") AND ("organizational" OR "management practices").

B. Inclusion and Exclusion Criteria

Inclusion: Publications related to innovation management in industrial or manufacturing contexts; studies addressing software tools or organizational approaches; peer-reviewed articles, conference papers, reports; publications in English; timeframe 2015–2025 [1] – [3], [6].

Exclusion: Studies not related to industrial enterprises; papers lacking relevance to innovation management; non-peer-reviewed sources (exceptions for high-quality reports); duplicate records [3], [5].

The selection process was carried out in several stages. First, an initial search yielded a broad set of publications. Second, titles and abstracts were screened to eliminate irrelevant studies. Third, full-text analysis was conducted on the remaining articles to assess their suitability based on the defined criteria.

Following this process, a refined set of relevant studies was selected for in-depth analysis.

The selected literature was analyzed using a qualitative content analysis approach. The studies were categorized into two main groups:

1. Software solutions (e.g., innovation management systems, ERP platforms, knowledge management systems, collaborative tools) [1] - [2], [6].
2. Organizational solutions (e.g., agile methodologies, open innovation models, structural and cultural practices) [6] - [8].

The analysis focused on identifying key functionalities and characteristics, benefits and limitations, implementation challenges, interdependencies between technological and organizational factors. [3], [4].

C. Limitations

Despite efforts to ensure methodological rigor, this study has several limitations. The selection of databases and keywords may have excluded some relevant publications. Additionally, the qualitative nature of the analysis introduces a degree of subjectivity. Nevertheless, the adopted approach provides a reliable and comprehensive overview of the current state of research in the field.

D. Literature review

Software Solutions for Innovation Management

The increasing complexity of innovation processes in industrial enterprises has led to the widespread adoption of specialized software solutions designed to support various stages of innovation management. In the context of Industry 4.0, these tools play a critical role in enabling data-driven decision-making, enhancing collaboration, and improving process efficiency.

Innovation management systems (IMS) represent one of the most prominent categories of software solutions. These platforms facilitate idea generation, evaluation, selection, and implementation by providing structured

workflows and integrated evaluation mechanisms. Many studies highlight that IMS platforms improve transparency and traceability in innovation processes, although their effectiveness depends heavily on user engagement and organizational culture [1], [3].

Enterprise Resource Planning (ERP) systems also contribute significantly to innovation management by integrating data across different functional areas. While traditionally focused on operational efficiency, modern ERP systems increasingly incorporate innovation-related functionalities, enabling better resource allocation and strategic planning. However, the rigidity of some ERP systems can limit their adaptability to dynamic innovation processes [6], [2].

Knowledge management systems (KMS) are another essential component, particularly in knowledge-intensive industrial environments. These systems support the creation, storage, sharing, and reuse of organizational knowledge, which is a key driver of innovation [1], [4]. Research indicates that effective knowledge management enhances organizational learning and fosters continuous innovation. Nevertheless, challenges such as knowledge silos and low participation rates often reduce their impact.

Additionally, collaborative digital tools – such as cloud-based platforms and communication systems – have gained importance in facilitating distributed innovation activities. These tools support cross-functional and geographically dispersed teams, aligning with the decentralized nature of Industry 4.0 environments. Despite their benefits, issues related to data security, interoperability, and system integration remain significant concerns [3], [5].

Table 1 presents a classification of the main software solutions supporting innovation management in industrial enterprises.

Organizational Approaches to Innovation Management

Alongside technological advancements, organizational solutions play a crucial role in shaping effective innovation management practices. The transition toward Industry 4.0 requires organizations to adopt more flexible, adaptive, and collaborative structures.

TABLE 1 CLASSIFICATION OF SOFTWARE SOLUTIONS FOR INNOVATION MANAGEMENT

Category	Description	Key Functions	Examples
Innovation Management Systems (IMS)	specialized platforms for managing ideas and innovation processes	Idea generation, evaluation, portfolio management	IdeaScale, Brightidea
Enterprise Resource Planning (ERP)	integrated resource management systems	Resource planning, data integration, process coordination	SAP, Oracle
Knowledge Management Systems (KMS)	knowledge management systems	Knowledge creation, storage, sharing, reuse	SharePoint, Confluence

Collaborative Digital Tools	collaboration platforms	Communication, teamwork, co-creation	Microsoft Teams, Slack
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Agile methodologies have been increasingly applied beyond software development to innovation management in industrial settings. Agile approaches emphasize iterative development, rapid feedback, and adaptability, making them well-suited to uncertain and dynamic innovation environments. However, their implementation in traditionally hierarchical industrial organizations can be challenging due to cultural resistance and structural constraints [6], [8].

Open innovation has also emerged as a key paradigm, encouraging organizations to leverage external knowledge sources, partnerships, and collaborations. This approach enhances innovation capacity by integrating ideas from customers, suppliers, research institutions, and other stakeholders. Nevertheless, managing intellectual property and ensuring effective collaboration across organizational boundaries remain critical challenges [3], [7].

Cross-functional teams are widely recognized as an effective organizational mechanism for fostering innovation. By bringing together diverse expertise and perspectives, such teams enhance creativity and problem-solving capabilities. In the context of Industry 4.0, cross-functional integration is particularly important due to the convergence of digital and physical systems [2], [8].

Furthermore, organizational culture plays a fundamental role in enabling or hindering innovation. A culture that promotes experimentation, knowledge sharing, and risk-taking is essential for successful innovation management. Conversely, rigid structures and risk-averse attitudes can significantly limit innovation potential [1], [5].

Table 2 summarizes the key organizational approaches that enable effective innovation management.

TABLE 2 ORGANIZATIONAL APPROACHES SUPPORTING INNOVATION MANAGEMENT

Approach	Description	Key Benefits	Challenges
Agile Methodologies	iterative and flexible approach	Flexibility, rapid response, continuous improvement	Resistance in traditional structures
Open Innovation	using external ideas and partnerships	Increased innovation capacity, knowledge inflow	IP management, coordination complexity
Cross-functional Teams	teams from different disciplines	Enhanced creativity, better decision-making	Communication barriers

Innovation-oriented Culture	organizational culture supporting innovation	Encourages experimentation and knowledge sharing	difficult to build
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Integration of Software and Organizational Solutions

A key insight emerging from the literature is that software and organizational solutions cannot be effectively implemented in isolation. The success of innovation management initiatives depends on the alignment and integration of technological tools with organizational practices [2], [3].

Studies indicate that the mere adoption of advanced software systems does not guarantee improved innovation performance. Instead, the effectiveness of such systems is contingent upon organizational readiness, employee competencies, and strategic alignment. In many cases, failures in innovation management can be attributed to the mismatch between technological capabilities and organizational structures [5], [9].

In the context of Industry 4.0, this integration becomes even more critical due to the increased complexity and interconnectivity of industrial systems. Organizations must develop holistic approaches that combine digital technologies with adaptive management practices [3], [7].

From a technical perspective, improving interoperability requires the adoption of standardized communication protocols, application programming interfaces (APIs), and service-oriented architectures that enable seamless data exchange between heterogeneous systems. Recent studies emphasize the role of cloud-based platforms, middleware solutions, and digital twin architectures in supporting interoperability across industrial environments. Such approaches facilitate real-time integration between innovation management systems, ERP platforms, and data analytics tools, thereby reducing information fragmentation and improving coordination within innovation processes.

Research Gaps and Future Directions

Despite the growing body of literature, several research gaps remain. First, there is a lack of comprehensive frameworks that integrate both software and organizational dimensions of innovation management [3], [7]. Most studies tend to focus on either technological tools or organizational practices, without adequately addressing their interdependencies.

Second, empirical evidence on the effectiveness of integrated solutions in real industrial settings is still limited. Many studies are conceptual or based on case studies with restricted generalizability [5], [9].

Third, there is a need for further research on the role of emerging technologies – such as artificial intelligence and

advanced analytics – in enhancing innovation management processes within industrial enterprises [2], [8].

Another important research direction concerns the ethical and cybersecurity implications of AI-driven innovation management systems. As industrial enterprises increasingly rely on artificial intelligence, big data analytics, and open innovation ecosystems, issues related to algorithmic transparency, data governance, intellectual property protection, and cybersecurity become increasingly critical. Future frameworks should therefore incorporate mechanisms for secure data sharing, explainable AI, and risk management in digitally interconnected innovation environments.

Finally, future research should explore the transition from Industry 4.0 toward more human-centric paradigms, such as Industry 5.0, and their implications for innovation management [7].

III. RESULTS AND DISCUSSION

The structured analysis of the selected literature reveals several key patterns in the adoption and application of software and organizational solutions for innovation management in industrial enterprises within the context of Industry 4.0.

First, software solutions can be categorized into four main groups: innovation management systems (IMS), enterprise resource planning (ERP) systems, knowledge management systems (KMS), and collaborative digital tools [1] - [2], [6]. Among these, innovation management systems are identified as the most specialized tools, providing end-to-end support for idea generation, evaluation, and implementation. ERP systems, while not primarily designed for innovation, contribute indirectly by enabling data integration and resource planning. Knowledge management systems support the codification and dissemination of organizational knowledge, whereas collaborative tools enhance communication and coordination across teams.

Second, the analysis shows that organizational solutions are equally important and can be grouped into agile methodologies, open innovation practices, and structural approaches such as cross-functional teams. Agile methodologies are increasingly adopted due to their flexibility and responsiveness to change, while open innovation models extend the innovation process beyond organizational boundaries. Cross-functional teams facilitate interdisciplinary collaboration, which is essential in complex industrial environments [6], [8].

Third, a recurring finding across the reviewed studies is the strong interdependence between software and organizational solutions. The effectiveness of digital tools is significantly influenced by organizational factors such as culture, leadership, and employee competencies [4], [2], [8].

Furthermore, several common challenges have been identified. These include limited interoperability between different software systems, resistance to organizational change, lack of digital skills, and difficulties in aligning

innovation strategies with broader business objectives [5], [9].

Finally, the results indicate a growing trend toward integrated and platform-based solutions that combine multiple functionalities, reflecting the increasing

complexity of innovation ecosystems in Industry 4.0 environments [3], [7].

Proposed Integrated Model for Innovation Management

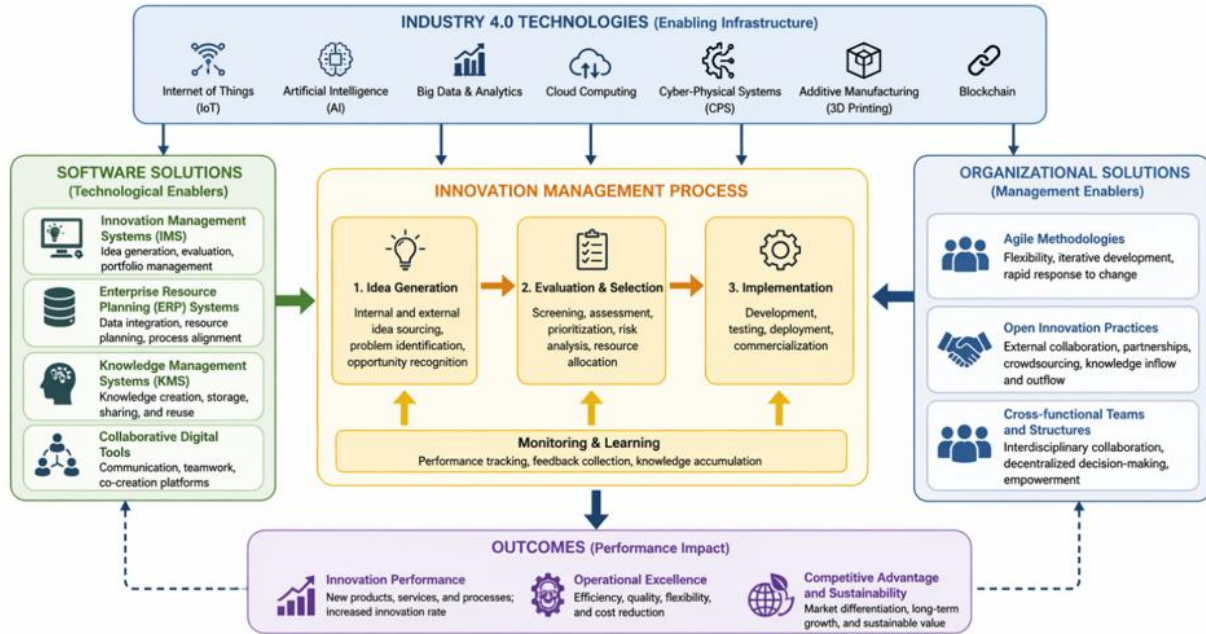


Fig. 1. Integrated framework for innovation management in the context of Industry 4.0.

Based on the findings of the conducted literature review, this study proposes an integrated model that conceptualizes the interaction between software and organizational solutions in supporting innovation management within industrial enterprises in the context of Industry 4.0.

The proposed model, presented in Fig. 1, is structured around three core components: enabling technologies,

innovation management processes, and performance outcomes. At the foundational level, Industry 4.0 technologies – including the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cyber-physical systems – provide the digital infrastructure that supports innovation activities. These technologies enable real-time data collection, advanced analytics, and enhanced connectivity across organizational units.

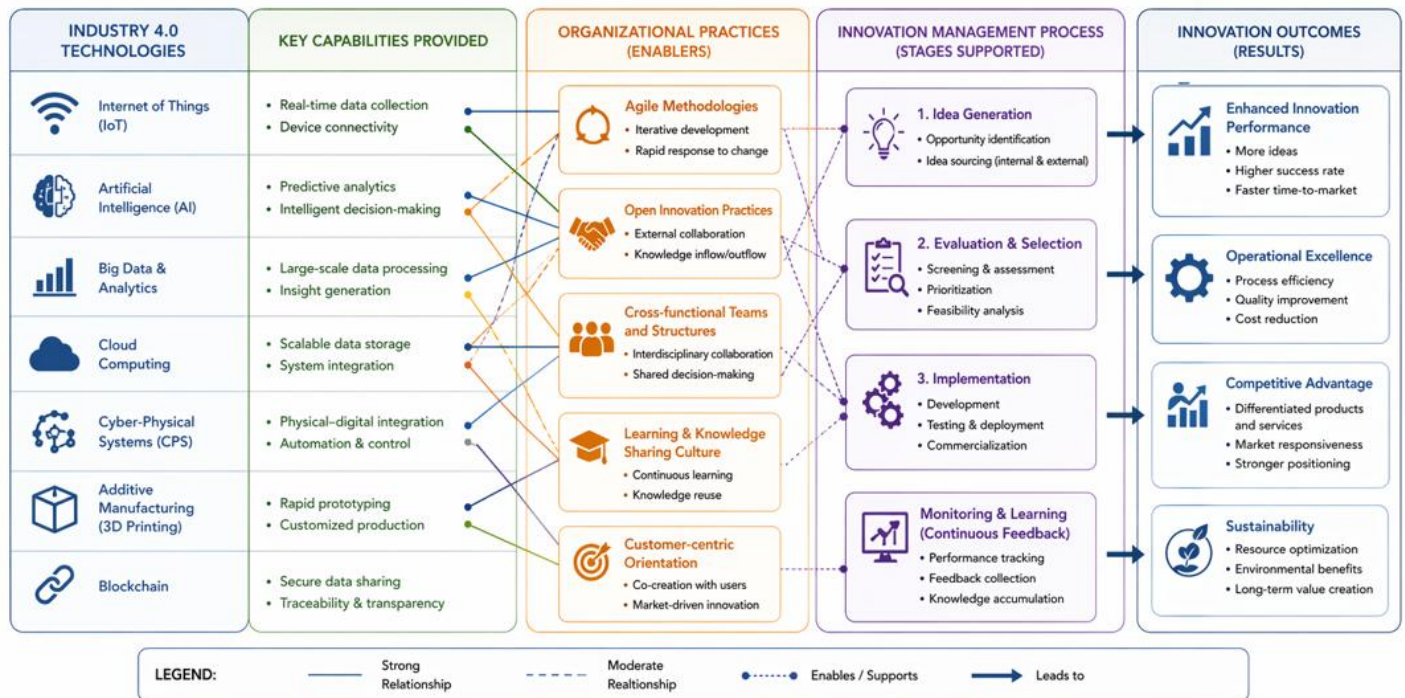


Fig. 2. Mapping between Industry 4.0 technologies, organizational practices and innovation management outcomes.

At the core of the model lies the innovation management process, which is conceptualized as a sequence of interconnected stages: idea generation, evaluation and selection, and implementation. These stages are supported by continuous monitoring and organizational learning mechanisms, which enable feedback loops and process improvement.

The model distinguishes between two primary categories of enablers: software solutions and organizational solutions. Software solutions, such as innovation management systems, enterprise resource planning platforms, knowledge management systems, and collaborative digital tools, facilitate the technical execution and coordination of innovation processes. In parallel, organizational solutions – including agile methodologies, open innovation practices, and cross-functional team structures – ensure the effective utilization of these technologies by fostering flexibility, collaboration, and knowledge sharing.

The final component of the model consists of performance outcomes, including improved innovation performance, operational excellence, and enhanced competitive advantage. The model emphasizes that these outcomes are achieved through the dynamic alignment and integration of technological and organizational factors.

Overall, the proposed framework provides a holistic perspective on innovation management in industrial enterprises, highlighting the importance of systemic integration in the era of Industry 4.0.

Fig. 2 illustrates how key Industry 4.0 technologies enable organizational practices, which in turn support different stages of the innovation management process and contribute to desired innovation outcomes. The mapping highlights the complementary nature of technological and organizational solutions and their synergistic impact on innovation performance.

Table 3 presents a mapping between key Industry 4.0 technologies and the organizational practices they enable, highlighting their combined impact on innovation management processes.

The findings of this study provide important insights into the evolving landscape of innovation management in industrial enterprises. One of the central observations is that the successful implementation of innovation management solutions depends not on the individual adoption of software tools or organizational practices, but on their effective integration [3], [2], [8].

In line with the principles of Industry 4.0, industrial enterprises are increasingly required to operate as interconnected and adaptive systems. This necessitates a shift from isolated innovation initiatives toward holistic innovation management frameworks that combine technological infrastructure with organizational capabilities [3], [5], [7].

The prominence of innovation management systems identified in the results reflects the growing need for structured and transparent innovation processes. However,

their effectiveness is contingent upon user engagement and organizational support. Without a supportive culture and appropriate incentives, even the most advanced systems may fail to deliver expected outcomes [1], [2].

Similarly, the role of organizational approaches such as agile methodologies and open innovation highlights the importance of flexibility and collaboration in modern industrial environments. These approaches enable organizations to respond more effectively to rapid technological changes and market uncertainties.

Nevertheless, their implementation often requires significant organizational transformation, which may encounter resistance [6], [8].

Another important implication of the findings is the critical role of alignment between innovation strategy and digital transformation initiatives. The lack of such alignment is frequently cited as a major barrier to successful innovation management. This suggests that organizations must adopt a strategic perspective, ensuring

TABLE 3 MAPPING BETWEEN INDUSTRY 4.0 TECHNOLOGIES AND ORGANIZATIONAL PRACTICES

Industry 4.0 Technology	Key Capabilities	Supported Organizational Practices	Impact on Innovation Management
Internet of Things (IoT)	Real-time data collection, connectivity	Agile methodologies, cross-functional teams	Faster decision-making, improved responsiveness
Artificial Intelligence (AI)	Predictive analytics, intelligent automation	Data-driven management, innovation-oriented culture	Enhanced idea evaluation and selection
Big Data & Analytics	Large-scale data processing, insights generation	Open innovation, strategic decision-making	Improved identification of innovation opportunities
Cloud Computing	Scalable infrastructure, system integration	Collaboration, remote teamwork	Increased flexibility and knowledge sharing
Cyber-Physical Systems (CPS)	Integration of physical and digital systems	Cross-functional integration, process optimization	Improved implementation of innovation processes
Additive Manufacturing (3D Printing)	Rapid prototyping, customization	Agile development, experimentation	Faster product development cycles
Blockchain	Secure and transparent data sharing	Open innovation, inter-organizational collaboration	Increased trust and collaboration in innovation ecosystems

TABLE 4 KEY CHALLENGES IN INTEGRATING INNOVATION MANAGEMENT SOLUTIONS

Challenge	Description	Impact on Innovation Management
System Interoperability	lack of compatibility between systems	Reduced efficiency and data silos
Resistance to Change	organizational resistance	Delayed or failed implementation
Lack of Digital Skills	insufficient competencies	Ineffective use of technologies
Strategic Misalignment	mismatch between strategy and technology	Poor innovation outcomes

that technological investments are closely linked to innovation objectives [5], [9].

The identified challenges – such as interoperability issues and skill gaps – also point to the need for continuous capability development. Industrial enterprises must invest not only in technologies but also in human capital and organizational learning processes.

Table 4 outlines the major challenges associated with the integration of software and organizational solutions.

Finally, the transition toward more advanced paradigms beyond Industry 4.0, including Industry 5.0, suggests that future innovation management models will increasingly emphasize human-centricity, sustainability, and resilience

[7]. This creates new research opportunities and practical challenges that require further investigation.

Implications and Future Research

The results of this study have both theoretical and practical implications. From a theoretical perspective, the paper contributes to the development of a more holistic understanding of innovation management in industrial enterprises. From a practical standpoint, it provides guidance for managers seeking to implement effective innovation management solutions in the context of Industry 4.0.

Illustrative Application of the Proposed Framework

To demonstrate the practical applicability of the proposed framework, we present an illustrative case study of a hypothetical industrial enterprise operating in the context of Industry 4.0.

The example considers a mid-sized manufacturing company undergoing digital transformation with the objective of improving its innovation performance. The company faces challenges related to inefficient idea management, limited cross-departmental collaboration, and lack of integration between digital tools and organizational processes.

In the first stage, the company adopts several software solutions, including an innovation management system for

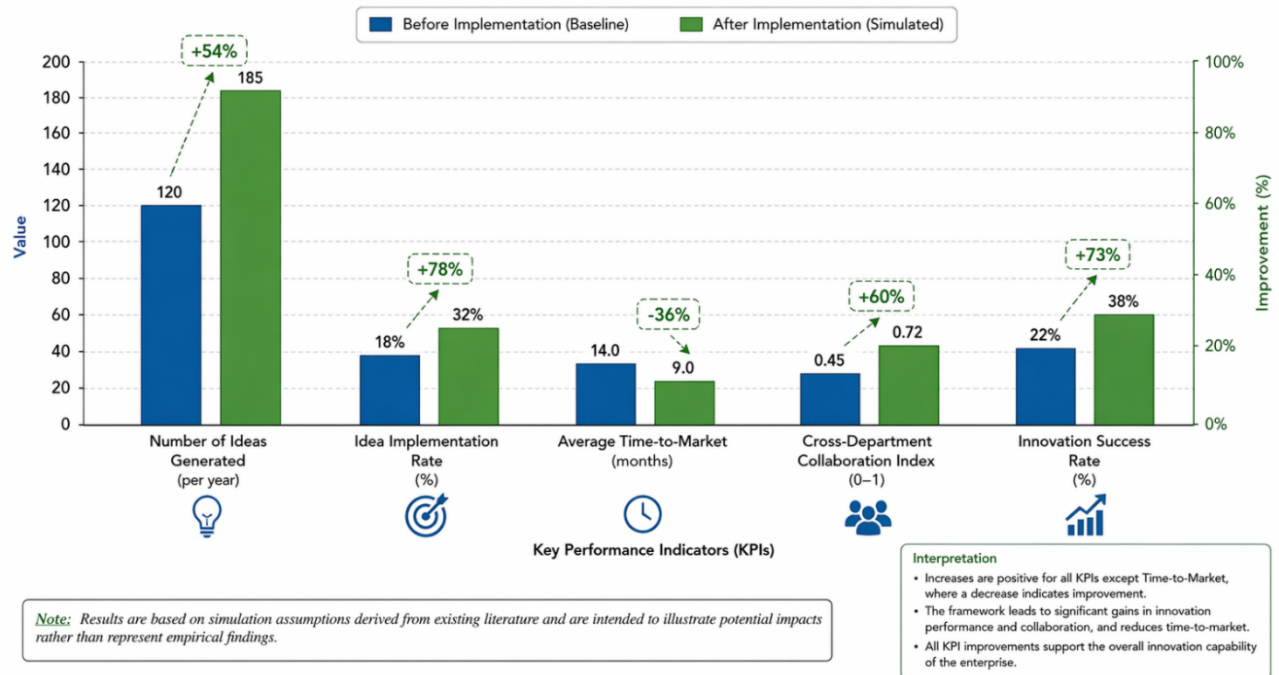
idea generation and evaluation, an enterprise resource planning system for resource coordination, and collaborative digital tools to support communication across teams. Additionally, data analytics tools are implemented to enable data-driven decision-making.

was conceptually estimated using a weighted aggregation of key performance indicators (KPIs), including idea generation, implementation rate, collaboration efficiency, innovation success rate, and time-to-market reduction. The generalized performance function can be expressed as:

$$KPI_{overall} = \sum_{i=1}^n w_i \cdot KPI_i$$

TABLE 5 APPLICATION OF THE PROPOSED FRAMEWORK IN THE CASE STUDY

Figure 3. KPI Improvement Chart – Before vs After Implementation
(Simulated Impact of the Proposed Framework)



Framework Component	Implementation in Case	Outcome
IMS	Idea platform introduced	Increased idea generation
Agile	Iterative development	Faster execution
AI Analytics	Data-driven evaluation	Better decision quality
Cross-functional Teams	Interdisciplinary collaboration	Improved innovation outcomes

Simultaneously, the organization introduces key organizational practices aligned with the proposed framework. Agile methodologies are applied to innovation projects, cross-functional teams are established to enhance collaboration, and open innovation practices are adopted to incorporate external knowledge from partners and customers.

As it is shown in Table 5, the integration of these technological and organizational elements enables the company to improve its innovation management process. Idea generation becomes more structured and inclusive, evaluation processes are supported by data analytics, and implementation is accelerated through better coordination and flexibility.

To provide a simplified quantitative interpretation of the simulated results, the overall innovation performance

where w_i represents the relative importance of each KPI within the innovation management process. The relative improvement of individual indicators was conceptually estimated using the following expression:

$$Improvement(\%) = \frac{KPI_{after} - KPI_{before}}{KPI_{before}} \times 100$$

The presented formulation is intended to provide methodological transparency for the illustrative simulation scenario rather than to represent a fully validated empirical model.

As a result, the company achieves measurable improvements in innovation performance, including reduced time-to-market, increased number of implemented ideas, and enhanced operational efficiency. Furthermore, the alignment between digital technologies and organizational practices contributes to a more adaptive and resilient innovation system.

This illustrative example demonstrates how the proposed framework can be applied in practice, highlighting the importance of integrating software and organizational solutions to achieve effective innovation management in industrial enterprises.

Fig. 3. Before vs After KPI Comparison (Simulated Impact of the Proposed Framework).

The simulation results suggest that the integrated implementation of software and organizational solutions leads to significant improvements across all key performance indicators.

The increase in idea generation is primarily driven by the adoption of collaborative platforms and open innovation practices. The improvement in implementation rate and innovation success is associated with the use of AI-based evaluation tools and structured innovation processes.

The reduction in time-to-market reflects the impact of agile methodologies and improved coordination enabled by ERP systems and cross-functional teams.

The collaboration index shows substantial improvement, indicating that organizational practices play a critical role in leveraging technological capabilities.

The simulation confirms innovation performance is maximized when technological and organizational elements are integrated, not implemented in isolation.

The presented results are based on simulation assumptions derived from existing literature and are intended to illustrate potential impacts rather than represent empirical findings.

Fig. 3 illustrates the simulated improvement in key performance indicators following the implementation of the proposed innovation management framework. The comparison highlights significant gains in idea generation, implementation rate, collaboration, and innovation success, along with a reduction in time-to-market.

IV. CONCLUSIONS

This paper presents a structured analysis of software and organizational solutions supporting innovation management in industrial enterprises within the context of Industry 4.0. The conducted literature review highlights the increasing importance of integrating digital technologies with organizational practices to enhance innovation performance in complex industrial environments.

The findings confirm that software solutions – such as innovation management systems, enterprise resource planning platforms, and knowledge management systems – play a critical role in enabling data-driven and efficient innovation processes. At the same time, organizational approaches, including agile methodologies, open innovation models, and cross-functional collaboration, are essential for ensuring the effective utilization of these technological capabilities.

A key conclusion of this study is that innovation performance in industrial enterprises is maximized when technological infrastructure and organizational capabilities are treated as interdependent components of a unified

innovation ecosystem. The proposed integrated perspective extends existing research by emphasizing interoperability, adaptive organizational structures, and the strategic alignment between digital transformation initiatives and innovation objectives.

Future research should focus on the development of integrated frameworks that combine technological and organizational dimensions, as well as on empirical validation of such models in real industrial settings.

Additionally, further studies are needed to explore the transition toward more human-centric and sustainable innovation paradigms associated with Industry 5.0, particularly regarding human–AI collaboration, resilient organizational systems, and socially sustainable innovation management practices.

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Development of a Methodological Framework for Integrating Intelligent Technologies in Engineering Innovation Management

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Abstract—This study develops and empirically validates a methodological framework for integrating intelligent technologies into engineering innovation management. In response to increasing technological complexity and data-driven transformation, organizations require structured approaches to effectively leverage artificial intelligence (AI), machine learning (ML), and advanced analytics within innovation processes. The proposed framework adopts a multi-layer architecture encompassing strategic alignment, technological infrastructure, data and analytics capabilities, and organizational readiness. A mixed-method research design is applied, combining conceptual modeling with empirical analysis based on survey data collected from engineering professionals. Statistical techniques, including regression analysis and correlation modeling, are employed to examine the relationships between technology adoption, organizational enablers, and innovation performance. The results indicate a significant positive impact of intelligent technology integration on innovation outcomes, with organizational and data-related factors acting as critical mediators. The study contributes to the literature by providing a structured and empirically grounded framework that bridges the gap between theoretical models and practical implementation. It offers actionable insights for organizations aiming to enhance innovation efficiency, reduce uncertainty, and achieve sustainable competitive advantage through intelligent technologies.

Keywords— *AI, engineering innovation, innovation management, intelligent technologies.*

I. INTRODUCTION

Engineering innovation is widely recognized as a key driver of industrial competitiveness, technological progress, and long-term economic sustainability. In the context of Industry 4.0 and accelerating digital transformation, organizations operate in environments characterized by increasing complexity, uncertainty, and rapid technological evolution. These conditions

fundamentally reshape how innovation processes are designed, managed, and evaluated, requiring more adaptive and data-driven approaches beyond traditional linear or stage-gate models [1].

The emergence of intelligent technologies such as artificial intelligence (AI), machine learning (ML), big data analytics, and the Internet of Things (IoT) has significantly transformed the innovation landscape. These technologies enable advanced capabilities including predictive analytics, real-time process monitoring, and semi-autonomous or autonomous decision-making. As a result, they enhance both the efficiency and the effectiveness of engineering innovation processes across multiple stages of the innovation lifecycle [2], [3]. AI-based systems support optimization in early design phases, simulation-driven engineering, and risk-informed decision-making, while data analytics enables evidence-based strategic planning and operational control [4], [5].

Despite these advances, the integration of intelligent technologies into engineering innovation management remains fragmented and methodologically underdeveloped. Existing research has largely focused on isolated technological applications or platform-specific innovations, while insufficient attention has been given to systemic integration across organizational, technological, and strategic dimensions [2], [6]. This limitation restricts the ability of organizations to fully leverage digital technologies for sustained innovation performance and long-term value creation.

Empirical evidence suggests that the successful implementation of intelligent technologies depends not only on technological readiness, but also on organizational and human factors. Leadership commitment, workforce digital competencies, and organizational agility are critical enablers of digital transformation in innovation contexts [7]. At the same time, data governance mechanisms and

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analytics maturity levels play a decisive role in transforming raw data into actionable knowledge, thereby directly influencing innovation outcomes [5].

However, the interplay between technological infrastructure, organizational capabilities, and strategic alignment remains insufficiently theorized, particularly in engineering-intensive environments. While several conceptual frameworks for digital innovation exist, many lack empirical validation or fail to capture the multidimensional nature of engineering innovation systems [8], [9]. This gap limits their applicability in real-world industrial contexts, where innovation processes are highly interdependent and data intensive.

In response to these limitations, this study aims to develop a comprehensive methodological framework for the integration of intelligent technologies into engineering innovation management. The proposed approach adopts a multi-layer perspective, integrating technological, organizational, and strategic dimensions into a unified model. By combining conceptual development with empirical considerations, the framework seeks to bridge the gap between theory and practice and to support more effective decision-making in innovation-intensive environments.

Ultimately, this research contributes to the evolving literature on digital and engineering innovation by providing a structured and empirically grounded perspective on intelligent technology integration. It aims to support organizations in navigating the complexity of digital transformation and achieving sustainable innovation performance and competitive advantage in increasingly data-driven industrial ecosystems [1], [2], [6].

II. MATERIALS AND METHODS

A. Literature review

Evolution of Engineering Innovation Management

Engineering innovation management has evolved from linear and sequential models toward more dynamic, iterative, and network-based approaches. Early frameworks, such as the stage-gate model, emphasized structured progression and risk control but have been criticized for their rigidity and limited adaptability in fast-changing environments. More recent perspectives highlight open innovation, agile development, and ecosystem-based innovation as key paradigms for managing technological complexity [5].

However, despite this evolution, many organizations still rely on hybrid or partially adapted models that fail to fully capture the non-linearity and data intensity of modern engineering innovation. This creates a mismatch between theoretical advancements and practical implementation, particularly in technology-intensive sectors.

Role of Intelligent Technologies in Innovation

The integration of intelligent technologies has significantly expanded the capabilities of innovation systems. Artificial intelligence and machine learning enable automation of cognitive tasks, predictive analytics,

and enhanced decision support, while big data technologies provide the foundation for extracting insights from large and heterogeneous datasets [3].

Empirical studies demonstrate that firms leveraging AI and data-driven approaches achieve higher innovation efficiency and improved performance outcomes [2]. Additionally, intelligent technologies facilitate faster prototyping, optimization of engineering designs, and real-time monitoring of innovation processes [4].

Nevertheless, the literature tends to focus predominantly on technological capabilities and performance outcomes, often overlooking the organizational and strategic conditions required for successful implementation. This results in an overemphasis on technology as an isolated driver of innovation, rather than as part of a broader socio-technical system.

Organizational and Data-Driven Enablers

Recent research underscores the importance of organizational and data-related factors in shaping innovation outcomes. Leadership support, digital skills, and organizational culture have been identified as critical enablers of successful digital transformation and technology adoption [7]. Similarly, data governance, data quality, and analytics maturity are essential for converting technological potential into measurable innovation value [10].

However, existing studies often treat these factors independently, without sufficiently exploring their interdependencies. For example, while organizational readiness is recognized as important, its interaction with data maturity and technological infrastructure is rarely modeled in a systematic way. This lack of integration limits the explanatory power of current research frameworks.

Digital Transformation and Innovation Performance

Digital transformation literature provides important insights into how intelligent technologies influence firm performance. Studies suggest that digital transformation is a multidimensional phenomenon involving technological, organizational, and strategic changes [1]. Successful transformation requires alignment across these dimensions, as well as continuous adaptation to external and internal dynamics.

Despite these advances, there is still limited empirical evidence linking digital transformation directly to engineering innovation performance. Many studies focus on general business outcomes rather than domain-specific innovation processes, leading to a gap in understanding how digital capabilities translate into engineering innovation results.

Critical Synthesis and Research Gap

The reviewed literature reveals several important limitations:

- Fragmentation of perspectives – technological, organizational, and strategic dimensions are often studied in isolation.

- Lack of integrated frameworks – few studies propose comprehensive models that capture the multi-layer nature of intelligent technology integration.
- Insufficient empirical validation – many conceptual models lack quantitative testing in real-world engineering contexts.
- Limited focus on engineering innovation – most research addresses general innovation or digital transformation without considering engineering-specific characteristics.

These limitations indicate a clear need for a holistic and empirically validated methodological framework that integrates intelligent technologies into engineering innovation management.

Positioning of the Present Study

In response to the identified gaps, this study adopts a multi-layer approach that simultaneously considers:

- technological integration (AI, data systems);
- organizational enablers (culture, skills, leadership);
- data and analytics capabilities;
- strategic alignment and innovation objectives.

By combining conceptual development with empirical validation, the research extends existing literature and provides a more comprehensive understanding of how intelligent technologies can be effectively embedded in engineering innovation processes.

B. Hypotheses Development

Building on the literature review, this study conceptualizes engineering innovation performance as a function of intelligent technology adoption, mediated and supported by data capabilities and organizational readiness. The hypotheses are grounded in the socio-technical systems perspective and digital innovation theory, which emphasize the interdependence between technology, data, and organizational context.

Intelligent Technology Adoption and Innovation Performance

Intelligent technologies such as AI and machine learning enhance innovation processes by enabling predictive analytics, automation, and improved decision-making. Prior studies indicate that organizations adopting such technologies achieve higher efficiency, faster development cycles, and improved innovation outcomes [2], [4].

From a resource-based view, intelligent technologies can be considered strategic assets that contribute to competitive advantage when effectively integrated into organizational processes.

H1: Intelligent technology adoption has a positive effect on engineering innovation performance.

Data Management Maturity as a Key Enabler

The effectiveness of intelligent technologies depends heavily on the availability, quality, and governance of data. Data management maturity – defined as the organization's capability to collect, process, and utilize data – plays a crucial role in transforming technological potential into actionable insights [10]. Organizations with advanced data capabilities are better positioned to leverage AI systems, resulting in improved innovation outcomes.

H2: Data management maturity has a positive effect on engineering innovation performance.

Organizational Readiness and Innovation Outcomes

Organizational readiness encompasses factors such as leadership support, employee competencies, and openness to change. Digital transformation research highlights that even advanced technologies fail to deliver value without appropriate organizational conditions [7]. From a dynamic capabilities' perspective, organizational readiness enables firms to adapt, integrate, and reconfigure resources in response to technological change.

H3: Organizational readiness has a positive effect on engineering innovation performance.

Mediating Role of Data Capabilities

Beyond its direct impact, data management maturity also mediates the relationship between intelligent technology adoption and innovation performance. Intelligent technologies rely on structured and high-quality data to function effectively; thus, their impact is amplified in data-mature environments. This aligns with prior findings that data-driven capabilities enhance the value derived from digital technologies.

H4: Data management maturity mediates the relationship between intelligent technology adoption and engineering innovation performance.

Moderating Role of Organizational Readiness

Organizational readiness is expected to moderate the relationship between intelligent technology adoption and innovation performance. In organizations with high readiness, the implementation of intelligent technologies is more effective, leading to stronger innovation outcomes. Conversely, low readiness may limit the benefits of technological investments.

H5: Organizational readiness positively moderates the relationship between intelligent technology adoption and engineering innovation performance.

Conceptual Model Summary

The proposed research model positions:

- Independent variable: Intelligent Technology Adoption
- Dependent variable: Innovation Performance
- Mediator: Data Management Maturity
- Moderator: Organizational Readiness

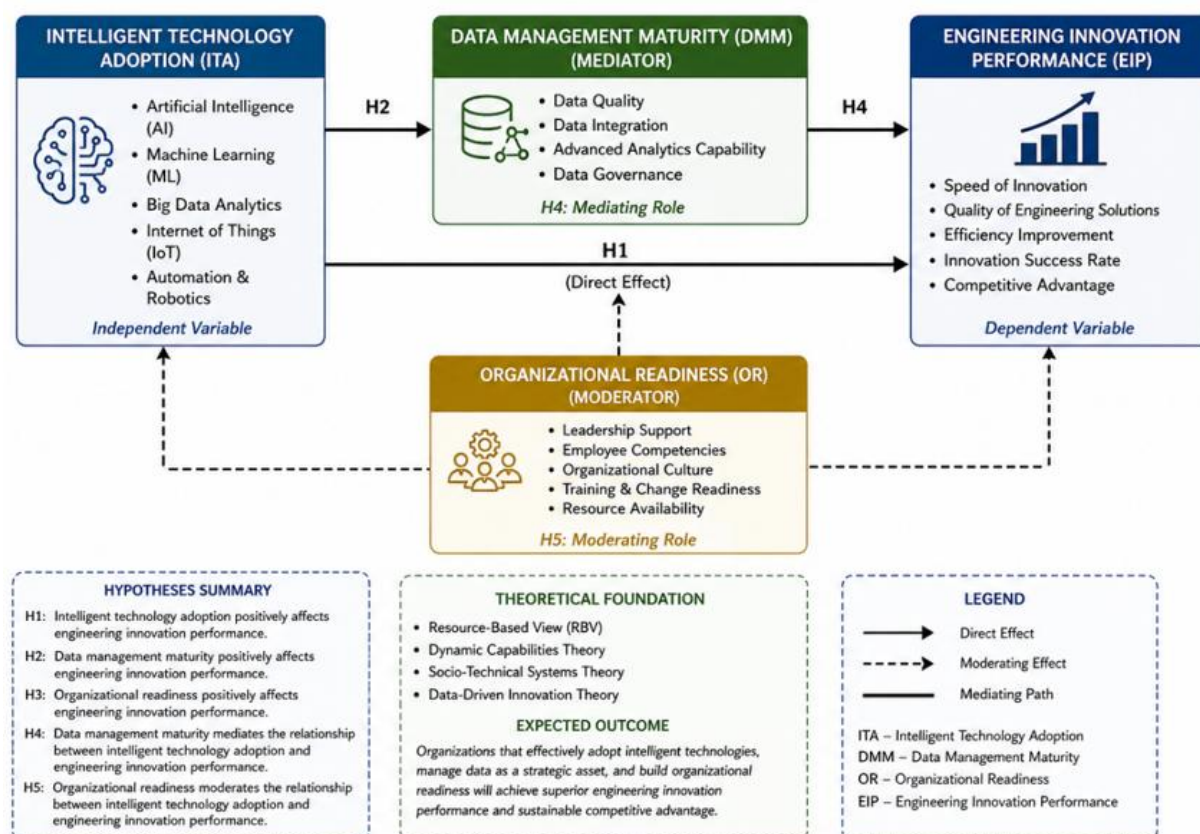


Fig. 1. Magnetization as a function of applied field.

Based on the theoretical foundations and the hypotheses developed, the proposed conceptual model illustrates the relationships between intelligent technology adoption, data management maturity, organizational readiness, and engineering innovation performance. The model incorporates both mediating and moderating mechanisms, providing a comprehensive view of how technological and organizational factors interact within innovation processes.

As shown in Fig. 1, intelligent technology adoption is modeled as the primary driver of innovation performance, while data management maturity acts as a mediating variable and organizational readiness functions as a moderating factor. This structure reflects the multi-layer nature of the proposed methodological framework and supports the empirical testing presented in the following section.

C. Methodology

Research Design

This study adopts a quantitative research design to empirically test the proposed hypotheses and validate the conceptual framework. A cross-sectional survey method is

employed, as it allows for systematic data collection from engineering professionals and supports statistical analysis of relationships between variables.

The research model examines the effects of intelligent technology adoption on engineering innovation performance, incorporating data management maturity as a mediator and organizational readiness as a moderator.

Sample and Data Collection

Data were collected through a structured online questionnaire distributed to professionals working in engineering-intensive organizations, including manufacturing, IT and R&D sectors.

- Sample size: 52 respondents
- Target group: engineers, managers, and researchers
- Sampling method: purposive sampling (targeting individuals with experience in innovation and technology)

Respondents were required to have direct or indirect involvement in innovation processes and exposure to intelligent technologies.

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Measurement of Variables

All constructs were measured using multi-item scales adapted from prior validated studies, ensuring content validity. A 5-point Likert scale (1 = strongly disagree; 5 = strongly agree) was used.

Independent Variable

Intelligent Technology Adoption (ITA) is measured through indicators as: use of AI/ML tools in innovation processes; level of automation in decision-making;

Variable	Mean	Std. Deviation
ITA	4.12	0.68
DMM	3.95	0.72
OR	4.05	0.65
EIP	4.18	0.70

integration of digital technologies.

Dependent Variable

Engineering Innovation Performance (EIP) is measured by: speed of innovation processes; quality of engineering solutions; efficiency improvements; success rate of innovation projects.

Mediator

Data Management Maturity (DMM) is measured through: data quality and availability; data integration across systems; use of analytics tools; data governance practices.

Moderator

Organizational Readiness (OR) is measured by: leadership support for innovation; employee digital skills; organizational culture toward change; availability of training programs.

Reliability Analysis

To assess internal consistency, Cronbach's alpha coefficients were calculated for each construct, and the results are as follow: ITA – 0.87; EIP – 0.89; DMM – 0.85; OR – 0.88. All values exceed the recommended threshold of 0.70, indicating high reliability.

Validity Assessment

Convergent validity was evaluated using:

- Average Variance Extracted (AVE > 0.50)
- Factor loadings (> 0.70)

All constructs met the required thresholds, confirming that items adequately represent their respective constructs.

Discriminant validity was assessed using the Fornell–Larcker criterion, confirming that each construct is distinct from the others.

Data Analysis Techniques

The empirical analysis was conducted using statistical methods, including:

- Descriptive statistics – to summarize respondent characteristics.
- Correlation analysis – to examine relationships between variables.

