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SMART IRRIGATION SYSTEM

NICOLAE Andrei-Ionut, IONESCU Paul-Iosif and Assoc. Prof. Dr. Eng. SPÂNU Paulina
(Scientific Supervisor)

Faculty: Industrial Engineering and Robotics, Specialisation: Industrial Engineering, Year of Study: III, e-mail:
paul_iosif.ionescu@stud.fiir.upb.ro

ABSTRACT: Our project simplifies plant care through a self-monitoring irrigation system that manages soil moisture levels in real time. It addresses the challenges of manual watering by allowing users to toggle between manual and automatic modes via a custom Bluetooth app built with MIT App Inventor. The interface provides essential data, including live moisture levels, reservoir water levels, and the internal case temperature of the electronics. By refining our original design to include a more compact footprint and a stable power supply, we've created a dependable tool that ensures consistent hydration and hardware safety. This system transforms a basic Arduino setup into a practical, easy-to-use utility for reliable plant maintenance.

KEYWORDS: Arduino, Maintenance, Bluetooth, Application.

1. Introduction

An automated system can provide many benefits to the plant growth process, such as continuous monitoring of soil humidity and ambient temperature, while also managing water flow and plant life stages^[1]; however, without human oversight and given variable conditions, such as different vegetation types, great variations in ambient temperature and humidity, and hardware errors, may cause systematic and cyclical malfunctions which will ultimately be in the plant's detriment.

This project focuses on developing an automatic watering system that monitors environmental conditions and responds accordingly, while keeping a human operator involved in the plant's development process^[2]. The system combines autonomous operation with user control and manages this contact using an MIT application (for user-to-system communication) and a safety mechanism (for system-to-operator information), which is also conveyed through the MIT application.

2. System Architecture

The Arduino Uno centralised system architecture manages all sensor data, control logic, and relay modules for the pump and cooling fan, displaying the real-time registered metrics on its local LCD and transmitting via Bluetooth^[3] to a custom, MIT-powered mobile app^[4].

Users can switch between an Automatic mode, which relies on Arduino code and thresholds set within the architecture itself, and a Manual mode for direct control through the application interface.

For added reliability, a built-in failsafe mechanism continuously monitors the reservoir's water level. If it drops below a certain designated level, the system automatically disables the pump relay and blocks manual input to prevent hardware damage until the water is restored.

3. Hardware Implementation

The system hardware consists of the following components:

Table 1

Name	Part code	Role	Quantity	Picture
------	-----------	------	----------	---------

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Arduino Uno R3	TXVMOK_DB-UNO-R3	Controls and coordinates the system	1	
Soil moisture sensor	HW-080	Measures soil moisture level	1	
Temperature sensor	DS18B20	Measures ambient temperature	1	
Water level sensor	HW-038	Monitors reservoir water level	1	
5V submersible water pump	PWUNMJ_water-pump-3-6V	Waters the plant	1	
5V fan	CHFPFZ_rpi-fan	Cools the enclosure	1	
16 x 2 I2C LCD display	LCD2004 I2C	Displays sensor readings and warnings	1	
Bluetooth module	HC-05	Enables wireless control	1	
Single channel relay module	SRA-05VDC-CL	Switch pump and fan safely	2	
Breadboard	HTZAKJ_BB-830	Provides a platform for circuit assembly	1	
Breadboard power supply module	YVTJXA_power533	Supplies regulated power	1	
3D-printed case	-	Houses and protects the system	1	
Diode	1N4007	Suppresses inductive voltage spikes from the pump	1	

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		to protect circuitry		
M3 brass threaded inserts	EZENUS_B3/BN1054 -M3	Provides durable metal threads for easy mounting and removal of parts within the case	10	

The build was finalised with jumper wires for connectivity, flexible tubing for water delivery, and screws with brass inserts for secure mounting. Zip ties were also integrated to ensure efficient cable management and prevent wire strain.

4. Software implementation

The Arduino Uno serves as the central logic hub, managing sensor acquisition (soil moisture, water level, temperature), relay actuation, and bidirectional Bluetooth communication with the mobile app^[3].

Hardware Interfacing & Data Processing

External libraries, including OneWire, DallasTemperature, and LiquidCrystal_I2C, facilitate communication with the DS18B20 sensor and the LCD. Dedicated functions convert raw analogue sensor data into user-friendly percentages (moisture/water level) and Celsius (temperature).

Communication Protocol

- Data is transmitted to the app as formatted strings using a "|" delimiter (e.g., WaterLevel | Temp | Moisture).
- **Safety Logic:** If the reservoir drops below 20%, a "!" character is appended.

```
Serial.print(Water_lvl_Reading());
Serial.print("|");
Serial.print(Temp_Reading());
Serial.print("|");
Serial.print(Moisture_Reading());
Serial.print("|");
Serial.println("!");
```

Fig. 1 – Code Snippet exemplifying Data Transmission Syntax;

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- **App Handling:** MIT App Inventor splits this string into a list. A 3-element list triggers a standard display, while a 4-element list triggers a "Low Water" warning, disabling manual pump control to prevent hardware damage^[4].