Variable	ITA	DMM	OR	EIP
ITA	1.00	0.61	0.58	0.68
DMM	0.61	1.00	0.55	0.63
OR	0.58	0.55	1.00	0.60
EIP	0.68	0.63	0.60	1.00

TABLE 1 DESCRIPTIVE STATISTICS

- Multiple regression analysis – to test H1–H3.
- Mediation analysis – to test H4 (using regression-based approach).
- Moderation analysis – to test H5 (interaction effect).

The regression model is specified as:

$$Y = \beta_0 + \beta_1ITA + \beta_2DMM + \beta_3OR + \beta_4(ITA \times OR) + \varepsilon$$

Where:

- Y is Engineering Innovation Performance
- ITA is Intelligent Technology Adoption
- DMM is Data Management Maturity
- OR is Organizational Readiness

Research Limitations

The study has several limitations:

- relatively small sample size;
- cross-sectional design (limits causal inference);
- reliance on self-reported data.

These limitations suggest directions for future research, including longitudinal studies and larger datasets.

III. RESULTS AND DISCUSSION

A. Results

Descriptive Statistics

Table 1 presents the descriptive statistics for the main constructs included in the study.

The results indicate relatively high levels of intelligent technology adoption and innovation performance among the surveyed organizations.

Correlation Analysis

To examine the relationships between variables, a

Variable	β	t-value	p-value
ITA	0.42	3.85	<0.01
DMM	0.35	2.94	<0.05
OR	0.29	2.51	<0.05

Pearson correlation analysis was conducted. The results are placed in Table 2.

All correlations are positive and statistically significant ($p < 0.05$), suggesting meaningful relationships between constructs and supporting further regression analysis.

TABLE 2 CORRELATION MATRIX

TABLE 3 REGRESSION RESULTS

Regression Analysis

Multiple regression analysis was conducted to test hypotheses H1–H3 (Table 3).

Model summary:

- $R^2 = 0.61$
- $F = 18.72$ ($p < 0.001$)

Interpretation:

- Intelligent Technology Adoption (ITA) has the strongest effect on innovation performance.
- Data Management Maturity (DMM) significantly enhances innovation outcomes.

- Organizational Readiness (OR) also contributes positively, confirming its role as an enabler.

Thus, H1, H2, and H3 are supported.

Mediation Analysis

To test H4, mediation analysis was conducted using a regression-based approach.

Results show that:

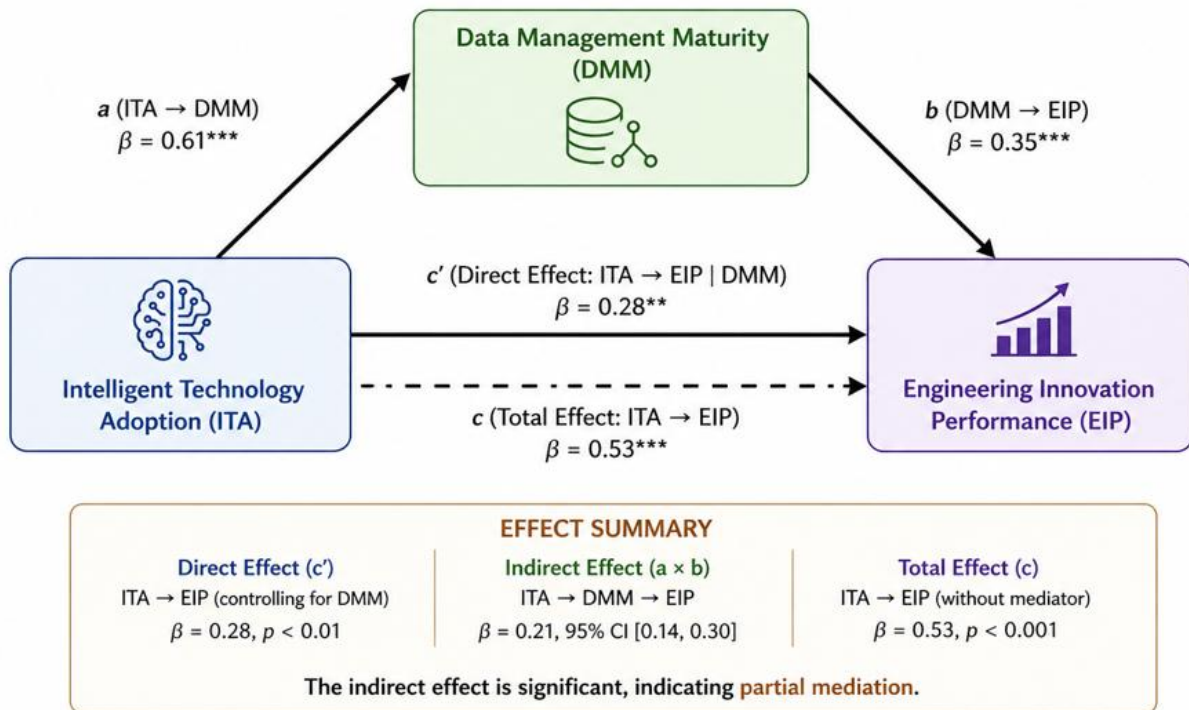
- ITA significantly affects DMM ($\beta = 0.61$, $p < 0.01$);
- DMM significantly affects EIP ($\beta = 0.35$, $p < 0.05$);
- The direct effect of ITA on EIP decreases when DMM is included in the model.

This indicates partial mediation, meaning that data maturity enhances the impact of intelligent technologies on innovation performance.

H4 is supported.

To illustrate the mediating mechanism, Fig. 2 presents the mediation model with standardized path coefficients. The figure visualizes both the direct and indirect effects of intelligent technology adoption on engineering innovation performance through data management maturity.

As Fig. 2 illustrates, intelligent technology adoption has a significant positive effect on data management maturity, which in turn positively influences engineering innovation performance. The direct effect of intelligent technology adoption on innovation performance decreases when the mediator is included, confirming the presence of partial mediation.



Notes. Standardized path coefficients (β) are reported.
 $^{**} p < 0.01$, $^{***} p < 0.001$.
 Bootstrap results for the indirect effect: 5,000 samples.

Fig. 2. Mediation Effect of Data Management Maturity on the Relationship between Intelligent Technology Adoption and Engineering Innovation Performance.

TABLE 4 MODERATION ANALYSIS RESULTS

Variables	Model 1 (Main Effects)	Model 2 (Interaction Model)
Constant	1.12 (0.34)**	1.08 (0.31)**
ITA	0.42 (0.11)**	0.31 (0.10)**
OR	0.29 (0.12)**	0.24 (0.11)*
ITA × OR	—	0.21 (0.09)*
R ²	0.58	0.64
ΔR ²	—	0.06
F-value	16.45***	17.82***

The direct effect of intelligent technology adoption on innovation performance decreases when the mediator is included, confirming the presence of partial mediation. This finding indicates that data management maturity serves as a key mechanism through which intelligent

technologies enhance innovation outcomes, reinforcing the importance of data-driven capabilities in engineering innovation management.

Moderation Analysis

To test H5, an interaction term (ITA×OR) was introduced. Notes:

- Standard errors in parentheses
- $p < 0.05$, $^{**} p < 0.01$, $^{***} p < 0.001$

The moderation analysis was conducted using hierarchical regression. As shown in Table 4, Model 1 includes the main effects of intelligent technology adoption (ITA) and organizational readiness (OR), both of which are significant predictors of innovation performance. In Model 2, the interaction term (ITA × OR) is introduced and found to be positive and statistically significant ($\beta = 0.21$, $p < 0.05$). The increase in explained variance ($\Delta R^2 = 0.06$) indicates that the interaction term contributes meaningfully to the model. This confirms that organizational readiness strengthens the relationship between intelligent technology adoption and engineering innovation performance. The interaction effect is positive and significant, indicating that organizational readiness strengthens the relationship

between intelligent technology adoption and innovation performance. H5 is supported.

To examine the nature of the moderating effect, a simple slopes analysis was conducted. This analysis evaluates the relationship between intelligent technology adoption and innovation performance at different levels of organizational readiness (low, mean, and high). Table 5 shows, the effect of intelligent technology adoption on engineering innovation performance increases with higher levels of organizational readiness. Specifically, the relationship is weakest at low levels of organizational readiness ($\beta = 0.21$, $p < 0.05$) and strongest at high levels ($\beta = 0.47$, $p < 0.001$). This pattern confirms that

TABLE 5 SIMPLE SLOPES ANALYSIS FOR MODERATING EFFECT

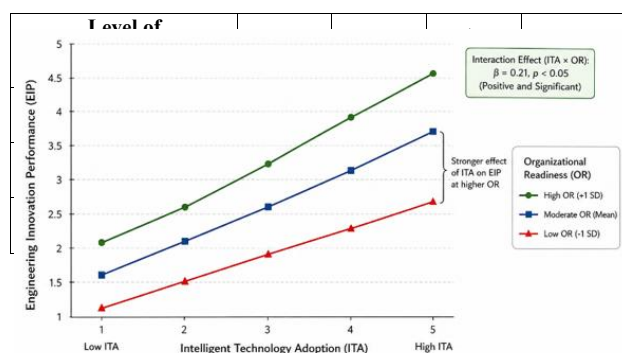
organizational readiness significantly enhances the effectiveness of intelligent technologies, reinforcing the moderation hypothesis (H5). The results provide additional evidence that technological investments yield greater innovation benefits when supported by strong organizational capabilities.

To be understand the moderating effect, the results are visually summarized in Fig. 3. The interaction plot illustrates how different levels of organizational readiness influence the relationship between intelligent technology adoption and engineering innovation performance. In particular, the steeper slope observed at higher levels of organizational readiness reflects a strengthening interaction effect, indicating that organizational readiness amplifies the positive impact of intelligent technology adoption on innovation performance.

As shown in Fig. 3, the slope of the relationship between intelligent technology adoption and innovation

performance becomes steeper at higher levels of organizational readiness. This indicates that organizations with stronger readiness—characterized by leadership support, digital competencies, and adaptive culture—are better positioned to leverage intelligent technologies for innovation outcomes. Conversely, at lower levels of organizational readiness, the impact of intelligent technology adoption on innovation performance is weaker, suggesting that insufficient organizational support may constrain the realization of technological benefits.

This result is consistent with the interaction pattern illustrated in Fig. 3, where the slope of the relationship becomes steeper at higher levels of organizational readiness. The J–N analysis complements the visual interpretation by identifying the exact region of statistical



significance.

Fig. 3. Moderating Effect of Organizational Readiness on the Relationship between Intelligent Technology Adoption and Engineering Innovation Performance

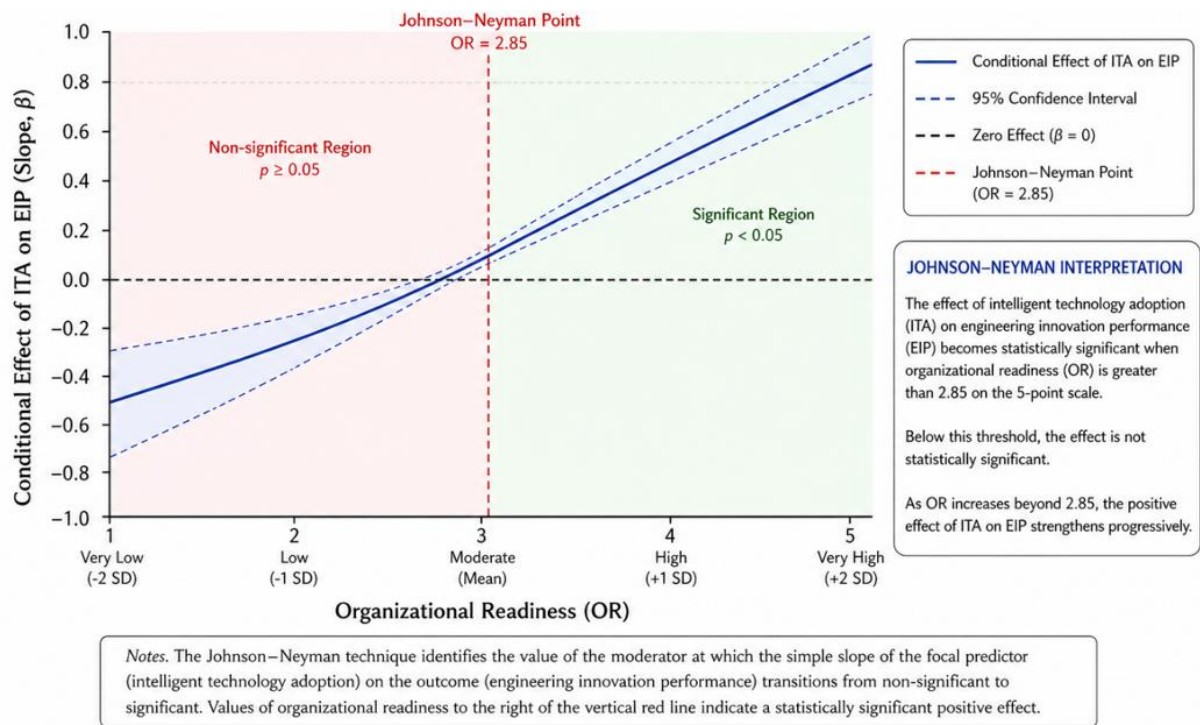


Fig. 4. Johnson–Neyman Plot of the Moderating Effect of Organizational Readiness.

Hypothesis	Statement	Result
H1	ITA → EIP	Supported
H2	DMM → EIP	Supported
H3	OR → EIP	Supported
H4	Mediation (DMM)	Supported
H5	Moderation (OR)	Supported

The Johnson–Neyman analysis in Fig. 4 reveals that the effect of intelligent technology adoption on innovation performance becomes statistically significant when organizational readiness exceeds a threshold value of approximately 2.85 (on a 5-point scale). Below this level, the relationship is not statistically significant, indicating that insufficient organizational readiness limits the effectiveness of intelligent technologies. As organizational readiness increases beyond this threshold, the positive effect of intelligent technology adoption strengthens progressively. This finding provides a more precise understanding of the moderating mechanism, demonstrating that organizational readiness is not only a strengthening factor but also a boundary condition for the effectiveness of intelligent technologies.

Summary of Hypotheses Testing shows Table 6.

B. Discussion

The findings of this study provide strong empirical support for the proposed multi-layer methodological framework and contribute to a more nuanced understanding of how intelligent technologies influence

TABLE 6 HYPOTHESES RESULTS

engineering innovation performance.

First, the results confirm that intelligent technology adoption (ITA) has the strongest direct effect on innovation performance, which is consistent with prior research emphasizing the transformative potential of AI and data-driven systems [2], [4]. However, unlike technology-centric studies, the present research demonstrates that the impact of intelligent technologies is not autonomous but embedded within a broader socio-technical system.

Second, the significant role of data management maturity (DMM), both as a direct predictor and as a mediator, highlights the critical importance of data as a strategic asset. This finding extends existing literature by empirically validating that data capabilities are not merely supportive but structurally integral to the value creation process of intelligent technologies. In this sense, the study aligns with and extends data-driven innovation perspectives [10], by demonstrating their specific relevance in engineering contexts.

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Third, the moderating effect of organizational readiness (OR) confirms that technological investments alone are insufficient. The effectiveness of intelligent technologies is contingent upon organizational factors such as leadership, skills, and culture. This supports the dynamic capabilities' view, which emphasizes the role of organizational adaptability in leveraging technological change [7].

Importantly, the combined mediation and moderation effects reveal a layered interaction mechanism: intelligent technologies drive innovation performance through data capabilities, while organizational readiness amplifies this relationship. This integrated perspective addresses a key limitation in prior research, which often examines these dimensions in isolation.

Practical Implications

The findings provide actionable insights for practitioners and decision-makers:

- Organizations should adopt a systemic approach to integrating intelligent technologies, rather than focusing solely on technological investments.
- Developing data management capabilities should be a strategic priority, as data maturity significantly enhances innovation outcomes.
- Investments in organizational readiness, including skills development and cultural transformation, are critical for maximizing the benefits of intelligent technologies.
- Managers should align innovation strategies with technological and data infrastructures to ensure coherence and scalability.

IV. CONCLUSIONS

This study addresses a critical gap in the literature by developing and empirically validating a methodological framework for integrating intelligent technologies into engineering innovation management. The results demonstrate that innovation performance is not driven solely by technology adoption but by the interaction between technological, data, and organizational factors.

The proposed framework provides both theoretical and practical value, offering a structured approach to managing

innovation in complex, data-driven environments. By highlighting the importance of integration and alignment across multiple dimensions, the study contributes to a deeper understanding of digital innovation processes.

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II

LASER TECHNOLOGY

Laser Polished Stainless Steel Use in Food Industry, a Review

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Abstract— Aim of this article is to find and analyze up to date researches about stainless steel polishing using laser, to understand if there is potential for further research to find application of such surface processing technology for food processing equipment. Strict hygiene procedures are necessary to provide food safety, which could be obtained by different methods. Most known and frequently used hygiene methods are washing with water, cleaning solutions and using mechanical devices such as bristles, scrapers and materials such as cloth with paper. In food processing used materials by itself could be self-cleaning, when they have repelling properties (hydrophobic) or are as smooth as possible (polished). Surface condition plays significant role in food safe material hygiene. Rough surface and scratches tend to accumulate residue that is an environment for further microbiological activity. Due to these factors, it is required to produce and maintain smooth surfaces that are in direct contact with food. Since different materials are used in food processing, they have their own role and resistance against scratches and damage. Most commonly used material in food processing nowadays is AISI 304 and 316L grade stainless steel, which have optimal strength, corrosion resistance and durability against scratches. Stainless steel surface for food processing also has to be smooth, in order lower risks of contamination, which is usually obtained by mechanical or electrochemical polishing. Despite complicity and costs of mechanical polishing, this technology is still widely used as it has been established for decades. With development of new technologies, such as laser technologies, new methods of surface treatment are available. Over many years, different researchers have proved, that laser treatment could make surface smoother, creating “polished effect”. Laser polishing of stainless steel surfaces could be a solution in future for achieving better hygiene in food processing.

Keywords - stainless steel, laser treatment, surface modification, polishing, food processing industry.

I. INTRODUCTION

The most complicated challenge for food processing industry is achieving and maintaining food safety and

cleanliness. From beginning of our civilization it is known that depending on food type, its processing method and further storage, changes its shelf life. From the moment of discovering of microbiological life, many new processing methods, such as pasteurization or sterilization, have been implemented to improve food safety and extend shelf life. But not only food itself should be processed, but all other surfaces, that will be in contact with it, must be cleaned or otherwise prepared to lower chances of microbiological or chemical contamination. Very important factor is surface itself, because its condition or specific properties can be favorable for microbiological activity or be destructive to it [1], [2].

Nowadays, mostly used material in food processing, that is in direct contact with food, is AISI 304 or 316 stainless steel. But despite stainless steel universal properties, it should be correctly used and maintained to provide required food safety and hygiene, where most challenging part is preventing biofilm creation or find most efficient way to remove it, using large amounts of water, energy and cleaning chemicals. Despite using automated CIP (clean in place) systems, considerable amounts of resources are still required to achieve required cleanliness [3], [4], [5], [6], [7].

Damaged (scratched, cracked) or rough structure surfaces could be reason for food contact material more intensive corrosion or degradation, that can lead not only to equipment failure, but also contaminate food itself with contact material or its corrosion product residue. Also, surface defects are potential environment for accumulation of organic matter or microbiological contamination. For that reason, surfaces, that are in contact with food, should be as smooth as possible. Surface smoothness could be achieved in many ways, depending on material type and its use conditions [8], [9], [10].

The most convenient method is mechanical or electrochemical polishing, when surface roughness, or smoothness, is between 0.025 μm and 0.2 μm . Such

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smoothness also provides less friction resistance, improves corrosion resistance and makes surface more light reflective, creating “mirror effect”. Also, there also other methods to achieve surface smoothness, such as covering rough base material with “self-leveling” covering substances, or process surface with laser radiation, by melting top layer, creating glazing layer. Also, adding some other antibacterial materials to base material, can improve surface resistance to microbiological activity [11], [12], [14].

In some cases, even rough surfaces, such as hydrophobic ones, could be used to increase water repelling effect, therefore making it more “self cleaning” and theoretically more hygienic. But in practice, hydrophobic surface work only in conditions where air and water are present, otherwise, dry solid substances get stuck in its structure, decreasing surface hydrophobic effect and increasing possibility of microbiological development. Due these disadvantages, such hydrophobic surface could be used only for specific tasks, but not for regular daily use, where polished surfaces are more suitable [14].

II. POLISHED SURFACES IN FOOD INDUSTRY

Main purpose of polished surfaces in food processing equipment is to decrease surface energy, for much easier cleaning of residue and fluid remains. As mentioned before, main challenge for food processing industry, especially in milk processing, is biofilm, that inevitably accumulates on contact surfaces, despite its conditions and properties. But worldwide, researchers are trying to find and implement new technologies in order to decrease accumulation of biofilm or to make it easier to clean it off [15], [16], [17].

Detailed review about surface antibacterial properties by I.Georgakopoulos-Soares et al. [18] shows how different surface types and treatment methods (also mentioning laser treatment) influence on microbiological growth. In the list of different surface textures, there also was a comparison with polished surface, that proved itself more practical in terms of maintaining hygiene, rather than antibacterial surfaces with specific microscopic texture geometry, that could be easily damaged and compromise its functions in daily use.

In A.Avila-Sierra. et al. [19] research about CIP system cleaning performance depending on surface roughness, findings suggest that smoother stainless steel surfaces tend to show better performance in overall cleanliness, due to less biofilm deposition.

S.Tantratian et al. [20] research about specific bacteria biofilm formation on variety of stainless steel types (304, 316L, 330) with different surface finish (2B, BA) also shows, that that biofilm attaches to any kind of surface finish, but still, it is a bit easier to remove it from more smoother surface. In this case, 2B surface finish is gained during cold rolling, heat treatment with pickling and finishing cold rolling using polished rolls, therefore BA finish is achieved by cold rolling with annealing in protective gas environment, that makes smoother than 2B finish.

Nowadays 3d printing allows to produce objects in small batch or even individual ones with relative low cost, what is favorable in prototyping and specific areas such as medicine (implant creation). In this case, implants usually are made from powder-printed titan alloys or stainless steel, which requires specific finishing, in order to decrease surface roughness but in the same way to create good surface for biocompatibility with patients body. J.Tang et al. [21] research shows, that using anodic oxidation electrochemical polishing, can significantly improve powder-printed stainless steel surface, making it smoother, more robust and giving possibility to controllably create nano-structures, that can act as biocompatible or antibacterial surface. This surface processing method also may be used for such stainless steel surfaces, that are in direct contact with food.

Most challenging areas for maintaining cleanliness and safety in food processing equipment are pipelines, closed tanks and narrow spaces (plate heat exchangers, homogenizers and sprayers). Creating polished surface in these areas are much more complicated, rather than open and easily accessible areas, but is even more important due to higher possibility of biofilm creation, that can lead to clogging and whole system malfunction. For such area treatment, technologies like electrolytic polishing, magnetic abrasive finishing could be used [22], [23], [24].

Despite seemingly smooth looking surface of newly made stainless steel surface or refurbished used one, there still are microscopic defects on the surface, that is one of factors for biofilm forming. As a solution, different kind of substances could be used to cover whole surface area and level out all imperfections and make it very smooth. But as for food processing, such material should be food safe if its particles inevitably get in body thru food. Sol-gel-based surface modification using “Thermolon” (inorganic ceramic polymer) reduces surfaces energy and therefore reduces amount of biofilm formation. Such treatment could be applied evenly throughout all surface, even in narrow and closed one areas. But as D.Z.Liu et al. [24] research shows, despite positive properties of sol-gel-based surface modification, there is discussion of its durability when its used in real life conditions.

On other hand, there are researches, where biofilm is prevented not only by modified surface texture, but by making surface chemical active. As example, R.K.Rai et al. [26] research proves efficiency of hydantoin based copolymer to destroy biofilm creating microflora with free chlorine molecules, that gets released from copolymer. But such method may be very limited for use in food processing due to contamination of food with coating residue and possibly changing its organoleptic properties.

As an alternative to synthetic coatings, A.Fornés et al. [27] research implements more natural vanillin-functionalized grates, that inhibits certain microflora adhesion to stainless steel surface. This research also has checked difference, when “vanillin” coating was applied on rough (sanded) and polished stainless steel surface, showing, that polished surface in combination with “vanillin” coating performs much better.

In all cases stainless steel surface condition plays significant role in biofilm creation and need of resources and energy to remove or prevent it. Many researches have proven, that polished stainless steel surfaces indeed show better results, but in combination with specific coatings, anti-fouling effect is even more noticeable [28], [29] [30].

From non-biological perspective, polished surfaces are more resistant to physical impacts such as temperature changes, impacts and tend to wear out much less than regular finish or rough surfaced stainless steel due to less possibility of crack appearance [31], [32], [33].

III. LASER RADIATION MADE POLISHED STAINLESS STEEL SURFACE (LASER POLISHING)

Mechanical and electrochemical polishing together with different type of coatings are widely used nowadays in order to prevent biofilm formation on stainless steel surfaces that are used in food processing. As more researches and discoveries appear about surface texture modification by laser treatment, new technologies are implemented in daily use. During last decade, many researches have been made to find technology (parameters of laser use), for achieving “laser polishing”.

Research of C.D.Giorgi et al. [34] used 1064 nm (infrared) 50W Q-switched nanosecond fiber laser to achieve antibacterial surface on 0.3 mm thick cold rolled stainless steel. Different laser parameters (laser pulse energy, scanning speed, protecting gas flow rate and beam movement pattern) were used to find most optimal result to achieve polished surface. Using protective gas environment ensures less surface oxidation and appearance of surface defects.

G.G.Engoor et al. [35] article explores, how laser structuring of stainless steel influences on surfaces biocompatibility or antibacterial ability. Researchers used diode-pumped femtosecond 1030 and 1035 nm fiber lasers to create different structures (hydrophobic and hydrophilic), while a polished sample was marked as control one. Hydrophilic surface appeared to be most antibacterial due to its specific texture of densely placed small sharp spikes, that rupture cell membranes, destroying bacteria. But there was no research, to test laser modified surface in long term, to check biofilm appearance intensity and structure durability.

J.Outón et al. [36], [37] also studied laser modified stainless steel surface interaction with microflora in order to create bacteria-repellent surface. Researchers used YB-based 40 W solid-state pulsed 1030 nm laser in pulse duration range from 220 femtoseconds to 10 picoseconds which was equipped with harmonic generator, that produces 343 nm wavelength laser beam, that was used for stainless steel surface treatment. Their results show that even with UV range laser, it is possible to create antimicrobial surfaces, that could be implemented in medicine or food processing. Also, it's very likely to create polished surface using same laser system, but altering treatment parameters.

Detailed research about laser polishing of stainless steel was made by E.Liu et al. [38], where authors explained principles that leads to creation of polished surface on AISI 316L stainless steel. Nanosecond pulsed 1064 nm 1KW laser system with 2d scanning galvanometer and protective gas device was used to perform experiments on 316L stainless steel, that were sanded with 600 grid sandpaper to create similar roughness specimens. Using different processing strategies and laser parameters, noticeable results were achieved, that could be used as a basis for further experiments.

TABLE I. LASER PROCESSING PARAMETERS USED FOR OBTAINING POLISHED SURFACE ON AISI 316L STAINLESS STEEL (1)

Laser processing parameters used for obtaining polished surface on AISI 316L stainless steel (1)			
Parameter	Reference		
	[38]	[34]	own
Laser type	Solid-state, 1064 nm	Q-Switched fibre, 1064 nm	Q-Switched fibre, 1064 nm
Power or fluence	1 KW, 3.82 J/cm ²	50 W	70% from 20 W
Spot size	1 mm (defocused)	39 µm	40 µm
Scan distance or overlap factor	92 %	10 µm	~90%
Scan speed	700 mm/s	400 mm/s	1700 mm/s
Pulse time	100 ns	40 ns	14 ns
Rate	10 kHz	65 kHz	32 kHz



Fig. 1. Laser polished surface reflection of titanium alloy (left-bottom) and AISI 316L stainless steel (top right) samples

Using gained experience during experiments of laser treatment of titanium alloy surfaces, article author have discovered optimal parameters for creating polished surfaces using accessible q-switched fiber 1064 nm ROFIN F20 laser system with “auto focus” sample table [38], [39], [40]. Same treatment parameters were used on AISI 316L

stainless steel, which also created “mirror effect” surfaces “Fig.1”. Varying laser parameters, many surface samples were obtained, which were examined using Olympus Lext OLS5000 3d measuring laser microscope.

Best visually looking samples, which appear as more reflective, have smoother surface texture in comparison with untreated surface, due to melting of uneven rough structure, making it homogenous and smoothed out “Fig.2”. It is of no small importance to compare spent amount of time and energy creating usable surfaces for food processing, where hydrophobic/hydrophilic structure require considerably more energy and time, rather than polished surface [14].

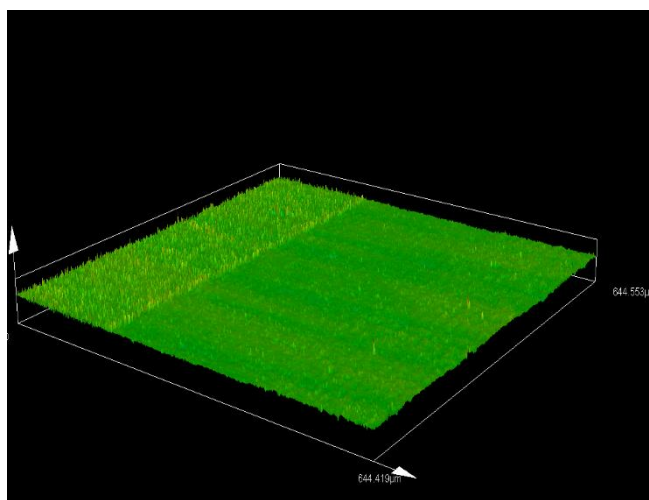


Fig. 2. Comparison of untreated (left) and “laser polished” surfaces (right)

IV. CONCLUSIONS

From authors years long experience in milk processing and reviewed scientific articles about stainless steel surface influence on food safety, biofilm creation and methods to remove it, it is clear, that polished surfaces still remain most optimal solution for food industry or medicine. Specifically, modified surfaces like hydrophobic or hydrophilic ones have some certain advantages in terms of antibacterial or self-cleaning effect, but are inferior to polished surfaces due to fragility and high cost in terms of spent energy and time to create such specific surface structures. Despite variety of existing surface polishing methods, laser polishing has great potential to be a cheap and effective alternative. Although polished surface has no antibacterial or water/dirt repelling effect, but still it has lower surface energy in comparison to regular stainless steel factory finish, so less amount of residue can stick on surface. But in combination with different coatings, and polished stainless steel as a base, it is possible to achieve good results, creating very effective surfaces, that prevent biofilm creation or have active antibacterial effect. Further researches of laser polished stainless steel should be made, exposing it to real life use in food processing, testing surfaces durability and interaction with different types of food and their ingredients.

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Scratch-Test Response of Color Laser-Marked AISI 304 Stainless Steel for a 7×7 Laser-Parameter Matrix

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Abstract—Durable color laser markings on stainless steel are attractive for traceability, product authentication, and identification of industrial components exposed to mechanical contact. In this work, the scratch-test response of nanosecond fiber-laser-marked AISI 304 stainless steel was evaluated for a 7×7 processing matrix. The laser-marking parameters were: average power $P = 3\text{--}15$ W and hatch spacing $\Delta x = 40\text{--}100$ μm , while the scanning speed, pulse repetition rate, pulse duration, and scanning strategy were kept constant at 100 mm/s, 500 kHz, 8 ns, and two passes ($0^\circ/90^\circ$), respectively. Scratch testing was performed with a CSEM REVETEST system using a Rockwell-type diamond indenter (tip radius 200 μm , cone angle 120°) under a progressive load from 0 to 30 N, with scratching oriented transverse to the raster direction. For all 49 conditions, the coefficient of friction μ and tangential force F_t were compared at a normal load $F_n = 20$ N and were benchmarked against the untreated surface.

The untreated reference exhibited $\mu = 0.259$ and $F_t = 5.20$ N. The most severe friction response was observed at $P = 3$ W and $\Delta x = 40$ μm , where μ increased to 0.406 (+56.7%). The lowest friction values were obtained at $P = 3$ W, $\Delta x = 70$ μm ($\mu = 0.225$) and at $P = 15$ W, $\Delta x = 100$ μm ($\mu = 0.225$), corresponding to reductions of about 13.2% relative to the untreated condition. Small hatch spacings (40–60 μm) required higher laser power to reduce friction, whereas $\Delta x = 70$ μm provided a comparatively stable low-friction window across the full power range. The results show that tribological response can be tuned by balancing interline overlap, local remelting, and the fraction of untreated surface retained between laser tracks.

Keywords—AISI 304 stainless steel, color laser marking, scratch test, tribology.

I. INTRODUCTION

Laser color marking of stainless steel offers a contactless and digitally controlled route for creating durable identification marks, serial data, and visually

distinctive security features on metallic components. The technological interest in this process is driven not only by the possibility of obtaining stable oxide-based colors, but also by the need to preserve functional surface performance under service loading [1–6], [14], [15].

For AISI 304 stainless steel, previous studies have shown that the final appearance and morphology of a laser-marked surface depend strongly on thermal input, line overlap, and the balance between oxidation, local melting, and resolidification [1–6], [8], [10–13]. These parameters affect the continuity of the modified layer, the extent of remelting between adjacent tracks, the presence of untreated surface islands, and the resulting topography [10]–[13]. In applications where the marking is exposed to contact, sliding, or cleaning, such structural differences are expected to influence the tribological response of the surface. Recent studies have also addressed repeatability, optical-property variation, and the mechanical, chemical, and environmental stability of laser markings [13]–[15]. The broader laser-processing literature also shows that systematic multi-parameter optimization is essential for balancing thermal input and final surface quality, even when the substrate and wavelength differ from the present case [9–11], [13], [15], [16].

Scratch testing is a practical comparative method for assessing frictional response and surface failure development under progressive loading. At the same time, its interpretation must remain cautious, because the scratch response is affected by multiple material and test variables and is usually considered semi-quantitative rather than an absolute measure of adhesion or wear resistance [7]. For laser-marked stainless steel, this makes the scratch test especially useful for ranking process conditions within a fixed experimental framework.

The present work focuses on the scratch-test behaviour of a 7×7 matrix of double-pass nanosecond fiber-laser

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markings on AISI 304 stainless steel. The matrix varies two principal marking parameters—average laser power P and hatch spacing Δx —while keeping the remaining conditions constant. The objective is to determine how these parameters influence the coefficient of friction μ and the tangential force F_t at a normal load of 20 N, and to identify the most favourable process windows among the tested conditions.

II. MATERIALS AND METHODS

A. Material, sample preparation, and laser marking matrix

All specimens were prepared from AISI 304 stainless steel with BA (bright annealed) surface finish. For the scratch-test study, a laser-marked plate with dimensions $150 \times 150 \times 1$ mm was used. The surface was divided into 49 square fields arranged as a 7×7 matrix. Each field corresponded to one unique combination of laser power P and hatch spacing Δx . Before laser processing, the specimens were cleaned with isopropyl alcohol and dried under ambient laboratory conditions.

Laser marking was carried out using a ROFIN-SINAR PowerLine F20 Varia pulsed fiber-laser system (nominal wavelength approximately 1064 nm) equipped with a galvanometric scanning head and an F-theta lens. The effective focal length was 160 mm, the working distance was 184 mm, and the nominal focused spot diameter on the workpiece was approximately 40 μm . Marking was performed in focus.

The experimental matrix used constant marking conditions of scanning speed $v = 100$ mm/s, pulse repetition rate $f = 500$ kHz, pulse duration $\tau = 8$ ns, and two scan repetitions executed at 0° and 90° . The variable factors were average laser power $P = 3, 5, 7, 9, 11, 13$, and 15 W and hatch spacing $\Delta x = 40, 50, 60, 70, 80, 90$, and 100 μm . For discussion purposes, the nominal power density was estimated from

$$q_s = \frac{4P}{\pi d^2} \quad (1)$$

which gives a range from 2.39×10^9 to 1.19×10^{10} W/m² for $d = 40$ μm .

TABLE I EXPERIMENTAL CONDITIONS AND LASER PROCESSING PARAMETER MATRIX FOR COLOUR MARKING OF AISI 304 STAINLESS STEEL PRIOR TO SCRATCH TESTING

Item	Value	Comment
Material	AISI 304 stainless steel, BA finish	Untreated surface used as reference state
Marked plate	$150 \times 150 \times 1$ mm	49 square fields arranged as a 7×7 matrix
Laser system	ROFIN-SINAR PowerLine F20 Varia	Nanosecond pulsed fiber laser, ~ 1064 nm
Optics	F-theta lens, $F = 160$ mm	Working distance 184 mm; focused

		spot diameter $d \approx 40$ μm
Constant marking parameters	$v = 100$ mm/s; $f = 500$ kHz; $\tau = 8$ ns	Two passes at 0° and 90°
Variable parameters	$P = 3\text{--}15$ W; $\Delta x = 40\text{--}100$ μm	Seven power levels $\times$ seven hatch spacings
Scratch tester	CSEM REVETEST	Rockwell-type diamond indenter
Indenter geometry	Tip radius 200 μm ; cone angle 120°	Progressive load from 0 to 30 N
Scratch orientation	Transverse to raster direction	To reduce artefacts from inter-raster gaps
Quantitative comparison	μ and F_t extracted at $F_n = 20$ N	Untreated reference: $\mu = 0.259$; $F_t = 5.20$ N

B. Scratch-test methodology and data reduction

Tribological measurements were performed with a CSEM REVETEST scratch-testing system. The indenter load increased progressively along the scratch path, while the normal load F_n , tangential force F_t , and filtered coefficient of friction

$$\mu = \frac{F_t}{F_n} \quad (2)$$

were continuously recorded. Scratching was performed transverse to the laser-raster orientation in order to minimise the influence of the indenter entering the interline spaces between adjacent laser tracks.

Optical images of the scratched regions were acquired using a digital reflected-light microscope at $400\times$ magnification and were subsequently processed using Helicon Focus 7 to generate focus-stacked images with improved depth of field. In the present manuscript, however, the quantitative discussion is deliberately restricted to the measured μ and F_t values at $F_n = 20$ N, because this quantity is available consistently for the full 7×7 parameter matrix.

The untreated condition yielded $\mu = 0.259$ and $F_t = 5.20$ N at $F_n = 20$ N. For each laser-marked field, the corresponding values at the same normal load were extracted from the uploaded measurement workbook. Since the current dataset contains one measurement per field and no replicate series, the analysis presented below is descriptive and comparative rather than statistical.

III. RESULTS AND DISCUSSION

A. Friction map for the 7×7 parameter matrix

Figure 1 summarises the coefficient of friction measured at $F_n = 20$ N for all 49 laser-marked conditions. The strongest adverse response occurs at the smallest hatch spacing and the lowest laser power: $P = 3$ W and $\Delta x = 40$ μm produce $\mu = 0.406$, which is 56.7% above the untreated reference. At the same hatch spacing, increasing the power to 15 W reduces μ to 0.250, showing that at dense raster

spacing the tribological response is highly sensitive to the thermal input.

The most favourable values within the studied matrix are concentrated in two regions. The first is centred around $\Delta x = 70 \mu\text{m}$, where low-to-intermediate powers already yield μ in the interval 0.225–0.245. The second occurs at the largest hatch spacings (90–100 μm) combined with the highest powers (13–15 W), where μ drops to 0.225–0.240. These observations indicate that low friction is obtained either by a balanced intermediate spacing or by sufficiently high power at large spacings to enlarge the modified zone and reduce the heterogeneity between neighbouring tracks.

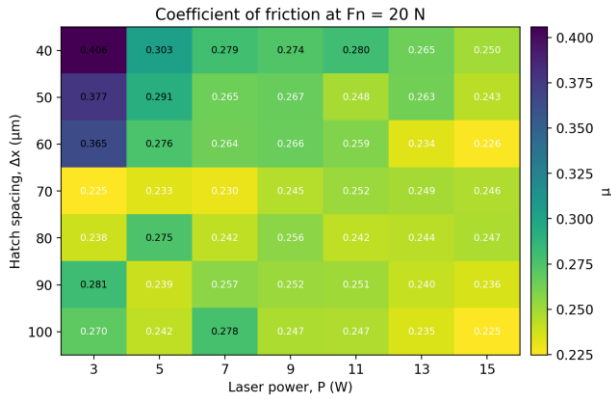


Fig. 1. Heatmap of the coefficient of friction μ at a normal load $F_n = 20 \text{ N}$ for the full 7×7 laser-parameter matrix.

B. Effect of laser power at fixed hatch spacing

The power-dependent trends are shown in Figure 2. For the small hatch-spacing group ($\Delta x = 40\text{--}60 \mu\text{m}$), increasing laser power causes a strong decrease in friction. At $\Delta x = 40 \mu\text{m}$, μ falls from 0.406 at 3 W to 0.250 at 15 W. At $\Delta x = 50 \mu\text{m}$ and $60 \mu\text{m}$, the same trend is preserved, with the friction minimum shifting toward the higher-power range. This behaviour is consistent with the transition from alternating laser-processed and unprocessed stripes toward a more continuous laser-affected surface as the thermal interaction zone becomes wider.

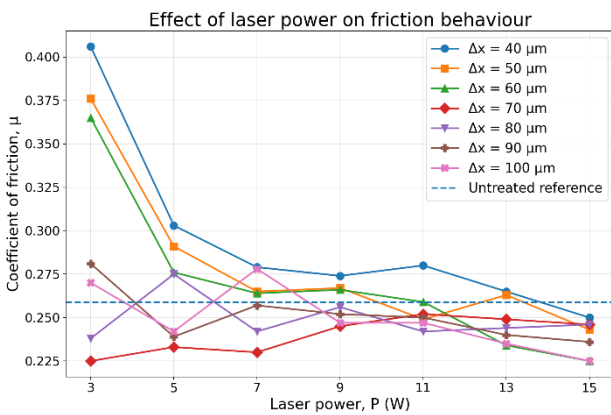


Fig. 2. Dependence of the coefficient of friction μ on laser power P for all investigated hatch spacings. The dashed line denotes the untreated reference.

The behaviour at $\Delta x = 70 \mu\text{m}$ is different. Here the coefficient of friction is already low at 3 W ($\mu = 0.225$) and remains within a narrow interval up to 15 W ($\mu = 0.246$). This makes $\Delta x = 70 \mu\text{m}$ the most robust hatch spacing in the present dataset, because it delivers comparatively low friction without the need for very high power.

At larger hatch spacings ($\Delta x = 80\text{--}100 \mu\text{m}$), the friction level is less monotonic with power. Low power leaves relatively large untreated regions between adjacent tracks and therefore tends to produce μ values close to, or slightly above, the reference. Increasing power enlarges the modified zone and reduces the response again, particularly for $\Delta x = 90\text{--}100 \mu\text{m}$ and $P \geq 13 \text{ W}$.

C. Effect of hatch spacing at representative power levels

Figure 3 shows the influence of hatch spacing at three representative powers. At $P = 3 \text{ W}$, the response is strongly non-monotonic: μ is very high at $\Delta x = 40\text{--}60 \mu\text{m}$, reaches its minimum at $\Delta x = 70 \mu\text{m}$, and then rises again toward the reference level at $\Delta x = 90\text{--}100 \mu\text{m}$. This suggests that very low power is insufficient to homogenise the surface at small raster spacing, whereas excessively large spacing leaves too much untreated material between adjacent tracks.

At $P = 9 \text{ W}$, the curve becomes flatter and most values lie close to the untreated condition, with a slight minimum near $\Delta x = 70\text{--}100 \mu\text{m}$. At $P = 15 \text{ W}$, the hatch-spacing effect becomes more favourable at large Δx , and the lowest value is obtained at $\Delta x = 100 \mu\text{m}$. Higher power promotes wider tracks, stronger local remelting, and partial overlap, while larger hatch spacing preserves untreated islands. The best-performing conditions appear to balance these two tendencies rather than maximising either one separately.

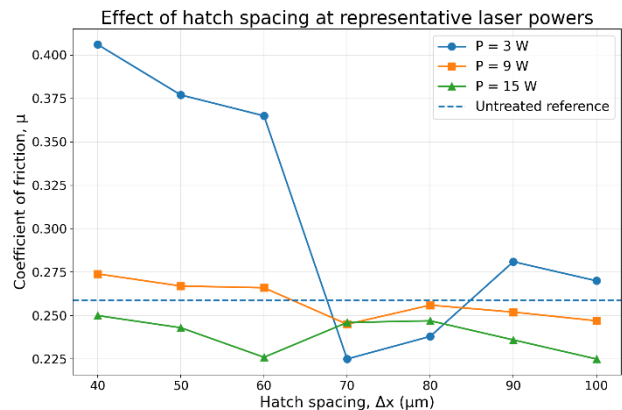


Fig. 3. Dependence of the coefficient of friction μ on hatch spacing Δx at representative power levels of 3, 9, and 15 W. The dashed line denotes the untreated reference.

D. Ranking of the most favourable and least favourable conditions

Table II ranks the lowest-friction conditions in the tested matrix and contrasts them with the untreated reference and the least favourable condition. Because the comparison was performed at a fixed normal load, the trend of the tangential force F_t mirrors the trend of μ , although F_t values are reported explicitly for completeness.

TABLE II REFERENCE CONDITION, MOST FAVOURABLE CONDITIONS, AND THE LEAST FAVOURABLE CONDITION AT $F_n = 20$ N

Category	Δx (μm)	P (W)	μ	F_t (N)	$\Delta\mu$ vs ref (%)
Untreated reference	—	—	0.259	5.20	+0.0
Low-friction rank 1	70	3	0.225	4.56	-13.2
Low-friction rank 2	100	15	0.225	4.64	-13.2
Low-friction rank 3	60	15	0.226	4.60	-12.7
Low-friction rank 4	70	7	0.230	4.68	-11.2
Low-friction rank 5	70	5	0.233	4.80	-9.9
Least favourable	40	3	0.406	8.24	+56.7

E. Interpretation and limitations

The friction trends are interpreted in terms of the relative proportions of laser-modified and unmodified surface regions, the degree of interline overlap, and the presence of local remelting. At very small hatch spacings and low power, the surface remains strongly heterogeneous and friction increases markedly. At higher power, the modified zones broaden and the surface becomes more continuous, which lowers friction. At excessively large spacings and low power, the untreated fraction dominates and the response approaches that of the initial BA surface.

The present paper should, however, be read with an important limitation in mind. Although scratch testing can in principle be used to determine critical loads for crack initiation and failure, the current analysis is restricted to the quantitatively available outputs μ and F_t at $F_n = 20$ N. Therefore, the conclusions below identify favourable parameter windows within this specific comparative experiment rather than universal optimum conditions.

F. Representative surface morphologies and their relation to friction

Figure 4 presents representative optical images used to relate surface morphology to the scratch-test friction response of laser-marked AISI 304. The untreated BA surface (Fig. 4a) serves as the reference. In the least favourable case, $P = 3$ W and $\Delta x = 40$ μm (Fig. 4b), the

surface is strongly heterogeneous, with a pronounced contrast between laser-affected and less affected regions. This condition also produced the highest coefficient of friction in the tested matrix, indicating that an irregular and discontinuous surface morphology promotes unstable contact during scratching.

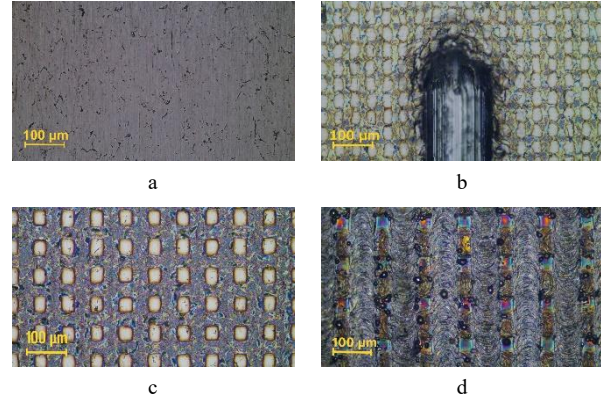


Fig. 4. Representative surface morphologies and their relation to scratch-test friction response: (a) untreated AISI 304 BA surface; (b) heterogeneous morphology and representative scratch track for $P = 3$ W and $\Delta x = 40$ μm ; (c) representative morphology for $P = 5$ W and $\Delta x = 70$ μm ; (d) representative morphology for $P = 15$ W and $\Delta x = 100$ μm .

In contrast, the surfaces obtained at $P = 5$ W and $\Delta x = 70$ μm (Fig. 4c) and at $P = 15$ W and $\Delta x = 100$ μm (Fig. 4d) show a more balanced and continuous morphology. The former is representative of the favourable parameter window around $\Delta x \approx 70$ μm , while the latter reflects stronger but more spatially uniform laser interaction at high power and large hatch spacing. The representative images support the conclusion that low power combined with small hatch spacing leads to increased heterogeneity and higher friction, whereas intermediate hatch spacing around 70 μm or large hatch spacing combined with high power provides a more favourable surface state for reduced friction.

IV. CONCLUSIONS

- A 7×7 scratch-test map was established for double-pass nanosecond fiber-laser markings on AISI 304 stainless steel by varying laser power $P = 3$ –15 W and hatch spacing $\Delta x = 40$ –100 μm under otherwise constant processing conditions.
- The untreated reference surface exhibited $\mu = 0.259$ and $F_t = 5.20$ N at $F_n = 20$ N. The highest-friction condition was $P = 3$ W and $\Delta x = 40$ μm ($\mu = 0.406$), whereas the lowest values were obtained at $P = 3$ W, $\Delta x = 70$ μm and $P = 15$ W, $\Delta x = 100$ μm ($\mu \approx 0.225$).
- For small hatch spacings (40–60 μm), increasing laser power substantially reduced friction, indicating that stronger thermal interaction and wider modified tracks mitigate the adverse effect of a highly heterogeneous surface. In contrast, $\Delta x = 70$ μm provided the most stable low-friction behaviour across the full power range.
- The most favourable process windows among the tested conditions were identified as: (i) intermediate

hatch spacing around $\Delta x = 70 \mu\text{m}$, especially at 3–7 W; and (ii) large hatch spacings of 90–100 μm combined with high power of 13–15 W. These regimes reduced both μ and F_t relative to the untreated reference.

- Because the dataset is descriptive, the reported trends should be treated as a practical ranking of the investigated conditions. Nevertheless, the results provide a clear basis for selecting laser-marking parameters when friction-sensitive and mechanically durable color markings are required on AISI 304 stainless steel.
- Future work should include replicate scratch tests, critical-load analysis from scratch-track damage, and correlation of friction with roughness, oxide-layer chemistry, and corrosion behaviour.

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Bayesian Method for Recursive Combination of Measurement and Prior Information for Accuracy Improvement in Video-Based Measurements

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Abstract— This paper presents a Bayesian method for the recursive combination of prior and measurement information aimed at improving the accuracy of video-based measurements. The proposed approach is based on a probabilistic formulation in which measurements are affected by stochastic noise with time-varying characteristics. The main contribution is the development of an adaptive mechanism for estimating the measurement noise variance, based on normalized innovation and a variable smoothing coefficient. This enables dynamic adjustment of the influence of measurements according to their current reliability, without the need for an explicit dynamic model. The effectiveness of the method is evaluated through simulations at different noise levels, with results demonstrating robust and accurate estimation, effective suppression of noise-induced deviations, and consistent uncertainty quantification. The method is applicable to machine vision and video-based object tracking tasks under varying measurement conditions.

Keywords— Video-based measurements; machine vision; object tracking; Bayesian estimation; recursive methods; measurement noise variance.

I. INTRODUCTION

Modern machine vision and video surveillance systems are widely used in various fields, including manufacturing automation, robotics, intelligent transportation systems, and security systems [1], [2]. In these applications, it is often necessary to determine the coordinates of observed objects with high accuracy based on information from sequential video frames [2], [3].

One of the main challenges in video-based measurements is the presence of measurement noise caused by limited image resolution, variable lighting conditions, image artifacts, and inaccuracies in visual data processing [4]-[7]. These factors lead to significant deviations between the measured and true coordinates and limit the accuracy of estimation [8], [9].

Probabilistic estimation methods based on the Bayesian framework, including the Kalman filter and its extensions, are widely used worldwide to address these issues [10]-[14]. These methods enable the combination of prior information and current measurements to reduce the influence of noise [15], [16]. However, in most cases, they rely on predefined or weakly adaptive parameters that

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determine the relative confidence in the measurements [17], [18].

A significant limitation of classical approaches is that the measurement noise variance is often assumed to be constant or determined a priori, without accounting for its temporal variation [19]-[22]. Under real-world conditions, however, measurement quality may vary dynamically, leading to a degradation in the performance of methods with fixed parameters [23]-[34].

This paper proposes a Bayesian method for the recursive combination of prior and measurement information, in which an adaptive mechanism for estimating the measurement noise variance is introduced. The proposed approach enables automatic adjustment of the influence of measurements according to their current reliability, without requiring an explicit dynamic model of the object's motion.

The primary contribution of this study is the development of an adaptive scheme for estimating the measurement noise variance, based on normalized innovation and a variable smoothing coefficient. This ensures improved robustness of the algorithm under varying measurement conditions and enhanced estimation accuracy.

II. FORMULATION OF THE PROPOSED APPROACH

The proposed approach is based on a recursive Bayesian scheme for state estimation in the presence of uncertainty and time-varying measurement quality. The main objective is to combine prior information and current measurements in a probabilistically consistent manner, while accounting for the dynamic variation in measurement reliability.

The algorithm is formulated in discrete time, where the index k denotes the current processing step or the corresponding video frame. The measurement process is described by an additive stochastic model that relates the object state to the measured value at step k .

$$z_k = x_k + v_k, \quad (1)$$

where x_k is the object state at step k , z_k is the measured value, and v_k is a random variable representing the measurement noise.

In the present study, x_k is considered as a scalar quantity derived from the image, for example, a coordinate in pixels along a selected axis. This assumption allows for a clear representation of the main relationships, while the obtained results can be readily extended to the multidimensional case.

In the model, the quantity v_k is assumed to have zero mean and variance $\sigma_z^2(k)$. Unlike the classical formulation, this variance is not considered constant, but rather as a time-varying quantity.

A. Recursive Bayesian Estimation

Prior to incorporating the current measurement, the available information about the object state is represented

by the prior estimate $\hat{x}_k^-$ and its corresponding variance σ_k^{2-} . Within the considered algorithm, the prior estimate at step k is formed based on the result of the previous iteration.

Under Gaussian assumptions, the updated estimate is given by:

$$\hat{x}_k = \hat{x}_k^- + K_k e_k, \quad (2)$$

where the innovation is defined as:

$$e_k = z_k - \hat{x}_k^-, \quad (3)$$

and the gain K_k is given by:

$$K_k = \frac{\sigma_k^{2-}}{\sigma_k^{2-} + \sigma_z^2(k)}. \quad (4)$$

The corresponding posterior variance is given by:

$$\sigma_k^2 = (1 - K_k) \sigma_k^{2-}. \quad (5)$$

From these relationships, it follows that the contribution of the measurement is automatically determined by its reliability. For low measurement noise variance, the gain K_k increases and the estimate approaches the measured value, whereas for higher uncertainty, the algorithm assigns greater weight to the prior information.

B. Adaptive Estimation of the Measurement Noise Variance

A key element of the proposed method is the adaptive estimation of the measurement noise variance $\sigma_z^2(k)$, which enables the algorithm to account for variations in measurement conditions.

The initial value of the variance is determined based on the spatial discretization of the image. Assuming a uniform distribution of the error within a single pixel, it can be expressed as:

$$\sigma_z^2(0) = \frac{\Delta^2}{12}, \quad (6)$$

where Δ is the equivalent pixel size along the corresponding coordinate.

To account for variations in measurement conditions, the variance is updated recursively. For this purpose, the normalized innovation is defined as:

$$r_k = \frac{e_k^2}{\sigma_z^2(k-1) + \varepsilon}, \quad (7)$$

where $\varepsilon > 0$ is a small constant ensuring numerical stability.

Based on this quantity, an adaptive coefficient is determined:

$$\lambda_k = \lambda_{\min} + \frac{\lambda_{\max} - \lambda_{\min}}{1 + \alpha r_k}, \quad (8)$$

where $0 < \lambda_{\min} < \lambda_{\max} < 1$, and $\alpha > 0$ determines the sensitivity of the adaptation.

The parameter α controls the extent to which the normalized innovation influences the value of λ_k . For larger values of α , even small variations in r_k lead to a significant decrease in λ_k , thereby accelerating the adaptation of the algorithm. Conversely, for smaller values of α , the variation of λ_k is smoother, resulting in more inertial behavior and higher robustness to noise.

- formation of the innovation,
- adaptive estimation of the measurement noise variance,
- updating of the estimate and its variance.

At each iteration k , the current measurement z_k is compared with the available prior estimate, resulting in the innovation e_k . This quantity is used both in the adaptive procedure for estimating $\sigma_z^2(k)$ and in the Bayesian state update.

The updated measurement noise variance $\sigma_z^2(k)$ serves a dual function: it is involved in the computation of the gain K_k at the current step and, at the same time, is used as an

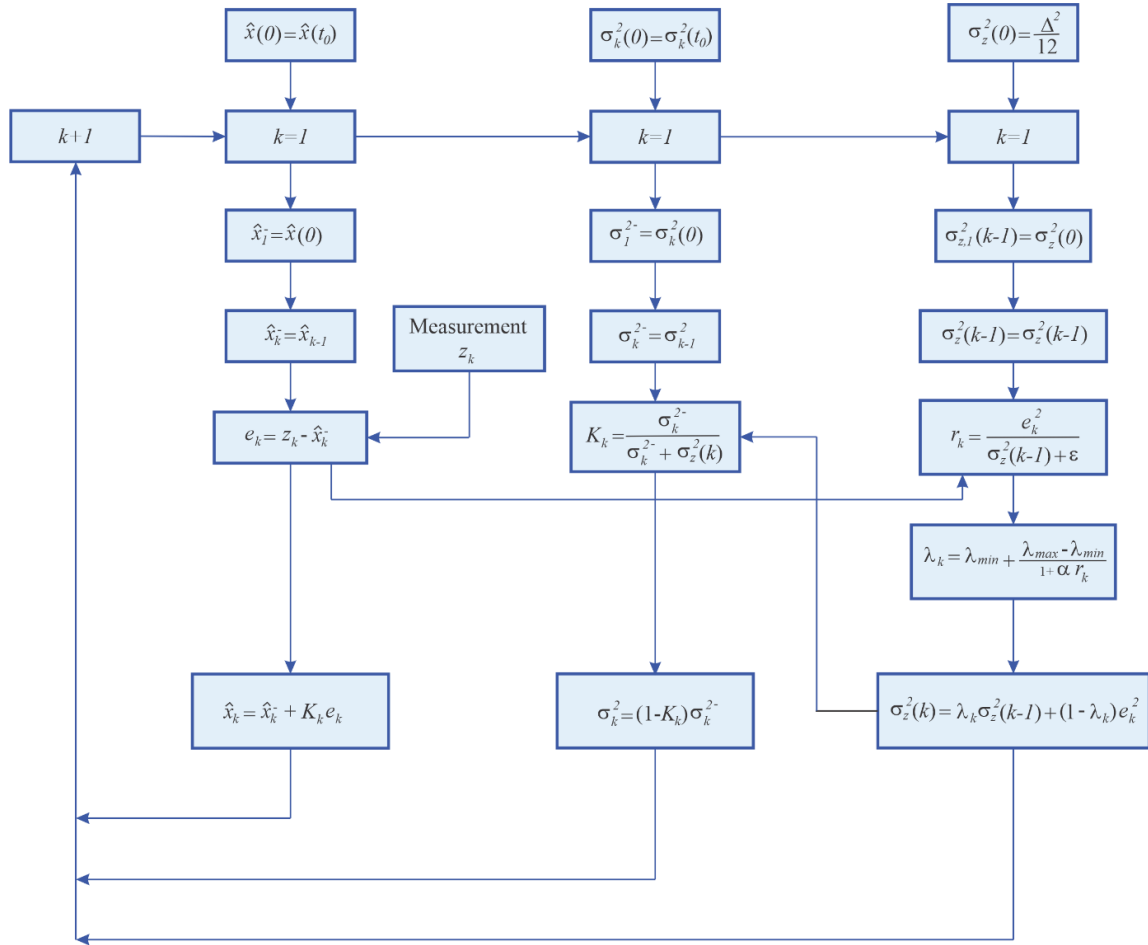


Fig. 1. Block diagram of the recursive algorithm and its parallel computational structure.

The measurement noise variance is updated as follows:

$$\sigma_z^2(k) = \lambda_k \sigma_z^2(k-1) + (1 - \lambda_k) e_k^2. \quad (9)$$

In this way, a two-stage adaptation mechanism is achieved: first, the variance is updated based on the current innovation, and second, the update rate is dynamically adjusted.

C. Algorithmic Structure

The proposed method is implemented as a recursive procedure consisting of three parallel computational branches that provide:

input quantity for the next iteration. Similarly, the obtained values of the estimate $\hat{x}_k$ and its variance σ_k^2 are used in the subsequent step, ensuring the recursive nature of the algorithm.

A graphical representation of the algorithm, based on the three parallel computational branches and their interconnections described above, is shown in Fig. 1.

III. SIMULATION RESULTS AND ANALYSIS

A. Simulation Conditions

The simulation study is focused on estimating the coordinate of an observed object in the presence of

measurement noise. A one-dimensional quantity corresponding to the object position, derived from a video image, is considered.

The measurement process is described by the additive stochastic model (1).

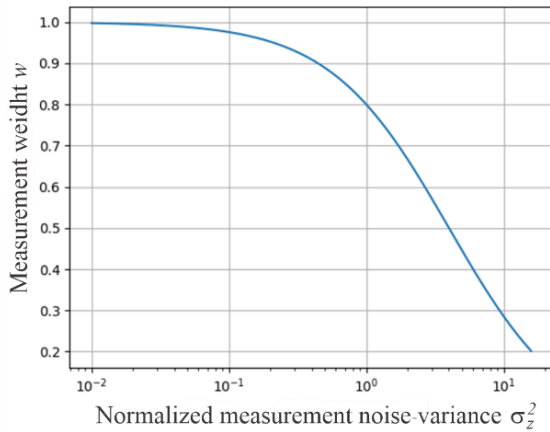
In the simulation, the noise v_k is assumed to have zero mean and variance $\sigma_z^2(k)$, which may vary over time in order to model different measurement conditions.

The initial value of the measurement noise variance is determined according to relation (6).

The prior and posterior state estimates, interpreted as the mean values of the corresponding probability distributions, are denoted by μ_k^- and μ_k^+ , respectively, with the posterior estimate given by:

$$\mu_k^+ = \frac{\sigma_{z,k}^2 \mu_k^- + \sigma_k^{2-} z_k}{\sigma_k^{2-} + \sigma_{z,k}^2}. \quad (10)$$

The prior estimate μ_k^- is obtained from the posterior estimate at the previous iteration, reflecting the absence of an explicit dynamic model in the considered approach.



a)

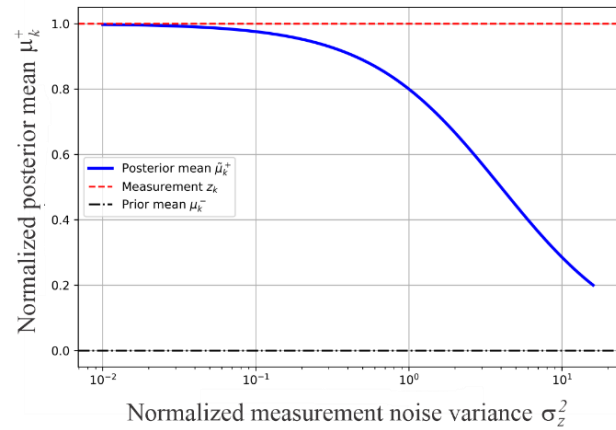
value of the coordinate, whereby both the coordinate and the corresponding variances are expressed in relative (dimensionless) units. This allows the results to be generalized independently of the specific image scale. For practical interpretation, the same relationships can be expressed in pixels $[px]$ and, accordingly, in $[px^2]$.

B. Effect of Noise Variance on Measurement Weight

In the Bayesian updating process, the weight of the measurement is determined by the coefficient w , introduced in (11). This quantity characterizes the relative contribution of the measured value with respect to the prior information in forming the estimate.

The dependencies of the weighting coefficient w and the normalized posterior estimate μ_k^+ on the measurement noise variance σ_z^2 are shown in Fig. 2a and Fig. 2b, respectively.

The figure shows a monotonic decrease in the weight w with increasing σ_z^2 . For low values of the measurement noise variance, w approaches unity, indicating that the measurement has a dominant influence on the updated estimate. Conversely, as σ_z^2 increases, the weight decreases, reducing the influence of the measurement and



b)

Fig. 2. Dependence of the weighting coefficient w and the normalized posterior estimate μ_k^+ on the measurement noise variance σ_z^2 : (a) weighting coefficient w ; (b) normalized posterior estimate μ_k^+ .

For the purposes of the analysis, a weighting coefficient is also introduced:

$$w = \frac{\sigma_k^{2-}}{\sigma_k^{2-} + \sigma_{z,k}^2}, \quad (11)$$

which determines the relative contribution of the measurement in the update of the estimate and is equivalent to the gain K_k introduced in Section 2.

The simulations were performed in the MATLAB environment, considering both static and dynamically varying measurement conditions by varying the measurement noise variance $\sigma_z^2(k)$.

In part of the study, normalized quantities are used. The normalization is performed with respect to a characteristic

increasing the role of the prior information.

The analysis of Fig. 2b shows that, for small values of σ_z^2 , the posterior estimate μ_k^+ approaches the measured value, which is consistent with the high weight of the measurement. As the measurement noise variance increases, the estimate gradually shifts toward the prior value, reflecting the reduced influence of the measurement. This transition is smooth and continuous, ensuring stable behavior of the algorithm under varying measurement conditions.

This relationship provides a natural mechanism for adaptation to the quality of the measurement. For reliable measurements, the algorithm follows the measured values, whereas in the presence of strong noise, it automatically suppresses their influence.

Therefore, the weighting coefficient w can be interpreted as an indicator of measurement reliability, determined entirely by the ratio of prior to measurement uncertainty.

C. Effect of Measurement Noise on the Posterior Variance

The posterior variance σ_k^{2+} characterizes the degree of uncertainty of the obtained estimate and represents a quantitative measure of the reliability of the algorithm. An analysis of the variation of σ_k^{2+} as a function of the measurement noise variance σ_z^2 is presented below. This relationship is illustrated graphically in Fig. 3.

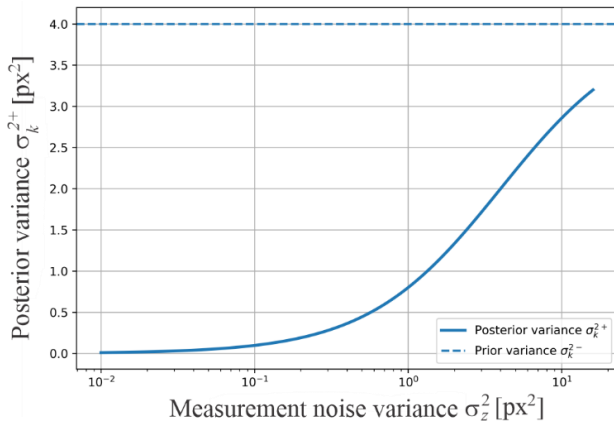


Fig. 3. Dependence of the posterior variance σ_k^{2+} on the measurement noise variance σ_z^2 .

The figure shows that, for small values of σ_z^2 , the posterior variance attains low values, indicating a high degree of confidence in the estimate. As the measurement noise increases, the variance grows and gradually approaches the prior variance, reflecting a decrease in the informativeness of the measurements.

A characteristic feature of the presented dependence is the presence of a clearly defined transition region, in which the increase of the posterior variance σ_k^{2+} becomes significantly more pronounced. This region corresponds to a range of values of σ_z^2 for which the ratio between the prior and measurement uncertainties changes substantially, leading to a redistribution of weight between the two sources of information. As a result, the algorithm transitions from a measurement-dominated regime to a regime in which the prior information exerts a dominant influence on the estimate.

This behavior is a direct consequence of Bayesian updating and provides a mechanism for preventing an unjustified increase in confidence in the estimate in the presence of noisy measurements.

Thus, the posterior variance can be interpreted as an indicator of the effectiveness of the algorithm under various measurement conditions, providing a quantitative assessment of the achieved improvement in accuracy.

D. Recursive Update of the Estimate in the Presence of Noise

Fig. 4 illustrates the recursive behavior of the proposed method in the presence of noisy measurements. The figure shows the true value of the coordinate, the measured values, and the posterior estimate μ_k^+ , obtained through sequential Bayesian updating. The measurements are characterized by significant random deviations from the true value, reflecting the presence of measurement noise.

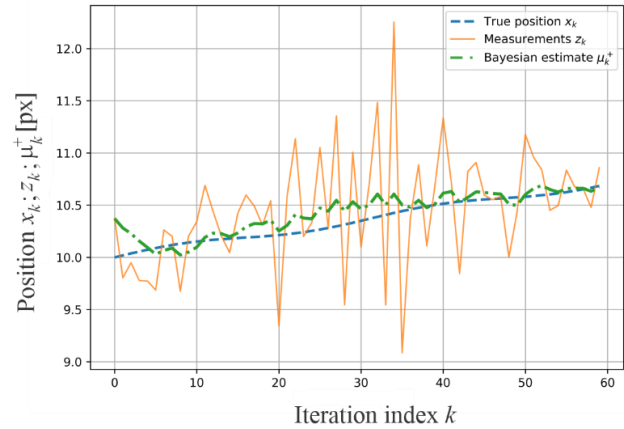


Fig. 4. Recursive update of the estimate μ_k^+ for measurements containing stochastic noise

Despite this, the posterior estimate smoothly follows the variation of the true value, effectively suppressing high-frequency noise components. This behavior results from the adaptive weighting between the prior information and the current measurement, realized through the coefficient w .

In the presence of abrupt changes in the measurements, the algorithm does not respond directly to instantaneous deviations but instead forms a stable estimate that reflects the overall trend of the process. Thus, effective filtering of noisy measurements is achieved without introducing an additional dynamic model.

The results demonstrate that the proposed approach provides reliable and robust estimation of the coordinate over a wide range of measurement conditions.

IV. CONCLUSION

This paper presents a Bayesian method for the recursive combination of prior and measurement information aimed at improving the accuracy of video-based measurements. The proposed approach is based on a probabilistic formulation of the estimation problem and employs an adaptive mechanism for estimating the measurement noise variance.

The main contribution of the study is the development of an adaptive scheme for estimating $\sigma_z^2(k)$, based on normalized innovation and a variable smoothing coefficient. This enables the algorithm to dynamically adapt to the current quality of the measurement information and to regulate the influence of the measurements in the estimation process.

Unlike classical approaches with fixed parameters, in which measurement reliability is assumed to be predefined, the proposed method evaluates it in real time based on the current data. This results in improved robustness under varying measurement conditions.

An additional advantage of the approach is that it does not require the introduction of an explicit dynamic model of the object motion. This makes it applicable in cases where the system dynamics are unknown or difficult to model, while still enabling effective suppression of noise-induced deviations.

The simulation results demonstrate that the proposed method provides more stable and reliable estimation compared to the direct use of measurements, while maintaining a consistent assessment of uncertainty through the posterior variance.

The proposed approach can be extended to multidimensional cases and combined with more complex models when necessary, making it a promising solution for applications in machine vision and object tracking systems.

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An Adaptive Kalman Filter for Video-Based Tracking with Dynamic Adaptation of Covariance Matrices

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Abstract— This paper presents an adaptive Kalman filter for video-based object tracking, in which the process and measurement covariance matrices are updated dynamically in real time. The proposed approach is based on a linear stochastic model without a control input, which is justified by the characteristics of video-based observation. The state vector includes position, velocity, and acceleration components, enabling a more accurate representation of motion dynamics. The main contribution of the study is the development of an adaptive algorithmic structure for estimating the covariance matrices based on innovation statistics. This approach improves consistency between the model and measurements under varying conditions and in the presence of noise. The effectiveness of the proposed method is evaluated through numerical simulation. The results demonstrate a significant reduction in the root mean square error (RMSE) in estimating position and velocity compared to unfiltered measurements and the classical Kalman filter. These results confirm the applicability of the proposed approach to video-based measurement systems.

Keywords—Adaptive Kalman filter, video-based object tracking, covariance matrix estimation, innovation-based adaptation, state estimation, measurement noise.

I. INTRODUCTION

In recent years, video-based observation has emerged as one of the most promising approaches for real-time measurement and tracking of object motion [1]-[4]. Owing to advances in digital imaging technologies, computer vision, and computational resources, this approach has found wide application in autonomous transportation systems, robotics, industrial automation, security systems, and intelligent transportation systems [5]-[8]. The main advantages include non-contact measurement, the ability to simultaneously observe multiple objects, and the relatively low cost of the measurement infrastructure [9], [10].

Despite these advantages, video-based measurements are associated with a number of limitations that significantly affect the accuracy of the obtained results [11]-[14]. These include image noise, limited spatial and temporal resolution, and inaccuracies in object localization. External factors such as illumination variations, occlusions, and dynamic scene changes also influence the results [15]-[18]. One significant challenge is velocity estimation, which is derived from position and is therefore sensitive to noise and discretization.

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In practice, these limitations are addressed using state estimation algorithms, among which the Kalman filter and its variants are the most widely used [19]. The classical Kalman filter provides optimal recursive estimation when the statistical characteristics of the noise are known; however, its performance strongly depends on the proper selection of the process and measurement covariance matrices [20]-[25]. Under real-world conditions, these parameters are often unknown or time-varying, which leads to degraded accuracy and the presence of systematic deviations in the estimates [19], [23], [26]-[31].

In this regard, adaptive approaches have been developed that update the covariance matrices during filter operation. In this paper, an adaptive Kalman filter for video-based object tracking is proposed, in which the process and measurement covariance matrices are dynamically estimated based on innovation statistics. Unlike classical implementations, the proposed method accounts for changing observation conditions and the dynamics of the tracked object, enabling improved agreement between the model and the measurement information.

The main contribution of this study is the development of an adaptive algorithmic framework that ensures improved accuracy and robustness in estimating the position and velocity of the object. By incorporating an extended state vector and dynamically adapting the covariance matrices, a more accurate representation of the process is achieved, along with improved suppression of noise effects under varying observation conditions.

II. MATHEMATICAL MODELING OF THE ADAPTIVE KALMAN FILTER

A. Problem Formulation and Model Selection

The mathematical model of the proposed algorithm is formulated as a linear stochastic model, which enables a formalized description of the dynamics of the observed object and the measurement process in the presence of uncertainty.

The choice of this type of model is motivated by the need to ensure:

- optimal recursive state estimation in the sense of minimum mean square error;
- the possibility for explicit representation and adaptive handling of uncertainty sources through the covariance matrices;
- agreement between the dynamic model and the measurement information under varying observation conditions.

In this context, the system dynamics and the measurement process are described by the following standard form:

$$x_k = Ax_{k-1} + w_k, \quad w_k \sim N(0, Q_k), \quad (1)$$

$$z_k = Hx_k + v_k, \quad v_k \sim N(0, R_k), \quad (2)$$

where x_k is the state vector; z_k is the measurement vector; w_k and v_k are stochastic variables representing the process uncertainty and measurement noise, respectively, with covariance matrices Q and R ; and H is the measurement matrix.

In general, a control input vector is included in the state equation to describe external influences acting on the system. In the considered formulation, however, the objects are observed via a video stream rather than controlled; thus, no physical control signal is available. The inclusion of such an input through numerical differentiation of the measurements (e.g., via acceleration estimation) amplifies noise components and increases uncertainty, since these quantities are not directly measurable and are highly sensitive to discretization errors and image processing inaccuracies.

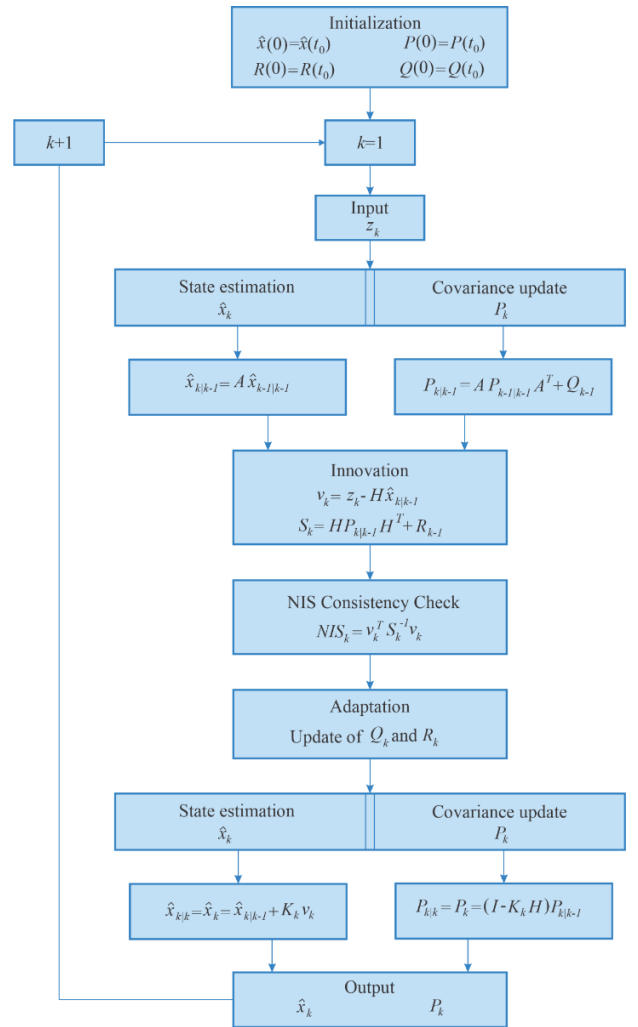


Fig. 1. Block diagram of the adaptive Kalman filter with NIS-based control and dynamic update of the covariance matrices

Therefore, the control input term is omitted from the model, which adopts the reduced form (1). This decision is justified from both physical and metrological perspectives, as it:

- eliminates unobservable quantities;

- reduces model uncertainty;
- enables more accurate estimation of the covariance matrices Q and R ;
- improves the robustness of the algorithm under noise, occlusions, and varying frame rates.

As a result, unmodeled variations in the object motion are captured by the stochastic term w_k and its covariance matrix Q , which is dynamically adapted.

The algorithmic structure of the proposed adaptive Kalman filter is presented in Fig. 1. The filtering process is organized into two parallel computational branches, corresponding to the state estimation and the covariance matrix update. These branches operate synchronously and are interconnected through the Kalman gain and the iterative structure of the algorithm.

At each iteration, a prediction of the state and covariance is performed, followed by the computation of the innovation and its covariance. The NIS (Normalized Innovation Squared) criterion is used as a control layer to assess the consistency between the predicted state and the current measurement.

Based on the NIS value, an adaptive update of the covariance matrices Q_k and R_k is carried out, enabling dynamic adjustment of the relative influence of the model and the measurement information at each iteration.

B. Definition of the State Vector

To describe the motion of the object in the image plane, an extended state vector is introduced, which includes the position, velocity, and acceleration components along both axes:

$$x_k = \begin{bmatrix} x_k \\ y_k \\ v_{x,k} \\ v_{y,k} \\ a_{x,k} \\ a_{y,k} \end{bmatrix}, \quad (3)$$

where x_k and y_k denote the current coordinates of the object center in the image plane, $\dot{x}_k$ and $\dot{y}_k$ represent the corresponding velocities, and $a_{x,k}$ and $a_{y,k}$ denote the accelerations along the coordinate axes.

This choice enables a simultaneous description of the current position of the object and its dynamics, accounting not only for the instantaneous velocity but also for its rate of change. The inclusion of acceleration components as states reduces systematic model error under real-world conditions, where motion is rarely characterized by constant velocity. Classical constant-velocity models account for such variations indirectly by increasing the process covariance, which results in increased uncertainty and reduced stability of the estimates. In this approach, acceleration is treated as part of the state, enabling a more physically grounded representation of the process and more accurate prediction of motion, particularly in the presence of abrupt changes or temporary loss of measurements.

From a metrological perspective, this results in a more accurate distribution of uncertainty, as the influence of acceleration is explicitly estimated through the corresponding components of the state covariance matrix rather than being absorbed into the stochastic term.

The selected state vector strikes a balance between model accuracy and computational complexity, while enabling effective adaptation of the process covariance matrix depending on the current dynamic regime.

C. State Transition Model

The state dynamics are described by (1), which defines the evolution of the state in discrete time through the state transition matrix A and the stochastic term w_k , representing the process uncertainty.

Assuming a nearly constant acceleration motion model and discretization with a sampling interval Δt , the state transition matrix A takes the following form:

$$A = \begin{bmatrix} 1 & 0 & \Delta t & 0 & \frac{\Delta t^2}{2} & 0 \\ 0 & 1 & 0 & \Delta t & 0 & \frac{\Delta t^2}{2} \\ 0 & 0 & 1 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta t \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \quad (4)$$

This structure is derived from the kinematic equations of uniformly accelerated motion and provides a physically grounded prediction of the state. Using a model that includes acceleration components reduces systematic error under variable velocity conditions and improves the robustness of the filter in the presence of temporary loss of measurements.

In the considered formulation, deviations from the idealized model are accounted for by the stochastic term w_k , whose intensity is defined by the covariance matrix Q_k , which is adapted in real time.

D. Measurement Model

In the basic formulation of video-based tracking, measurement information is typically limited to the object coordinates in the image plane. In the proposed approach, this model is extended by incorporating velocity components derived from consecutive frames, as they provide additional information about motion dynamics and improve the agreement between the measurement and prediction models.

Therefore, the measurement information is extracted from the video stream in the form of object coordinates and their rates of change [32]. This defines the linear nature of the measurement model described by (2).

In accordance with the defined state vector, the measurement is assumed to include the object coordinates and their velocities; therefore, the measurement matrix takes the following form:

$$H_k = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}, \quad (5)$$

and the measurement vector is given by:

$$z_k = \begin{bmatrix} x_m(k) \\ y_m(k) \\ \dot{x}_m(k) \\ \dot{y}_m(k) \end{bmatrix}, \quad (6)$$

where $x_m(k)$ and $y_m(k)$ are the measured coordinates of the object center in the image plane, and $\dot{x}_m(k)$ and $\dot{y}_m(k)$ are the corresponding velocities, obtained from consecutive frames or estimated using a motion estimation algorithm.

In this formulation, accelerations are estimated recursively using the Kalman filter rather than being measured directly. This enables the use of available measurement data while maintaining an extended representation of the object dynamics.

Measurement uncertainty is characterized by the covariance matrix R_k , which accounts for errors in determining the coordinates and velocities. Since the velocities are derived from the measured coordinates, their variances are larger and should be evaluated in accordance with the employed image processing algorithm. The initial values of R_k are determined based on calibration data or a preliminary experimental assessment of the measurement noise. During operation, the matrix is adapted online through analysis of the filter innovations, while the agreement between prediction and measurement is monitored using the Normalized Innovation Squared (NIS) criterion.

This enables dynamic adjustment of the confidence in the measurement data depending on its current quality, ensuring a metrologically sound and data-consistent state estimation in video-based tracking.

E. Process Noise Covariance Matrix

The process noise covariance matrix Q_k characterizes the uncertainty associated with inaccuracies in the dynamic model and unmeasured influences acting on the motion of the object.

In the considered case, these influences are modeled as stochastic variations in acceleration, assuming that its derivative (jerk) is a white noise process. Under this assumption, the process covariance matrix is defined as follows:

$$Q_k = \sigma_j^2 \begin{bmatrix} \frac{\Delta t^5}{20} & 0 & \frac{\Delta t^4}{8} & 0 & \frac{\Delta t^3}{6} & 0 \\ 0 & \frac{\Delta t^5}{20} & 0 & \frac{\Delta t^4}{8} & 0 & \frac{\Delta t^3}{6} \\ \frac{\Delta t^4}{8} & 0 & \frac{\Delta t^3}{3} & 0 & \frac{\Delta t^2}{2} & 0 \\ 0 & \frac{\Delta t^4}{8} & 0 & \frac{\Delta t^3}{3} & 0 & \frac{\Delta t^2}{2} \\ \frac{\Delta t^3}{6} & 0 & \frac{\Delta t^2}{2} & 0 & \Delta t & 0 \\ 0 & \frac{\Delta t^3}{6} & 0 & \frac{\Delta t^2}{2} & 0 & \Delta t \end{bmatrix}, \quad (7)$$

where σ_j^2 is a parameter defining the intensity of the stochastic variations in acceleration.

This structure ensures agreement between the kinematic model and the stochastic description of the dynamics, accounting for the interdependence between position, velocity, and acceleration.

In the proposed approach, the parameter σ_j^2 is treated as an adaptive quantity, updated in real time based on the innovation statistics. In this way, the matrix Q_k dynamically reflects the current motion regime of the object:

- under smooth motion, its values decrease, increasing the confidence in the model;
- under abrupt changes, they increase, allowing for a more flexible response of the filter.

From a metrological perspective, Q_k determines the contribution of model uncertainty to the overall uncertainty of the estimate. Its adaptive determination ensures agreement between the mathematical model and the real process and is a prerequisite for reliable state estimation under varying dynamic conditions.

F. Measurement Noise Covariance Matrix

The measurement noise covariance matrix R_k characterizes the statistical properties of the errors arising in the observation of the quantities in the vector z_k and reflects the uncertainty associated with extracting coordinates and velocities from the video data.

In the general case of two-dimensional coordinate measurements, the matrix takes the following form:

$$R_k = \begin{bmatrix} \sigma_{x,q}^2 & \rho_{xy}\sigma_{x,q}\sigma_{y,q} \\ \rho_{xy}\sigma_{x,q}\sigma_{y,q} & \sigma_{y,q}^2 \end{bmatrix}, \quad (8)$$

where $\sigma_{x,q}^2$ and $\sigma_{y,q}^2$ are the variances of the measurements, and ρ_{xy} is the correlation coefficient.

In the practical formulation, the measurements along the two axes are assumed to be independent, i.e., $\rho_{xy} = 0$, and the matrix reduces to a diagonal form. For the considered extended measurement vector, the matrix R_k is specified as:

$$R_k = \begin{bmatrix} \sigma_x^2 & 0 & 0 & 0 \\ 0 & \sigma_y^2 & 0 & 0 \\ 0 & 0 & \sigma_{\dot{x}}^2 & 0 \\ 0 & 0 & 0 & \sigma_{\dot{y}}^2 \end{bmatrix}. \quad (9)$$

In (9), the variances of the velocity components are higher, as they are not measured directly but are obtained through numerical differentiation of the coordinates, which leads to amplification of measurement noise.

The matrix R_k summarizes the influence of the main sources of error, including image discretization, sensor noise, inaccuracies in object localization, illumination variations, and calibration errors.

The initial values of the elements of R_k are determined experimentally through analysis of the variations of the measured coordinates for a static object.

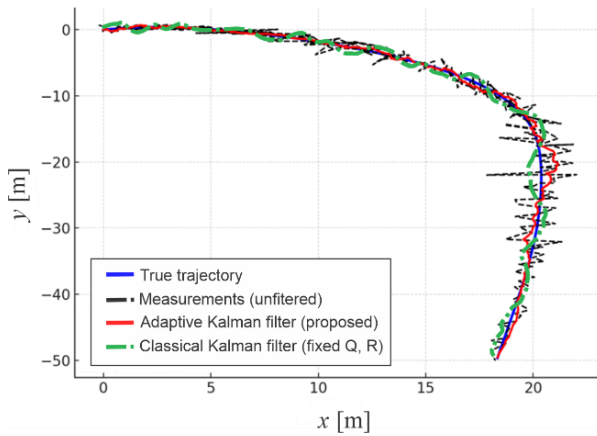
In real time, the matrix R_k is adapted based on the innovation:

$$v_k = z_k - H_k \hat{x}_{k|k-1}, \quad (10)$$

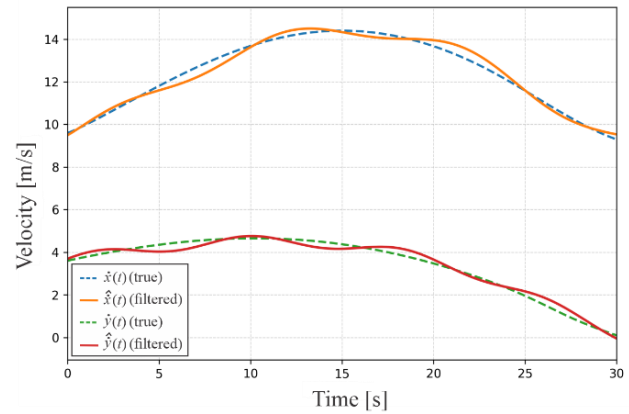
using exponential weighting

$$R_k = (1 - \lambda_R)R_{k-1} + \lambda_R(v_k v_k^T - H_k P_{k|k-1} H_k^T), \quad (11)$$

where $\lambda_R \in (0,1)$ is the adaptation coefficient; $\hat{x}_{k|k-1}$ is the a priori (predicted) estimate of the state vector at time k , computed based on the information available up to time $k-1$; and $P_{k|k-1}$ is the corresponding covariance matrix of the prediction error [33].



a)



b)

Fig. 2. Simulation results of the proposed adaptive Kalman filter: (a) object trajectory in the image plane - comparison between true, measured, and estimated trajectories; (b) velocity components - comparison between true velocities $\dot{x}(t), \dot{y}(t)$ and estimated velocities $\hat{\dot{x}}(t), \hat{\dot{y}}(t)$.