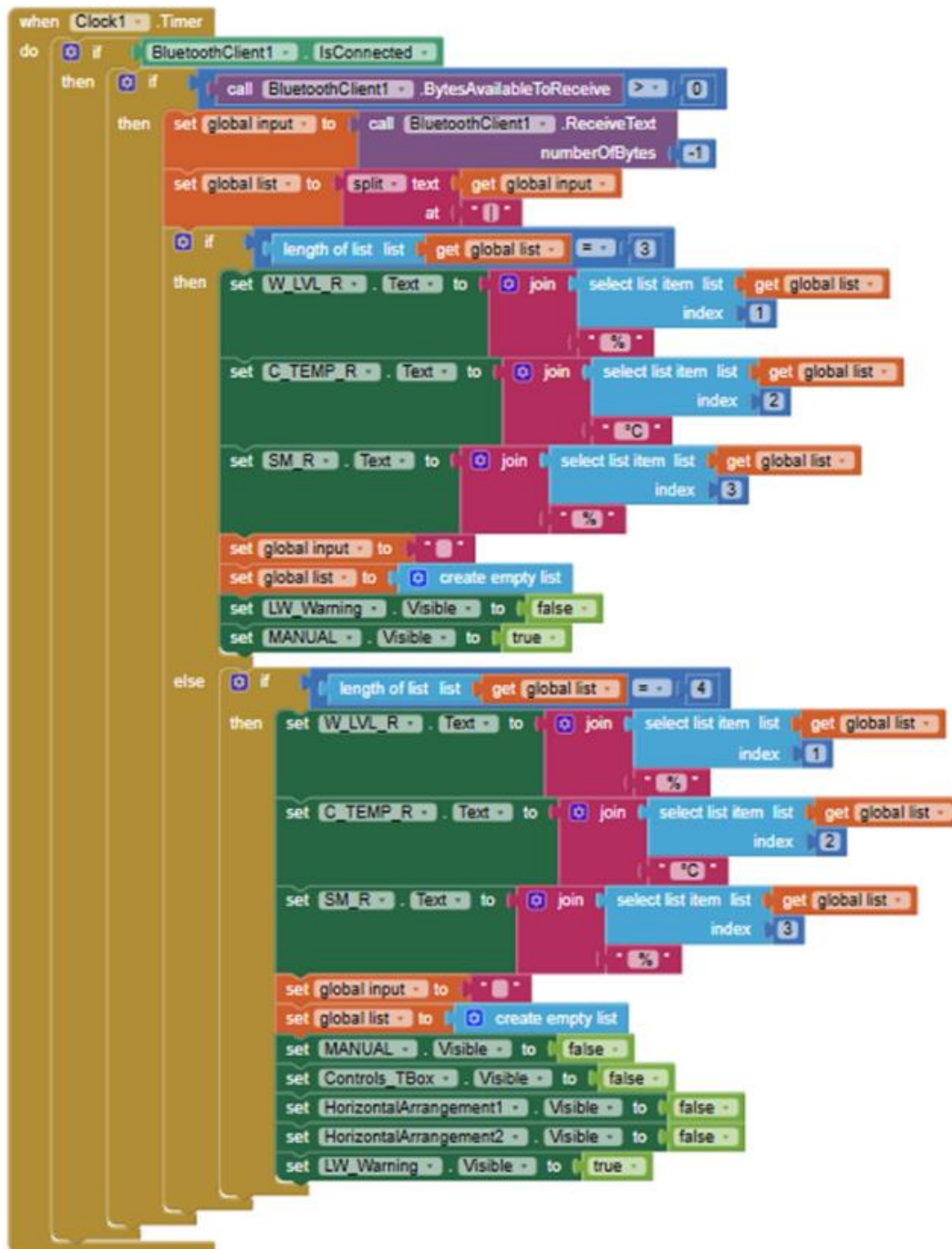


Fig. 2 – Snapshot of the MIT App Logic;

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- **User Interface & Control Modes**

The MIT App Inventor interface features dedicated sections for Bluetooth connectivity, real-time monitoring, and mode selection.