The agreement between the model and the measurements is evaluated using the Normalized Innovation Squared (NIS) criterion:

$$\text{NIS}_k = v_k^T S_k^{-1} v_k, \quad S_k = H_k P_{k|k-1} H_k^T + R_k, \quad (12)$$

where the value of NIS_k is compared with the confidence bounds of the χ^2 distribution with degrees of freedom equal to the dimension of the measurement.

The NIS criterion is used to monitor the agreement between the model and the measurements, serving as the basis for adaptive updating of the covariance matrices at each iteration of the algorithm.

If a deviation occurs outside the permissible interval, the matrix R_k is adjusted, which reduces the influence of inconsistent measurements and ensures robust filter performance under noisy or atypical conditions.

From a metrological perspective, R_k defines the confidence bounds of the measurements and, together with Q_k , determines the overall uncertainty of the estimate. Its adaptive determination ensures statistical agreement and metrological traceability under varying observation conditions.

III. MODELING AND SIMULATION ANALYSIS

Numerical simulations of the motion of the object's projection in the image plane, described by a discrete stochastic model, were performed to evaluate the effectiveness of the proposed adaptive Kalman filter. The state dynamics and the measurement process are represented by the equations defined in Section 2, while uncertainties are modeled through the covariance matrices Q_k and R_k , which are dynamically adapted over time.

The simulation was implemented in the MATLAB environment using a constant sampling interval $\Delta t = 0.1$ s. The motion included smooth variations in velocity and random variations in acceleration. The coordinate

measurements were modeled by adding Gaussian noise with different variances along the coordinate axes to mimic real-world observation conditions in video-based measurement systems.

The simulation results are presented in Fig. 2. Fig. 2a shows the trajectory of the object in the image plane, where a good agreement between the true and estimated

trajectories is observed, along with a significant reduction of noise-induced deviations in the measurements. The filtered trajectory smoothly follows the true motion, effectively attenuating the high-frequency components caused by measurement noise.

The quantitative evaluation of accuracy is performed using the root mean square error (RMSE), defined as:

$$RMSE = \sqrt{\frac{1}{N} \sum_{k=1}^N (x_k - \hat{x}_k)^2}, \quad (13)$$

where x_k and $\hat{x}_k$ denote the true and estimated coordinates of the object, respectively.

From the graphical representation, it can be observed that the unfiltered measurements are strongly affected by noise, resulting in significant deviations from the true trajectory. When a classical Kalman filter is applied, effective attenuation of high-frequency noise is achieved; however, due to the use of fixed covariance matrices, inertia in the estimate is observed, manifested as lag and local systematic deviations in regions with faster variations in motion.

The proposed adaptive filter reduces this effect through dynamic adaptation of the covariance matrices, enabling faster response to changes in the signal and providing improved estimation accuracy over the entire motion range.

The quantitative results presented in Table 1 confirm the above analysis.

TABLE 1 ROOT MEAN SQUARE ERROR (RMSE) FOR POSITION AND VELOCITY ESTIMATION USING DIFFERENT METHODS

Estimated quantity	Method	RMSE
Position (coordinates)	Unfiltered measurements	1.2944 m
Position (coordinates)	Classical Kalman filter	0.5173 m
Position (coordinates)	Adaptive Kalman filter	0.2140 m
Velocity ($\dot{x}(t)$)	Adaptive Kalman filter	0.238 m/s
Velocity ($\dot{y}(t)$)	Adaptive Kalman filter	0.203 m/s

Fig. 2b presents a comparison between the true velocities $\dot{x}(t)$ and $\dot{y}(t)$ and the estimated velocities $\hat{\dot{x}}(t)$ and $\hat{\dot{y}}(t)$ obtained using the proposed adaptive filter. From the graphical representation, it can be observed that the estimated velocities closely follow the overall trend of the true velocities under smoothly varying motion conditions.

The small deviations observed between the true and estimated values are attributed to the influence of measurement noise and the recursive nature of the estimation process. The obtained results indicate that the proposed filter provides stable estimation of the velocity components $\dot{x}(t)$ and $\dot{y}(t)$, without introducing significant high-frequency oscillations in the estimates.

The quantitative evaluation of accuracy is performed using the root mean square error (RMSE), with (13) applied

analogously to the velocity components. The corresponding quantitative results for the velocity estimation error are summarized in Table 1.

IV. CONCLUSION

In this work, an adaptive Kalman filter for video-based object tracking is developed, in which the process and measurement covariance matrices are dynamically updated in real time. The proposed approach is based on a linear stochastic model without the inclusion of a control input, which is justified by the characteristics of video-based observation.

By incorporating position, velocity, and acceleration components into the state vector, a more accurate representation of motion dynamics is achieved, providing improved agreement between the model and the measurements. The adaptive estimation of the covariance matrices enables the filter to adjust to changing noise characteristics and dynamic regimes, resulting in enhanced robustness and estimation accuracy.

From a scientific perspective, the main contribution of this study lies in the development of an adaptive algorithmic structure in which the filter parameters are updated based on the statistical characteristics of the innovation. The use of the Normalized Innovation Squared (NIS) criterion as a control mechanism enables a formalized assessment of the filter behavior and provides the basis for targeted adjustment of its parameters according to the current observation conditions. In this way, a mechanism for dynamic balancing between the model and the measurement information is achieved, extending classical approaches based on fixed parameters.

From a metrological perspective, the proposed approach can be interpreted as a mechanism for dynamic management of uncertainty in the estimation process. In this context, the covariance matrices acquire the role of carriers of confidence-related information, which is updated in real time depending on the quality of the measurements and the nature of the motion. This enables the integration and weighting of information with different levels of reliability, ensuring more robust algorithm performance in the presence of noise and varying observation conditions.

The simulation results demonstrate a significant reduction in root mean square error compared to unfiltered measurements, as well as additional improvement when applying the proposed adaptive approach. The obtained results confirm the effectiveness of the method for both position estimation and velocity determination.

The results indicate that the proposed approach is suitable for application in video-based tracking systems operating under noisy and time-varying observation conditions.

Despite the achieved results, the proposed approach offers opportunities for further development. Future research may focus on experimental validation under real-world conditions, as well as on extending the model to nonlinear dynamic systems. In addition, the integration

with advanced image processing algorithms and adaptive parameter estimation methods could lead to enhanced robustness in the presence of complex scenes, occlusions, and varying observation conditions. Furthermore, the influence of the selection of adaptive parameters and the characteristics of the measurement noise on the stability of the algorithm represents an important direction for more in-depth investigation.

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Laser Marking on Samples With Chromium-Nickel Coating

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Abstract — In the 21st century, laser marking is increasingly used. Very good results are achieved when working on resistant materials such as plexiglass or chromium-nickel samples, where good color marking is also achieved.

Products that are made of or coated with chromium-nickel are used in the manufacture of a number of parts and products. This is especially true for products that are produced in the enterprises of the military-industrial complex. Marking such products in the current complex international situation and the conduct of military operations in Ukraine, Israel, Yemen and other countries will make tracking military production a much easier task. The experiments were conducted on thin samples of chromium-nickel and the change in marking quality with changes in the speed and power of the laser and the roughness of the material were studied. The results obtained were analyzed and this will provide an opportunity both for using the results obtained and for continuing research. These studies were conducted at the Laser Center of Rezekne Academy of Technology during an Erasmus internship.

Keywords — *chromium-nickel, laser, marking, power, roughness, speed.*

1. INTRODUCTION

Joint research in the field of laser technologies between the Rezekne Academy of Technology, as the lead partner, and the National Military University "Vasil Levski" began in 2018. The partnership between the educational institutions is even older, as the first framework agreements for cooperation and agreements under the Erasmus program were signed more than 10 years ago. There is a regular exchange of students and lecturers between the two educational institutions, and joint research projects are developed and research is conducted, mainly in the field of laser technologies.

Teachers, cadets and students from the military educational institution from Bulgaria have also visited the Latvian university many times. During practical training, cadets and students from the National Military University under the leadership of Prof. Lazov have conducted research and data processing from experimental and theoretical studies of various materials in the laser center in Rezekne.

Laser marking on chromium-nickel is a process in which a laser beam is used to create permanent markings on the surface of the material. This method is popular due to its high precision and the ability to create detailed and complex designs [1], [2], [3].

The laser marking process occurs when the laser generates a concentrated beam of light, which is directed at the surface of the chrome-nickel. The material absorbs the energy from the laser, which leads to local heating and a change in the surface structure. Depending on the laser settings, a different effect can be achieved - from a color change to deep engraving [4], [5].

Laser marking on chrome-nickel has a number of time-proven advantages:

1. High contrast is achieved, in which the markings are clearly visible and legible, even at small sizes.
2. It has very high durability, because laser markings are resistant to wear, corrosion and high temperatures.
3. It has high marking precision, with the ability to create complex and detailed designs with high resolution.
4. The process does not violate the integrity of the material and does not lead to mechanical damage [6], [7].

This method is widely used in various industries, including automotive, medical and electronic, for marking parts, tools and components, as well as in military production [8]

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II. MATERIALS AND METHODS

Laser Procedure Setup and Parameters Stainless steel contains chromium in its composition, which provides chemical stability and high heat resistance of the alloy and makes it suitable for use in the laser process [9], [10], [22]. In this study, 2 mm thick chromium-nickel steel plates with an initial roughness level $R_z = 8.42 \mu\text{m}$, reflectivity $R(\lambda=1.06 \mu\text{m}) = 0.75$, thermal diffusivity $a = 3 \times 10^{-6} \text{ m}^2/\text{s}$, thermal conductivity $k = 37 \text{ W/mK}$, melting point $= 1800^\circ\text{C}$ and boiling point $= 3145^\circ\text{C}$ were used. At the initial stage, the surfaces were cleaned with acetone to avoid any dirt or stains. As a source of laser radiation with a wavelength of $1055 < \lambda < 1075 \text{ nm}$, generating pulses with a duration of 4 seconds, a nanosecond pulsed ytterbium fiber laser supplied by IPG Photonics Corporation $< \tau < 200 \text{ ns}$ at a repetition rate of $1.6 < f < 1000 \text{ kHz}$ was selected. The configuration of the laser processing system developed for the purposes of scribing and marking is presented in Fig. 1 and consists of 1) IPG Photonics nanosecond fiber laser, 2) optical fiber transfer, 3) SCANLAB scanning system, 4) 100 mm objective, 5) Neff-Wiesel linear drive for vertical movement, 6) XY coordinate stage, 7) Kollmorgen ACD servo drives.



Fig. 1. The configuration of the laser processing system [4].

A fiber pulsed ytterbium laser was emitted and fed into a collimating system via an optical fiber to form a parallel beam output. A dual-axis galvanometer scanning system (hurrySCAN II 14 digital scanning head from SCANLAB corp.) was installed to move along the X and Y axes. A focusing lens with a focal length of 100 mm was used to focus the laser radiation onto the surface of a steel plate [11, 12, 24]. Additional horizontal movements and vertical movements can be performed using a multi-axis linear motor coordinate stage, which allows for an extension of the working space to $250 \times 250 \text{ mm}$. The laser radiation parameters and scanning speed can be changed using the developed labVIEW code. Also, all vertical and horizontal movements can be controlled by the same code.

The coatings and markings of the products must withstand different environmental conditions and must not change during the period of use of the product [1], [9], [13]. This is extremely important in the production of military products. In this study, an environmental test was

performed in a chamber based on several different operating conditions [14], [18], [23]. The products were tested under extreme conditions, at temperature and humidity values that are rarely encountered in real conditions, but due to the specificity of the products, such environmental parameters were selected as a combination of extremely low or high temperatures ($-40, -20, 40, 100^\circ\text{C}$) with high humidity (70%, 90%). In this way, the stability of the samples under normal conditions for a long period in different parts of the globe and under extreme operating conditions is guaranteed. At the same time, this way the short duration of the test exposure (24 hours) compared to the actual operating time is compensated. The first test was carried out under environmental conditions with a temperature of -20°C and a humidity of 70% [4], [15], [17]. The result shows that there is no change in the colors or materials after 36 hours in the environmental test chamber. No damage or defects were found in the surface layers in the optical microscope analyses.

III. RESULTS AND DISCUSSION

The process of color laser marking on chromium-nickel steel involves the sequential melting and solidification of the material, which leads to oxidation and nitriding of the surface of the material. The final surface and the formation of an oxide film are the result of repeated work with a pulsed laser, which varies depending on the heat of the laser and the value of the overlap of the laser pulses [4], [16], [19], [20]. The resulting surface relief and color are affected by almost all parameters of the laser source. In this study, the dependence of the microhardness of a series of samples on the scanning speed, laser power, pulse duration and laser pulse frequency is investigated. The study of the dependence of the resulting color on the surface relief is not the goal of this study, the goal of the study was to obtain high-quality and durable marking on chrome-nickel steel [4], [21].

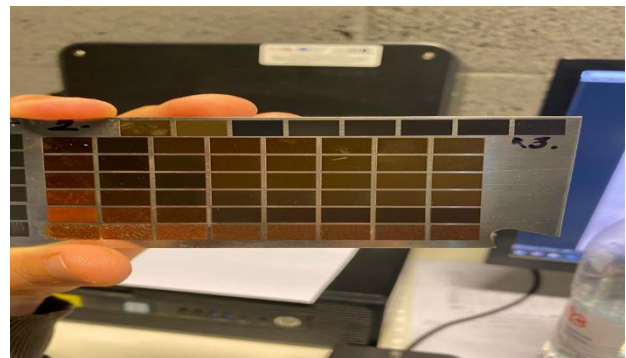


Fig. 2. Matrix of the study of sample 2

Due to the impossibility of presenting the entire study due to its large volume, we will focus on some basic data and graphs that were obtained after measuring the results and analyzing them.

Fig. 2 shows the results obtained for measuring the microhardness of the surface of sample No. 2. Measurements were made at a constant speed of 100 m/s. of the laser beam and at a laser emission frequency of 500

kHz. During the measurement, a 7x7 field matrix was made, with the variable values being the laser power and the marking step. The results of the study are shown in Table 1.

TABLE 1 MEASUREMENT OF MICROHARDNESS OF CHROMIUM-NICKEL STEEL, SAMPLE 2

Speed: 100m/s ; Frequency: 500 kHz; Pulse duration: 8n/s; Loop1-90° Loop2 0°							
Step (μm)	10	12	14	16	18	20	22
25	0,431	0,492	0,474	0,513	0,563	0,675	0,695
50	0,339	0,572	0,424	0,53	0,607	0,646	0,676
75	0,357	0,424	0,518	0,629	0,726	0,79?	0,82?
100	0,228	0,465	0,537	0,67	0,629	0,692	0,712
125	0,14	0,424	0,486	0,622	0,622	0,619	0,642

The obtained results are also shown in fig. 3. There the dependence of the untreated surface SQ on the marking steps is shown. It is clearly seen that up to the fifth step the change is close to linear with increase. After that, however, a sharp change in the picture occurs and no dependence can be determined because the change is different for each measurement.

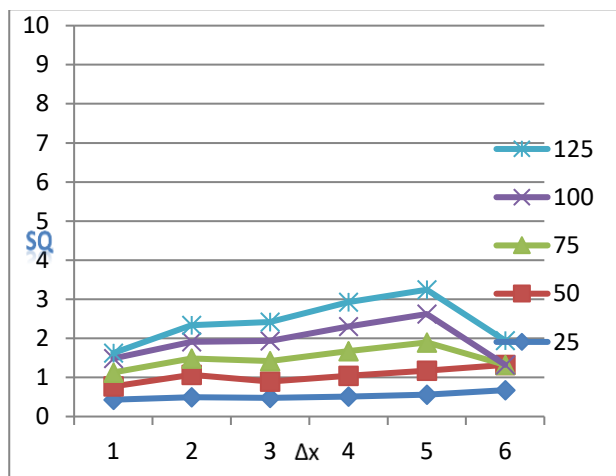


Fig. 3. Dependence of Microhardness on the power and step of the laser beam for sample 2

Measurements were made on 6 samples, with the results up to 4-5 steps having a similar growth rate, and after the fifth step, divergence of the indicators was observed and no definite regularity of the change could be detected, because the changes did not converge in the results obtained. This indicates that to obtain good indicators of laser marking of chromium-nickel steel, the laser equipment must work with small steps up to 50 μm . Similar results were obtained for the other samples studied, which confirms the accuracy of the study and the results obtained.

From Fig. 4 it is clearly seen that the results for other samples have a similar nature.

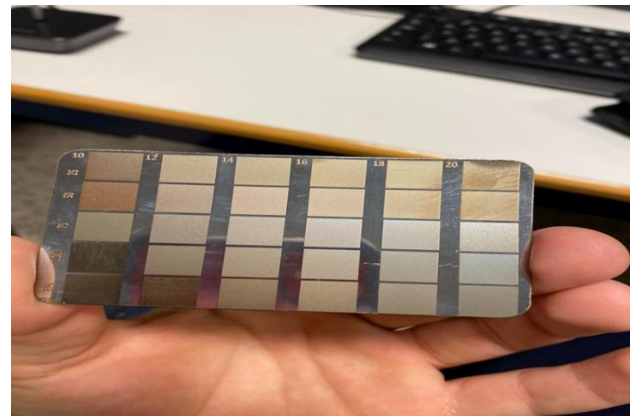


Fig.4. Sample 3

Figure 5 shows the graphical dependences of SQ on the change in x and the step of the laser beam, the graph being built on the basis of the results obtained for marking chromium-nickel steel on sample 3, where very good dependences were obtained. Due to the volume of the report, the results obtained for the remaining samples are not presented, but the authors can further analyze the results and present them in subsequent reports.

Parallel to these studies, studies were also conducted on the achieved quality of the marking and the microroughness of the resulting treated surface. Plates of the same samples of chromium-nickel steel and the same laser were used, with the variable values here being the speed, power and step of the laser beam. The matrix that was developed and the resulting image quality are shown in Fig. 5.



Fig. 5. Plate with matrix from the tests of the quality of roughness of the marking

The data from the measurements made on plate No. 7 are shown in table 2.

TABLE 2 MEASUREMENT OF THE QUALITY OF ROUGHNESS OF THE MARKING ON CHROMIUM-NICKEL STEEL, SAMPLE 7

Step	Power, W	6	12	18	36	42	48	54	60
	554	445,2	461,6	454,8	453,5	472,3	467,8	479,8	474,1

454	444	440,6	457	466,7	480,8	481,8	488,1	497,1
354	441,1	469,3	469,3	473,2	481,6	487,7	483,5	497,8
254	429	447,3	474,1	478,3	472,9	480,8	478,1	479,2
154	463,6	467,2	452,4	481,3	469,6	487,6	483,5	493,3
54	437,4	457,5	497,9	426	427,2	470,4	433,9	458,9

Accordingly, the obtained results were processed and graphs of the dependences of the measurements made on 12 plates with chromium-nickel coating were constructed. Fig. 6 shows the obtained graph of sample 7.

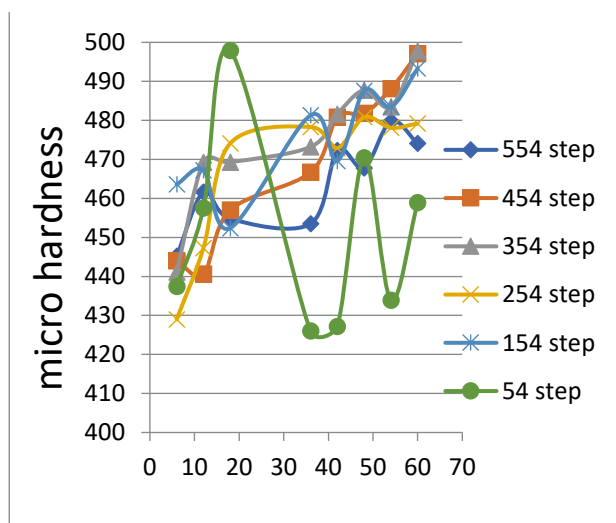


Fig. 6. Graph of the dependence of microhardness on the power of the laser beam

Out of the many measurements made, the results of only one sample are shown, due to the limited volume of the report. The results obtained from the overall study, which was carried out within 2 months, are many and could not be presented in such a small volume.

IV. CONCLUSIONS

The laser processing system developed for the purposes of this research work is based on a nanosecond ytterbium fiber laser on a multi-axis platform for the workpiece and the possibility of vertical movement of the laser scanning head. In the preliminary phase, the scanning system was calibrated and the specifications of the laser beam at the focal point were determined. In order to find the appropriate value of the power density, the distribution of the laser spot on the surface was measured. The dependence of the obtained colors on the parameters of the laser processing, including the scanning speed, pulse duration, radiation power and pulse repetition frequency, was studied.

Based on the analysis, 12 blanks were prepared for the three experiments, and a suitable matrix was developed for

each experiment. Each blank from the first study consists of 49 squares with different power and laser beam path indicators and dimensions of 8×15 mm. The obtained oxide films were examined using optical microscopy and scanning electron microscope (SEM). The surface topology was established using atomic force microscopy (AFM).

In a similar way, the samples for the second and third experiments were prepared, and here the number of fields was 30. The results confirm that the created samples have appropriate consistency, brightness and cover approximately all spectral regions.

In the joint work of the representatives of the National Military University "Vasil Levski" and the Rezekne Academy of Technology, the algorithms for working and conducting the study to find the optimal parameters for marking different color spectra on chromium-nickel steel were initially compiled. The research was carried out during a practical training at the Academy in Rezekne and the obtained matrices were examined with the equipment available at the laser center. The results obtained contributed to finding the optimal marking mode on this material and obtaining the highest quality surface marking. The results obtained so far will be developed in subsequent experiments.

The results obtained are the basis for further research on marking chromium-nickel steel, taking into account the operating conditions of the obtained surface. Based on the results obtained, the most suitable speeds and beam path were selected to obtain excellent marking with good indicators of the obtained surface. Marking with a laser beam power higher than 11 watts was excluded from further research and, depending on the desired result, a corresponding step of the laser beam is selected. The participants in the study are ready to continue the research and find even more accurate marking values on other surfaces that are used in special production and are relevant in view of the current international situation.

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Method for Synthesis of State Controller with Observer for an Electrohydraulic Power Transmission System

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Abstract— This paper deals with the synthesis of state controller with observer for an electrohydraulic power transmission system. There is shown a method for synthesis of the state controller with observer and the realization for electrohydraulic system. The controller coefficients are obtained from preliminary defined performance definitions. The system has been modeled, and step responses curves are obtained from computer simulation. Main results are given in a few graphics.

Keywords— state controller with observer, electrohydraulic system, dynamic processes modeling and simulation

I. INTRODUCTION

The dynamic characteristics of hydraulic drive systems can be improved by using modern control methods. Hydromechanical regulators, servo valves with mechanical feedback on the position of the plunger, etc. are used. [1], [2], [3], [4]. For processing and transmission of signals in hydraulic drive systems, electrical and electronic components are used. This makes it possible to improve the static and dynamic properties of hydraulic systems by applying electronic control circuits. The power and cost of microprocessors today allow the development of more modern control concepts, and thus the achievement of more successful control systems. Researchers have made numerous attempts to increase the accuracy of the dynamic positioning of electrohydraulic systems by improving algorithms for control and evaluation of states. Popular approaches include classical feedback and compensation schemes, as well as variants of state observers and Kalman filters, including linear and nonlinear extensions [7], [8], [9], [10]. Analogous control approaches are also used in electropneumatic positioning systems [9], [10]. When analyzing the performance of electro-hydraulic traction systems, it is important to evaluate positioning errors in dynamic mode [11], [12], [13].

II. STATE CONTROLLER DESIGN

In real technical systems, controllers are used to impose a certain static and dynamic behavior on the output variable of interest. The limited possibilities of influence in the often used single-loop feedback and PID controllers can be expanded by using multi-loop controls. The common feature of this approach is the "State Controller" method, in which all state variables are used as feedback [1], [5], [9], [10].

A prerequisite for using this concept is knowledge of the dynamic behavior of the object to be controlled. In general, it is described by a system of first-order nonlinear differential equations of the form:

$$\frac{d\mathbf{x}(t)}{dt} = \dot{\mathbf{x}}(t) = f(\mathbf{x}(t), \mathbf{u}(t));$$

$$\mathbf{y}(t) = g(\mathbf{x}(t));$$

(

1)

where, $\mathbf{x}(t)$, $\mathbf{u}(t)$, $\mathbf{y}(t)$ - state, input and output vector.

For the nonlinear description of the system defined in this way, there is no general rule for forming a controller. The theory of linear systems is considered complete and its application in the synthesis of a control system is to some extent accessible, starting from the linear approximate description of the object in the form [1], [3]

$$\frac{d\mathbf{x}(t)}{dt} = \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{b}\mathbf{u}(t); \quad (2)$$

$$\mathbf{y}(t) = \mathbf{c}\mathbf{x}(t).$$

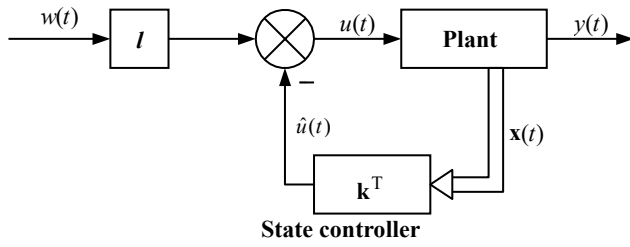


Fig. 1. System with state controller.

Figure 1 shows the fundamental structure of a “State Controller” system. The error signal is formed by a linear combination of the state variables.

$$\hat{u}(t) = \sum_{i=1}^n k_i x_i(t) = \mathbf{k}^T \mathbf{x}(t)$$

3)

By selecting the individual feedback coefficients, the behavior of the system in dynamic mode can be influenced. This concept is applicable when the state variables are measurable quantities. When the state variables cannot be technically captured or are unmeasurable, approximate quantities are created and used instead of the actual ones. One of these possibilities is the approximate differentiation of the measured output quantity. In this way, the velocity and acceleration can be obtained from the displacement coordinate. The disadvantage of this approach is that it results in a noisy signal, which can be cleaned by low-pass filtering, but ultimately leads to unsuitable results when differentiating.

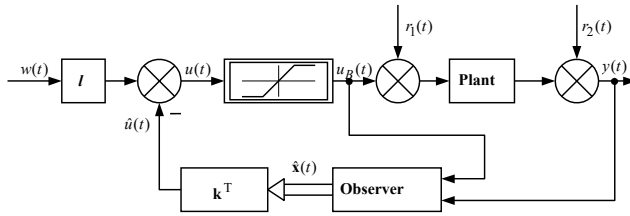


Fig. 2. System with state loop and observer.

It is recommended to observe the state, in which the required quantities are obtained by knowing the input and output quantities of the object. The application requires complete observability of the system, i.e., to be able to see all its internal movements at the output of the object. For the system, when an observer is included, the structure shown in Fig. 2 is obtained.

In this scheme, the observer represents a dynamic system that can be sized so that the vector of output quantities $\hat{\mathbf{x}}(t)$ in the case without disturbances ($r_1 = r_2 = 0$) transitions with a given dynamics to the states of the object $\mathbf{x}(t)$ and tracks them with zero dynamic error.

When removing the initially existing observation error, it is irrelevant for the behavior of the system that approximate values $\hat{x}_i(t)$ are used instead of the true state

variables $x_i(t)$. The aforementioned restriction on the error signal does not lead to an observation error if it is reproduced before the input to the object. As shown in Fig. 2. with an artificially limited error signal $u_B(t)$, the observer is given the input signal that actually affects the object after the restriction.

In this approach, known as time domain representation, the design of the observer is reduced to some simplification of the linear functional $\hat{u}(t) = \mathbf{k}^T \mathbf{x}(t)$. The error signal is given by $u(t) = I w(t) - \hat{u}(t)$.

The design of a state observer controller is conveniently done in the frequency domain [1], using the well-developed apparatus of transfer functions. The transfer function of the object can be determined by:

$$W_O(s) = \frac{Y(s)}{U(s)}, \quad (4)$$

with

$$W_O(s) = \mathbf{C}^T (s\mathbf{I} - \mathbf{A})^{-1} \mathbf{b} \quad (5)$$

or directly by object identification. In this case, the latter approach does not often require complex modeling of the internal structure. The output signal of the controller $U(s)$ as a function of $Y(s)$, $W(s)$, $U_B(s)$, is represented in the form

$$U(s) = \frac{Z_{Ry}(s)}{\Delta(s)} Y(s) + \frac{Z_{Rw}(s)}{\Delta(s)} W(s) - \frac{Z_{Ru}(s)}{\Delta(s)} U_B(s) \quad (6)$$

The transfer functions

$$\frac{Z_{Ry}(s)}{\Delta(s)}, \frac{Z_{Rw}(s)}{\Delta(s)}, \frac{Z_{Ru}(s)}{\Delta(s)}$$

of the individual control channels describe the relationship between the input variables $Y(s)$, $W(s)$, $U_B(s)$ and the output variable $U(s)$. The polynomial $\Delta(s)$ in the denominator is called the observer polynomial, the polynomials Z_{Ry} , Z_{Ru} and Z_{Rw} , must be defined in such a way that the desired behavior of the system is achieved for a given polynomial $\Delta(s)$.

Before determining the unknown polynomials of the controller, the question of the existing possibilities for formulating the desired behavior of the system must be clarified. In state control, it is customary to specify the internal values of the controlled system (assigning the poles). This method is easy to implement and helps with little experience in designing appropriate controllers.

The transfer functions of the closed system are defined as the basis for determining the poles by disturbance:

$$W_{r1}(s) = \frac{Z_O(s)[\Delta(s) + Z_{Ru}(s)]}{N_O(s)[\Delta(s) + Z_{Ru}(s)] + Z_O(s)Z_{Ry}(s)} \quad (7)$$

$$W_{r2}(s) = \frac{N_O(s)[\Delta(s) + Z_{Ru}(s)]}{N_O(s)[\Delta(s) + Z_{Ru}(s)] + Z_O(s)Z_{Ry}(s)} \quad (8)$$

on assignment

$$W_w(s) = \frac{Z_{Rw}(s)Z_O(s)}{N_O(s)[\Delta(s) + Z_{Ru}(s)] + Z_O(s)Z_{Ry}(s)} \quad (9)$$

The coefficients of the still unknown polynomials $Z_{Ry}(s)$ and $Z_{Ru}(s)$ must be determined in such a way that the characteristic polynomial of the closed system has the desired poles, these are the poles of the transfer functions $W_{r1}(s)$, $W_{r2}(s)$ and $W_w(s)$.

The design of the controller is based on the fact that the poles of the observer must also be poles of the closed system. Thus $\Delta(s)$, must be a divisor of the polynomial in the denominator of (7), (8) and (9). The remaining poles are summed in the polynomial $\tilde{N}(s)$.

The design equation for setting poles is

$$N_O(s)[\Delta(s) + Z_{Ru}(s)] + Z_O(s)Z_{Ry}(s) = \tilde{N}(s)\Delta(s) \quad (10)$$

The solution of the design equation using the known polynomials $N_O(s)$ and $F_O(s)$ (each of the n -th degree, corresponding to the order of the object) and the polynomials that should be given $\Delta(s)$ (degree n_B) and $\tilde{N}(s)$ (degree n). The unknown polynomials $Z_{Ry}(s)$ and $Z_{Ru}(s)$ are also taken with degree. Thus, on the left side of the design equation, a polynomial of degree $(n + n_B)$ with total $2(n_B + 1)$ unknown coefficients in the polynomials $Z_{Ry}(s)$ and $Z_{Ru}(s)$ is obtained. On the right

side of equation (10) is also a polynomial of degree $(n + n_B)$, whose coefficients are known.

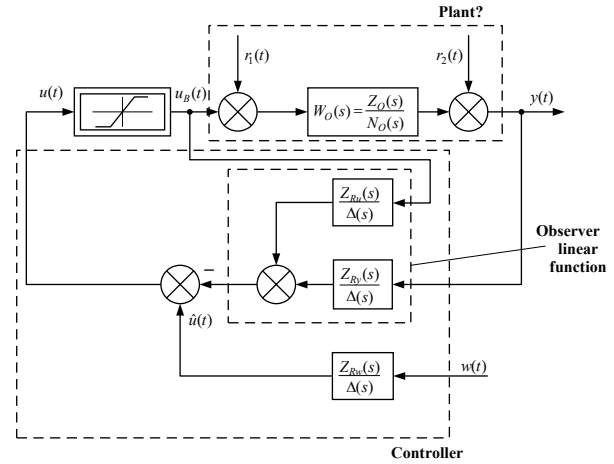


Fig. 3. Block diagram of a regulator with observer.

Equating the coefficients in front of the same degrees s of the left and right sides of the design equation leads to $n + n_B + 1$ equations with $2(n_B + 1)$ unknowns. Generalized, they form a system of linear equations with unknown coefficients – Fig. 4. Before solving them with standard software, the solvability of the linear system of equations must be determined in principle. Depending on the degree of the observer n_B , this system of equations must be uniquely determined. Unique solvability is obtained when the number of unknowns is equal to the number of linearly independent equations, i.e.

$$2(n_B + 1) = n + n_B + 1 \quad (11)$$

This leads to the choice of observer degree

$$n_B = n - 1 \quad (12)$$

solution of the polynomial equation $Z_O(s)Z_{Ry}(s) + N_O(s)Z_{Ru}(s) = [\tilde{N}(s) - N_O(s)]\Delta(s)$

polynomial		coefficients	
$Z_O(s)$	$< n$	$f_0, f_1, \dots, f_{n-1}$	Plant
$N_O(s)$	n	$g_0, g_1, \dots, g_n ; g_n = 1$	
$Z_{Ry}(s)$	n_B	$a_0, a_1, \dots, a_{n_B}$	Controller
$Z_{Rr}(s)$	n_B	$b_0, b_1, \dots, b_{n_B}$	
$Z_{Ru}(s)$	n_B	$c_0, c_1, \dots, c_{n_B} ; c_{n_B} = 0$	
$\Delta(s)$	n_B	$d_0, d_1, \dots, d_{n_B} ; d_{n_B} = 1$	Poles
$\tilde{N}(s)$	n	$e_0, e_1, \dots, e_n ; e_n = 1$	

$$\begin{bmatrix} f_0 & 0 & 0 & 0 & \dots & 0 & g_0 & 0 & 0 & 0 & \dots & 0 \\ f_1 & f_0 & 0 & 0 & \dots & 0 & g_1 & g_0 & 0 & 0 & \dots & 0 \\ \vdots & f_1 & f_0 & 0 & \dots & 0 & \vdots & g_1 & g_0 & 0 & \dots & 0 \\ f_{n-1} & \vdots & f_1 & - & - & 0 & g_{n-1} & \vdots & g_1 & - & - & 0 \\ 0 & f_{n-1} & \vdots & - & - & f_0 & 1 & g_{n-1} & \vdots & - & - & g_0 \\ 0 & 0 & f_{n-1} & - & - & f_1 & 0 & 1 & g_{n-1} & - & - & g_1 \\ 0 & 0 & 0 & - & - & \vdots & 0 & 0 & 1 & - & - & \vdots \\ \vdots & \vdots & \vdots & - & - & f_{n-1} & \vdots & \vdots & \vdots & - & - & g_{n-1} \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{n_B} \\ c_0 \\ c_1 \\ \vdots \\ c_{n_B} \end{bmatrix} = \begin{bmatrix} e_0 - g_0 & & & & & \\ e_1 - g_1 & e_0 - g_0 & & & & \\ \vdots & e_1 - g_1 & e_0 - g_0 & & & \\ e_n - g_n & \vdots & e_1 - g_1 & \ddots & & \\ 0 & e_n - g_n & \vdots & \ddots & e_0 - g_0 & \\ 0 & 0 & e_n - g_n & - & e_1 - g_1 & \\ \vdots & 0 & 0 & 0 & \vdots & \\ \vdots & \vdots & \vdots & \ddots & - & \\ 0 & 0 & 0 & 0 & e_n - g_n & \end{bmatrix} \begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_{n_B} \end{bmatrix}$$

$n + n_B + 1$ $2(n_B + 1)$ $n + n_B + 1$ $n_B + 1$

Fig. 4. Linear system of equations for solving the design equation (10)

III. IMPLEMENTING A CONTROLLER WITH A STATE OBSERVER IN ANALOG TECHNOLOGY

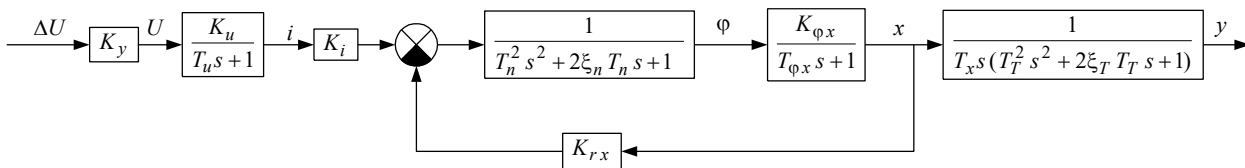
The synthesis of the regulator is reduced to determining the coefficients in the transfer functions in the three branches of the regulator Fig. 3. The implementation of the regulator is carried out by building analog networks, whose behavior at the input and output is characterized by the transfer functions. By separately building the individual branches based on the common polynomial – denominator $\Delta(s)$, it is possible to give a generalized idea of the system. In the practical implementation of the regulator, this is an advantage due to the reduced number of structural elements - integrators. Fig. 6 shows an analog model of the regulator in the normal form of the observer with a minimum number of integrators n_B . The

electrohydraulic system is represented by a linear model [2], whose structural diagram and transfer function are shown in Fig. 5. The transfer function of the open system is recorded at reception $K_m = 0$.

$$K_1 = \frac{K_u K_i K_{\phi x} K_y}{T_x (1 + K_{\phi x} K_{rx})} \quad - \text{total gain of the open system;}$$

$$T_1 = \sqrt{\frac{T_n^2 T_{\phi x}}{1 + K_{\phi x} K_{rx}}}; T_2 = \sqrt{\frac{T_n^2 + 2\xi_n T_n T_{\phi x}}{1 + K_{\phi x} K_{rx}}};$$

$$T_3 = \frac{T_{\phi x} + 2\xi_n T_n}{1 + K_{\phi x} K_{rx}} \quad - \text{time constant}$$



$$W(s) = \frac{Y(s)}{\Delta U(s)} = \frac{K_1}{s(1+T_\nu s)(T_T^2 s^2 + 2\xi_T T_T s + 1)(T_1^3 s^3 + T_2^2 s^2 + T_3 s + 1)} \quad (13)$$

Fig. 5. *Structural diagram of the open system*

After opening the brackets and arranging by powers of ω and neglecting some of the small coefficients, the transfer function of the open system can be written in the form:

$$W_O(s) = \frac{\beta_1}{g_0 s^4 + g_1 s^3 + g_2 s^2 + g_3 s} \quad (14)$$

IV. SYNTHESIS THE CONTROLLER

The regulator is designed with the degree of the observer being one less than the degree of the regulated object. The values of the roots of the observer are recommended by [1].

$$n_B = n - 1 = 3$$

$$\Delta(s) = (s - s_1)(s - s_2)(s - s_3); s_{1,2,3} = -300\text{s}^{-1}$$

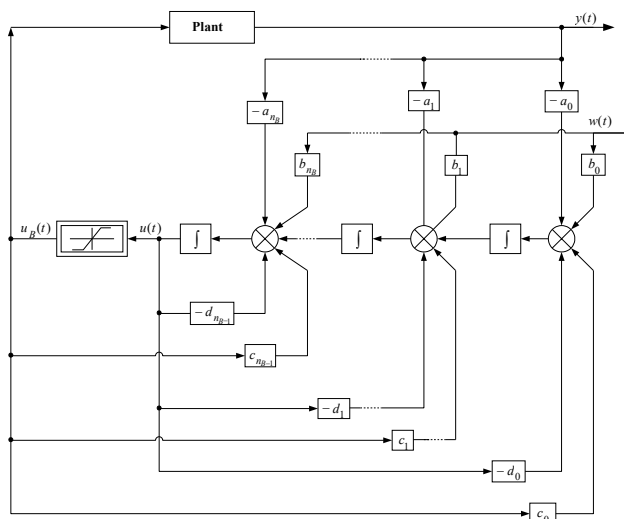


Fig. 6. Analog model of a state controller with an observer

For the auxiliary polynomial in the design equation (10), the degree must match the degree of the object [1].

$$\begin{aligned} n &= 4 \\ \tilde{N}(s) &= (s - s_1)(s - s_2)(s - s_3)(s - s_4) \\ s_1 &= -160\text{s}^{-1}; s_{2,3} = (-160 \pm j160)\text{s}^{-1}; \\ s_4 &= -2000\text{s}^{-1} \end{aligned}$$

The design equation is solved by solving the linear system of equations – Fig. 4 using the MathCad software. The results are shown in Table 1.

TABLE I. THE RESULTS SOLVING THE LINEAR SYSTEM OF EQUATIONS

Polynomial	Power	Coefficients	
$Z_O(s)$	3	925925, 3, 0, 0, 0	Plant
$N_O(s)$	4	85185.185, 855.5, 14, 1	
$Z_{Ry}(s)$	3	$4.78 \cdot 10^{11}$, $0.109 \cdot 10^{11}$, $0.11 \cdot 10^9$, $5.49 \cdot 10^{11}$	Controller
$Z_{Rw}(s)$	3	1, 0, 0	
$Z_{Ru}(s)$	3	$1.79 \cdot 10^9$, $3.23 \cdot 10^6$, $2.46 \cdot 10^3$, 0	
$\Delta(s)$	3	$2.7 \cdot 10^7$, $2.7 \cdot 10^5$, 900, 1	Poles according equation (10)
$\tilde{N}(s)$	4	$1.64 \cdot 10^{10}$, $2.13 \cdot 10^8$, $1.06 \cdot 10^6$, 2480, 1	

The electrohydraulic system with a state controller with an observer is modeled using the MatLab Simulink software. The transient processes for a rectangular and sawtooth input signal are simulated. Fig. 7 and Fig. 8 show the graphs of the output quantity, speed and acceleration.

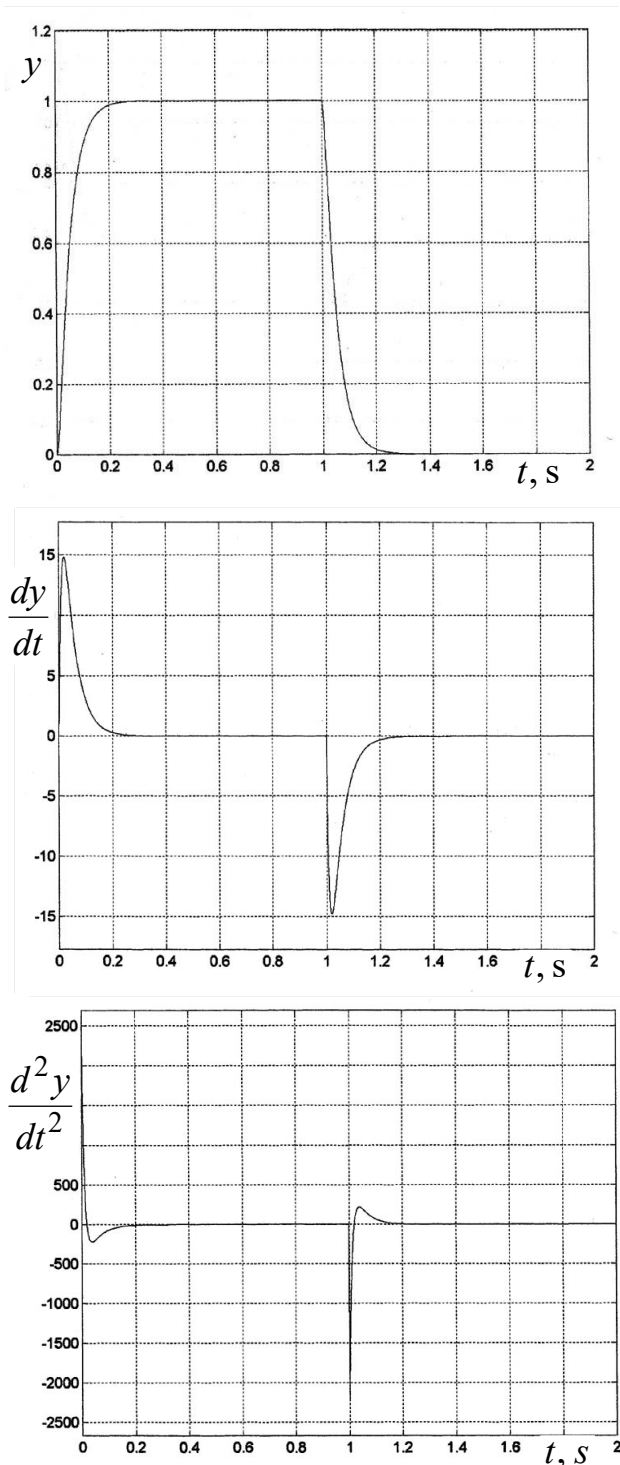
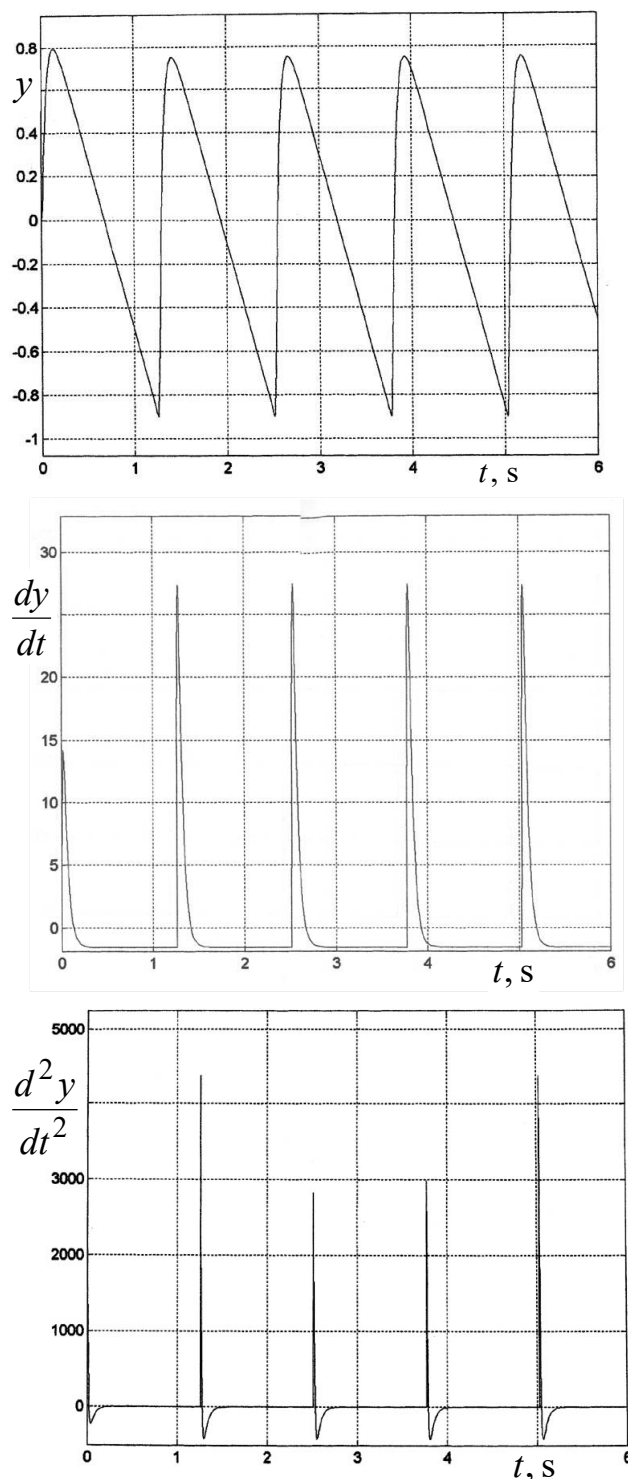


Fig. 7. Transient processes in an electrohydraulic system with a state controller with an observer for a rectangular input signal

V. RESULTS AND DISCUSSION

A method for synthesis of state controller with an observer for controlling an electrohydraulic system for

linear models of low-order objects is presented. For the good operability of the system, it is necessary to accurately determine the parameters of the object. It is recommended to use identification of the unknown parameters by experimental dynamic characteristics [3].



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Fig. 8. Transient processes in an electrohydraulic system with a state controller with an observer at a sawtooth input signal

VI. CONCLUSION

In addition to an analog implementation of a controller with an observer, a digital one can also be made, in which microprocessor technology is used to control the system. Improved operation of the observer is achieved by incorporating guiding and perturbing models to compensate for disturbances and good task tracking.

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<https://doi.org/10.3390/s25164922>

An Experimental Study of the Frequency Response of an Electropneumatic Positioning System with a Rodless Cylinder Four High Speed Pneumatic Valves and PWM Control

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Abstract— This paper presents an experimental investigation into the frequency response of an electropneumatic positioning system, which includes a rodless pneumatic cylinder and four 2/2-way high speed pneumatic valves operated via pulse width modulation. The experimental procedures are captured and analyzed in real-time using a dedicated virtual instrument. The amplitude and phase Bode plots for the electropneumatic positioning system were obtained through experimentation and subsequently analyzed, leading to the identification of the system's critical frequency. The findings are illustrated through various graphs.

Keywords — Frequency response, electropneumatic positioning system, critical frequency, rodless pneumatic cylinder.

I. INTRODUCTION

Electropneumatic positioning systems are characterized by structural simplicity, reliability, and the ability to implement rapid work cycles. Various types of valves are used for controlling pneumatic actuators, such as pneumatic cylinders with different constructions and purposes – most commonly, they are three types: proportional, servo valves, and high speed electromagnetic valves with PWM control. The use of proportional valves and servo valves allows for smooth control; however, these solutions are characterized by their higher commercial price and more complex construction, requiring

maintenance by specialized personnel. Therefore, due to the simplicity and reliability of controlling electropneumatic positioning systems, in recent years, high speed electromagnetic valves type 2/2, controlled by pulse-width modulation (PWM), have been used in a number of practical applications, offering an excellent alternative at a lower commercial price. PWM control allows for effective regulation of flow and pressure but leads to the emergence of specific dynamic processes in the electropneumatic positioning system. This necessitates a more in-depth investigation of the dynamic processes in pneumatic systems using fast-acting 2/2 electromagnetic valves and PWM control [3], [6].

For the analysis of electropneumatic positioning systems and the synthesis of control algorithms, frequency characteristics (amplitude-frequency and phase-frequency) are widely used to describe the dynamic properties of the system. Experimental determination of frequency characteristics allows for a detailed study of their features and the creation of mathematical models that can be used to design systems with a high level of reliability and accuracy. The difference in the design of pneumatic cylinders will lead to a difference in the dynamics of the system. Therefore, research in this area is necessary when applying cylinders without rod construction [1], [7], [9], [10]. It is important to evaluate positioning errors in dynamic mode [15].

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II. MATERIALS AND METHODS

For the experimental investigation of the frequency characteristics of an electropneumatic tracking system with a pneumatic rodless cylinder, a laboratory workbench has been developed (see Fig. 1). The developed virtual instrument in the LabVIEW environment represents a control and measurement system for the electropneumatic positioning system, implemented through pulse-width modulation of high-speed pneumatic valves. The virtual instrument is designed for experimental studies and precise positional control of pneumatic actuators, utilizing a closed-loop control system with feedback on displacement (position) and a PID controller to generate the control action. The virtual instrument consists of a user panel and a block diagram, which together implement the measurement, processing, control, and visualization of the measured and controllable quantities in real time [8].

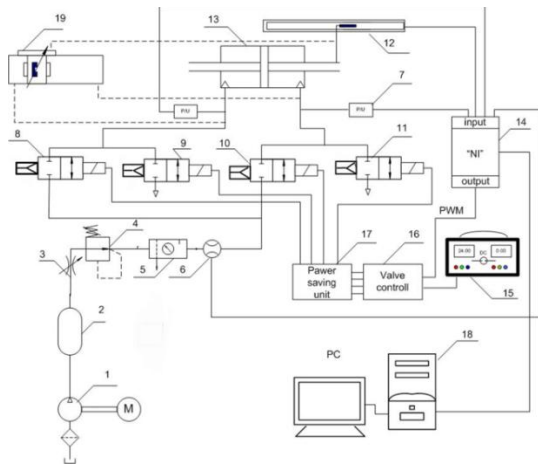


Fig. 1. General view of the experimental stand for capturing frequency characteristics.

1 - screw compressor; 2 - receiver; 3 - throttle valve; 4 - pressure-reducing valve; 5 - air preparation system preparatory; 6 - flowmeter; 7 - pressure transducer; 8, 9, 10, 11 high speed pneumatic on/off valve; 12 - potentiometric sensor; 13 - double-rod pneumatic cylinder; 14 - terminal board (NI); 15 - power supply unit; 16 - Valve Controller; 17 - Power saving unit; 18 - PC; 19 - rodless pneumatic cylinder

The user panel provides an interface for entering set values (see Fig. 2), selecting the control mode, adjusting the regulator parameters, and graphically visualizing the displacement of the rodless pneumatic cylinder, as well as the pressures, flow rates, and control signals (see Fig. 3), [3], [6], [12], [13].

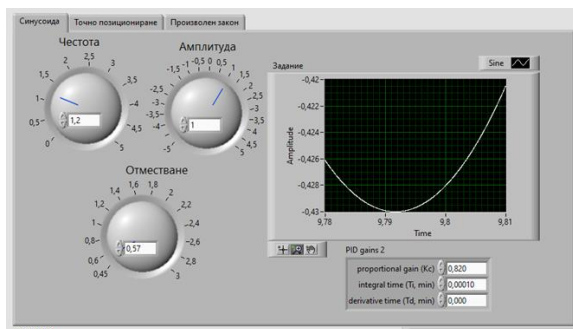


Fig. 2. Panel provides an interface for entering set values.

The block diagram implements the control logic, algorithms for calibrating the measurement channels, and the formation of PWM signals for the high-speed pneumatic valves. The system uses analog input channels to measure the essential physical quantities necessary for the operation of the electropneumatic positioning system.

By changing the output voltage of a potentiometric sensor, the linear displacement of the rodless pneumatic cylinder is measured, which serves as feedback in the control block. Additionally, the pressures in the left and right chambers of the pneumatic cylinder and the flow rate of the supplied compressed air to the electropneumatic positioning system are measured, allowing for the analysis of dynamic processes in the electropneumatic positioning system with PWM control.

The control outputs of the virtual instrument provide voltages realized in the form of pulse-width modulated signals, which sequentially control the motion of the rodless pneumatic cylinder in both forward and reverse directions. The PWM signal enables the paired switching of the high speed pneumatic valves and ensures continuous flow regulation. To ensure accurate measurement, calibration of all measurement channels has been implemented.

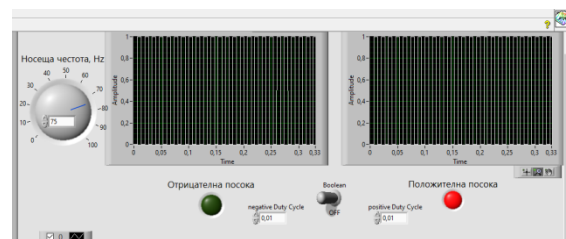


Fig. 3. Formation of PWM signals.

The input analog signals, represented as voltages, are converted in the virtual instrument into real physical quantities through linear dependencies defined by the characteristics of the sensors used. The pressure, flow, and displacement channels are pre-calibrated. The main control algorithm is implemented through a PID controller operating in a closed loop with feedback on displacement. The set position of the rodless pneumatic cylinder is compared with the currently measured position, and the resulting error serves as input to the controller. The PID controller generates a control signal based on the proportional, integral, and derivative components, allowing for good dynamics, minimal steady-state error, and stable system operation. The output of the controller is used to generate a pulse-width modulated signal that controls the electropneumatic high-speed valves. By changing the fill ratio of the PWM signal, the supplied airflow to the rodless pneumatic cylinder is regulated, ensuring smooth and precise movement. The virtual instrument is designed to implement an input law for specifying the movement of the pneumatic rodless cylinder, including a sinusoidal input law used for investigating dynamic characteristics and obtaining its frequency response. The investigated system

consists of the following elements: a screw compressor, four high-speed pneumatic valves for on/off control, a pneumatic rodless cylinder „Camoszi 52M2P32A0450”, as well as measuring equipment, a regulator, and an energy-saving block. The position control of the pneumatic cylinder with a double-acting piston is achieved through four HSPV “SX 12 F-AH valves, which operate as follows: when all four valves are closed (Off), the piston remains in the desired position. When valve 1 and valve 4 are open (On), the piston moves to the left. Similarly, when valve 2 and valve 3 are open, the piston moves to the right, thus performing reciprocating motion (see Fig. 3). The solenoid is activated by PWM control [1], [2], [4], [11], [14], [15].

Eigenfrequency (Critical) – This refers to the rate at which the input signal changes that the electropneumatic system can effectively respond to. The system's frequency response is illustrated through two graphs:

Amplitude-Frequency Response (AFR)

This graph shows the ratio of the amplitude at measured frequencies to that at very low frequencies, expressed in decibels (dB) and plotted on a logarithmic scale. An amplitude ratio of -20 dB indicates that the amplitude at a specific frequency is ten times smaller than the amplitude at low frequencies. The collection of amplitudes for all measured frequencies results in the amplitude-frequency response.

Phase-Frequency Response (PFR)

This measures the delay of the output signal relative to the input signal, expressed in angular degrees. A phase delay of 360° signifies that the output signal lags by one complete cycle. The graphical representation of the phase shift as a function of frequency is known as the phase-frequency response. When the amplitude of the input signal changes by 10%, the cylinder should only move a small distance, allowing it to respond to such variations even at higher frequencies. The amplitude and phase characteristics deviate from the horizontal line primarily at high frequencies. If the input signal amplitude changes by 90%, the distance the pneumatic cylinder must travel increases ninefold, making it struggle to follow variations in the input signal. Deviations from the horizontal line are also observed at low frequencies.

Critical Frequency

The critical frequency is determined from the amplitude-frequency response and is identified as the frequency at which the amplitude falls to 70.7% or -3 dB.

The limitations of using HSPV- "SX 12 F-AH (0.15~0.7 MPa) SMC Japan" with PWM control are defined by the maximum pressure specified by the manufacturer. Procedure for Conducting the Experiment

The selected operating pressure for the experiment is set at 4 bar (the experiment can be conducted at various pressures).

The operating parameters for the virtual instruments created for the experiment have been configured. A sinusoidal input signal with various amplitudes — 1 V, 1.3 V, and 1.6 V—and a frequency ranging from 0.1 Hz to 1.4 Hz has been set. The PWM control of the high-speed

pneumatic valves is also set to a frequency of 70 Hz and a duty cycle of 50%. The initial position of the electropneumatic tracking system has been established. After preliminary tests of the control and measurement loops, the experimental study begins. The obtained results, input signals, and set output signals are displayed on the screen, recorded, archived, and processed for graphical representation [1], [5].

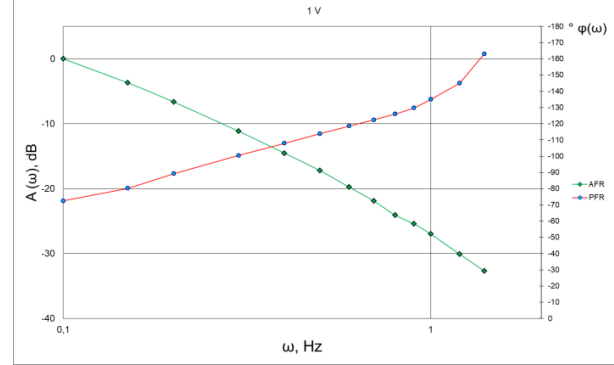


Fig. 4. AFR and PFR at an input signal amplitude of 1 V.

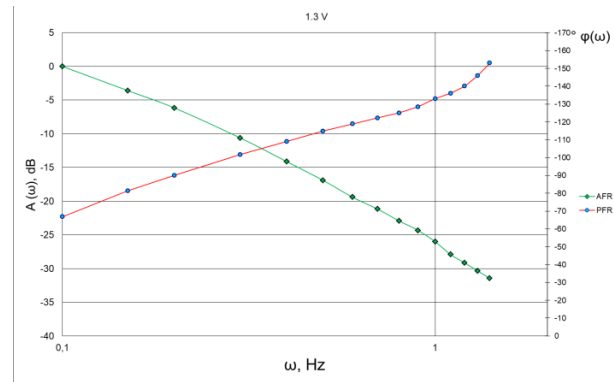


Fig. 5. AFR and PFR at an input signal amplitude of 1.3 V.

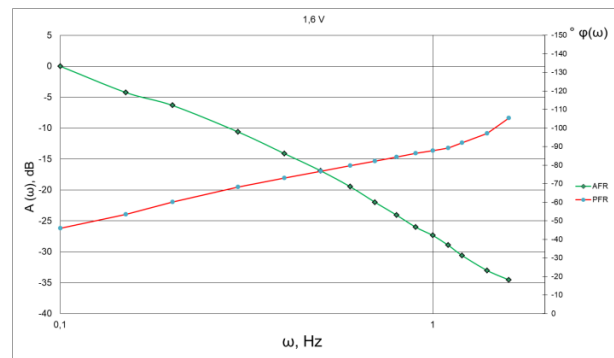


Fig. 6. AFR and PFR at an input signal amplitude of 1.6 V.

III. RESULTS AND DISCUSSION

Figure 4, 5, 6 presents the amplitude-frequency (AFR) and phase-frequency response (PFR) of the pneumatic positioning system at an input signal amplitude of 1, 1.3 and 1.6 V. The experiment is repeated as many times as necessary to eliminate errors.

For the experimental analysis of the frequency characteristics of the pneumatic positioning system, it is assumed that the instruments have significantly smaller time constants than those of the system being tested. In practice, their transient processes occur much more quickly, and they are regarded as ideal first-order aperiodic units with time constants that are much smaller than the time constant of the system being investigated [1], [5].

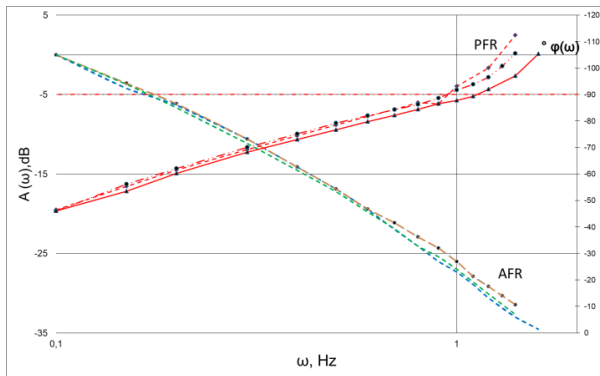


Fig. 7. Amplitude-frequency and phase-frequency response of an electropneumatic positioning system with a rodless cylinder at input signal amplitudes of 1, 1.3 and 1.6V.

CONCLUSIONS

The electropneumatic tracking system, featuring PWM control, high-speed pneumatic valves, and a rodless pneumatic cylinder, has a critical eigenfrequency of -90° at control signal amplitudes of 1, 1.3, and 1.6 V, ranging from 0.95 to 1.1 Hz.

ACKNOWLEDGMENTS

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State Controller Synthesis for an Electrohydraulic Power Transmission System

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Abstract— This paper deals with the synthesis of state controller for an electrohydraulic power transmission system. There are shown the mathematical model of the electrohydraulic system and state controller synthesis method with state space feedbacks. The controller coefficients are obtained from preliminary defined error performance index. The response curves are obtained from computer simulation. The results are given in a few graphics.

Keywords— *electrohydraulic transmission systems, state controller, modeling and simulation*

I. INTRODUCTION

Hydraulic power transmission systems, in comparison with other types of drives, have lower stiffness and damping, which is a disadvantage in conditions of significant dynamic loads [1], [2], [3], [4]. The control elements of aircraft, presses and mobile machines are inertial objects [5], [6] with a significant mass, are mounted on elastic supports and are connected to the drive system with elastic mechanical connections.

The design and synthesis of stabilizing and correcting devices is an important stage in the design of hydraulic systems. One of the approaches to increasing the damping of the system is the introduction of a state regulator [2], [3]. The advantage of the state regulator is primarily that it provides high dynamic characteristics of the system in combination with increased damping. Thanks to the state regulator, the system responds faster to external influences. Popular approaches include classical feedback and compensation schemes, as well as variants of state observers and Kalman filters, including linear and nonlinear extensions [7], [8], [9], [10]. Analogous control approaches are also used in electropneumatic positioning systems [11], [12]. When analyzing the performance of electro-hydraulic traction systems, it is important to evaluate positioning errors in dynamic mode [13], [14].

II. STATE CONTROLLER DESIGN

The state controller is multi-loop, in which the state parameters are covered by feedback loops. The transfer function of the open electrohydraulic system consists of the product:

$$W(s) = W_{\text{exy}}(s) W_x(s) W_m(s) \frac{1}{T_y(s)} \quad (1)$$

where $W_{\text{exy}}(s)$ - transfer function of electrohydraulic amplifier, often approximated to a oscillating unit; $W_x(s)$, $W_m(s)$ - transfer function of the hydraulic and mechanical part of the system (can be approximated to aperiodic units of the first order); $\frac{1}{T_y(s)}$ - an integrating

unit converting the velocity coordinate into the position coordinate of the system. In this way, the typical electrohydraulic system is described by a 5th order differential equation. If in the system the speed of the electro-hydraulic amplifier is significantly greater than the speed of the hydraulic cylinder together with the load ($\omega_{\text{exy}} \gg \omega_o$), then without significant error it can be considered that the system can be approximated to a third-order system and therefore it is sufficient to introduce feedbacks on three parameters – displacement, speed, acceleration or pressure drop in the cylinder. steam distributor, which has a relatively small natural frequency.

The meaning of feedback on the state parameters is concluded in the following. The transfer function of the closed loop consists of a section of the control system $W(s)$ covered by feedback (with transfer function ($W_{fb}(s)$)):

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$$\Phi(s) = \frac{W(s)}{1 + W(s)W_{fb}(s)} \quad (2)$$

$$\text{If } W(s)W_{fb}(s) \gg 1, \text{ hence } \Phi(s) = \frac{1}{W_{fb}(s)}. \quad (3)$$

Thus, in the frequency range in which the inequality $W(s)W_{fb}(s) \gg 1$ is satisfied, the characteristic of the loop is generally determined by the characteristics of the feedback.

To implement the system with state control, it is necessary to install speed and acceleration sensors or double differentiation of the signal from the position sensor. When installing the sensors, the cost of the system increases, and complexity arises in their installation. In the case of signal differentiation, the system becomes very sensitive to high-frequency impacts and obstacles. An alternative solution is the use of a “state observer” or systems with state control with an “observer”. The main task in improving the dynamics of hydraulic drive systems is to eliminate the resonance of the output part of the drive, while increasing the speed gain coefficient K_{vy} , which determines the system’s speed and static stiffness.

One of the directions of the theory of systems is connected with design of regulators providing the desired dynamics of the system, based on creation of feedback on the coordinates of the state, transmitting to closed-position tracking systems the desired arrangement of roots of the characteristic equation of its linear model (poles of the transfer function). The arrangement of roots of characteristic equation of the drive system on the complex plane in many cases completely determines the regulated indicators of the dynamics of the system and has visual interpretations [3]. A structural diagram of an electrohydraulic drive system with a state regulator is shown in Fig. 1.

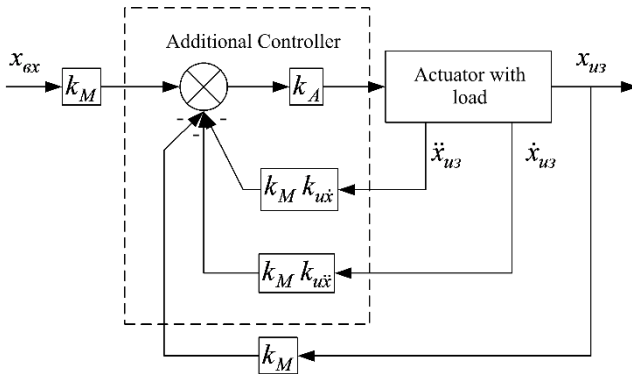


Fig. 1. Hydraulic system with state controller.

The transfer function of the linear model of the system with this state regulator, reflecting its most essential dynamic properties, has the form:

$$\frac{x_{u3}}{x_{6x}} = \frac{1}{\frac{s^3}{\omega_0^2 K_{vy}} + \left[\frac{2\xi_0}{\omega_0 K_{vy}} + \bar{k}_{u3} \right] s^2 + \left[\frac{1}{K_{vy}} + \bar{k}_{u3} \right] s + 1} \quad (4)$$

where:

$$k_{u3} = \frac{k_{u3}}{k_M}; \quad \bar{k}_{u3} = \frac{k_{u3}}{k_M}.$$

For $s = \frac{s}{\omega_c}$ (where: $\omega_c = \sqrt[3]{\omega_0^2 K_{vy}}$) the characteristic equation is:

$$s^{-3} + as^{-2} + bs^{-1} + 1 = 0, \quad (5)$$

where a and b are:

$$a = \left[\frac{2\xi_0}{\omega_0 K_{vy}} + \bar{k}_{u3} \right] \sqrt[3]{(\omega_0^2 K_{vy})^2}; \quad (6)$$

$$b = \left[\frac{1}{K_{vy}} + \bar{k}_{u3} \right] \sqrt[3]{\omega_0^2 K_{vy}} \quad (7)$$

For each set of design parameters of the system $\{k_i\}$, there corresponds a pair of generalized coefficients $a(k_i), b(k_i)$, defining a mapping point on the coefficient plane a, b .

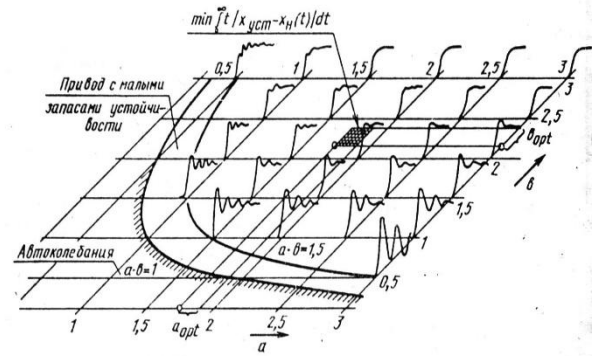


Fig. 2. System transients with a step input signal for different points on the generalized coefficient plane (a, b) - [1, 3].

The stability limit is determined by the ratios $a > 0, b > 0, a.b = 1$. A region with a margin of stability in amplitude, above 0.33, is located above the curve $a.b = 1.5$ (Fig. 2).

Fig. 2 [1, 3] shows an example of the transient processes of the system with a step input signal for different points on the plane of the generalized coefficients (a, b) . As practice shows, the best compromise between the fast action of the mechanism and its oscillation is achieved by minimizing an integral criterion characterizing the magnitude of the error between the desired trajectory of the output link and the duration of the transient process [1], [2], [3]:

$$ITAE = \int_0^{\infty} \frac{t}{E(t)} dt, \quad (8)$$

where, $E(t)$ - error;

$$E(t) = \frac{1 - x_{u3}(t)}{x_{ycm}} \quad (9)$$

The optimal synthesis task in the sense of minimum of the integral criterion determines a set of controller parameters $k_{onm} = \{K_{vy}; r_e; \bar{k}_{u\dot{x}}; \bar{k}_{u\ddot{x}}\}_{onm}$, such that the integral criterion k_{onm} takes on a minimum value, i.e. $ITAE(k_{onm}) = \min ITAE$.

Research shows [2] that the optimal values $a_{onm}; b_{onm}$ of the parameters that provide a minimum of the criterion $ITAE$ have the following estimates:

$$a_{onm} = 1,75 - 1,89; \quad (10)$$

$$b_{onm} = 2,15 - 2,38. \quad (11)$$

Using these estimates, it can be obtained that the optimal ratio between the natural frequency of the drive system ω_0 and the speed gain K_{vy} (without additional correcting devices) is in the range:

$$\left[\frac{K_{vy}}{\omega_0} \right]_{onm} = 0,27 - 0,35, \quad (12)$$

However, at these ratios undesirable oscillatory processes may occur in the system, which is unacceptable in some operating modes.

To obtain the desired dynamics of the system with a fast-damping transient process and satisfactory frequency properties, it is necessary to determine such $\bar{k}_{u\dot{x}}$ and $\bar{k}_{u\ddot{x}}$, which would ensure that the imaging point falls into a region corresponding to optimal values in terms of speed a_{onm} and b_{onm} . The values of these coefficients from (6) and (7) are obtained in the following form:

$$\left[\bar{k}_{u\dot{x}} \right]_{onm} = \frac{b_{onm}}{\sqrt[3]{\omega_0^2 K_{vy}}} - \frac{1}{K_{vy}} \quad (13)$$

$$\left[\bar{k}_{u\ddot{x}} \right]_{onm} = \frac{a_{onm}}{\sqrt[3]{(\omega_0^2 K_{vy})^2}} - \frac{2\xi_0}{\omega_0 K_{vy}} \quad (14)$$

The determination of the main parameters of the electrohydraulic system occurs after identification of the parameters made on a laboratory stand and a corresponding identification procedure [7].

The results obtained from the experimental studies and identification [7] are:

Natural frequency of the electrohydraulic system with a spring load with a constant $C_T = 51000$ N/m - $\omega_0 = 20.19$,

Damping coefficient $\xi_0 = 0.921$,

Speed gain coefficient $K_{vy} = 2.43$ s⁻¹

The following values are accepted for the coefficients:

$$a = 1.75; b = 2.3;$$

From equations (13) and (14) we obtain:

$$\bar{k}_{u\dot{x}} = 207.53; \quad \bar{k}_{u\ddot{x}} = 93.62; \quad (15)$$

III. MATHEMATICAL MODEL OF AN ELECTRO-HYDRAULIC SYSTEM WITH A STATE REGULATOR

The mathematical model of the electrohydraulic system is shown in [7, 8]. To this model are added the equations of the additional feedback on the state variables:

Equation of the hydraulic cylinder with the load:

$$m \frac{d^2 y}{dt^2} + f \frac{dy}{dt} + C_S y = p_1 A_1 - p_2 A_2 - F_C(v) \quad (16)$$

where: $F_C(v) = F_{C0} \text{Sign}(v)$ и $v = \frac{dy}{dt}$

- Pressure in the cylinder chambers

for $x_a < x < x_m$

$$\frac{dp_1}{dt} = \frac{E}{V_1(y)} \left[\frac{G(x) \sqrt{p_s - p_1}}{\bar{Q}_1} - A_1 \frac{dy}{dt} \right]$$

$$\frac{dp_2}{dt} = \frac{E}{V_2(y)} \left[-\frac{G(x) \sqrt{p_2 - p_0}}{\bar{Q}_2} + A_2 \frac{dy}{dt} \right] \quad (17)$$

for $-x_a < x < -x_m$

$$\frac{dp_1}{dt} = \frac{E}{V_1(y)} \left[\frac{G(x) \sqrt{p_1 - p_0}}{\bar{Q}_1} - A_1 \frac{dy}{dt} \right]$$

$$\frac{dp_2}{dt} = \frac{E}{V_2(y)} \left[-\frac{G(x) \sqrt{p_s - p_2}}{\bar{Q}_2} + A_2 \frac{dy}{dt} \right]$$

(18)

- Hydraulic conductivity:

$$G(x) = \begin{cases} K_o[x - x_a \text{Sign}(x)] & x_a < |x| < x_m \\ G_m \text{Sign}(x) & |x| = x_m \end{cases} \quad (19)$$

$$K_o = \mu b \sqrt{\frac{2}{\rho}} \quad G_m = \mu b (x_m - x_a) \sqrt{\frac{2}{\rho}}$$

- Volumes of the left and right cylinder chambers

$$V_1(y) = V_{01} + A_1 y \quad V_2(y) = V_{02} + A_2 y \quad (20)$$

- Physical limitations in the hydraulic system:

$$|y| \leq y_m \quad |v| \leq v_m \quad |x| \leq x_m \quad (21)$$

$$0 < p_1 < p_S \quad 0 < p_2 < p_S \quad (22)$$

- Servo valve baffle rotation:

$$T_f^2 \frac{d^2 \varphi}{dt^2} + 2\zeta_f T_f \frac{d\varphi}{dt} + \varphi = k_i i - k_{rx} x \quad (23)$$

- Displacement of the servo valve plunger

$$T_{\varphi x} \frac{dx}{dt} + x = k_{\varphi x} \varphi \quad (24)$$

Electromechanical converter

$$T_i \frac{di}{dt} + i = k_U U_P \quad (25)$$

- Electronic amplifier and feedback on state variables –

$$y, \quad \frac{dy}{dt} = v, \quad \frac{d^2 y}{dt^2} = a$$

$$U_P = K_a \Delta U \quad \Delta U = U_v - U_y - U_{\dot{y}} - U_{\ddot{y}}$$

$$U_y = K_y y \quad U_{\dot{y}} = K_{\dot{y}} \frac{dy}{dt} \quad U_{\ddot{y}} = K_{\ddot{y}} \frac{d^2 y}{dt^2} \quad (26)$$

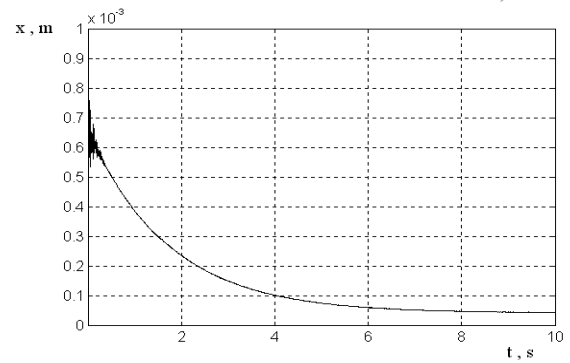
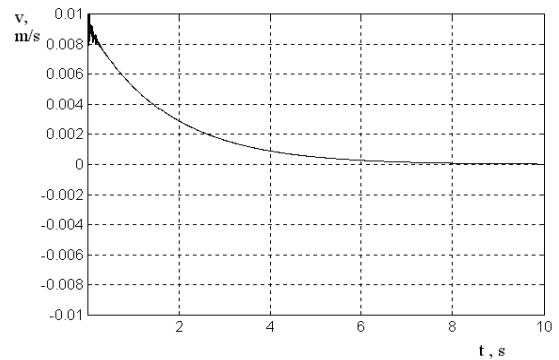
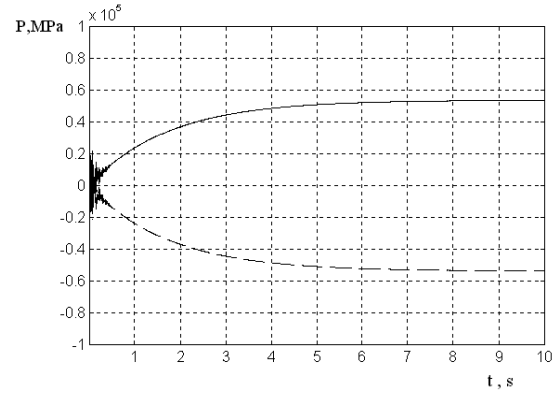
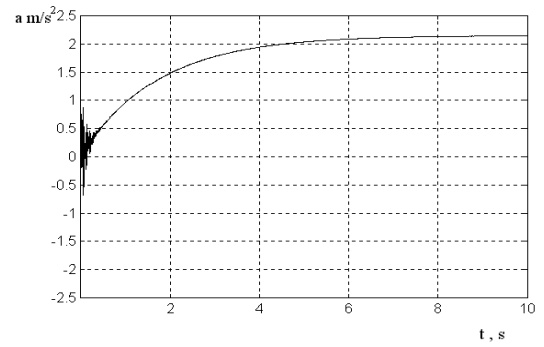
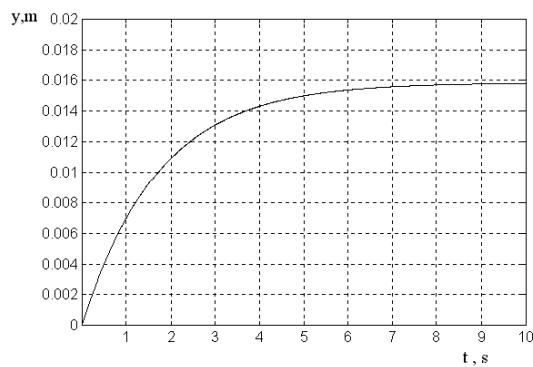


Fig. 3. Step responses in the no-load system

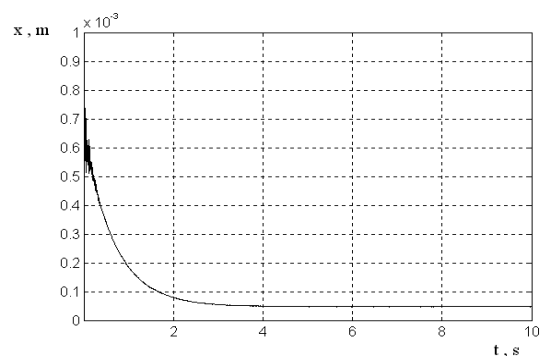
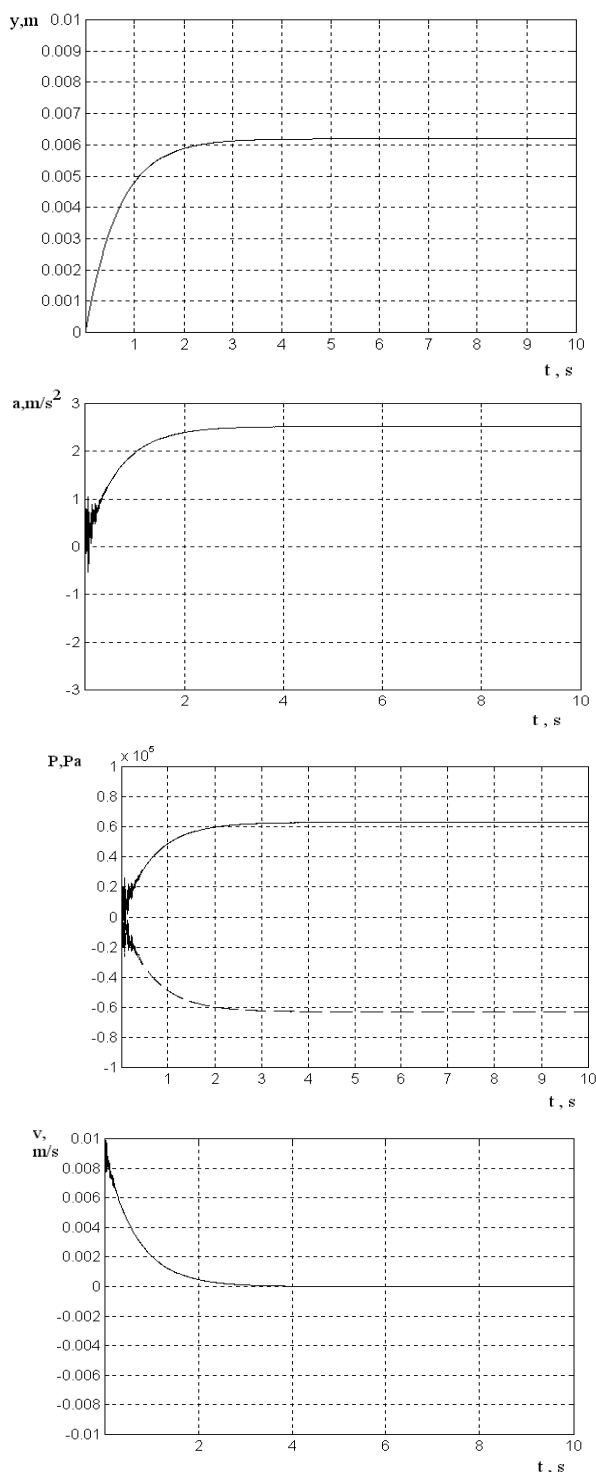


Fig. 4. Step responses in the system with load ($C_T = 51000 \text{ N/m}$)

IV. RESULTS FROM COMPUTER SIMULATION OF THE MATHEMATICAL MODEL

Equations (17-27) are used in the computer modeling of the electrohydraulic drive system with a state regulator. The dynamic processes obtained after the simulation of the mathematical model are shown in Fig. 3 and 4. The numerical values of the coefficients used in the simulation of the model and their determination are shown in [7], [8]. Fig. 3 shows the transient processes in the electrohydraulic system with a state regulator, without load elasticity - $C_T = 0 \text{ N/m}$. Fig. 4 shows the transient processes in the electrohydraulic system with a state regulator, with load elasticity load $C_T = 51000 \text{ N/m}$.

V. RESULTS AND CONCLUSION

From the analysis of the transients obtained after the computer simulation, it can be concluded:

1. The system speed increases, while the type of transient remains aperiodic.
2. Due to the feedback from the acceleration, high-frequency oscillations are observed at the beginning of the transient. To avoid these oscillations, it is advisable to use an appropriate filter.
3. Instead of acceleration feedback (or double differentiation of the displacement), feedback based on the difference in pressures in the chambers of the hydraulic cylinder can be used.

VI. SYMBOLS USED IN EQUATIONS

A_1, A_2	effective areas of the hydraulic cylinder	$[\text{m}^2]$
a	acceleration of the hydraulic cylinder rod	$[\text{m/s}^2]$
b	acceleration of the hydraulic cylinder rod	$[\text{m}]$
m	reduced mass of all moving parts to the axis of the hydraulic cylinder	$[\text{Kg}]$
C_S	elastic load constant	$[\text{N/m}]$

E	bulk modulus of elasticity of the fluid	[Pa]	V_{01}	Initial volumes in the left and right chambers of the hydraulic cylinder	[m ³]
f	coefficient of viscous friction	[Ns/m]	V_{02}		
F_{C0}	Coulomb dry friction force	[N]	x	Displacement of the servo distributor plunger	[m]
$F_C(v)$	Coulomb dry friction force	[N]	x_m	maximum plunger travel	[m]
$G(x)$	hydraulic conductivity	[m ³ /s.Pa ^{-1/2}]	y	moving the hydraulic cylinder rod	[m]
G_m	maximum hydraulic conductivity	[m ³ /s.Pa ^{-1/2}]	y_m	moving the hydraulic cylinder rod	[m]
i	current in the servo valve	[A]	φ	rotating the baffle in the servo valve	[rad]
K_a	amplifier gain	[-]	ρ	hydraulic oil density	[kg/m ³]
K_y	displacement feedback gain	[V/m/s]	μ	flow rate coefficient	[-]
$K_{\dot{y}}$	velocity feedback gain	[V/m/s ²]	ζ_f	damping coefficient of the barrier	[-]
$K_{\ddot{y}}$	acceleration feedback gain	[V/m]	ζ_0	damping coefficient of the drive system	
K_{vy}	speed gain coefficient of the electrohydraulic system	[s ⁻¹]	ω_0	natural frequency of the drive system	
k_M	scale factor	[-]			
$\bar{k}_{u\dot{x}}$	velocity feedback coefficient	[-]			
$\bar{k}_{u\ddot{x}}$	acceleration feedback coefficient	[-]			
K_o	conductivity coefficient	[-]			
k_i	current gain	[rad/A]			
k_U	gain of an electromechanical converter	[A/V]			
k_{rx}	mechanical feedback coefficient in the servo valve	[rad/m]			
$k_{\varphi x}$	rotation coefficient of the partition	[m/rad]			
p_1, p_2	pressures in the cylinder chambers	[Pa]			
p_S	supply pressure	[Pa]			
p_0	return pressure	[Pa]			
Q_1, Q_2	flow rates through the hydraulic cylinder	[m ³ /s]			
T_f	the barrier time constant	[s]			
T_i	time constant of electromechanical converter	[s]			
$T_{\varphi x}$	the time constant of the plunger	[s]			
U_y	displacement feedback voltage	[V]			
$U_{\dot{y}}$	speed feedback voltage	[V]			
$U_{\ddot{y}}$	acceleration feedback voltage	[V]			
U_P	voltage from the electronic amplifier	[V]			
U_v	input voltage	[V]			
ΔU	voltage from the electronic adder	[V]			
v_r	cylinder rod speed	[m/s]			
v_m	maximum rod speed	[m/s]			
$V_1(y)$	volumes in the left and right chambers of the hydraulic cylinder	[m ³]			
$V_2(y)$					

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Modeling and Simulating Dynamic Processes in an Electropneumatic Positioning System with PWM Control at Different Lengths of the Pneumatic Lines

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Abstract— The electropneumatic drive system with PWM control is used in machines and equipment where it is necessary for the actuator to be positioned at a significant distance from the control valves. This leads to changes in the dynamic characteristics of the systems, depending on the length of the connecting pneumatic lines. The paper presents a mathematical model of an electropneumatic positioning system with PWM control, taking into account the length of the connecting pneumatic lines. The mathematical model has been implemented in the MATLAB Simulink programming environment. A verified and tested model has been used to simulate the dynamic processes in the pneumatic lines. Transient processes have been simulated for different lengths of lines and for various PWM control parameters.

Keywords— *electropneumatic positioning system, modeling and simulating, pneumatic lines, PWM control.*

INTRODUCTION

To achieve linear and stable operation of an electropneumatic positioning system with good dynamic characteristics using high-speed pneumatic valves, a control approach based on Pulse Width Modulation (PWM) is recommended. Many technical developments in electrical engineering utilize PWM control effectively. This method provides linearity, reliability, responsiveness, and energy efficiency for the electropneumatic positioning system. PWM signal frequencies depend on the valve's response time and typically range from 20 to 100 Hz. The main nonlinearities in the dynamic characteristics of the electropneumatic positioning system arise from the relationships between motion and pressure, pressure and flow rate, as well as friction forces in the pneumatic cylinders and changes in the length of the connecting

pneumatic lines. The challenge lies in maintaining accuracy in positioning the piston of the pneumatic cylinder. A displacement feedback controller has been employed for each linear positioning model. The final version of the system controller has been developed as a PID controller. Experimental results show that this PWM-controlled PID controller can effectively handle the dominant nonlinearities of the system [11], [13], [17], [18], [21], [23], [24], [25].