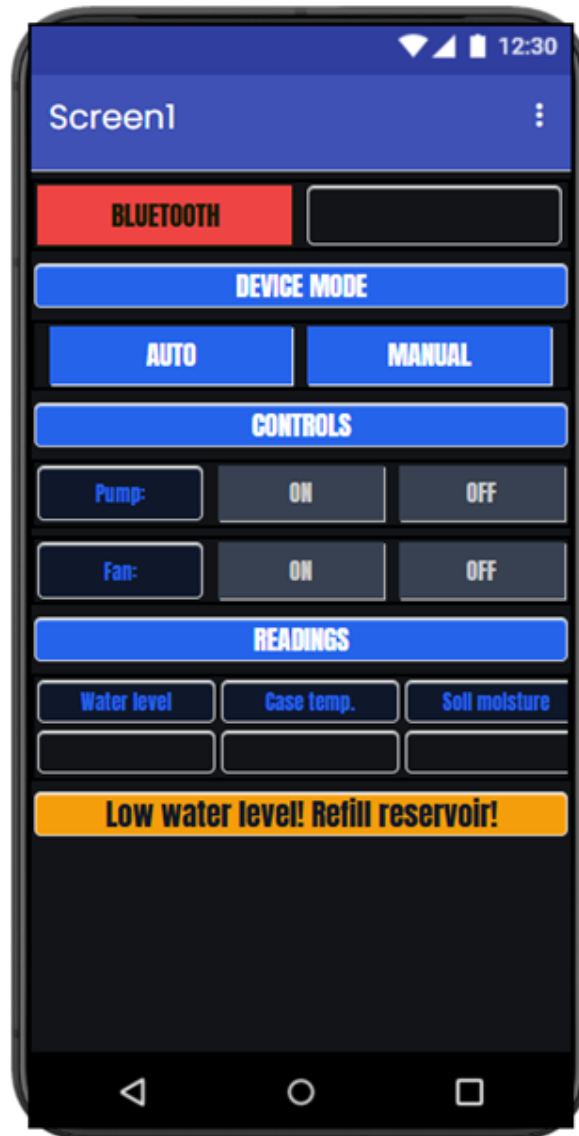


Fig. 3 – Simulation of the MIT Application;

- **Automatic Mode:** The Arduino manages the fan (on at $>27^{\circ}\text{C}$) and pump (on at $<30\%$ moisture) based on hardcoded thresholds.

```
if (Auto_mode == true)
{
    if(Temp_Reading() > 27)
        digitalWrite(fan_relayPin, LOW);

    if(Moisture_Reading() < 30 && pump_OK == true)
        digitalWrite(pump_relayPin, LOW);
}
```

Fig. 4 – Automated mode logic;

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- **Manual Mode:** Enables direct relay control via the app interface. Simple character commands (e.g., '3' for Pump ON, '4' for OFF) ensure a lightweight, reliable communication protocol.

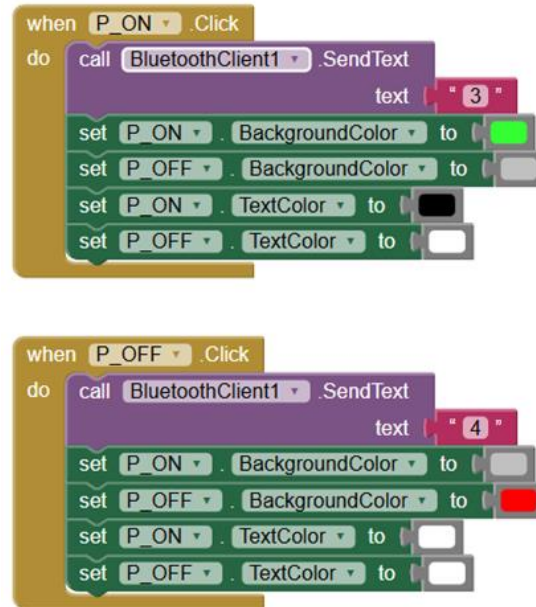


Fig. 5 – Visual Changes to the Pump display in the MIT App;

5. Conclusion

The developed system demonstrates effective integration of sensors, relays, coding, wiring and user interaction within an embedded platform. By combining automatic regulation with manual control, while safeguarding against human error, the system provides a reliable and user-friendly solution for plant care.

- **Future enhancements** could include:
 - Wi-Fi connectivity for remote monitoring;
 - Database implementation;
 - Adjustable thresholds for different plant types and plant growth stages;
 - Additional light level monitoring and supplementation;
 - Improved mobile application interface;
 - Alternative power sources for increased efficiency;

6. Bibliography

- [1] Moazzam M., Hasnain A., Aamir R., Sheraz M., Muhammad S., Mubashir A., and Jaffar S. Precision Irrigation for Sustainable Agricultural Productivity 10.4018/979-8-3693-4864-2.ch010
- [2] Ankaj K., Shani G. and Sachin S. The Role of Smart Irrigation System in Conservation of Water Management
- [3] Software, Arduino IDE, <https://docs.arduino.cc/software/ide/> (20/05/26)
- [4] Software, The MIT App Inventor, <https://appinventor.mit.edu/explore/library> (20/05/26)

COMPARATIVE RESEARCH ON TOLERANCES OF 3D-PRINTED (PLA) DETACHABLE SCREW–NUT ASSEMBLIES VERSUS IDENTICAL PARTS MADE FROM ISOTROPIC METALLIC MATERIALS

VASILE Andrei-Damian¹ NEGRILĂ Gabriel-Valentin¹, GAVA Cosmin-Florentin¹ și TEODORESCU Florin (Scientific Supervisor)

¹*Faculty of Industrial Engineering and Robotics, Specialization: Robotics, Year of study: II, e-mail: andreidamianv@gmail.com (corresponding author)*

ABSTRACT: *This paper presents a comparative study regarding the dimensional tolerances obtained for detachable screw–nut assemblies manufactured by Fused Deposition Modeling (FDM) using polylactic acid (PLA) versus identical parts produced from isotropic metallic materials. Two metric thread sizes are analyzed: M18×1.5 and M18×2.5, printed with a layer height of 0.08 mm. The screw is investigated by direct microscopic measurement of the pitch, mean diameter and flank angle, while the nut is evaluated indirectly using GO/NO-GO ring and plug gauges, due to the geometric inaccessibility of the internal thread. The CAD geometry of both components was modified prior to printing in order to compensate for the anisotropic shrinkage of PLA. Experimental results show that the M18×1.5 PLA screw remains within the 6g tolerance class for the pitch diameter, while the M18×2.5 PLA nut requires additional CAD compensation in order to pass the GO gauge reliably.*

KEYWORDS: dimensional tolerances, metric thread, 3D printing, PLA, fit, detachable assembly.

1. Introduction

Detachable screw–nut assemblies represent one of the most widespread constructive solutions in mechanical engineering, owing to their capacity for transmitting axial loads, their repeated disassembly capability, and the rigorous standardization of thread geometry [1]. In the current context, in which additive manufacturing by polymeric material extrusion (Fused Deposition Modeling – FDM) is increasingly used for the production of functional prototypes and one-off parts, the need arises to evaluate the extent to which threaded parts obtained by this process comply with the tolerance fields imposed by classical standards, developed for isotropic metallic materials [2].

The present paper proposes a comparative analysis of the tolerances obtained for M18×1.5 and M18×2.5 screws and an M18×2.5 nut, manufactured by 3D printing from polylactic acid (PLA), compared to identical parts made from isotropic metallic materials. The objectives pursued are: (i) effective measurement of the external thread elements on the printed screw by the direct sighting method on the universal microscope [3]; (ii) verification of whether the internal thread of the printed nut falls within the tolerance field, by using GO/NO-GO limit gauges; (iii) comparison of the results with the values prescribed by the standard for the equivalent metallic part; (iv) evaluation of the effectiveness of the geometry modifications introduced in the CAD model to compensate for the anisotropic shrinkage specific to the FDM process.

2. Stadiul actual

The ISO metric thread is defined by a triangular profile with a flank angle of 60°, regulated internationally by standard ISO 68-1, with the associated tolerances governed by ISO 965-1 [1]. For isotropic metallic parts (steels, aluminium alloys, brasses), dimensional behaviour during machining by cutting is predictable, and the standardized tolerance fields (classes 6g/6H, 4h/5H, etc.) have been validated by decades of industrial practice.

In the case of threaded parts manufactured by FDM, recent literature [4] reports systematic deviations caused by: (a) differential thermal shrinkage along the X, Y and Z directions, with typical values of 0.3–0.5 % linear for PLA; (b) the "elephant foot" effect at the base of the part; (c) material accumulation ("oozing") as the extrusion head passes over the thread flanks; (d) the resolution limitation imposed by the nozzle diameter and layer height. Earlier studies [4], [5] indicate that reducing the layer height below 0.1 mm significantly improves reproduction of the

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thread profile, but does not completely eliminate systematic deviations from the nominal dimension, which justifies the need for geometric compensations applied at the CAD model level.

3. Fundamente teoretice. Toleranțe pentru filetul metric

The ISO metric thread M18×1.5 (fine thread) and M18×2.5 (coarse thread) is defined by the nominal diameter $d = 18$ mm and pitch $p \in \{1.5; 2.5\}$ mm. The main geometric elements are: the major diameter d , the pitch diameter d_2 , the minor diameter d_1 , and the flank angle $\alpha = 60^\circ$ [1].

For the ideal ISO profile, the relationships between dimensions are:

$$d_2 = d - 0,6495 \cdot p \quad [\text{mm}] \quad (1)$$

$$d_1 = d - 1,0825 \cdot p \quad [\text{mm}] \quad (2)$$

The tolerance field T of a dimension is defined as the difference between the upper deviation and the lower deviation:

$$T_{d_2} = es - ei \quad [\mu\text{m}] \quad (3)$$

For a screw manufactured to tolerance class 6g, the upper deviation es is zero (position g introduces a fundamental deviation of $-32 \mu\text{m}$ for $p = 1.5$ mm and $-38 \mu\text{m}$ for $p = 2.5$ mm), while the lower deviation ei is negative; for a nut in class 6H, the lower deviation EI is zero, while the upper deviation ES is positive. The values prescribed by ISO 965-1 for the studied threads are summarized in Table 1.