To verify the mathematical model of the electropneumatic positioning system and understand its dynamic characteristics, a series of experimental studies were conducted, resulting in an accurate mathematical model and simulation model of the electropneumatic positioning system created in the MATLAB Simulink programming environment [10], [12], [14], [20], [22].

In the electropneumatic positioning system, one of the main issues is accounting for the signal delay along the pneumatic line. Most research is based on laminar flow through the pneumatic line. To find an adequate mathematical model for the mass flow rate through the pneumatic lines, it is necessary to consider the turbulent flow regime as well [1], [3], [5], [10]. It is important to evaluate positioning errors in dynamic mode [19], [20].

The mathematical model must be convenient for calculating the output mass flow rate through pneumatic lines, serving to control pneumatic positioning systems. The model can also be applied to select an effective length of the connecting pneumatic line, which affects the time delay [4], [6], [8], [21].

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I. GENERAL REGULATIONS

Based on the mathematical model developed and described in detail in [1] and the description of the mathematical model of the pneumatic lines, taking into account their length L_t , in [2], [7] for the electro-pneumatic positioning system and the experimental studies conducted on the dynamic characteristics and operational stability of the system when controlled by pulse-width modulation of high-speed pneumatic valves and pneumatic lines of varying lengths L_t (1 m, 5 m, and 10 m) and diameters ($D=6$ mm; $d=4$ mm) at an operating pressure of 4 bar. Data from the pressure, flow rate, and displacement sensors are

visualized, processed, and recorded using a custom-built virtual instrument. The experimental results were obtained from a laboratory bench developed for the purposes of the study, shown in Fig. 1 and described in [9]. For easier analysis, the results are presented graphically (1 m, 5 m, and 10 m) and diameters ($D=6$ mm; $d=4$ mm) at an operating pressure of 4 bar. Data from the pressure, flow rate, and displacement sensors are visualized, processed, and recorded using a custom-built virtual instrument. The experimental results were obtained from a laboratory bench developed for the purposes of the study, shown in Fig. 1 and described in [9]. For easier analysis, the results are presented graphically.

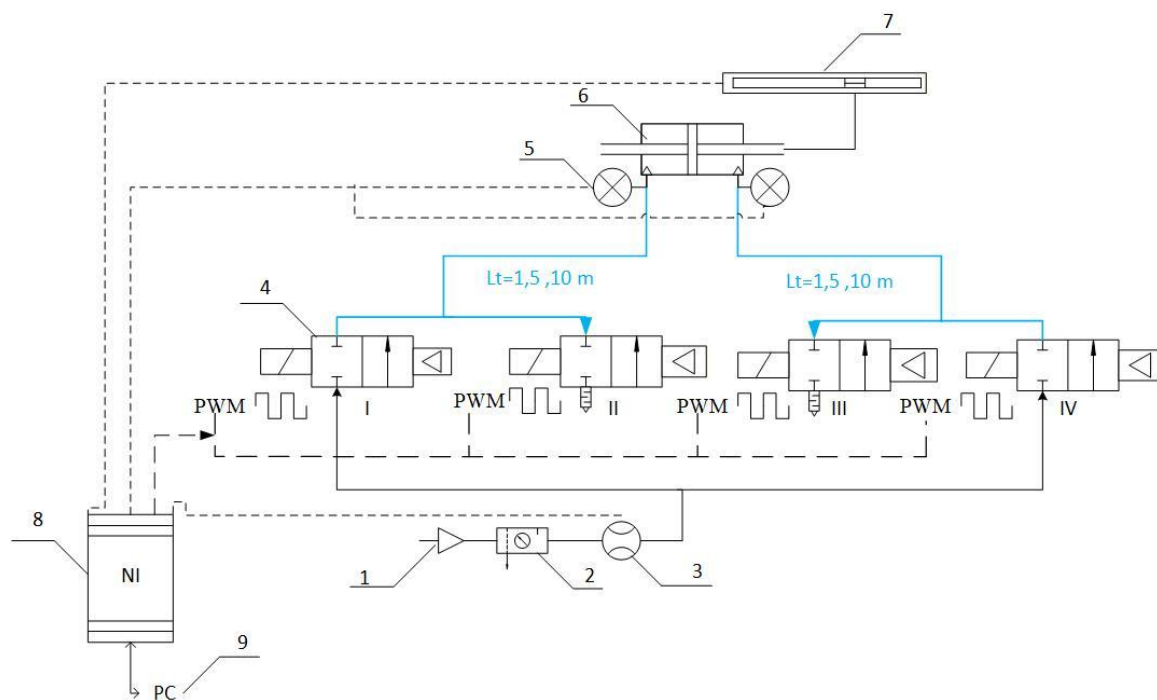


Fig. 1. Principle diagram of the experimental stand for investigating the influence of pneumatic lines with different lengths.

1. Compressed air source; 2. Air preparation unit; 3. Flow meter; 4. High-speed pneumatic valves; 5. Pressure sensor; 6. Pneumatic cylinder; 7. Displacement sensor; 8. Terminal block NI; 9. Personal computer

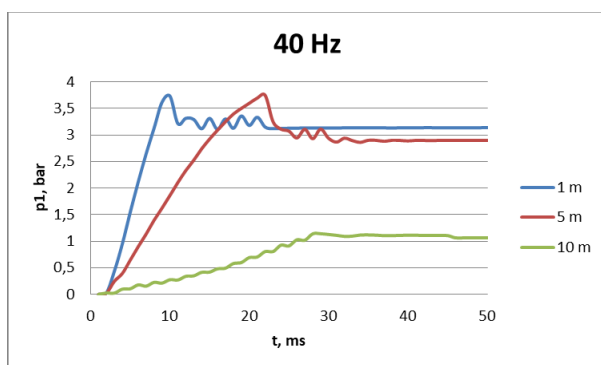


Fig. 2. Experimental data on the change in pressure p_1 entering the left chamber of the pneumatic double-acting cylinder.

Three experiments are conducted for each of the different lengths of the pneumatic lines, and the root mean square error of the measurements is calculated. For a pneumatic line length of 1 m at frequencies of 40, 60, and 80 Hz with a 50% duty cycle, data from the pressure sensors located before the inlet and outlet of the pneumatic double-acting cylinder are recorded in real time. The displacement of the pneumatic cylinder piston is recorded by the potentiometric position sensor, which also serves as the feedback to the PID controller.

Mathematical model of pneumatic lines.

The mass flow rate of the air through the line is given in [1], [2], [3], [7] the equation editor to create your equations.

$$M = \frac{R^2 L_t}{8 a_s \rho^2} \ell^{-\frac{R L_t}{2 \rho a_s}} f \left(t - \frac{L_t}{a_s} \right) \quad (1)$$

where:

a_s -speed of sound; L_t -length of the pneumatic lines;
 R -gas constant of the air; ρ -density; t -time variable.

A flow sensor is installed on the supply pneumatic line leading to the electro-pneumatic control system. The experiments are conducted similarly for pneumatic line lengths of 5 and 10 m.

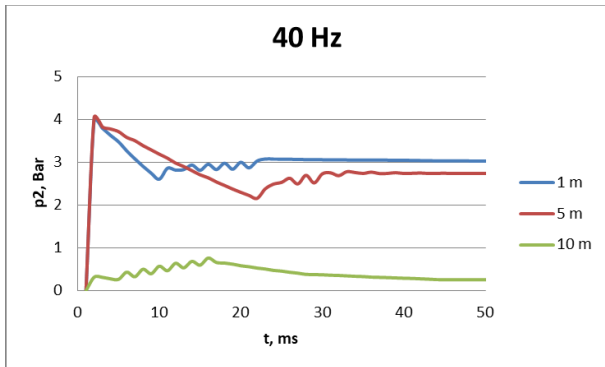


Fig. 3. Experimental data on the change in pressure p_2 exiting the right chamber of the pneumatic double-acting cylinder

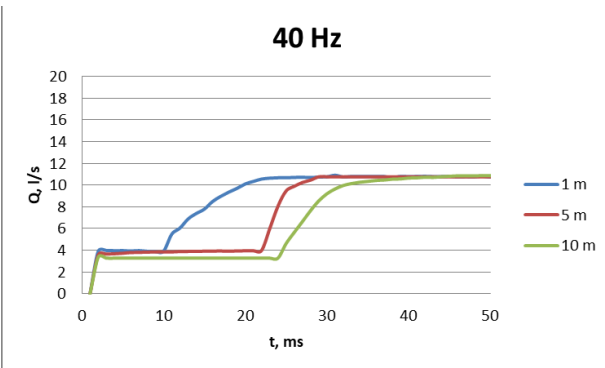


Fig. 4. Experimental data on changes in the flow rate to the electro-pneumatic positioning system

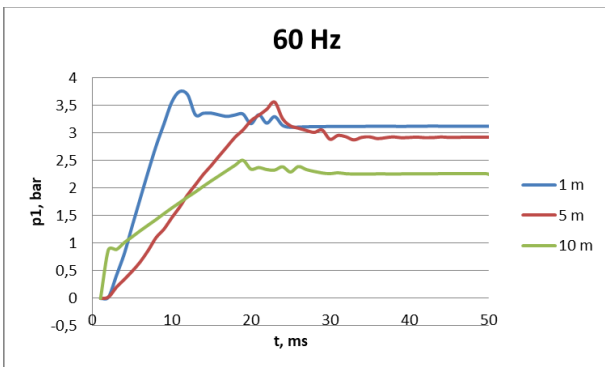


Fig. 5. Experimental data on the change in pressure p_1 entering the left chamber of the pneumatic double-acting cylinder.

approximately 0.30 s, with the flow rate changing to 10.7 l/s and the pressure at the inlet of the pneumatic cylinder reaching 3.15 bar, while the outlet pressure of the pneumatic cylinder is 3.08 bar.

At a frequency of 60 Hz and 1 meter length of the pneumatic line, the duration of the transition process is approximately 0.25 s, with the flow rate changing to 10.54 l/s and the pressure at the inlet of the pneumatic cylinder reaching 3.11 bar, while the outlet pressure is 3.04 bar (see Fig. 5, 6, 7).

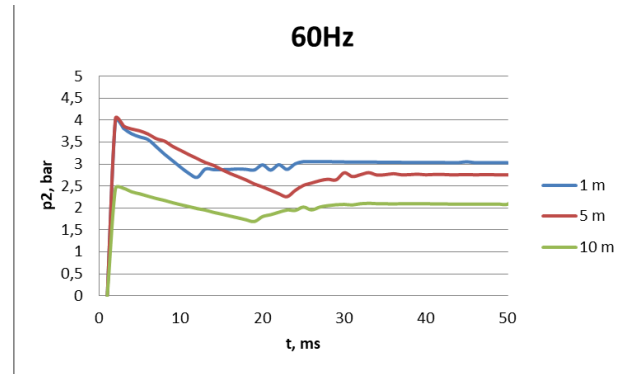


Fig. 6. Experimental data on the change in pressure p_2 exiting the right chamber of the pneumatic double-acting cylinder

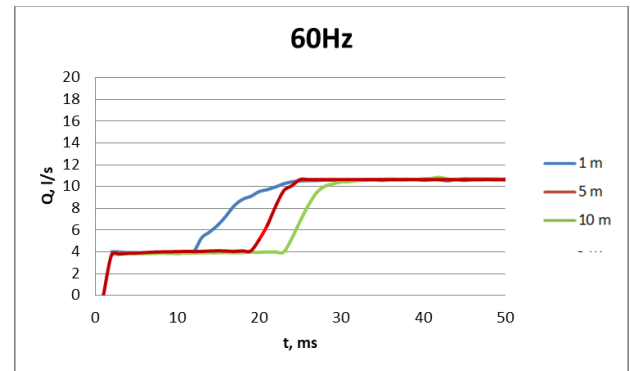


Fig. 7. Experimental data on changes in the flow rate to the electro-pneumatic positioning system

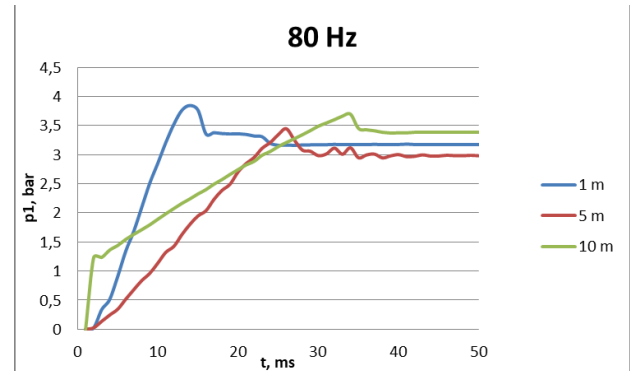


Fig. 8. Experimental data on the change in pressure p_1 entering the left chamber of the pneumatic double-acting cylinder.

In fig. 2, 3 and 4 at 40 Hz and 1 meter length of the pneumatic line, the duration of the transition process is

At a frequency of 80 Hz and 1 meter length of the pneumatic line, the duration of the transition process is

approximately 0.23 s, with the flow rate changing to 10.21 l/s and the pressure at the inlet of the pneumatic cylinder reaching 3.16 bar, while the outlet pressure is 3.05 bar see Fig. 8, 9, 10). The signal delay time along the line at 1 meter for different frequencies ranges from 0.23, 0.25, and 0.30 s, which is solely due to the PWM control and not significantly affected by the length and hydraulic resistance in the line. The experimental results for pneumatic line lengths of 1, 5, and 10 meters are presented in TABLE 1.

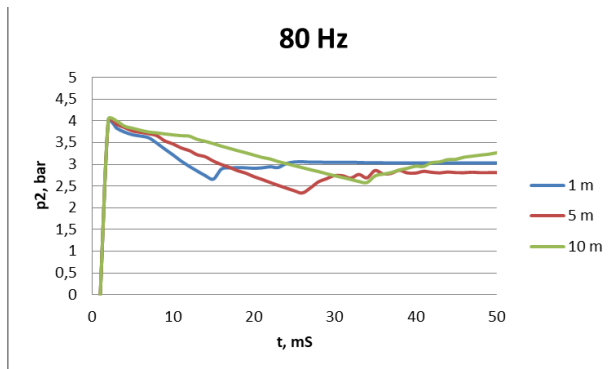


Fig. 9. Experimental data on the change in pressure p_2 exiting the right chamber of the pneumatic double-acting cylinder

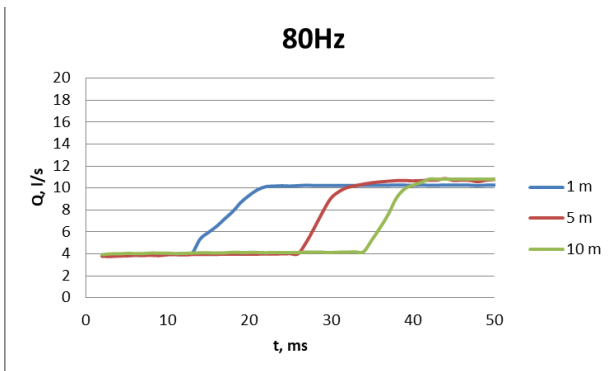


Fig. 10. Experimental data on changes in the flow rate to the electro-pneumatic positioning system

For a pneumatic line length of 5 meters, the duration of the transition processes at 40, 60, and 80 Hz is 0.58, 0.35, and 0.45 s, respectively, with noticeable differences in the changes in pressure at the inlet and outlet of the pneumatic cylinder. The flow rate reaches a value of 10.5 l/s.

The influence of the greater length of the pneumatic line is clearly observed, as it affects the shape and duration of the transition process. Here, the influence of PWM control is also evident, as it delays the signal at lower frequencies. For a pneumatic line length of 10 meters, the duration of the transition processes at 40, 60, and 80 Hz is 0.63, 0.52, and 0.55 s, respectively, with noticeable differences in the changes in pressure at the inlet and outlet of the pneumatic cylinder.

The flow rate reaches a value of 10.5 l/s. The influence of the greater length of the pneumatic line is again clearly

observed, affecting the shape and duration of the transition process. It is evident that the influence of PWM control at lower frequencies again affects the signal delay.

In the MATLAB Simulink environment, a simulation model [1] of a pneumatic positioning system has been created and executed. This system consists of four high-speed pneumatic valves, a double-acting pneumatic cylinder, a PWM generator, and a PID controller.

TABLE 1 EXPERIMENTAL DATA

length L_t	40 Hz 50% duty cycle			
	p_1 , bar	p_2 , bar	Q, l/s	t, ms
1 m	3.15	3.08	10.70	0.30
5 m	3.11	3.04	10.54	0.58
10 m	1.06	0.25	11.29	0.63

length L_t	60 Hz 50% duty cycle			
	p_1 , bar	p_2 , bar	Q, l/s	t, ms
1 m	3.11	3.04	10.51	0.25
5 m	2.93	2.75	10.55	0.35
10 m	2.22	2.14	10.64	0.52

length L_t	80 Hz 50% duty cycle			
	p_1 , bar	p_2 , bar	Q, l/s	t, ms
1 m	3.16	3.05	10.21	0.23
5 m	3.11	3.04	10.58	0.45
10 m	3.38	3.73	10.79	0.55

An analysis of the simulated dynamic characteristics will also be performed, comparing the theoretical and experimental dynamic processes in an electropneumatic positioning system with high-speed pneumatic valves using PWM. The model consists of a collection of elements assembled as subsystems. The first elements are those of the compressor unit, necessary for creating and adjusting the input air parameters. Four high-speed pneumatic valves have been added to implement the desired system. Pneumatic lines with corresponding configured parameters and lengths have also been included.

A model of a pneumatic cylinder with specified operating parameters has been added, with parameters that change according to the requirements for the respective experiments. Elements for measuring the corresponding pressures and flow rates at the inlet before the pneumatic unit, as well as before and after each of the valves, have been included. PID and PWM modules have been added, with parameters that change according to the desired settings for the respective simulation. Modules for inputting and converting data from conducted and recorded experimental results from other software, necessary for verifying the model and simulation, have also been added. The comparison data is displayed on screens and presented graphically [5], [15], [16].

In Figure 11, 12, 13 the comparative results from the experiments and simulations of the displacement of the pneumatic cylinder are presented graphically, under PWM

control at frequencies of 40, 60, and 80 Hz, with a duty cycle (DC) of 50%, and pneumatic line lengths of 1 m, 5 m, and 10 m. The conducted experiments and simulations have been carried out in a pneumatic positioning system using PWM with a PID controller and a specified displacement of the pneumatic cylinder piston stroke of 100 mm.

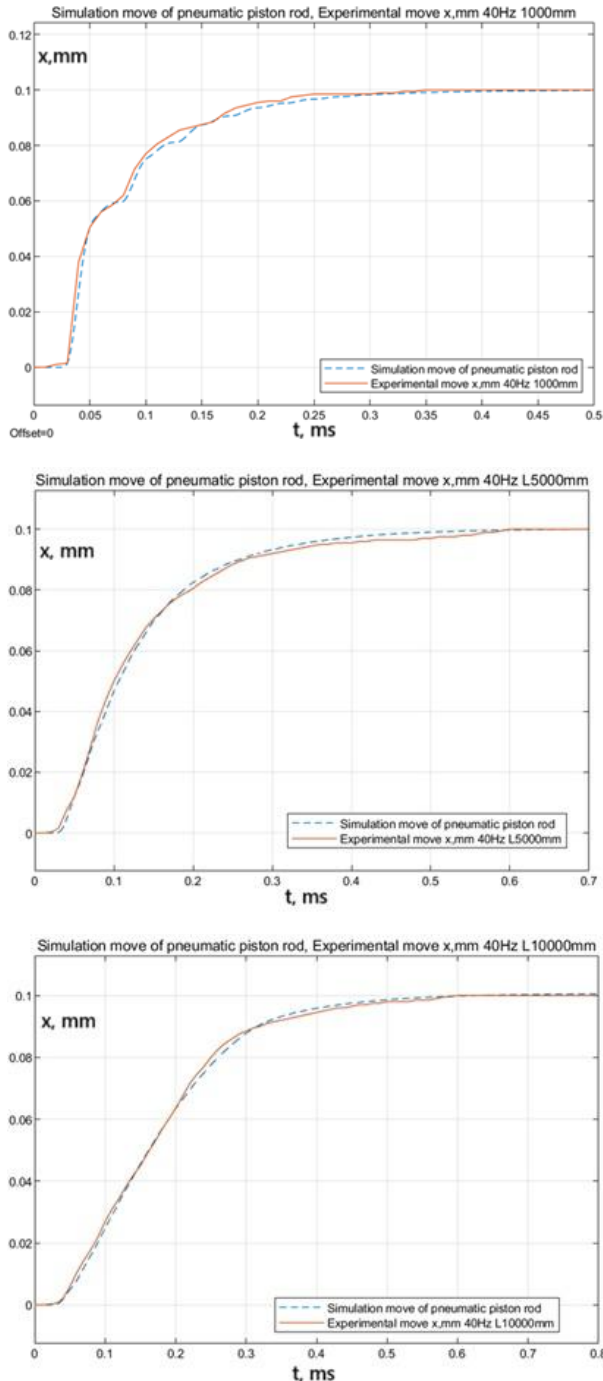


Fig. 11. Simulation move of pneumatic piston rod, experimental move 40 Hz, 1,5 and 10 m.

conducted experiments and the corresponding simulations. The graphs have a process duration of 0.8 s, due to the necessary longest duration for the process to be completed, specifically at 40 Hz and a 50% duty cycle with a pneumatic line length of 10 m, allowing for better visual comparison of the obtained results.

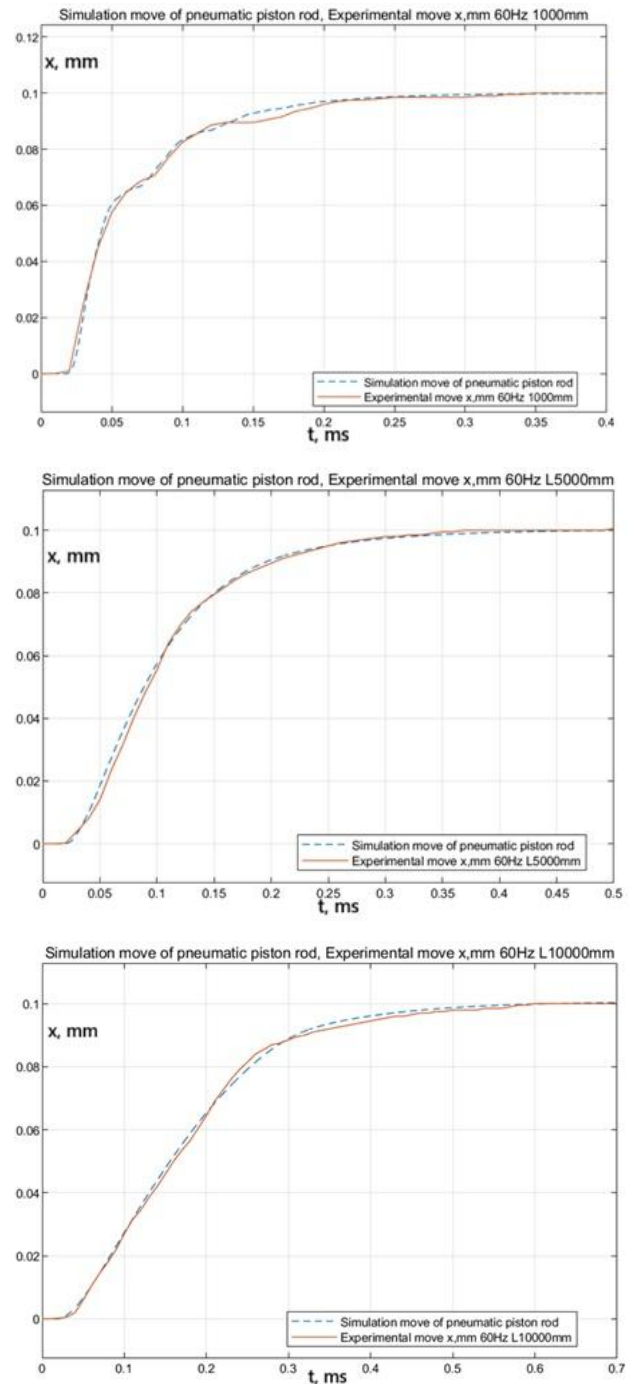


Fig. 12. Simulation move of pneumatic piston rod, experimental move 60 Hz, 1,5 and 10 m.

The presented graphs provide a concise and visually enhanced illustration of processed tabular data from the

The input effect changes uniformly in a stepwise manner according to the input setpoint, which is the electrical voltage. The variables are presented in actual

values. The value of the input signal is within the working stroke of the pneumatic cylinder.

From the experimental data and the simulation model fig. 11, 12 and 13, it is evident that the experimental curves and the theoretical data are very close.

This proves the adequacy of the model of the pneumatic lines and their influence on the dynamics of the electropneumatic tracking system with four high-speed pneumatic valves and PWM control.

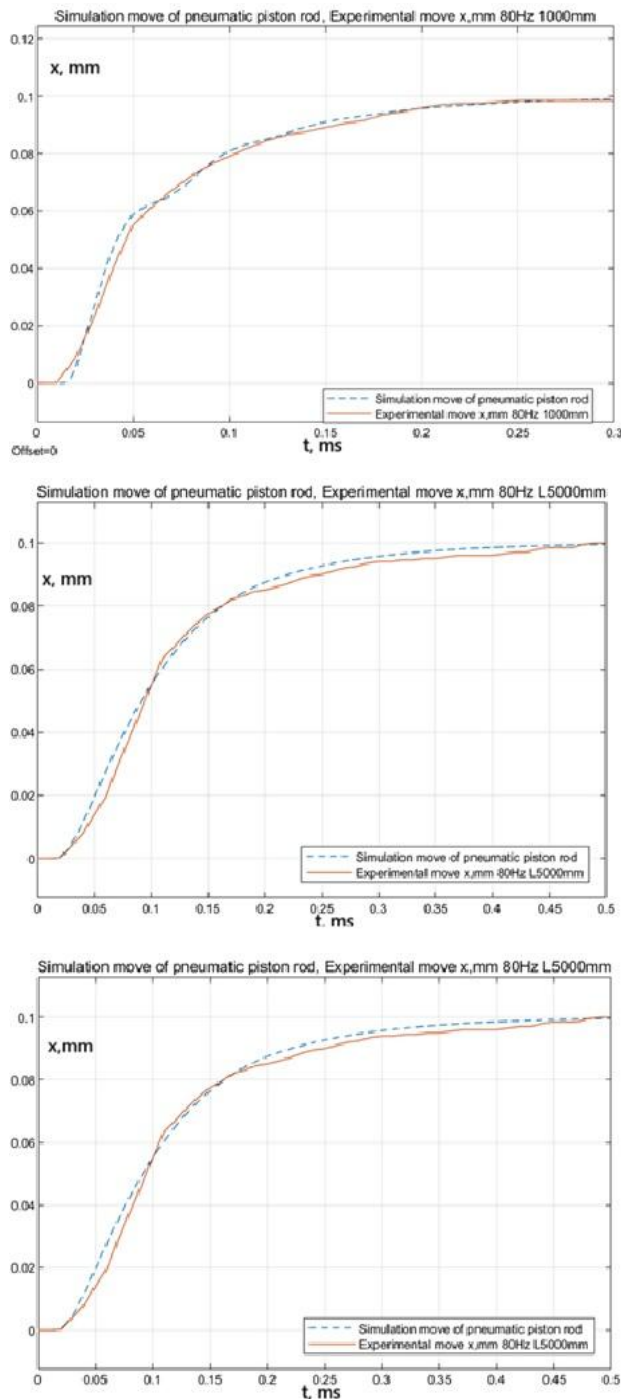


Fig. 13. Simulation move of pneumatic piston rod, experimental move 80 Hz, 1,5 and 10 m.

CONCLUSION

When comparing simulations with different lengths of pneumatic lines, the results indicate that the lengths of 5 and 10 meters significantly impact the parameters of the electropneumatic positioning system during transient processes. Longer pneumatic lines affect system dynamics, particularly regarding time delay and amplitude decay. The influence of PWM at lower frequencies, such as 40 Hz, is also evident and similarly impacts the system's performance. To mitigate the effects of pneumatic line length, it is crucial to consider these lengths and to operate at frequencies above 60 Hz in PWM control. The proposed mathematical model accounts for the mass flow rate through pneumatic lines under turbulent flow conditions, aligning well with experimental results and demonstrating its applicability. This model is sufficiently straightforward for implementation in real-time control applications. The mass flow equation shows that the flow profile at the outlet is delayed in relation to the inlet, corresponding to the time required for the wave to traverse the entire length of the tube. As a result, we can determine the effective tube length L_t associated with this time delay. Additionally, some validation experiments for the model are presented.

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Development of a Method for Calibration of a Semiconductor Temperature Measurement Sensor

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Abstract— Temperature is one of the most commonly measured quantities in science and industry. Temperature can have a significant impact on the course of various processes therefore, its accurate measurement and control is a task of particular importance for every process in everyday life, science, and industry. Precise temperature measurement is used in all fields - electronics, communications, mechanical engineering and medicine, and determines the quality of the manufactured product. In this study, an experimental calibration was performed on a semiconductor thermistor with a nominal resistance of 10 k Ω in the temperature range from 0°C to 90°C. Based on the experimental data obtained, the coefficients of the Steinhart–Hart equation were determined, which allow for a more precision determination of the temperature from the measured resistance of the sensor.

Keywords— *Semiconductor thermistor, Nominal resistance, Steinhart–Hart, Temperature measurement.*

I. INTRODUCTION

Precise temperature measurement is one of the fundamental requirements in modern science, engineering, medicine, and industrial production. Temperature directly influences the physical, chemical, electrical, mechanical, and biological properties of materials and systems. Even

small deviations in temperature may lead to significant changes in the behavior of technological processes, measurement accuracy, product quality, and operational safety. For this reason, the development and application of highly accurate temperature measurement methods have become an essential task in many scientific and industrial fields [6].

In scientific research, temperature measurements play a key role in experimental validation and data reliability. Many physical phenomena, including thermal expansion, electrical resistance variation, optical properties, and phase transitions, are strongly temperature-dependent. Consequently, insufficient temperature accuracy may introduce systematic errors and reduce the credibility of experimental results. High-precision temperature measurements are particularly important in metrology, nanotechnology, laser systems, and environmental monitoring, where external influences and thermal instability can significantly affect measurement uncertainty.

Precise temperature monitoring is equally important in medicine and healthcare. Medical diagnostics, laboratory analysis, sterilization procedures, and patient monitoring systems rely on accurate temperature determination. Small

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temperature variations can provide critical information about physiological conditions or the effectiveness of medical treatment. Similarly, in environmental sciences, precise temperature measurements are necessary for climate monitoring, atmospheric analysis, and ecological studies, where long-term accuracy and stability are essential for identifying trends and predicting environmental changes.

Therefore, the study and refinement of methods for precise temperature measurement are of great scientific and practical importance, and research in this field contributes to improving the reliability and accuracy of measurements.

II. DESIGN OF HARDWARE PLATFORM FOR TEMPERATURE MEASUREMENT SYSTEM USING AN NTC THERMISTOR

The Hardware concept consists of the following modules:

ANALOG FRONT: This module contains two main blocks:

NTC DIVIDER: A voltage divider composed of a precision reference resistor with a value of 10 k Ω and a 10 k Ω NTC thermistor. The midpoint of the divider sends a signal to the ADC module.

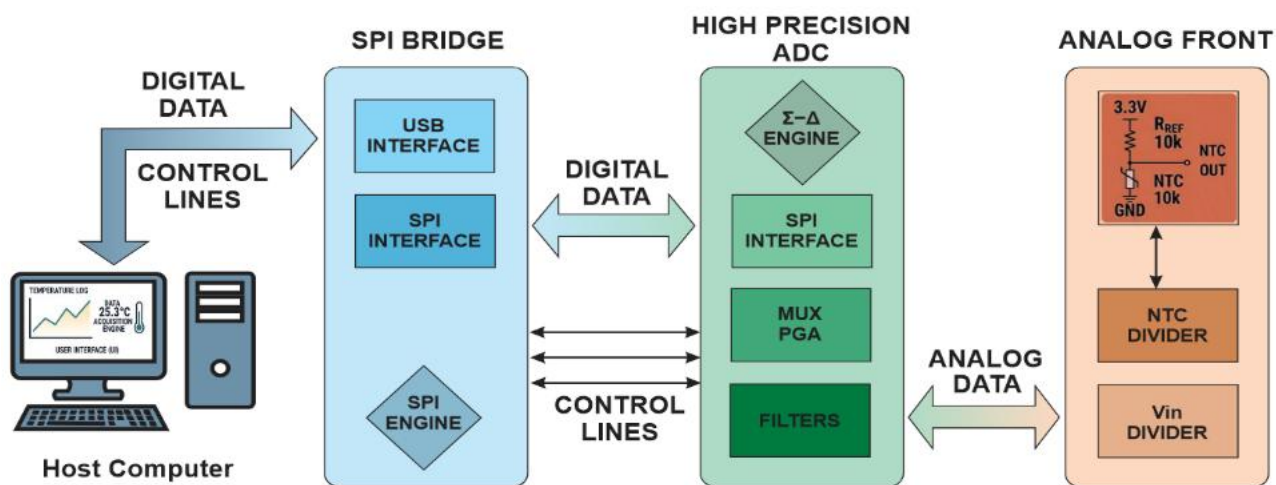


Fig. 1. Block diagram of the developed hardware platform for temperature measurement system.

Vref DIVIDER: A resistive divider consisting of 2 precision reference resistors that allow real-time measurement of the current power supply voltage. The midpoint of the divider sends a signal to the ADC module.

HIGH PRECISION ADC: Contains the following main blocks:

FILTERS: Built-in, software-controlled filters for noise suppression in various frequency ranges.

MUX, PGA: Multiplexer and amplifiers for reading data from multiple inputs simultaneously and amplifying the data when necessary.

Σ - Δ ENGINE: Ensures the conversion of analog signals from the sensors into a 24-bit digital signal with low noise.

SPI INTERFACE: A serial peripheral interface for communication with other devices.

SPI BRIDGE: Contains the following main blocks:

SPI INTERFACE: An interface that facilitates communication with peripheral devices communicating via a serial peripheral interface (SPI).

SPI BRIDGE: Contains the following main blocks:

SPI INTERFACE: An interface that enables communication with peripheral devices that communicate

via a Serial Peripheral Interface (SPI). The choice of this type of model is motivated by the need to ensure:

optimal recursive state estimation in the sense of minimum mean square error;

the possibility for explicit representation and adaptive handling of uncertainty sources through the covariance matrices;

agreement between the dynamic model and the measurement information under varying observation conditions.

The signal from the NTC sensor is fed into the NTC Divider via a voltage divider, the signal is sent to the ADC module. At the same time, a signal from the Vin Divider, containing the value of the supply voltage at the moment of measurement, is also sent to the ADC module. The two signals are read practically simultaneously in a single measurement cycle, filtered, digitized, and packaged into SPI packets, which are then transmitted via the SPI bus to the SPI Bridge module. The SPI Bridge module unpacks the SPI packet, repackages it into a USB packet, and

transmits it to the USB interface. Via the USB interface, the host computer receives the data and transmits it for further processing to the DAQ software, which converts it into data suitable for direct reading by the operator.

The DAQ software provides the operator with data on the status of all modules during the measurement, the exact time of the measurement, the value of the supply voltage at the time of measurement (V_{in}), the voltage value at the midpoint of the divider in the NTC Divider (V_{out}), and the resistance value of the NTC sensor (R_{ntc}) calculated using the formula

$$R_{NTC} = R_{ref} \frac{V_{out}}{V_{in} - V_{out}} \quad (1)$$

By including the measured input voltage V_{in} in the calculation for each measurement, the error caused by fluctuations in the supply voltage during the measurement process is effectively eliminated.

III. SOFTWARE ALGORITHM OF THE SYSTEM

At the beginning, the program attempts to initialize the SPI module. Only a successful initialization leads to the next step, since without communication with the SPI module, subsequent communication with the ADC and reading data from the Analog Front module are not possible.

After successful initialization of the SPI module, an attempt is made to initialize the ADC module upon successful initialization, the operating mode and filters are configured, and the inputs for data reading are defined.

Data is read from the ADC, the read data is digitalized and formed into a packet that is sent to the SPI module for transmission. The SPI module converts the SPI packet into a USB packet and transfers it to the host computer via the USB interface [4].

The host computer receives the packet and passes it to the DAQ software, which calculates values for R and T and displays the data for V_{in} , V_{out} , R, and T to the operator.

The program terminates only if the operator press the button stop. Until this button is pressed, the cycle of reading, calculating, and visualizing the data runs automatically every 10 seconds.

The software module is developed in C# as a desktop application (Windows Forms) and is intended for periodic measurement and visualization of analog signals through an external measurement interface [7].

The application automatically initializes the connection, performs measurements at a defined interval, and calculates parameters such as voltage and resistance, while displaying and logging the results in real time.

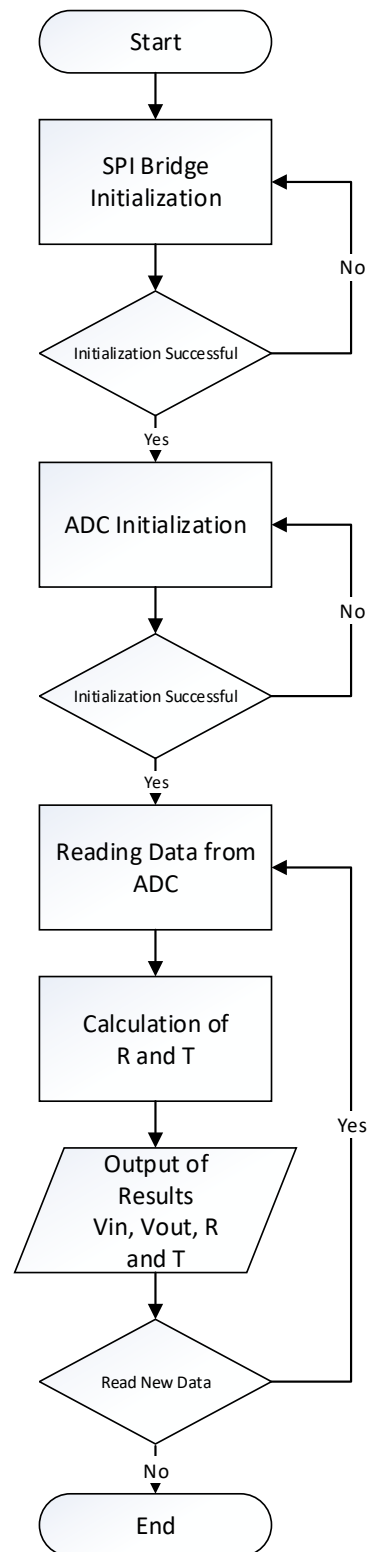


Fig. 2. Software algorithm of the system.

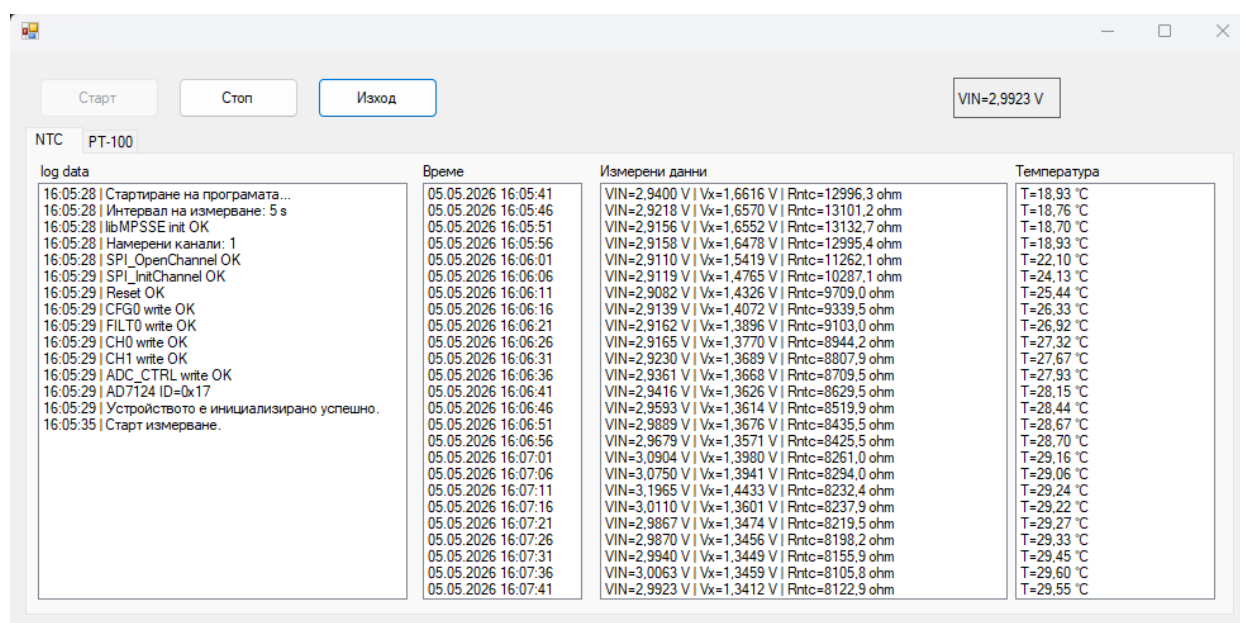


Fig. 3. User interface of the developed software module.

The software module allows for the initialization of the communication interface, the start and stop of the measurement process, as well as the real-time display of the measured parameters.

The interface displays and records data on the current status of the entire measurement circuit, the date and time of the measurement, the supply voltage at the time of measurement, the voltage across the thermistor divider, and the calculated thermistor resistance and temperature. System messages are displayed in separate information panels from the measurement data, allowing for quick differentiation between the measured values and fast, easy access to the information generated during system operation.

The developed software architecture ensures stable communication with the measurement hardware, periodic data collection from the sensors, automatic processing of the measured values, and continuous visualization of the calculated parameters.

IV. EXPERIMENTAL SETUP

Fig. 5 shows the experimental setup with which the measurements were made.

The temperature measurement and thermistor calibration system shown in the image represents a laboratory setup designed to create stable and controlled thermal conditions for accurate temperature measurements and calibration of thermistors. The system operates by heating a liquid medium inside a glass beaker while continuously mixing the liquid in order to maintain a uniform temperature distribution throughout the entire

volume. At the base of the setup there is a constant-temperature magnetic stirrer that combines two important functions: controlled heating and magnetic stirring. The heating plate raises the temperature of the liquid bath to a desired value, while the magnetic stirring mechanism rotates a magnetic stir bar located inside the beaker. This continuous mixing process prevents the formation of local temperature gradients and ensures that all immersed sensors are exposed to the same thermal conditions.

Inside the beaker there is a distilled water for calibration procedures. The liquid serves as a thermal transfer environment with high heat capacity and good temperature uniformity. During operation, the heated liquid surrounds the temperature sensors and enables accurate transfer of thermal energy from the heater to the sensing elements. The magnetic stirring significantly improves the homogeneity of the temperature field, which is essential for precise calibration measurements because even small temperature differences within the liquid may introduce additional uncertainty in the obtained results.



Fig. 4 Calibration measuring system

Two sensing elements are immersed in the liquid bath. One of them acts as a reference temperature sensor, usually a precision platinum resistance thermometer such as Pt100 with known metrological characteristics. This sensor provides the actual reference temperature of the liquid bath and serves as the standard against which the thermistor is calibrated. Alongside the reference sensor, the thermistor under investigation is also immersed in the liquid medium. The thermistor is positioned close to the reference sensor so that both devices experience nearly identical thermal conditions during the calibration process.

The entire sensing assembly is mounted using a laboratory support stand equipped with clamps and holders. This mechanical structure ensures stable positioning of the probes, constant immersion depth, and protection against movement caused by liquid stirring.

During operation, the temperature of the bath is gradually changed through a predefined range. At each temperature point, the value indicated by the reference thermometer is recorded together with the electrical resistance of the thermistor. These experimentally obtained temperature–resistance pairs are later used to determine the thermistor calibration characteristics and mathematical model. The Steinhart–Hart equation is used to describe the nonlinear relationship between thermistor resistance and temperature.

Using experimentally measured calibration points, the coefficients A, B, and C are calculated, allowing the thermistor to achieve significantly improved measurement accuracy over a wide temperature range.

V. EXPERIMENTAL RESULTS

TABLE 1

R_t	T_1	T_2	T_3
Ω	$^{\circ}\text{C}$	$^{\circ}\text{C}$	$^{\circ}\text{C}$
32470	0	0.11	-0.02

19790	10	10.12	9.96
11790	21	21.29	21.08
7945	30	30.33	30.07
5246	40	40.37	40.04
3560	50	50.30	49.88
2356	61	61.51	60.97
1716	70	70.60	69.96
1228	80	80.70	79.93
887	90	91.05	90.13

Table 1 shows the experimental measurement results. The experimental measurement results are shown in Table 1. T_1 denotes the temperature measured [9] by the reference sensor, T_2 denotes the temperature measured by the thermistor before calibration [10], and T_3 denotes the temperature measured by the thermistor after calibration.