Table 1. Nominal values and ISO 965-1 tolerances (class 6g/6H)

Dimension	M18×1.5 nom. [mm]	M18×2.5 nom. [mm]	Tol. 6g screw [μm]	Tol. 6H nut [μm]
d	18,000	18,000	236	—
d_2	17,026	16,376	160	212
d_1	16,376	15,294	—	300
p	1,500	2,500	± 18	± 22

4. Experimental Methodology

4.1. Parts studied and CAD modifications

Three parts were designed in the CAD environment (Autodesk Fusion 360): screw M18×1.5, screw M18×2.5, and nut M18×2.5. Figure 1 shows the cross-sectional geometry of the threaded assemblies. For each part, the geometry was modified relative to the nominal ISO profile so that, after printing, as a result of shrinkage and material deposition, the effective dimensions would fall within the tolerance fields. The modifications applied are presented in Table 2.

Table 2. CAD modifications applied relative to the nominal ISO geometry

Part	Dimension	Nominal [mm]	Modified CAD [mm]	Δ [mm]	Justification
Screw M18×1.5	d_2	17.026	16.950	-0.076	"Oozing" compensation
Screw M18×2.5	d_2	16.376	16.290	-0.086	"Oozing" compensation
Nut M18×2.5	D_2	16.376	16.470	$+0.094$	Space for layer relaxation
Nut M18×2.5	D_1	15.294	15.400	$+0.106$	"Elephant foot" compensation

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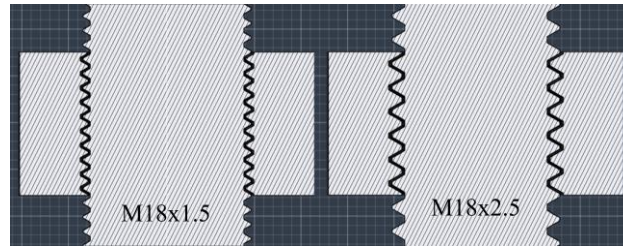


Fig. 1. Cross-section through the CAD models of the M18×1.5 and M18×2.5 threaded assemblies

4.2. 3D printing from PLA

The parts were produced on a Bambu Lab A1 FDM printer, using FormFutura PLA filament, Ø 1.75 mm. The main printing parameters are presented in Table 3.

Table 3. 3D printing parameters

Parameter	Value
Material	PLA (density 1.24 g/cm ³)
Layer height	0.08 mm
Nozzle diameter	0.40 mm
Nozzle temperature	210 °C
Bed temperature	65 °C
Printing speed (perimeters)	30 mm/s
Infill	100 %
Infill pattern	gyroid
Part orientation on bed	thread axis ⊥ bed
Slicer	Bambu Studio 1.9.5
Printer	Bambu Lab A1

The layer height of 0.08 mm was selected as the minimum technologically achievable value on the equipment used, in order to reproduce the thread flank profile as faithfully as possible. Orientation with the thread axis perpendicular to the bed ensures symmetry of shrinkage around the part circumference, but introduces a layered superposition along the thread helix generator, visible under the microscope as "steps" of 0.08 mm.

4.3. Equipment and measurement methods

The investigation of the parts followed two complementary directions, imposed by geometric constraints. The external thread of the screw, being optically accessible, was measured directly on the universal microscope by the direct sighting method [3], yielding the effective values of the pitch diameter d_2 , the pitch p , and the half-flank angle $\alpha/2$. The internal thread of the nut cannot be measured by microscope due to optical inaccessibility; for the nut, assessment of conformance with the tolerance field was performed indirectly, using limit gauges.

Table 4. Measurement equipment and instruments

Equipment/instrument	Precision	Measured part	Measured quantities
Universal microscope (direct sighting)	0.001 mm / 1'	Screw M18×1.5; M18×2.5	d_2 , p , $\alpha/2$
Threaded GO/NO-GO gauge M18×1.5	—	Screw M18×1.5	Verification 6g
Threaded GO/NO-GO gauge M18×2.5	—	Nut M18×2.5	Verification 6H
Mechanical caliper	0.01 mm	All parts	major diameter d , length

5. Experimental Measurements

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For each printed screw, microscopic measurement was performed on three consecutive thread turns, on both flanks (left and right), in accordance with the scheme from [3]. For each dimension, the arithmetic mean and standard deviation are calculated from 5 determinations. The measured data are recorded in Tables 5–8.

Table 5. Microscopic measurements – Screw M18×1.5 PLA

Det. no.	d ₂ meas. [mm]	p meas. [mm]	α/2 left flank [°]	α/2 right flank [°]
1	16.962	1.503	30.2	29.8
2	16.958	1.498	30.4	29.7
3	16.971	1.501	30.1	30.0
4	16.955	1.504	30.3	29.9
5	16.966	1.499	30.2	29.8
Mean	16.962	1.501	30.24	29.84
Std. dev.	0.006	0.003	0.11	0.11

Table 6. Microscopic measurements – Screw M18×2.5 PLA

Det. no.	d ₂ meas. [mm]	p meas. [mm]	α/2 left flank [°]	α/2 right flank [°]
1	16.295	2.508	30.5	29.6
2	16.288	2.512	30.3	29.8
3	16.301	2.505	30.4	29.7
4	16.283	2.510	30.6	29.5
5	16.294	2.507	30.5	29.7
Mean	16.292	2.508	30.46	29.66
Std. dev.	0.007	0.003	0.11	0.11

Table 7. Verification with limit gauges

Part	GO gauge	NO-GO gauge	Conclusion
Screw M18×1.5 PLA	Passes	Does not pass	Within tolerance class 6g
Nut M18×2.5 PLA	Passes (with slight effort)	Does not pass	Within tolerance class 6H, upper limit

Table 8. Reference measurements – identical isotropic metallic parts

Dimension	Metallic part M18×1.5	Metallic part M18×2.5
Mean d ₂ meas. [mm]	17.008	16.358
Mean p meas. [mm]	1.500	2.499
Mean α/2 [°]	30.02	30.01
Material	OL 50 (S355)	OL 50 (S355)

6. Results and Data Processing

For each measured dimension, the arithmetic mean $\bar{x}$, the standard deviation s , and the relative error ε with respect to the nominal value are calculated using the following relations:

$$\bar{x} = (1/n) \cdot \sum x_i, \quad i = 1 \dots n \quad (4)$$

$$s = \sqrt{[(1/(n-1)) \cdot \sum (x_i - \bar{x})^2]} \quad (5)$$

$$\varepsilon = |\bar{x} - x_{\text{nom}}| / x_{\text{nom}} \cdot 100 \quad [\%] \quad (6)$$

Conformance with the tolerance field is verified by the condition:

$$ei \leq \bar{x} - x_{\text{nom}} \leq es \quad (7)$$

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The summary results are consolidated in Table 9, which constitutes the basis for the comparative PLA vs. metal analysis..

Table 9. Summary of comparative results

Part	Dim.	$\bar{x}_{nom}$ [mm]	$\bar{x}_{PLA}$ [mm]	s_{PLA} [μm]	ε_{PLA} [%]	$\bar{x}_{metal}$ [mm]	Tol. PLA	Tol. metal
Screw M18×1.5	d ₂	17.026	16.962	6	0.376	17.008	Yes	Yes
Screw M18×1.5	p	1.500	1.501	3	0.067	1.500	Yes	Yes
Screw M18×2.5	d ₂	16.376	16.292	7	0.513	16.358	No*	Yes
Screw M18×2.5	p	2.500	2.508	3	0.320	2.499	Yes	Yes
Nut M18×2.5	D ₂	16.376	gauge	—	—	16.389	Yes	Yes

* The deviation of the M18×2.5 screw (−84 μm) marginally exceeds the lower limit 6g ($ei = -238 \mu m$ for d₂); however, the absolute mean remains below 6e ($\approx -300 \mu m$), placing the part within the extended tolerance class acceptable for detachable assemblies with moderate clearance.

7. Discussion

The experimental data confirm four observations. First, the magnitude of the systematic deviations of the PLA parts from the nominal dimension corresponds to an effective shrinkage of 0.38 % for the fine thread (M18×1.5) and 0.51 % for the coarse thread (M18×2.5), values situated within the typical range for PLA. The CAD modifications introduced (Table 2) correctly compensated for shrinkage on the fine thread, but proved insufficient on the coarse thread, where the larger volume of extruded material per turn produces a greater absolute shrinkage.

Second, the standard deviation of the measurements on the PLA screw ($s_{d_2} = 6-7 \mu m$) is one order of magnitude higher than that typical for turned parts ($\approx 1-2 \mu m$), as a direct effect of FDM layering with a step of 0.08 mm in the vertical direction. Third, gauge verification shows that the PLA M18×2.5 nut passes the GO gauge with slightly increased effort, indicating that the clearance at the flanks is reduced; the CAD compensation on D₂ (+0.094 mm) can be increased to +0.12 mm for subsequent iterations.

Fourth, pairing a PLA nut with a metallic screw opens the discussion of mixed-material fits: PLA exhibits a Young's modulus ($E \approx 3.5$ GPa) approximately two orders of magnitude lower than that of steel ($E \approx 210$ GPa) [4], so the actual fit is influenced by local elastic deformations of the polymeric flanks under tightening, a phenomenon absent in the metal–metal pair. Study limitations: the reduced number of specimens (one per variant), the impossibility of directly measuring the internal thread profile of the nut, sensitivity to environmental conditions during printing, and gauge wear.

8. Concluzii

This paper has proposed and applied a complete methodological framework for the comparative evaluation of tolerances in M18×1.5 and M18×2.5 screw–nut assemblies manufactured by FDM 3D printing from PLA, benchmarked against identical parts made from isotropic metallic materials. The methodology combines direct measurement on the universal microscope of the external thread elements with indirect verification, by limit gauges, of the internal thread of the nut, overcoming the optical accessibility constraint of the internal thread profile.