The measurements obtained before calibration (T_2) show systematic deviations relative to the reference sensor (T_1). In nearly all measured points, the thermistor indicates temperatures higher than the reference values. The magnitude of the deviation increases with increasing temperature. At low temperatures, the error is relatively small, reaching only about $+0.11^{\circ}\text{C}$ at 0°C and $+0.12^{\circ}\text{C}$ at 10°C . However, as the temperature rises, the error becomes progressively larger. At 40°C the deviation reaches approximately $+0.37^{\circ}\text{C}$, while at 70°C and 80°C the errors increase to approximately $+0.60^{\circ}\text{C}$ and $+0.70^{\circ}\text{C}$, respectively. The largest deviation is observed at 90°C , where the thermistor measurement before calibration differs from the reference value by approximately $+1.05^{\circ}\text{C}$. These results indicate that the uncalibrated thermistor exhibits nonlinear measurement errors that become increasingly pronounced at higher temperatures [13].

After calibration, the results represented by T_3 show a substantial improvement in accuracy. The measured temperatures become significantly closer to the reference sensor values across the entire measurement range. At 0°C the deviation is reduced to approximately -0.02°C , while at 10°C the error becomes approximately -0.04°C . In the middle part of the temperature range, the deviations remain very small, typically within $\pm 0.1^{\circ}\text{C}$. For example [11], at 30°C the calibrated thermistor differs from the reference temperature by only $+0.07^{\circ}\text{C}$, and at 50°C the deviation is approximately -0.12°C . Even at higher temperatures, where the initial errors were most pronounced, the calibration significantly reduces the deviations [14]. At 80°C the error decreases from approximately $+0.70^{\circ}\text{C}$ before calibration to approximately -0.07°C after calibration, while at 90°C the deviation is reduced from $+1.05^{\circ}\text{C}$ to approximately $+0.13^{\circ}\text{C}$.

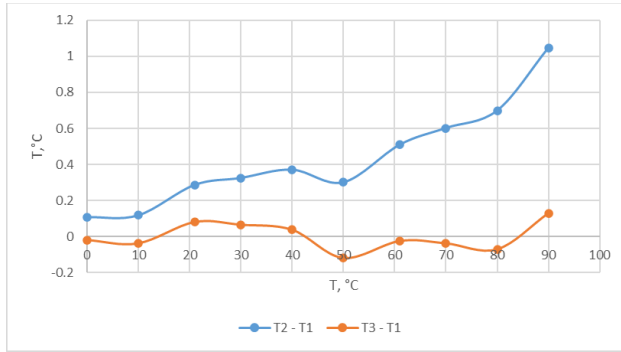


Fig. 5 Graphical representation of table 1

The obtained results demonstrate that the calibration process successfully compensates for the nonlinear characteristics and systematic measurement errors of the thermistor. The calibration procedure leads to a considerable reduction in measurement uncertainty and improves the agreement between the thermistor readings and the reference sensor values. Overall, the experimental data confirm that the applied calibration method provides a substantial enhancement in measurement accuracy over the entire investigated temperature range and makes the thermistor suitable for precision temperature measurement applications.

Fig. 6 shows the experimental characteristic of the tested NTC sensor [1].

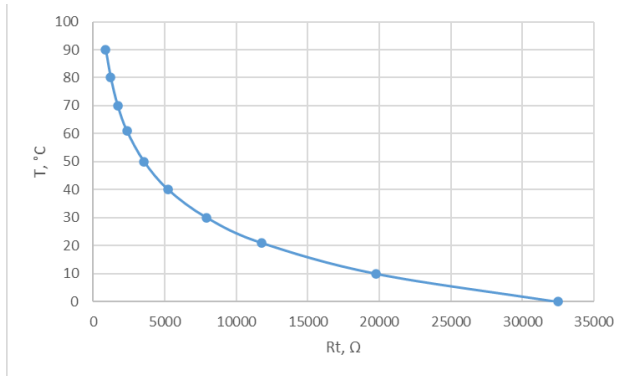


Fig. 6 Experimental Characterization of NTC Thermistor

VI. METHODOLOGY FOR DETERMINING THE STEINHART-HART COEFFICIENTS

The temperature-resistance characteristic of the NTC thermistor is described by the Steinhart-Hart [8] equation:

$$\frac{1}{T} = A + B \ln(R_t) + C [\ln(R_t)]^3 \quad (2)$$

where T is the absolute temperature in Kelvin, R_t is the thermistor resistance in ohms, and A , B , and C are the unknown coefficients [12].

The first step is to convert all experimentally measured temperatures from degrees Celsius to Kelvin:

$$T_K = T_{°C} + 273.15 \quad (3)$$

Then, for each experimental resistance value R_t , the natural logarithm is calculated:

$$x = \ln(R_t) \quad (4)$$

After that, the third power of the logarithmic value is calculated:

$$x^3 = [\ln(R_t)]^3 \quad (5)$$

For every experimental point, one equation is obtained in the following form:

$$\frac{1}{T_i} = A + B \ln(R_i) + C [\ln(R_i)]^3 \quad (6)$$

For example, for the first experimental point:

$$T = 0^\circ\text{C}$$

$$T_K = 273.15 \text{ K}$$

$$R_t = 32470 \Omega$$

$$\ln(32470) = 10.3881$$

$$[\ln(32470)]^3 = 1120.89$$

$$\frac{1}{273.15} = 0.003661$$

Therefore, the first equation becomes:

$$0.003661 = A + 10.3881B + 1120.89C \quad (7)$$

The same calculation is performed for all experimental points. Since there are more than three experimental points, the system is overdetermined [15]. Therefore, the coefficients are not obtained from only three selected points, but from all measured points using the least-squares method.

The system can be written in matrix form [2] as:

$$Y = XK \quad (8)$$

where:

$$Y = \begin{bmatrix} 1/T_1 \\ 1/T_2 \\ 1/T_3 \\ \vdots \\ 1/T_n \end{bmatrix} \quad (9)$$

$$X = \begin{bmatrix} 1 & \ln(R_1) & [\ln(R_1)]^3 \\ 1 & \ln(R_2) & [\ln(R_2)]^3 \\ 1 & \ln(R_3) & [\ln(R_3)]^3 \\ \vdots & \vdots & \vdots \\ 1 & \ln(R_n) & [\ln(R_n)]^3 \end{bmatrix} \quad (10)$$

The least-squares solution is calculated by:

$$K = (K^T X)^{-1} X^T Y \quad (11)$$

After substituting the experimental data into the matrices and solving the system, the following coefficients are obtained:

$$A = 1.15970841 \times 10^{-3}$$

$$B = 2.30118380 \times 10^{-4}$$

$$C = 9.90697264 \times 10^{-8}$$

Therefore, the final Steinhart–Hart equation for the investigated NTC thermistor [5] is:

$$\frac{1}{T} = 1.15970841 \times 10^{-3} + 2.30118380 \times 10^{-4} \ln(R_t) + 9.90697264 \times 10^{-8} [\ln(R_t)]^3 \quad (12)$$

where T is in Kelvin and R_t is in ohms.

To calculate the temperature from a measured resistance value, the equation is rearranged as:

$$T_K = \frac{1}{A+B \ln(R_t)+C[\ln(R_t)]^3} \quad (13)$$

Finally, the temperature in degrees Celsius is obtained by:

$$T_{\circ C} = T_K - 273.15 \quad (14)$$

This procedure provides a mathematical model that represents the experimental temperature–resistance characteristic of the NTC thermistor with high accuracy [3].

VII. CONCLUSION

The experimental results demonstrate that the thermistor calibration procedure significantly improves the accuracy of temperature measurement over the entire investigated temperature range. Before calibration, the thermistor exhibited systematic measurement errors that increased with temperature, reaching deviations of more than 1 °C at higher temperatures. After calibration, the measured values became much closer to those obtained from the reference sensor, with most deviations reduced to within approximately ± 0.1 °C. The calibration process successfully compensates for the nonlinear characteristics of the thermistor and substantially decreases measurement uncertainty. As a result, the calibrated thermistor provides considerably higher precision and reliability, making it suitable for accurate temperature measurement applications.

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Comparative Analysis of Numerical and Experimental Results in Laser Hardening of 42CrMo4 Steel

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Abstract— Laser hardening of steels is a modern technological process widely used in the automotive, aerospace, and tooling industries. In the present study, a comparative analysis between numerical modeling results and experimental data for the laser hardening process of 42CrMo4 steel samples is performed. Numerical calculations were used to determine preliminary operating intervals of power density at different processing speeds, based on the heat conduction equation and the thermal balance equation with applied approximations. For comparison purposes, in-house experimental results obtained using a 4 kW diode laser were employed. A good correlation between the numerical and experimental results is observed. The obtained findings are useful for operators of laser processing systems as well as for researchers in the field of laser hardening of steels.

Keywords— laser hardening, numerical calculations, experiments, power density, speed, operating intervals.

I. INTRODUCTION

In recent decades, laser surface treatment technologies have gained significant importance in modern manufacturing due to their precision, flexibility, and efficiency. Among these technologies, laser hardening has emerged as a highly effective method for improving the surface properties of metallic materials, particularly steels used in demanding engineering applications. The process

enables localized heating of the material surface above the austenitization temperature, followed by rapid self-quenching, which leads to the formation of a hardened martensitic layer without affecting the bulk properties of the component [1 – 6].

Laser hardening is widely applied in industries such as automotive, aerospace, and tooling, where components are subjected to severe wear, fatigue, and contact stresses. Compared to conventional heat treatment methods, laser hardening offers several advantages, including minimal distortion, precise control of the treated area, reduced processing time, and the elimination of additional quenching media. These benefits make it particularly suitable for complex geometries and high-value components where dimensional accuracy and surface integrity are critical [7] – [9].

The effectiveness of the laser hardening process depends strongly on the proper selection and control of process parameters, such as laser power, scanning speed, beam size, and interaction time. These parameters directly influence the thermal cycle experienced by the material, which in turn determines the depth of hardening, microstructural transformations, and resulting mechanical properties. However, the optimization of these parameters is a complex task due to the highly transient and nonlinear

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nature of heat transfer during laser-material interaction [10] – [17].

To address these challenges, numerical modeling has become an essential tool for predicting temperature fields, phase transformations, and hardened layer characteristics. Models based on the heat conduction equation and thermal balance principles allow researchers and engineers to simulate the process under various conditions, reducing the need for extensive experimental trials. Nevertheless, numerical models often rely on simplifying assumptions, such as constant material properties or idealized boundary conditions, which may limit their accuracy in real-world applications [18] – [22].

Therefore, experimental validation remains a crucial step in verifying the reliability of numerical predictions. A comparative approach, combining simulation and experimental investigation, provides deeper insight into the process mechanisms and helps refine modeling strategies. This synergy between numerical and experimental methods enables more accurate determination of optimal processing windows and enhances process stability and repeatability.

The steel grade 42CrMo4 is widely used in engineering applications due to its excellent combination of strength, toughness, and wear resistance. Understanding the response of this material to laser processing conditions is therefore of both scientific and industrial interest.

In the present study, a comparative analysis between numerical modeling results and experimental data for the laser hardening of 42CrMo4 steel is performed. Numerical calculations are used to estimate suitable operating ranges of power density at different processing speeds, based on simplified thermal models. These results are then compared with experimental data obtained from laser hardening tests conducted using a high-power diode laser system. The objective is to evaluate the degree of agreement between predicted and measured outcomes and to assess the applicability of the numerical approach for practical process optimization.

The findings of this work contribute to a better understanding of the relationship between process parameters and hardening results, and they provide useful guidelines for both industrial practitioners and researchers working in the field of laser surface treatment of steels.

II. MATERIALS AND METHODS

A. Material

42CrMo4 steel is a high-quality steel widely used in industry. It is used in the Automotive Industry for the manufacture of Crankshafts, Connecting rods, Axles and drive shafts Gears and transmission parts. It is used to make High-strength shafts, Bolts and studs, Hydraulic components and Machine tool parts for Mechanical and Heavy Engineering. In the Energy Sector it is used to make Wind turbine components, Power plant shafts and Drilling equipment. It is also used in the Tool and Die Industry.

Table 1 presents the chemical composition of 42CrMo4 steel in accordance with the requirements of the EN 10083.

This composition is carefully balanced to ensure an optimal combination of high strength, good hardenability, and fatigue resistance.

Carbon (C), with a content of 0.38–0.45%, determines the potential for achieving high hardness and strength after heat treatment. Chromium (Cr), in the range of 0.90–1.20%, plays a significant role in increasing the hardenability of the steel as well as its wear resistance. In addition, it improves the material's resistance to oxidation and corrosion under moderate conditions. The addition of molybdenum (Mo) (0.15–0.30%) contributes to increased strength at elevated temperatures and helps reduce temper embrittlement. Molybdenum also improves creep resistance under load. Manganese (Mn) (0.60–0.90%) enhances hardenability and helps bind sulfur through the formation of manganese sulfides, thereby reducing the detrimental effect of sulfur on mechanical properties.

The combined effect of these elements defines 42CrMo4 as a low-alloy structural steel with excellent mechanical properties, particularly suitable for applications involving dynamic loading and for use after heat treatment (quenching and tempering).

TABLE 1 CHEMICAL COMPOSITION OF STEEL 42CrMo4

Element	Content, %	Element	Content, %
C	0.38 – 0.45	Si	< 0.40
Cr	0.90 – 1.20	P	< 0.025
Mo	0.15 – 0.30	S	< 0.035
Mn	0.60 – 0.90	Fe	Balance

TABLE 2 BASIC OPTICAL AND THERMOPHYSICAL PARAMETERS OF THE MATERIAL

Parameter	Value
Thermal conductivity k , W/m·K	42.5
Density ρ , kg/m ³	7815
Specific heat c , J/(kg·K)	470
Thermal diffusivity a , m ² /s	1.157×10^{-5}
Melting temperature T_m , K	1716
Latent heat of melting L_m , J/kg	2.514×10^5
Initial temperature T_0 , K	293

B. Laser system

The laser hardening experiments were performed using a high-power diode laser system with a maximum output

power of 4 kW. The laser operates in continuous wave (CW) mode, providing a stable and uninterrupted energy input, which is essential for uniform surface heating during the hardening process. The emitted radiation lies in the near-infrared spectral range, with a wavelength between 900 and 1080 nm, a range that is well absorbed by ferrous alloys (including steel) and therefore suitable for surface heat treatment applications.

The diode laser system is characterized by a relatively high electrical-to-optical efficiency of approximately 45%, which is significantly higher than that of many other industrial laser types. This high efficiency reduces overall energy consumption and minimizes thermal losses. The beam quality factor ($M^2 = 4$) is typical for high-power diode lasers, indicating a moderately divergent beam that is well suited for applications requiring larger, homogeneous irradiation areas rather than fine focusing.

The laser processing cell was fully automated and consisted of a robotic manipulation system based on a Fanuc M20-iD industrial robot, which ensured precise and repeatable movement of the laser head relative to the workpiece. In addition, a single-axis positioner was integrated into the system to allow controlled rotation or positioning of the samples, enabling uniform treatment of complex geometries and improving process flexibility.

The laser module was powered by an LDM4000-100 laser power supply, which provided stable power delivery and precise control over the laser output parameters. The laser beam was delivered to the workpiece through an OTZ-5 VR laser processing head equipped with vari-optics. This optical system allowed continuous adjustment of the laser spot size within a range from 5×8 mm to 22×44 mm. Such flexibility in spot size enabled optimization of the energy density and heating profile depending on the specific processing conditions and material requirements.

For real-time process monitoring and control, the system incorporated an integrated two-color pyrometer (Model LDC01, Mergenthaler). This non-contact temperature measurement device operates by detecting thermal radiation at two different wavelengths, allowing accurate temperature readings that are less sensitive to variations in surface emissivity. The pyrometer was used to continuously monitor and regulate the surface temperature during laser hardening, ensuring consistent thermal cycles and preventing overheating or insufficient hardening.

Overall, the combination of a high-power diode laser, adaptable beam shaping, robotic handling, and closed-loop temperature control enabled precise, efficient, and reproducible laser surface hardening operations.

C. Theoretical aspect

Laser hardening is a complex technological process, depending on a number of parameters. They are in complex interdependencies with each other. What temperature is obtained on the surface of the material is largely determined by the power density of the laser radiation, the hardening rate and the optical and thermophysical

properties of the material. Therefore, there is a relationship between these parameters. It can be obtained from the heat conduction equation and the heat balance equation with certain approximations. For temperatures below the melting point, the power density is given by the expression

$$q_s = \frac{k(T - T_0)}{2A} \sqrt{\frac{\pi v}{ab}}, \quad T < T_0 \quad (1)$$

where T_0 is initial temperature (ambient temperature).

The critical melting power density is given by the expression

$$q_{scm} = \frac{(1+s)k(T_m - T_0)}{2A} \sqrt{\frac{\pi v}{ab}}, \quad T = T_m \quad (2)$$

where s is parameter, which is given by the formula

$$s = \frac{L_m}{c(T_m - T_0)} \quad (3)$$

D. Methodology

The studies to determine the preliminary working density intervals for the hardening process of 42CrMo4 steel samples using a fiber laser proceed in the following sequence:

- Determination of the power density for different speeds at a temperature of 1123 K by formula (1). The necessary material parameters are taken from table 2. Calculations are made for two laser beam profiles, presented in Fig. 1. They are rectangles with dimensions: for the first profile (Fig. 1a) – $a = 15$ mm and $b = 5$ mm and for the second profile (Fig. 1b) – $a = 5$ mm and $b = 15$ mm;
- Determination of the critical power density for different speeds by formulas (2) and (3). The necessary material parameters are taken from table 2. Calculations are made for two laser beam profiles;
- From the obtained results, graphs of the dependence of the critical power density and the power density at a temperature of 1123 K on the speed for both laser beam profiles are drawn;
- The results of the numerical calculations are analyzed and summarized;
- The method is validated with numerical calculations using experimental results that we have obtained at our research center.

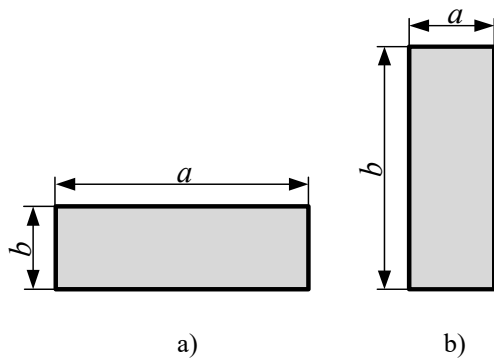


Fig. 1. Laser beam profiles of the fiber laser hardening system

III. RESULTS AND DISCUSSION

According to the adopted methodology, numerical calculations were carried out to determine both the critical power density required for melting and the power density necessary to reach the hardening temperature for different processing speeds. The calculations were based on equations (1) – (3), using the thermophysical parameters of 42CrMo4 steel listed in Table 2. The scanning speed was varied within the range of 3 mm/s to 15 mm/s, with a step of 2 mm/s, in order to cover a representative interval of practical processing conditions.

Two different laser beam profiles were considered in the analysis, corresponding to rectangular spot geometries with dimensions 15×5 mm and 5×15 mm. These profiles simulate different energy distributions along and across the scanning direction, which significantly affect the thermal field and the resulting hardening conditions.

The calculated results are presented graphically in Figures 2a and 2b, where the dependence of power density on processing speed is illustrated. The blue curves represent the critical power density required to initiate melting of the material, while the green curves correspond to the power density necessary to reach the target hardening temperature (approximately 850 K).

A detailed analysis of these dependencies shows that both the critical power density and the required hardening power density increase nonlinearly with increasing scanning speed. This behavior can be explained by the reduced interaction time between the laser beam and the material at higher speeds. As the exposure time decreases, a higher energy input per unit area (i.e., higher power density) is required to achieve the same thermal effect. This nonlinear trend reflects the transient nature of heat conduction and the increasing dominance of heat dissipation at higher speeds.

An important observation from the graphs is that the feasible operating region for laser hardening is bounded between the two curves. The lower boundary (green curve) represents the minimum power density required to reach the austenitization temperature necessary for phase transformation, while the upper boundary (blue curve) indicates the onset of melting. Therefore, effective laser

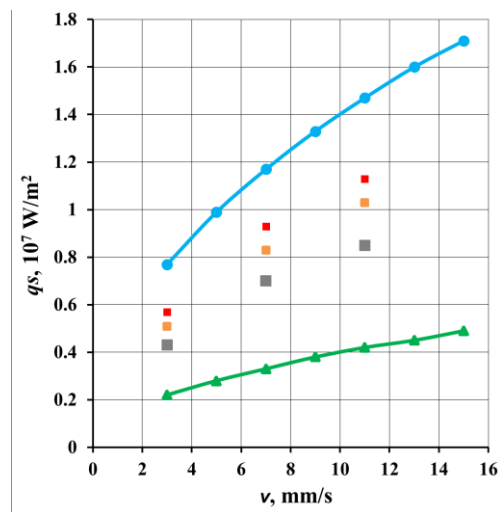
hardening without surface melting can only be achieved within this process window. This region defines the optimal combination of power density and scanning speed for the given material and beam geometry.

For the first laser beam profile (15×5 mm), the critical melting power density varies from approximately 1.33×10^7 W/m² to 2.97×10^7 W/m², while the power density required to reach the hardening temperature ranges from 0.38×10^7 W/m² to 0.84×10^7 W/m² over the investigated speed interval. In contrast, for the second profile (5×15 mm), the corresponding values are significantly lower, ranging from 0.77×10^7 W/m² to 1.74×10^7 W/m² for melting, and from 0.22×10^7 W/m² to 0.49×10^7 W/m² for hardening.

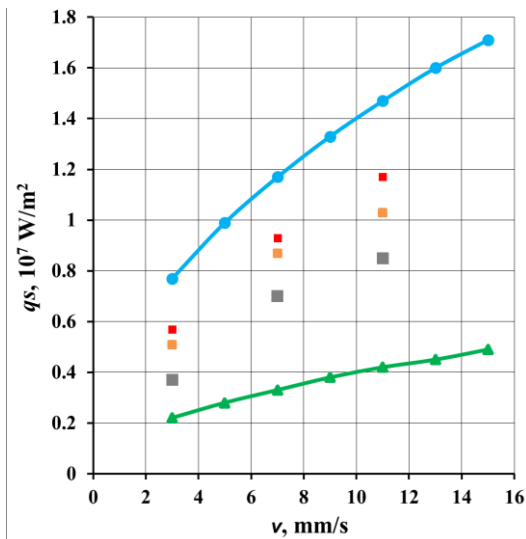
The observed difference between the two profiles is primarily due to the variation in energy distribution and heat flow conditions. The elongated profile in the scanning direction (15×5 mm) results in a shorter interaction width and higher heat concentration, requiring greater power density to achieve the same thermal penetration. Conversely, the wider profile perpendicular to the scanning direction (5×15 mm) promotes more efficient heat accumulation and distribution, thereby reducing the required power density.

Furthermore, the significantly higher values of the critical power density compared to those required for hardening can be attributed to the additional energy needed not only to raise the material temperature to the melting point but also to supply the latent heat of fusion. This energy contribution is substantial and leads to a clear separation between the two curves, ensuring a relatively wide processing window for safe operation.

Overall, the results demonstrate that both scanning speed and beam geometry play a crucial role in determining the thermal response of the material. The selection of appropriate process parameters must therefore consider these factors to ensure sufficient heating for phase transformation while avoiding surface melting. The presented numerical analysis provides a reliable basis for defining such operating intervals, which can subsequently be validated through experimental investigation.



a)



b)

Fig. 2. Graph of the dependence of the critical power density of melting on the speed for steel 42CrMo4 (blue color). Graph of the dependence of the power density on the speed at a temperature of 850 K for steel 42CrMo4 (green color); with laser profiles: a) $a = 15$ mm and $b = 5$ mm; b) $a = 5$ mm and $b = 15$ mm.

A more detailed analysis of the obtained numerical results shows that the relationship between scanning speed and required power density is strongly nonlinear for both investigated laser beam profiles. This behavior is primarily due to the transient heat transfer conditions during laser-material interaction. As the scanning speed increases, the interaction time between the laser beam and the material surface decreases significantly. Consequently, less time is available for heat to penetrate into the material, and a higher power density is required to achieve the same thermal effect, i.e., to reach the austenitization temperature necessary for hardening.

At lower scanning speeds (3–5 mm/s), the interaction time is relatively long, allowing sufficient heat

accumulation even at lower power densities. In this regime, the process is more stable and less sensitive to small variations in parameters. However, as the speed increases beyond 9–11 mm/s, the process becomes increasingly sensitive, and a relatively small increase in speed requires a disproportionately higher increase in power density. This explains the observed nonlinear growth of both the critical melting power density and the hardening power density.

The graphical representation clearly shows that the feasible operating region for laser hardening is confined between the two characteristic curves. The lower boundary corresponds to the minimum energy input required to achieve phase transformation (austenitization), while the upper boundary represents the threshold beyond which surface melting begins. This intermediate region defines the technological window in which effective laser hardening can be performed without undesirable effects such as surface melting, excessive roughness, or microstructural degradation.

A comparison between the two beam profiles reveals a significant influence of the beam geometry on the process parameters. For the first profile (15 × 5 mm), the required power density is consistently higher across the entire speed range. This can be attributed to the elongated geometry in the scanning direction, which reduces the effective interaction time per unit area and leads to increased heat dissipation along the scanning path. As a result, higher energy input is necessary to compensate for these losses.

In contrast, the second profile (5 × 15 mm), which is wider perpendicular to the scanning direction, promotes more efficient heat accumulation in the treated zone. The increased width allows better overlap of thermal fields and reduces heat losses, resulting in lower required power densities. Quantitatively, the required power density for the first profile is approximately 1.7 times higher than that for the second profile under identical processing conditions, confirming the strong dependence of the process on beam shaping.

The analysis of the preliminary operating intervals (Tables 3 and 4) further confirms these observations. It is evident that increasing the scanning speed by a factor of five (from 3 mm/s to 15 mm/s) leads to an increase in the required power density by approximately 2.25 times. This result highlights the importance of careful parameter selection, particularly when aiming to increase productivity through higher processing speeds.

TABLE 3 PRELIMINARY WORKING INTERVALS OF POWER DENSITY I LASER HARDENING OF 42CrMo4 STEEL SAMPLES WITH A DIODE LASER FOR THE FIRST LASER BEAM PROFILE

Speed v , mm/s	Power density q_s , 10^7 W/m 2
3	0.38 – 1.33
5	0.49 – 1.71
7	0.58 – 2.03
9	0.65 – 2.30

11	0.72 – 2.54
13	0.79 – 2.76
15	0.84 – 2.97

TABLE 4 PRELIMINARY WORKING INTERVALS OF POWER DENSITY I
LASER HARDENING OF 42CrMo4 STEEL SAMPLES WITH A DIODE LASER
FOR THE SECOND LASER BEAM PROFILE

Speed v , mm/s	Power density q_s , 10^7 W/m ²
3	0.22 – 0.77
5	0.28 – 0.99
7	0.33 – 1.17
9	0.38 – 1.33
11	0.42 – 1.47
13	0.45 – 1.60
15	0.49 – 1.71

A key aspect of the present study is the comparison between numerical predictions and experimental results. The experimental data points, corresponding to surface temperatures of 1173 K (in gray), 1273 K (in orange), and 1373 K (in red), are located entirely within the region bounded by the calculated curves. This confirms that the numerical model successfully predicts the practical operating window for laser hardening.

Furthermore, the experimental results follow the same trend as the numerical calculations, namely an increase in required power density with increasing scanning speed and target temperature. The slight deviations between numerical and experimental values can be attributed to factors not fully accounted for in the model, such as temperature-dependent material properties, surface oxidation, variations in absorptivity, and heat losses due to convection and radiation.

Despite these simplifications, the observed agreement between numerical and experimental results can be considered very good. This validates the applicability of the proposed numerical approach for preliminary process design and optimization. It demonstrates that relatively simple analytical models, when properly formulated, can provide reliable estimates of the process parameters and significantly reduce the need for extensive experimental trials.

IV. CONCLUSIONS

The present study provides a comprehensive comparative analysis of numerical and experimental results in the laser hardening of 42CrMo4 steel using a high-power

diode laser system. Based on the obtained results, the following conclusions can be drawn:

- A numerical approach based on the heat conduction equation and thermal balance principles was successfully applied to determine preliminary operating intervals of laser power density for different scanning speeds.
- The analysis revealed a nonlinear relationship between scanning speed and required power density. Increasing the speed leads to a significant increase in power density due to reduced interaction time and enhanced heat dissipation.
- The feasible process window for laser hardening is clearly defined between the minimum power density required for austenitization and the critical power density for surface melting. This region represents the optimal operating range for achieving high-quality hardening without thermal damage.
- The geometry of the laser beam profile has a substantial influence on the process. The elongated profile in the scanning direction requires approximately 1.7 times higher power density compared to the transverse profile, due to differences in heat distribution and interaction conditions.
- Experimental results obtained at different surface temperatures and scanning speeds show very good agreement with the numerical predictions. All experimental data points fall within the calculated operating intervals, confirming the validity of the proposed model.
- The slight discrepancies between numerical and experimental results are mainly due to simplifying assumptions in the model, such as constant material properties and neglect of certain heat loss mechanisms.
- The developed methodology can be effectively used for preliminary selection of process parameters, reducing the need for extensive experimental trials and improving the efficiency of process design.

From an application point of view, the obtained results have significant practical importance for industrial laser processing:

- The defined operating intervals of power density and scanning speed can be directly used for process optimization in industrial laser hardening systems, reducing the need for costly and time-consuming trial-and-error experiments.
- The results enable predictive selection of process parameters depending on the desired hardening depth and surface quality, which is particularly important in industries such as automotive, aerospace, and heavy machinery, where

components operate under high wear and fatigue conditions.

- The demonstrated influence of beam geometry provides guidance for selection and design of laser optics and beam shaping systems, allowing engineers to tailor the energy distribution according to specific technological requirements.
- The validated numerical model can be integrated into computer-aided manufacturing (CAM) and simulation software, supporting digital process planning and enabling faster implementation of laser hardening technologies in production environments.
- The ability to accurately define the process window contributes to improving process stability, repeatability, and energy efficiency, which are critical factors in modern sustainable manufacturing.
- Furthermore, the methodology can be extended to other steels and laser processing techniques, making it a useful tool for broader applications in laser surface engineering, including hardening, cladding, and surface modification.

In conclusion, the combination of numerical modeling and experimental validation provides a reliable, efficient, and practically applicable approach for optimizing laser hardening processes. The results obtained in this study offer valuable guidance for both industrial practitioners and researchers, contributing to the advancement of laser surface treatment technologies and their wider implementation in engineering practice.

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Influence of Pass Configuration, Raster Step, and Scanning Speed on Laser Color Marking of AISI 304 Steel

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Abstract—Experiments were carried out on the process of color marking with a fiber laser on AISI 304 steel samples. The influence of the number of passes - one (at 0°), two (at 0° and 90°) and three (at 0°, 60° and 120°), the raster step and the scanning speed on the roughness and the resulting colors was studied. R/G/B coordinates of all marked squares were obtained. The positions of the individual colors in the color space were determined. Graphs of the dependence of the roughness on the raster step were constructed for three speeds and for the three types of passes. The obtained results were analyzed and summarized.

Keywords— *lase rmarking, steel AISI 304, raster step, speed, color difference, chromatic distance.*

I. INTRODUCTION

Laser marking has become a widely adopted technology in modern manufacturing due to its high precision, flexibility, and non-contact nature [1] – [8]. Among the various laser-based surface processing techniques, color laser marking has gained significant attention, particularly for stainless steels, where it enables the generation of stable and reproducible colors without the use of pigments or coatings. This process relies on the controlled formation of thin oxide layers on the material surface, which produce colors through light interference effects.

AISI 304 stainless steel is one of the most commonly used austenitic steels due to its excellent corrosion resistance, mechanical properties, and wide applicability in industries such as food processing, medical equipment, construction, and consumer goods. The ability to perform color marking on this material expands its functional and

aesthetic applications, including product identification, anti-counterfeiting, branding, and decorative design.

The quality and characteristics of laser-induced colors strongly depend on process parameters such as laser power, pulse duration, scanning speed, raster step, and scanning strategy. These parameters determine the thermal input, oxidation kinetics, and surface morphology, which in turn influence both the optical properties and the roughness of the treated surface. In particular, raster-based marking strategies and multi-pass configurations introduce complex interactions between overlapping laser tracks, affecting energy distribution and heat accumulation [9] – [17].

Previous studies have shown that surface roughness plays a crucial role in color formation, as it affects light scattering and interference conditions. At the same time, scanning speed and raster step control the energy density delivered to the material, thereby influencing oxide layer thickness and uniformity [18] – [24]. However, the combined effect of these parameters, especially when different pass configurations are applied, remains insufficiently explored.

The present study aims to investigate the influence of raster step, scanning speed, and pass configuration (single-, double-, and triple-angle marking) on the surface roughness and color characteristics of AISI 304 stainless steel during fiber laser marking. By systematically analyzing these parameters and correlating them with RGB (red, green, blue) color data and surface measurements, the work seeks to provide a deeper understanding of the mechanisms governing laser color marking and to identify optimal processing conditions for achieving high-quality and reproducible results. 08X18H10

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II. MATERIALS AND METHODS

A. Material

AISI 304 stainless steel is one of the most widely used stainless steels. Нейните основни индустриални приложения са in the food-beverage industry (processing equipment, storage tanks, kitchen appliances), the construction and architecture (structural components, railings, decorative finishes), the chemical industry (piping systems, heat exchangers, storage vessels for chemicals), the medical and pharmaceutical products (surgical instruments, sterile processing systems), automotive industry (exhaust components, structural parts) and consumer products (sinks, cookware, cutlery, washing machines, water heaters).

The chemical composition of AISI 304 steel is given in Table 1. This composition is carefully balanced to ensure an optimal combination of corrosion resistance, workability, and cost.

Alloying elements influence the steel's internal structure. Carbon influences strength, hardness and ductility and weldability. It is low carbon steel and is soft, ductile and easy to weld. The high chromium content improves the corrosion resistance of this steel by making it stainless (a passive oxide layer is formed by passivation). Nickel increases its toughness and stabilizes the austenite phase.

TABLE 1 CHEMICAL COMPOSITION OF AISI 304 STEEL

Element	Content, %	Element	Content, %
C	<0.08	Ni	8.0 – 10.5
Cr	18.0 – 20.0	Mg	< 2.0
Si	< 1.0	P	< 0.045
S	< 0,03	Fe	Balance

Some physical properties of the steel are presented in Table 2. This steel has a density typical of steels and a relatively high specific heat capacity, which requires more energy to heat than low-alloy steels. Thermal conductivity is moderate, the coke is typical of stainless steels, which are not good heat conductors. It has a relatively low thermal diffusivity, as heat spreads slowly inside the material and the surface heats up faster.

TABLE 2 BASIC OPTICAL AND THERMOPHYSICAL PARAMETERS OF AISI 304 STEEL

Parameter	Value
Coefficient of thermal conductivity k , W/(m·K)	17
Density ρ , kg/m ³	7850
Specific heat capacity c , J/(kg·K)	504
Coefficient of thermal diffusivity a , m ² /s	4.3×10^{-6}

B. Laser system

A laser technological system equipped with a fiber laser Rofin PowerLine F20 Varia was used to conduct the experiments. The main technical parameters of both the laser system and the laser source are summarized in Table 3.

The laser operates in the near-infrared spectral range at a wavelength of 1064 nm, which is characteristic of ytterbium-doped fiber lasers and ensures good absorption in metallic materials such as stainless steels. The system functions in pulsed mode, allowing precise control over energy input and minimizing excessive thermal loading of the treated surface.

The laser source is distinguished by its excellent beam quality ($M^2 < 1.1$), which enables tight focusing of the beam to a small spot diameter of approximately 70 μm . This results in high power density and makes the system particularly suitable for localized surface treatment processes such as laser marking, hardening, micro-processing, and precision structuring.

Another important feature of the system is its wide operating frequency range (20–250 kHz), which allows flexibility in adjusting the interaction between the laser radiation and the material. The short pulse duration (100 ns) combined with adjustable pulse energy (0.08–1.00 mJ) and high peak power (up to 10 kW) ensures efficient energy delivery within a very short time interval. This promotes rapid heating and cooling cycles, which are essential for achieving controlled microstructural transformations without affecting the bulk material.

In addition, the laser system is characterized by high positioning accuracy ($\pm 2.5 \mu\text{m}$), enabling precise control of the processing path and repeatability of the results. The relatively high efficiency (approximately 40%) of the fiber laser contributes to reduced energy consumption and stable operation during extended experimental runs.

Overall, these characteristics make the laser system highly suitable for advanced material processing applications requiring precision, repeatability, and controlled thermal input, particularly in the treatment of stainless steels such as AISI 304.

TABLE 3 MAIN PARAMETERS OF THE LASER SYSTEM FOR MARKING WITH FIBER LASER

Parameter	Value
Wavelength λ , nm	1064
Power P , W	20
Frequency ν , kHz	20 – 250
Pulse duration τ , ns	100
Pulse energy E_p , mJ	0.08 – 1.00
Pulse power P_p , kW	0.80 - 10
Diameter in focus d , μm	70
Beam quality M^2	< 1.1
Positioning accuracy	$\pm 2.5 \mu\text{m}$

Efficiency, %	40
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C. Methodology

The experimental study was carried out through a sequence of systematically organized stages aimed at evaluating the influence of key technological parameters – namely raster pitch and scanning speed – on the surface characteristics and color properties obtained during raster laser marking of AISI 304 stainless steel.

To investigate the effect of laser scanning strategies, three marking configurations were developed:

Single-angle marking (0°)

Double-angle marking (0° and 90°)

Triple-angle marking (0° , 60° , and 120°)

For each configuration, a matrix consisting of 3 rows and 8 columns (24 squares in total) was designed, as illustrated in Figure 1. Each square had dimension of 5 mm and was raster-marked under distinct processing conditions.

Within each matrix, the raster step (distance between adjacent scan lines) was varied in the range $20\ \mu\text{m}$ to $80\ \mu\text{m}$. The scanning speed was varied from $25\ \text{mm/s}$ to $125\ \text{mm/s}$, with increments of $50\ \text{mm/s}$.

The preparation of the test specimens was the next step to ensure repeatability and reliability of results. The procedure included:

- Cutting the AISI 304 stainless steel samples to the required dimensions
- Surface grinding and polishing to obtain a uniform initial roughness
- Cleaning the surfaces to remove contaminants that could affect laser-material interaction

Proper surface preparation ensured that any observed changes in roughness and color were solely due to the laser processing parameters.

The experiments were conducted using a fiber laser system (Rofin PowerLine F20 Varia), operating in pulsed mode in the near-infrared range ($\lambda = 1064\ \text{nm}$).

Raster marking was performed by scanning the laser beam line-by-line over each square area. The variation of raster pitch and scanning speed directly influenced energy input per unit area and overlap between successive laser tracks. These factors are essential in determining the formation of oxide layers responsible for color generation on stainless steel surfaces.

Surface roughness was measured using a laser scanning microscope OLS5100, which provides high-resolution, non-contact surface profiling. The roughness analysis allowed assessment of surface morphology changes and correlation between processing parameters and surface texture

The color of each marked square was recorded and expressed in terms of RGB (Red, Green, Blue) coordinates, which represent the digital color space.

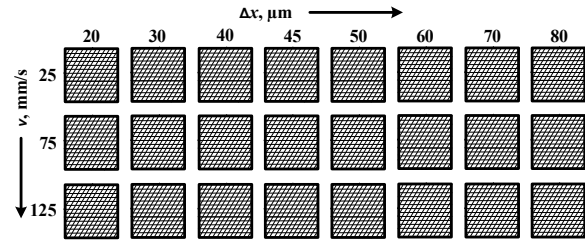


Fig. 1. Scheme of the matrix for conducting experiments on laser color marking

III. RESULTS AND DISCUSSION

After conducting the experiments and the necessary measurements, the influence of the raster pitch on the surface roughness of single-angle, double-angle and triple-angle marking and comparative analysis for a scanning speed of $125\ \text{mm/s}$ was analysed. The raster pitch varies in the range from $20\ \mu\text{m}$ to $80\ \mu\text{m}$, and three marking speeds were studied: $25\ \text{mm/s}$, $75\ \text{mm/s}$ and $125\ \text{mm/s}$. The roughness of the untreated surface is $R_a = 0.223\ \mu\text{m}$.

A. Influence of raster step on roughness

- Single-angle marking (0°)

The graphs of the dependence of the surface roughness on the raster step for three scanning speeds $25\ \text{mm/s}$, $75\ \text{mm/s}$ and $125\ \text{mm/s}$ are presented in Fig. 2. From their analysis, the following findings can be made:

- With increasing the raster step, a nonlinear increase in surface roughness is observed for the three studied speeds, which indicates that the spatial distribution of laser energy plays an important role in the formation of surface morphology;

- In the raster step interval from $20\ \mu\text{m}$ to $50\ \mu\text{m}$, the rate of increase in roughness is greater compared to that in the interval from $50\ \mu\text{m}$ to $80\ \mu\text{m}$. This behavior is explained by the scanning overlap coefficient. In the first interval, the overlap is larger, the absorbed energy is greater and surface melting occurs. In the second interval, the overlap is significantly smaller, reducing the absorbed energy compared to the first interval, which leads to a slower increase in roughness;

- At a speed of $25\ \text{mm/s}$, the roughness increases from $0.49\ \mu\text{m}$ to $0.62\ \mu\text{m}$. At a speed of $75\ \text{mm/s}$, the roughness changes from $0.43\ \mu\text{m}$ to $0.56\ \mu\text{m}$. At $125\ \text{mm/s}$, R_a increases from $0.38\ \mu\text{m}$ to $0.53\ \mu\text{m}$.

- It is indirectly obtained that with increasing speed, a decrease in roughness is observed. Moreover, at the same raster steps, the roughness at $25\ \text{mm/s}$ is about 13% higher than at $75\ \text{mm/s}$ and 30% higher than at $125\ \text{mm/s}$. It is explained by stronger thermal effects at lower scanning speeds.

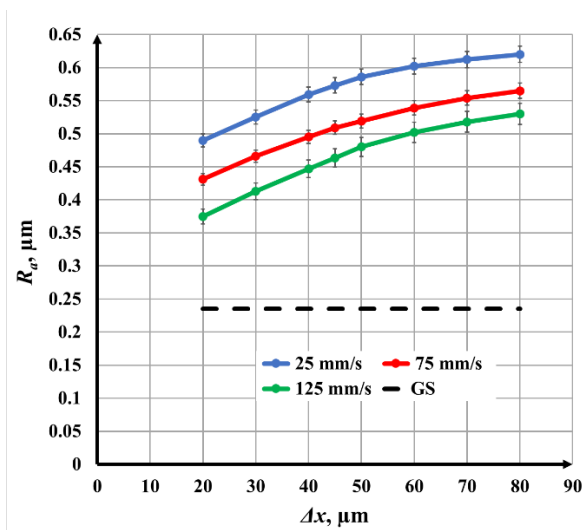


Figure 2. Graphs of roughness versus raster step for single-angle marking for three scanning speeds: blue color — 25 mm/s; orange color — 75 mm/s, and green color — 125 mm/s. The black dashed line is the roughness of the untreated surface.

- Double-angle marking (0° and 90°)

The graphs of the dependence of roughness on the raster pitch for double-angle marking are presented in Figure 3. From their analysis, the following conclusions can be drawn:

- The same trends are observed as for single-angle marking – a nonlinear increase in roughness with increasing raster step for the three studied speeds, the curves in the interval from 20 μm to 50 μm are steeper than from 50 μm to 80 μm;

- At a speed of 25 mm/s, the roughness increases from 0.41 μm to 0.54 μm. At a speed of 75 mm/s, the roughness varies from 0.34 μm to 0.49 μm. At a speed of 125 mm/s, the roughness changes from 0.29 μm to 0.45 μm;

- With increasing speed, a decrease in roughness is again observed. At a given raster step, the roughness at 25 mm/s is approximately 18% higher than at 75 mm/s and 37% higher than at 125 mm/s.

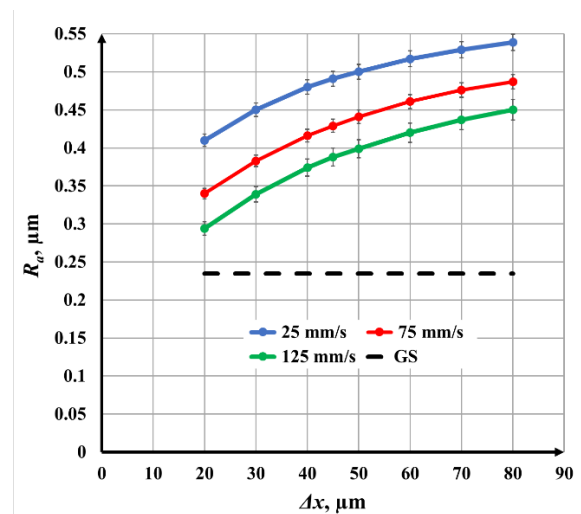


Figure 3. Graphs of roughness versus screen pitch for double-angle marking for three speeds: blue — 25 mm/s; orange — 75 mm/s and green — 125 mm/s. The black dashed line is the roughness of the unprocessed surface.