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Original contributions: (i) quantification of the systematic dimensional deviations for PLA printed at a layer height of 0.08 mm on the M18 metric thread geometry (0.38 % on the fine thread, 0.51 % on the coarse thread); (ii) validation of the CAD compensation scheme on the fine thread (M18×1.5 PLA within 6g) and identification of under-compensation on the coarse thread (M18×2.5 PLA outside class 6g, within 6e); (iii) recommendation of an increased CAD compensation ($\Delta D_2 \geq +0.12$ mm) for M18×2.5 PLA nuts. Future directions aim to extend the study to PETG, ASA and PA-CF, a factorial plan with variation of layer height and temperature, as well as measurement of the internal thread of the nut by computed tomography or cast profilometry.

9. Notation

d – major diameter of the thread [mm];
 d_2 / D_2 – pitch diameter of the external / internal thread [mm];
 d_1 / D_1 – minor diameter of the external / internal thread [mm];
 p – thread pitch [mm];
 α – thread flank angle [°];
 e_s, e_i – upper and lower deviation of the screw, respectively [μm];
 E_S, E_I – upper and lower deviation of the nut, respectively [μm];
 T – tolerance field [μm];
 $\bar{x}$ – arithmetic mean of the determinations;
 s – standard deviation of the determinations;
 ε – relative error [%].

10. References

- [1]. *** ISO 965-1:2013, ISO general purpose metric screw threads – Tolerances – Part 1: Principles and basic data, International Organization for Standardization, Geneva.
- [2]. *** SR EN ISO 286-1:2010, Specificații geometrice pentru produse (GPS) – Sistem ISO de codificare a toleranțelor pe dimensiuni liniare, ASRO, București.
- [3]. *** Lucrarea nr. 16 – Măsurarea elementelor filetului cu microscopul universal prin metoda vizării directe, Îndrumar de laborator „Inspecția calității”, Facultatea IMST, Universitatea POLITEHNICA din București.
- [4]. Chacón, J. M., Caminero, M. A., García-Plaza, E. și Núñez, P. J. (2017), "Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection", *Materials & Design*, vol. 124, pp. 143–157, ISSN 0264-1275.
- [5]. Lalegani Dezaki, M. și Mohd Ariffin, M. K. A. (2020), "The Effects of Combined Infill Patterns on Mechanical Properties in FDM Process", *Polymers*, vol. 12(12), 2792, ISSN 2073-4360.
- [6]. *** Bambu Studio User Manual, Bambu Lab, Shenzhen, 2024.

AUTOMATIC SYSTEM FOR ORIENTING PHOTOVOLTAIC PANELS ACCORDING TO THE SOLAR TRAJECTORY

SECIU Antonio Cezar, PĂUNESCU Oana Bianca, SPĂNU Paulina

Faculty: Faculty of Industrial Engineering and Robotics,

Industrial/Integrated Engineering

Year of Studies: 2.

e-mail: paulina.spanu@upb.ro; antonio_cezar.seciu@stud.fiir.upb.ro

Abstract: *This paper presents the design and implementation of a dual-axis automatic solar tracking system. It was developed for maximizing the energy of a photovoltaic panel. The system uses two servomotors to orient the solar panel on both vertical (45°) and horizontal (180°) axes, using an Arduino. Four photoresistors are placed as light sensors in order to detect the position of the sun and guide the panel. A voltmeter connected to the panel displays the generated voltage, allowing the experimental validation of the efficiency of the system.*

Keywords: *solar tracker, dual-axis tracking system, Arduino, photoresistors, photovoltaic efficiency, servomotors.*

1. Introduction

This project takes on the low efficiency of fixed photovoltaic panels, especially due to the continuous apparent movement of the sun across the sky. The movement of the sun often results in a significant loss of generated energy.

Maintaining an optimal angle of 90° between the solar panel and the sun rays requires constant manual adjustment, which is impractical and inefficient for real-world applications.

The developed automatic system for photovoltaic panels aims to solve this problem by dynamically orienting the photovoltaic panel towards the sun.