- Triple-angle marking (0°, 60° and 120°)

The graphs of the dependence of roughness on the raster pitch for triangular marking are given in Figure 4. From their analysis it follows:

- With increasing raster step, a nonlinear increase in roughness occurs. In the interval from 20 μm to 50 μm, the rate of increase in roughness is greater than that in the interval from 50 μm to 80 μm;

- At a speed of 25 mm/s, the roughness increases from 0.34 to 0.46 μm for the studied interval of the raster step. At a speed of 75 mm/s, the roughness varies from 0.29 μm to 0.41 μm. At a speed of 125 mm/s, the roughness varies from 0.25 μm to 0.37 μm;

- At equal raster steps, the roughness at 25 mm/s is approximately 15% higher than at 75 mm/s and 35% higher than at 125 mm/s.

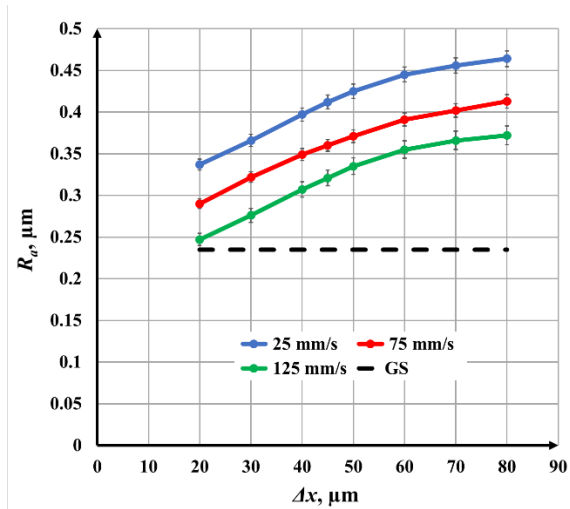


Figure 4. Graphs of the dependence of roughness on the raster step in triple-angle marking for three speeds: blue color — 25 mm/s; orange color — 75 mm/s and green color — 125 mm/s. The black dotted line is the roughness of the untreated surface.

- Comparative analysis at 125 mm/s for roughness

A comparison of single-angle, double-angle and triple-angle marking at 125 mm/s is given in Figure 5. For all scanning strategies, increasing the raster step leads to a nonlinear increase in roughness. Their roughness values differ significantly. The highest roughness is observed for single-angle marking. The roughness for double-angle marking decreases by about 18%. The reduction in roughness compared with single-angle repetition is attributed to the cross-scanning strategy, which redistributes material and partially smooths anisotropic surface characteristics. Triple-angle marking has about 32% less roughness than single-angle marking. This comparison shows that the scanning strategy has as much of a role and influence in controlling surface roughness as the raster step and scanning speed. Multidirectional scanning not only changes the surface morphology but also improves the uniformity of the marking, which is critical for stable and reproducible color generation.

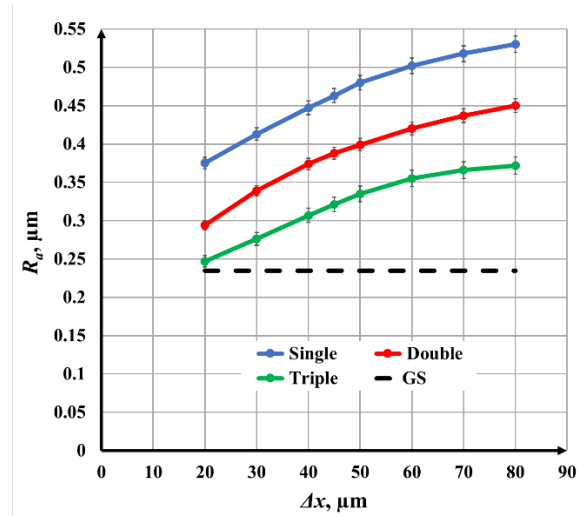


Figure 5. Graphics of the dependence of roughness on the raster step for speeds $v = 125$ mm/s: blue color – single-angle marking; red color – double-angle marking and green color – triple-angle marking. The black dotted line is the roughness of the unprocessed surface.

B. Influence of raster step on color

The color characteristics R/G/B for single-angle (0°), double-angle (0° and 90°) and triple-angle marking (0° , 60° and 120°) are summarized in Table 4, where each marked square is identified by its scanning speed and raster-step position - Table 4a for single-angle marking, Table 4b for double-angle marking and Table 4c for triple-angle marking. After using specialized software, the positions of the points in the color diagram that correspond to a specific color for each individual marked square were determined. In addition, all obtained RGB coordinates were converted to $L^*a^*b^*$. Most of the obtained colors fall within the yellow spectral region, with noticeable variations in saturation.

TABLE 4 MAIN PARAMETERS OF THE LASER SYSTEM FOR MARKING WITH FIBER LASER

$\Delta x, \mu m$ $v, mm/s$	20	30	40	45	50	60	70	80
25	1.1.1 12/0/136	1.1.2 15/36/130	1.1.3 13/135/63	1.1.4 13/135/53	1.1.5 65/140/52	1.1.6 155/230/150	1.1.7 255/255/182	1.1.8 255/255/185
75	1.3.1 255/255/90	1.3.2 255/255/144	1.3.3 255/255/173	1.3.4 255/255/183	1.3.5 255/255/195	1.3.6 255/255/205	1.3.7 255/255/212	1.3.8 255/255/219
125	1.5.1 255/255/102	1.5.2 255/255/156	1.5.3 255/255/186	1.5.4 255/255/200	1.5.5 255/255/210	1.5.6 255/255/221	1.5.7 255/255/232	1.5.8 255/255/245

a)

b)

$\Delta x, \mu\text{m}$ $v, \text{mm/s}$	20	30	40	45	50	60	70	80
25	2.1.1 0/0/151	2.1.2 0/36/145	2.1.3 0/135/29	2.1.4 0/135/42	2.1.5 50/145/57	2.1.6 140/230/145	2.1.7 255/255/166	2.1.8 255/255/170
75	2.3.1 255/255/75	2.3.2 255/255/129	2.3.3 255/255/158	2.3.4 255/255/169	2.3.5 255/255/180	2.3.6 255/255/190	2.3.7 255/255/197	2.3.8 255/255/204
125	2.5.1 255/255/87	2.5.2 255/255/141	2.5.3 255/255/171	2.5.4 255/255/185	2.5.5 255/255/195	2.5.6 255/255/206	2.5.7 255/255/217	2.5.8 255/255/230

c)

$\Delta x, \mu\text{m}$ $v, \text{mm/s}$	20	30	40	45	50	60	70	80
25	3.1.1 0/0/166	3.1.2 0/36/160	3.1.3 0/135/15	3.1.4 0/135/31	3.1.5 50/155/55	3.1.6 140/230/170	3.1.7 255/255/153	3.1.8 255/255/157
75	3.3.1 255/255/60	3.3.2 255/255/114	3.3.3 255/255/143	3.3.4 255/255/154	3.3.5 255/255/165	3.3.6 255/255/175	3.3.7 255/255/182	3.3.8 255/255/189
125	3.5.1 255/255/72	3.5.2 255/255/126	3.5.3 255/255/156	3.5.4 255/255/170	3.5.5 255/255/180	3.5.6 255/255/191	3.5.7 255/255/202	3.5.8 255/255/215

- Single-angle marking (0°)

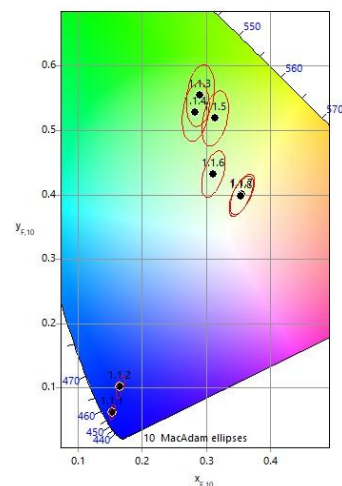
Figure 6a shows the color diagram for 25 mm/s for single-angle marking. At small raster steps (20–30 μm), low speed and small raster steps corresponding to large coverage lead to high energy absorption, melting in the impact zone and the formation of darker colors, including violet-blue tones. With increasing raster step, the scanning overlap coefficient decreases and a transition from partial melting to oxidation occurs, corresponding to a transition through a green color with various shades to a yellow color.

Figure 6b shows the resulting color diagram for a scanning speed of 75 mm/s. Due to the significantly lower energy absorption at a speed of 25 mm/s, all marked areas remain in the yellow region. A decrease in their saturation with an increase in the raster step is observed, which is explained by the gradual formation of thinner oxide layers.

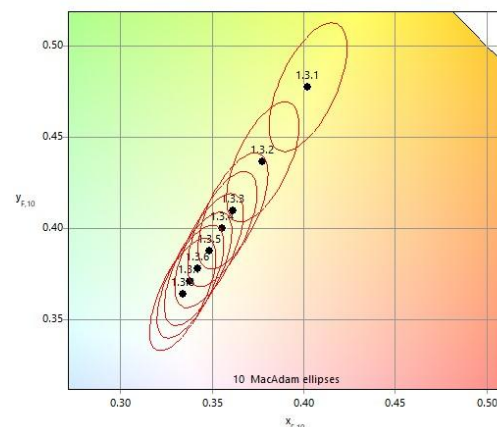
Figure 6c illustrates the results for a scanning speed of 125 mm/s. Again, yellow colors are obtained for the entire interval of the raster step and the trend of decreasing saturation with increasing raster step is maintained. Overall, the colors are less saturated than at 75 mm/s.

The analysis of the obtained results leads to the following generalizations for single-angle marking:

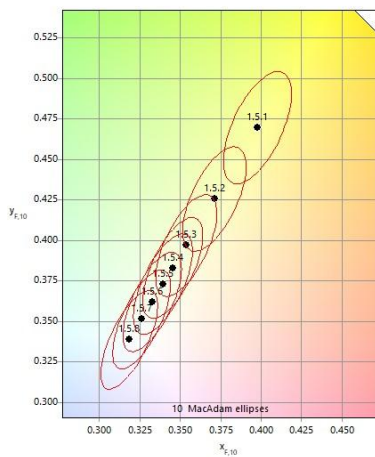
- With increasing roughness and raster step, a tendency for colors to move from darker to lighter or from more saturated to less saturated is observed;
- For a speed of 125 mm/s, the saturation of the obtained yellow colors is less than that for a speed of 75 mm/s for the entire studied interval of the raster step.



a)



b)



c)

Figure 6. Color diagram for single-angle marking for raster step in interval from 20 μm to 80 μm and speeds: a) 25 mm/s; b) 75 mm/s and c) 125 mm/s.

- Double-angle marking (0° and 90°)

Figure 7a shows the color diagram for 25 mm/s for double-angle marking. Again, the same trends are observed as with single-angle marking, namely:

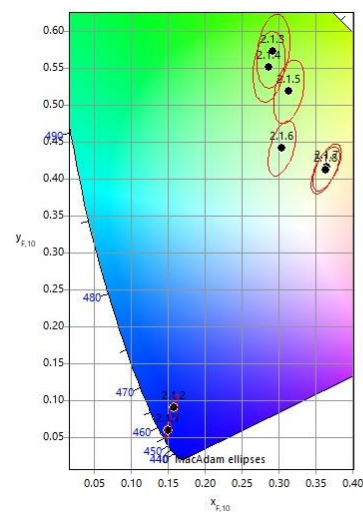
- With increasing raster step, the colors transition from dark to lighter – from blue through green to yellow with different shades;
- For a certain raster step, the saturation of the corresponding color is greater than that when marking at an angle.

Figure 7b shows the color chart for 75 mm/s for double-angle marking. Again, the same trends are observed as for single-angle marking, namely:

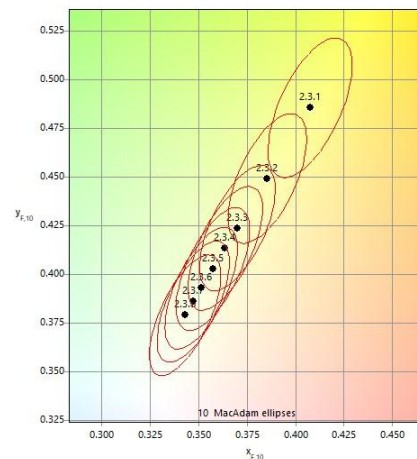
- As the raster step increases, the colors go from dark to lighter - from blue to green to yellow with different shades;
- For a given raster step, the saturation of the corresponding color is less than that at a speed of 25 mm/s.

The color diagram for 125 mm/s is presented in Figure 7c. Again, similar findings can be made as for 25 mm/s and 75 mm/s:

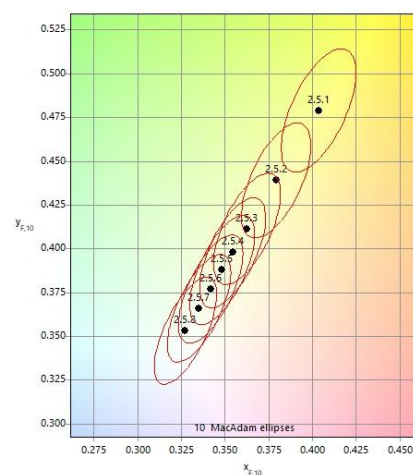
- With increasing raster step, the colors go from dark to lighter - from blue through green to yellow with different shades;
- The difference from the previous two cases is that for the speed of 125 mm/s, the color saturation for the individual raster steps is the smallest.



a)



b)



c)

Figure 7. Color diagram for double-angle marking for raster step in interval from 20 μm to 80 μm and speeds: a) 25 mm/s; b) 75 mm/s and c) 125 mm/s.

- Triple-angle marking

The color chart for 25 mm/s in triple-angle marking is presented in Figure 8a. The following trends are observed:

- With increasing raster step and roughness, the colors go from dark to lighter;
- For a given raster step, the saturation of the corresponding color is greater than that for single-angle and double-angle marking.

The color chart for 75 mm/s in triple-angle marking is given in Figure 8b. The following trends are observed:

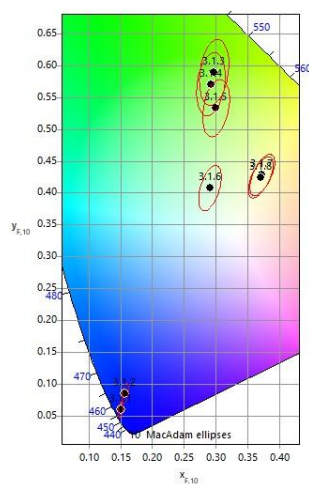
- With increasing raster step, the colors go from dark to lighter - from blue to green to yellow with different shades;
- For a given raster step, the saturation of the corresponding color is less than that at 25 mm/s.

The color chart for 125 mm/s is given in Figure 8c. From their analysis, the following conclusions can be drawn:

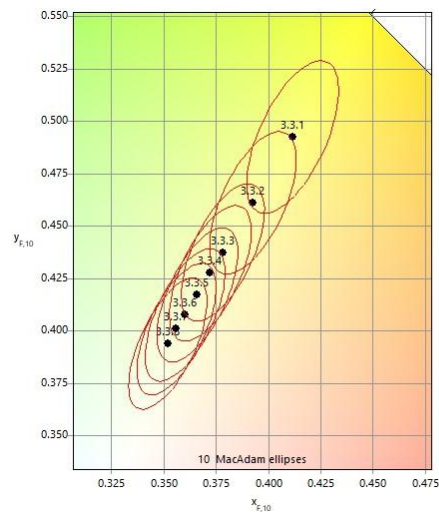
- As the raster step increases, the colors go from dark to lighter;
- For a speed of 125 mm/s, the color saturation for the individual raster steps is the lowest.

The following main conclusions can be drawn for raster color marking of AISI 304 stainless steel samples:

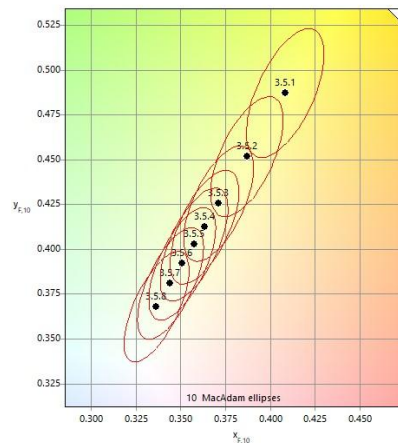
- For single-angle, double-angle and triple-angle marking, with increasing raster step and roughness, either a transition from darker colors to lighter colors or from a more saturated yellow color to a less saturated color is observed;



a)



b)



c)

Figure 8. Color diagram for double-angle marking for raster step in interval from 20 μm to 80 μm and speeds: a) 25 mm/s; b) 75 mm/s and c) 125 mm/s.

- With increasing speed, a decrease in color saturation is observed. Of the speeds studied, the least saturated colors are obtained at 125 mm/s;
- The most saturated colors are obtained with triple-angle marking, and the least saturated colors are obtained with single-angle marking.

IV. CONCLUSIONS

The present study investigates the influence of the raster pitch, scanning speed and pass configuration on the surface roughness and color characteristics obtained during laser marking of AISI 304 stainless steel.

Based on the experimental results obtained by the authors and their analysis, the following main conclusions can be drawn:

- Increasing the raster step leads to a nonlinear increase in surface roughness for all marking strategies. At the same time, it causes a transition from darker, more saturated colors to lighter, less saturated ones, due to the reduced energy load and the formation of a thinner oxide layer.
- Increasing the scanning speed leads to a decrease in surface roughness and color saturation. Higher speeds limit thermal build-up, which leads to thinner oxide layers and reduced intensity of the resulting colors.
- The scanning strategy has a significant influence on both roughness and color quality. Single-angle marking results in the highest roughness and least uniform colors. Double-angle marking improves uniformity and reduces roughness. Triple-angle marking provides the best results, with the lowest roughness and highest color saturation
- There is a strong relationship between surface morphology and optical properties. Lower roughness enhances light interference effects, resulting in more stable and saturated colors.

The results provide valuable guidance for industrial laser marking applications where precise color control and surface quality are required.

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Optimization-Based First-Order Synthesis of Infrared Triplet Systems for LWIR Imaging

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Abstract — This paper presents an optimization-based approach for the first-order design of infrared triplet systems in the LWIR spectral range. The method is based on paraxial optical theory and formulates the design task as a multi-parameter optimization problem aimed at minimizing chromatic aberrations and Petzval curvature under given constraints. Numerical optimization techniques are applied to determine the optical powers and spacing between the lenses. The obtained results demonstrate stable and physically realizable first-order solutions, validated through convergence of the iterative optimization procedure. The proposed framework provides an efficient and extensible approach for preliminary infrared optical system design.

Keywords—chromatic aberration correction, infrared optical systems, LWIR imaging, paraxial synthesis.

I. INTRODUCTION

The rapid advancement of infrared imaging technologies has significantly increased the demand for efficient and reliable optical design methodologies, particularly in the long-wavelength infrared (LWIR) spectral range (8–12 μm) [1] – [4]. Systems operating in this range are widely employed in applications such as thermal imaging, surveillance, environmental monitoring, laser material processing and industrial diagnostics, where high image quality and robust performance are essential [5] – [8].

Among classical optical configurations, triplet systems provide a compact and effective solution capable of correcting primary aberrations while maintaining moderate complexity [9] – [12]. Although originally developed for the visible spectrum, triplet-based designs remain highly relevant for infrared applications due to their favorable balance between performance, manufacturability, and system compactness [3], [5], [13]. However, extending these configurations to the LWIR range introduces

additional challenges, including limited material availability, wavelength-dependent refractive properties, and increased sensitivity to design parameters [13] – [14].

The first-order design stage plays a critical role in optical system development, as it establishes the initial distribution of optical power and element spacing, providing a foundation for subsequent high-order optimization [2], [15], [16]. In infrared optics, accurate determination of these parameters is particularly important due to the strong coupling between system geometry and optical performance.

Several studies have investigated LWIR optical systems, including thermally compensated triplets [17], diffractive–refractive configurations [18] – [20], and achromatic infrared optics [17], [21], [22]. However, many existing approaches remain application-specific, rely on complex optical elements, or lack a systematic optimization-based formulation at the first-order design level [14], [20], [21], [23]. This motivates the development of a computationally efficient framework for reproducible first-order infrared optical design.

The main contribution of this work is the formulation of the first-order design of infrared triplet systems as a constrained multi-parameter optimization problem. The proposed approach integrates paraxial optical modeling with numerical optimization techniques, enabling systematic determination of lens powers and spacing parameters while satisfying key optical requirements, including focal length, chromatic aberrations, and Petzval curvature.

The proposed framework provides a computationally efficient and physically consistent methodology suitable for preliminary optical design, serving as a reliable starting point for further refinement in advanced optical design environments.

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This underscores the current relevance of developing unified and computationally efficient methodologies for infrared optical system design. In this context, the aim of the present work is to develop a reduced-parameter optimization-based framework for the first-order synthesis of infrared triplet systems operating in the LWIR spectral range.

II. MATERIALS AND METHODS

A. Problem formulation

The design of optical systems is inherently a complex and iterative process, requiring the application of successive approximations in order to converge toward a feasible optical configuration. A critical stage in this process is the determination of a reliable first-order (paraxial) solution, which provides the initial distribution of optical power and axial separations and serves as the basis for subsequent higher-order aberration correction and numerical refinement.

Due to the nonlinear coupling between optical powers, ray heights, ray angles, and axial separations, direct analytical determination of the first-order solution is generally difficult. In addition, the governing equations may produce mathematically valid but physically impractical solutions, characterized by unrealistic lens powers or excessive axial distances. Consequently, iterative numerical procedures are commonly employed in order to determine physically meaningful first-order configurations.

For a three-element infrared triplet system, the first-order optical configuration is described by a set of external parameters independent of the detailed lens geometry. These parameters include the optical powers of the individual lenses and the axial separations between consecutive elements. Accordingly, the first-order parameter space can be represented by:

$$x = [\Phi_a, \Phi_b, \Phi_c, t_1, t_2]^T \quad (1)$$

where:

- Φ_a, Φ_b, Φ_c denote the optical powers of the first, second, and third lenses, respectively;
- t_1, t_2 denote the axial air spaces between the optical elements.

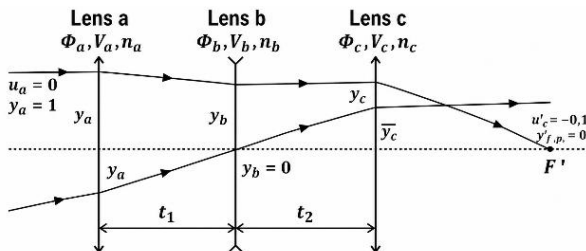


Fig. 1. Paraxial optical model of the infrared triplet

The principal paraxial quantities used in the first-order model are illustrated in Fig. 1, where y_i and $\bar{y}_i$ denote the heights of the axial and oblique paraxial rays, respectively; u'_i denotes the paraxial ray angle after the corresponding optical element.

These quantities represent the actual first-order design parameters of the optical system and define the physical configuration of the infrared triplet.

However, direct iterative optimization with respect to all components of the vector x is computationally inconvenient due to the strong interdependence between the parameters. In particular, the optical powers and axial separations are coupled through the paraxial ray-tracing equations and the chromatic and Petzval correction conditions.

For this reason, the optimization problem is reformulated using a reduced iterative parameterization [1], [2], [24], [25]. Instead of directly varying all first-order parameters, the iterative procedure is performed with respect to the axial ray angle after the first lens u'_a and the axial separation t_1 . The remaining system parameters are then determined sequentially through paraxial ray tracing, geometrical relationships, and the imposed first-order conditions.

Thus, for a fixed configuration parameter R , the reduced iterative parameter vector is defined as

$$x_R = [u'_a, t_1]^T \quad (2)$$

while the remaining quantities $\Phi_a, \Phi_b, \Phi_c, t_2$ are treated as dependent variables determined during the iterative solution process.

This reformulation significantly reduces the complexity of the optimization problem while preserving the physical interpretation of the first-order optical configuration. As a result, the proposed approach enables stable and efficient determination of physically realizable infrared triplet solutions in the LWIR spectral range.

B. Preliminary Conditions

The first-order model of the investigated infrared triplet system is formulated under a set of preliminary assumptions defining the physical and optical conditions of operation. These assumptions establish a consistent paraxial framework and simplify the initial design stage.

All optical elements are considered as thin lenses, while lens thicknesses and higher-order geometrical effects are neglected. The object is assumed to be located at infinity, corresponding to collimated incident radiation. The aperture stop is positioned at the second lens, defining the pupil configuration of the optical system.

The investigated optical system operates in the long-wavelength infrared (LWIR) spectral range 8–12 μm , which determines the relevant material properties and dispersion characteristics of the optical elements.

The effective focal length of the system is fixed at $f' = 10 \text{ mm}$.

The normalized height of the axial paraxial ray at the first lens is selected as $y_a = 1$.

The entrance angle of the axial ray is $u_a = 0$.

The focal length condition is imposed through the final angle of the axial paraxial ray after the third lens $u'_c = -0.1$.

The optical materials are selected according to their transmission properties in the LWIR spectral range. For the investigated triplet configuration, germanium (Ge) is used for the first and third lenses, while zinc selenide (ZnSe) is used for the middle lens.

C. Optical Constraints and Design Conditions

The first-order design of the investigated infrared triplet system is carried out under a prescribed set of optical constraints defining the required paraxial performance of the system.

The total optical power of the system must satisfy the effective focal length condition $\Phi_{sys} = 1/f'$.

At the paraxial level, the primary chromatic aberrations are required to be corrected. Therefore, the lateral and axial chromatic aberration constraints are imposed as $PAC_{target} = 0$ and $PLC_{target} = 0$.

The field curvature is controlled through the prescribed Petzval condition $PTZ_{target} = -0.3\Phi_{sys}$.

Unlike the chromatic aberration constraints, the Petzval sum is intentionally not forced to zero. A prescribed negative Petzval value is retained in order to provide controlled first-order field curvature, which can subsequently support balancing of higher-order aberrations during further optical refinement.

In addition, the geometrical constraints $t_1 > 0$ and $t_2 > 0$ must be satisfied in order to ensure physically realizable optical configurations.

These constraints define the admissible first-order solution space used in the subsequent iterative optimization procedure.

D. Mathematical Model

The first-order mathematical model describes the nonlinear relationships between the optical powers, axial separations, and paraxial ray parameters of the infrared triplet system.

The first-order design problem requires determination of physically admissible values of $\Phi_a, \Phi_b, \Phi_c, t_1, t_2$ satisfying the imposed optical constraints.

$$\begin{cases} \Phi_{sys} = \frac{1}{f'} = 0.1 \\ PLC(x) = PLC_{target} = 0 \\ PAC(x) = PAC_{target} = 0 \\ PTZ(x) = PTZ_{target} = -0.3\Phi_{sys} \end{cases} \quad (3)$$

Here x is a physical first-order parameter vector, not an iterative optimization vector. The reduced iterative parameterization used in the numerical procedure is introduced separately in Section E.

The total optical power of the system is given by:

$$\Phi_{sys} = \Phi_a + \Phi_b + \Phi_c - t_1\Phi_a\Phi_b -$$

$$-t_2\Phi_b\Phi_c - (t_1 + t_2)\Phi_a\Phi_c + t_1t_2\Phi_a\Phi_b\Phi_c \quad (4)$$

The Petzval sum is defined as

$$PTZ = -\sum_{i=a}^c \frac{\Phi_i}{n_i} \quad (5)$$

The chromatic correction conditions are defined as

$$PLC = \sum_{i=a}^c \frac{\Phi_i}{V_i} \quad (6)$$

$$PAC = \sum_{i=a}^c \frac{y_i\Phi_i}{V_i} \quad (7)$$

Equations (4)–(7) define the nonlinear algebraic system governing the first-order design problem

$$\begin{cases} \Phi_{sys} = \Phi_a + \Phi_b + \Phi_c - t_1\Phi_a\Phi_b - t_2\Phi_b\Phi_c - \\ \quad -(t_1 + t_2)\Phi_a\Phi_c + t_1t_2\Phi_a\Phi_b\Phi_c = 0.1 \\ PLC(x) = \sum_{i=a}^c \frac{\Phi_i}{V_i} = 0 \\ PAC(x) = \sum_{i=a}^c \frac{y_i\Phi_i}{V_i} = 0 \\ PTZ(x) = -\sum_{i=a}^c \frac{\Phi_i}{n_i} = -0.3\Phi_{sys} \end{cases} \quad (8)$$

System (8) represents a nonlinear algebraic system with respect to the unknown parameters $\Phi_a, \Phi_b, \Phi_c, t_1, t_2$, defining the feasible first-order configurations of the optical system under the imposed constraints.

E. Methodology

The determination of the first-order solution for the investigated infrared triplet system is performed through a constrained iterative optimization procedure based on paraxial optical theory. The proposed methodology combines a reduced parameterization of the design problem with sequential paraxial ray tracing and aberration evaluation.

Unlike conventional approaches based on direct optimization of all first-order parameters, the present method employs a reduced iterative parameter vector (2) for a fixed spacing ratio $R = t_2/t_1$.

The remaining first-order parameters $\Phi_a, \Phi_b, \Phi_c, t_2$ are determined sequentially during the iterative process through the paraxial governing equations and the imposed optical constraints.

The optimization problem is formulated through the objective function:

$$F(u'_a, t_1; R) = w_1 PAC^2 + w_2 (PTZ - PTZ_{target})^2 \quad (9)$$

where:

- w_1 and w_2 are weighting coefficients;
- $PTZ_{target} = -0.3\Phi_{sys}$.

Since the lateral chromatic aberration condition $PLC = 0$ is imposed structurally through the adopted

parameterization and material assignment, it is not included explicitly in the objective function.

The proposed iterative methodology consists of the following computational steps.

Step 1 — Selection of the Spacing Ratio

A value of the spacing ratio $R = t_2/t_1$ is prescribed.

This parameter determines the proportional relationship between the axial separations and, through the lateral chromatic correction condition, establishes a functional dependency between the optical powers of lenses a and c .

Step 2 — Initialization of the Iterative Variables

An initial approximation of the reduced parameter vector is selected

$$\mathbf{x}_R^{(0)} = [u_a^{(0)}, t_1^{(0)}]^T \quad (10)$$

The initialization is guided by first-order optical design heuristics $t_1^{(0)} \approx 0.3f'$ while $y_a = 1$ and $u_a = 0$ are preserved during the entire iterative process.

The second axial separation is determined from

$$t_2 = Rt_1 \quad (11)$$

Step 3 — Material Assignment

The optical materials are fixed according to their transmission properties in the LWIR spectral range:

- first lens a : Germanium (Ge);
- second lens b : Zinc Selenide (ZnSe);
- third lens c : Germanium (Ge).

Thus $V_a = V_c$ which enables structural implementation of the lateral chromatic correction condition.

The optical properties of the selected LWIR materials are:

$$Ge \left(\begin{matrix} V_a = V_c = 869.13 \\ n_a = n_c = 4.02 \end{matrix} \right) \text{ and } ZnSe \left(\begin{matrix} V_b = 57.18 \\ n_b = 2.42 \end{matrix} \right)$$

Step 4 — Structural Chromatic Constraint

The lateral chromatic aberration condition $PLC = 0$ is imposed directly as a structural condition.

Using $PLC = \sum_{i=a}^c \frac{\Phi_i}{V_i} = 0$ and the identical material assignment for lenses a and c , a functional relationship is obtained between the optical powers of the first and third lenses.

Step 5 — Paraxial Ray Tracing

For the current iterative state

$$\mathbf{x}_R^{(k)} = [u_a^{(k)}, t_1^{(k)}]^T \quad (12)$$

the paraxial ray tracing procedure is performed sequentially through the optical system

$$y_{i+1} = y_i + t_i u_i' \text{ and } u_i' = u_i - y_i \Phi_i \quad (13)$$

These relations provide the ray geometry required for evaluation of the first-order aberrations.

Step 6 — Determination of the Optical Powers

Using the paraxial propagation equations together with the imposed constraints $\Phi_{sys} = \frac{1}{f'}$ and $PLC = 0$ the optical powers Φ_a, Φ_b, Φ_c are determined sequentially for the current iterative state.

Step 7 — Aberration Evaluation

The first-order aberrations are evaluated for the current configuration $PAC^{(k)}$ and $PTZ^{(k)}$ using the governing equations of the mathematical model.

Step 8 — Objective Function Evaluation

The objective function value is computed.

$$F^{(k)} = w_1(PAC^{(k)})^2 + w_2(PTZ^{(k)} - PTZ_{target})^2 \quad (14)$$

It provides a scalar measure of deviation from the required optical performance.

Step 9 — Iterative Update

The reduced parameter vector is updated iteratively

$$\mathbf{x}_R^{(k+1)} = \mathbf{x}_R^{(k)} + \Delta \mathbf{x}_R^{(k)} \quad (15)$$

corresponding to directed modification of u_a' and t_1 in order to minimize the objective function. The iterative corrections $\Delta \mathbf{x}_R^{(k)}$ are selected adaptively according to the current deviation from the imposed first-order constraints. At each iteration, the update direction is chosen so as to reduce the objective function value, while the step magnitude is adjusted empirically in order to ensure stable numerical convergence and preservation of physically realizable optical configurations.

Step 10 — Convergence Criterion

The iterative process continues until convergence is achieved

$$|F^{(k+1)} - F^{(k)}| < \varepsilon \quad (16)$$

or equivalently $PAC \approx 0$ and $PTZ \approx PTZ_{target}$, where $\varepsilon = 10^{-6}$. The convergence tolerance was selected sufficiently small to ensure numerical stability and accurate satisfaction of the imposed paraxial constraints.

Step 11 — Final First-Order Solution

Upon convergence, the obtained values $\Phi_a^*, \Phi_b^*, \Phi_c^*, t_1^*, t_2^*$ represent the optimized first-order solution of the infrared triplet system.

The resulting configuration provides a physically realizable paraxial starting point suitable for subsequent higher-order optical refinement and detailed numerical optimization.

The flowchart of the proposed iterative optimization algorithm is presented in Fig. 2.

III. RESULTS AND DISCUSSION

A. Iterative Optimization Results

The proposed optimization-based methodology was applied to the first-order design of an infrared triplet system operating in the LWIR spectral range 8–12 μm . The investigated optical configuration consisted of a positive-negative-positive triplet using germanium (Ge) for the first and third lenses and zinc selenide (ZnSe) for the middle lens.

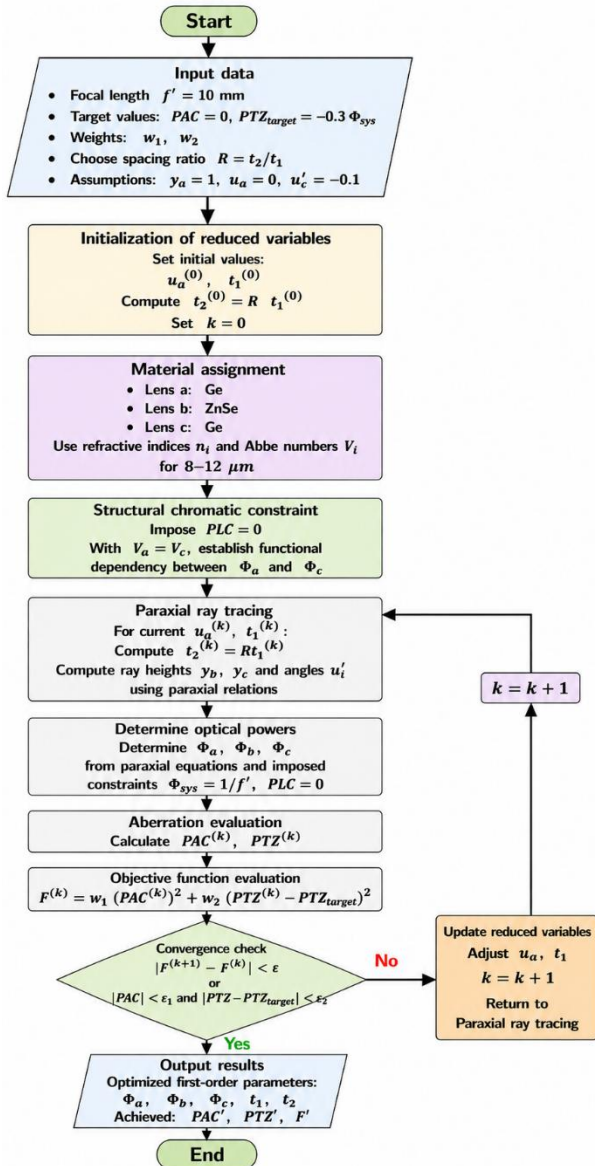


Fig. 2. Flowchart of the proposed optimization-based methodology illustrating the reduced-parameter iterative optimization procedure

The optimization procedure was performed for several prescribed values of the spacing ratio R . For each selected value of R , the reduced iterative parameter vector $\mathbf{x}_R = [u'_a, t_1]^T$ was iteratively updated until convergence of the objective function was achieved. During the iterative process, the optical powers Φ_a , Φ_b , and Φ_c , together with the axial separation t_2 , were determined sequentially through the paraxial governing equations and the imposed first-order constraints.

The optimization process converged successfully for all investigated configurations, producing physically realizable first-order solutions satisfying the imposed optical conditions (3).

The obtained results demonstrate that the proposed reduced-parameter formulation provides stable convergence behavior while preserving the physical consistency of the infrared triplet configuration.

Table I summarizes the optimized first-order solutions obtained for different values of the spacing ratio R .

TABLE I OPTIMIZED FIRST-ORDER SOLUTION FOR DIFFERENT VALUES OF THE SPACING RATIO R

R	u'_a	t_1 [mm]	t_2 [mm]	Φ_a [mm ⁻¹]	Φ_b [mm ⁻¹]	Φ_c [mm ⁻¹]
0.5	-0.03942	5.313	2.657	0.03942	-0.00891	0.09598
1.0	-0.06374	3.286	3.286	0.06374	-0.00891	0.07166
1.5	-0.07814	2.680	4.020	0.07814	-0.00891	0.05725
2.0	-0.08771	2.388	4.775	0.08771	-0.00891	0.04768
2.5	-0.09454	2.215	5.538	0.09454	-0.00891	0.04086
3.0	-0.09965	2.101	6.304	0.09965	-0.00891	0.03574
3.5	-0.10363	2.021	7.073	0.10363	-0.00891	0.03177
4.0	-0.10681	1.961	7.843	0.10681	-0.00891	0.02859
4.5	-0.10941	1.914	8.613	0.10941	-0.00891	0.02599
5.0	-0.11158	1.877	9.384	0.11158	-0.00891	0.02382

Fig. 3 illustrates the variation of the optical powers of the three triplet elements as a function of the spacing ratio R . The obtained results demonstrate redistribution of optical power between the first and third lenses with increasing values of R , while the optical power of the negative middle lens remained nearly constant throughout the investigated range. This behavior confirms the stability of the proposed reduced-parameter optimization framework and preserves the classical positive-negative-positive triplet configuration.

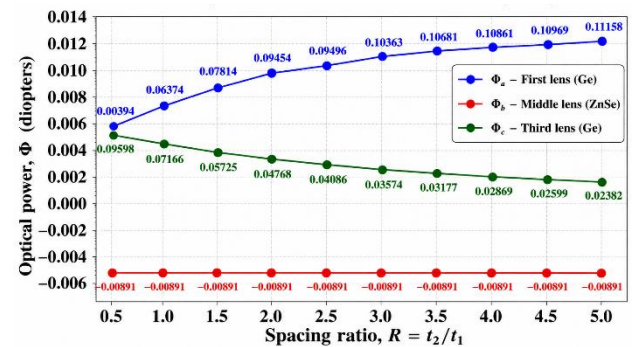


Fig. 3. Variation of optical powers as a function of the spacing ratio $R = t_2/t_1$.

The results indicate that the lateral chromatic aberration remained structurally corrected throughout the optimization process due to the adopted material configuration and parameterization strategy. Consequently, the iterative optimization was primarily focused on minimization of the axial chromatic aberration and control of the Petzval curvature.

It was observed that increasing the spacing ratio R modifies both the distribution of optical powers and the axial geometry of the system. Larger values of R generally resulted in increased axial separation t_2 , accompanied by redistribution of optical power between the first and third lenses in order to preserve the imposed first-order constraints.

B. Convergence Behavior of the Iterative Procedure

The obtained numerical results demonstrated stable convergence behavior for all investigated configurations. In all examined cases, the objective function decreased monotonically during the iterative process, indicating stable numerical performance of the proposed optimization framework.

Table II presents a representative convergence sequence obtained for $R = 1$.

TABLE II REPRESENTATIVE CONVERGENCE SEQUENCE FOR $R = 1$

k	u'a	t1 [mm]	PAC	u'c	F
0	-0.05000	3.000	-3.88×10^{-6}	-0.10415	1.72×10^{-5}
1	-0.07030	2.971	2.82×10^{-6}	-0.10252	6.37×10^{-6}
2	-0.06379	3.254	2.67×10^{-8}	-0.10026	6.57×10^{-8}
3	-0.06374	3.286	-2.40×10^{-10}	-0.10000	3.24×10^{-17}
4	-0.06374	3.286	2.30×10^{-15}	-0.10000	4.93×10^{-24}

The convergence sequence confirms rapid reduction of the objective function and stabilization of the iterative variables after a limited number of iterations. The axial chromatic aberration converged toward zero, while the Petzval condition approached the prescribed target value with high numerical accuracy.

Fig. 4 illustrates the convergence behavior of the objective function during the iterative optimization process.

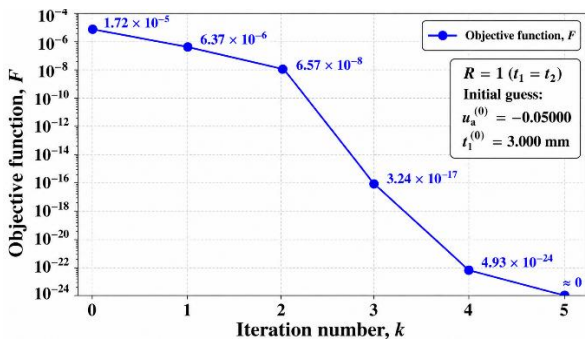


Fig. 4. Convergence of the objective function during the iterative optimization procedure for $R = 1$.

The obtained convergence characteristics indicate stable numerical behavior and physically consistent first-

order solutions throughout the investigated range of spacing ratios R .

C. Influence of the Spacing Ratio R

The obtained results demonstrate that the spacing ratio R acts as an effective first-order control parameter governing both the optical power distribution and the axial geometry of the infrared triplet system. Increasing values of R lead to redistribution of positive optical power from the third lens toward the first lens, while preserving physically realizable positive-negative-positive triplet configurations.

D. Physical Interpretation of the Obtained Solutions

The obtained first-order solutions preserve the classical positive-negative-positive triplet structure characteristic of Cooke-type optical systems. The selected Ge/ZnSe/Ge material combination enables simultaneous satisfaction of the imposed chromatic and Petzval constraints while maintaining physically realizable optical configurations suitable for subsequent higher-order refinement.

IV. CONCLUSIONS

A first-order methodology for the design of infrared triplet optical systems operating in the LWIR spectral range (8–12 μm) has been presented. The proposed approach formulates the paraxial synthesis problem as a constrained multi-parameter optimization task in which the optical powers of the three lenses and the axial separations between them are determined simultaneously under predefined first-order conditions. The design procedure combines paraxial ray tracing with iterative numerical optimization in order to satisfy the imposed constraints related to system optical power, chromatic correction, and Petzval balance.

The obtained results demonstrate that physically meaningful infrared triplet configurations can be achieved for a wide range of spacing ratios $R = t_2/t_1$. The performed analysis shows that the parameter R acts as an effective first-order control variable governing both the axial geometry and the optical power distribution within the system. Increasing values of R lead to systematic redistribution of positive optical power toward the first lens, accompanied by a corresponding reduction of the optical power of the third lens. Simultaneously, the axial geometry of the system changes in a predictable manner while preserving the required first-order aberration conditions.

The study further demonstrates that the imposed paraxial constraints $PLC = 0$, $PAC = 0$ and $PTZ = -0.3\Phi_{\text{sys}}$ can be satisfied simultaneously through appropriate selection of the optical powers and air gaps. The obtained solutions confirm the strong coupling between chromatic correction, Petzval compensation, and axial spacing in infrared triplet systems. Consequently, the spacing ratio should not be interpreted merely as a geometrical parameter, but rather as a governing variable influencing the global first-order balance of the optical system.

The proposed methodology is based on a paraxial thin-lens approximation and therefore does not include higher-order aberrations, real lens geometries, diffraction effects, or thermo-optical influences. Nevertheless, the obtained first-order solutions provide a stable and physically consistent initial configuration suitable for subsequent detailed optical optimization.

Future work will include extension of the proposed methodology toward real optical surfaces, incorporation of higher-order aberration correction, thermo-optical analysis for infrared materials, and numerical validation using professional optical design software environments such as Zemax Optic Studio, CODE V and OSLO.

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