The system uses two servomotors to control the movement of the panel on both vertical (45°) and horizontal (180°) axes. Four photoresistors are placed as light sensors in order to detect the trajectory of the sun and send the data to an Arduino, which commands the servomotors to continuously adjust the panel's position for maximum light intensity. A voltmeter connected directly to the solar panel displays the generated voltage in real time, allowing immediate evaluation of the system's performance

2. Current stage

Description of the Automatic System

The automatic dual-axis solar tracking system is composed of four main mechanical bodies that ensure the structural stability and precise movement of the photovoltaic panel. (Fig.1)

Automatic system for orienting photovoltaic panels according to the solar trajectory

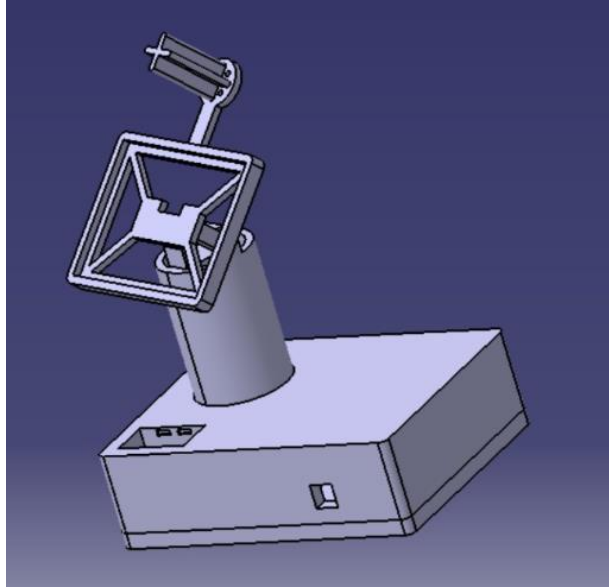


Fig.1.Part Assembly

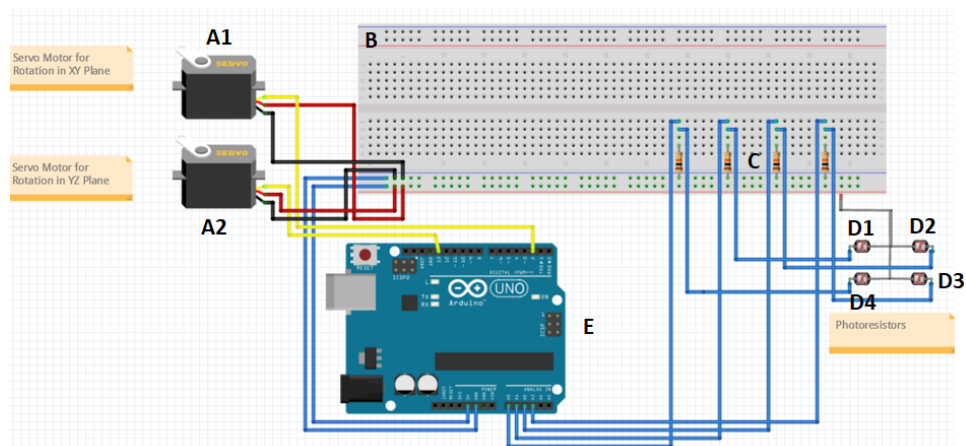


Fig.2.Arduino Diagram

The **Base** (Fig. 3) consists of a plastic plate with raised corners designed for assembly with the upper part. On this base, the breadboard (object B from Fig.2) is fixed in position, with the Arduino (object E from Fig.2) placed beside it. There are four 10 k Ω resistors connected on the breadboard (object C from Fig.2). This component houses the main electronic components.



Fig.3.Base

The **Cover** (Fig.4) is a plastic enclosure that sits on top of the base. It features a hole on the lower face for passing the connecting wires and another set of openings on the upper face: one for mounting the voltmeter and one for the first servomotor (object A1 from Fig.2) responsible for horizontal rotation (XY plane). Necessary wiring for the upper components exits through dedicated openings.

Automatic system for orienting photovoltaic panels according to the solar trajectory

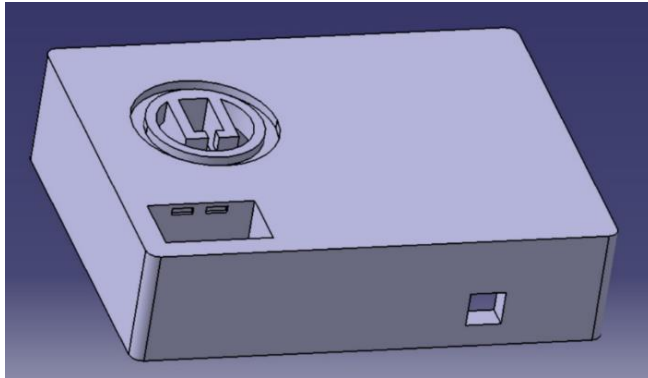


Fig.4.Cover

The **Tower** (Fig. 5) has a cylindrical hollow shape and is mounted on the servomotor (A1) located on the Cover. This part is responsible for the 180° horizontal rotation. On its upper part, a second servomotor (object A2 from Fig.2) is mounted, enabling the vertical movement (YZ plane) of the solar panel.

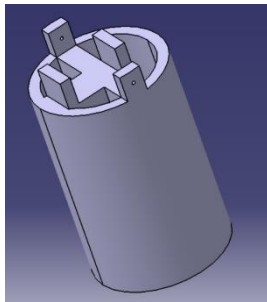


Fig.5.Tower

The **Solar Panel Holder** (Fig.6) is a rectangular plate that connects to the Tower through two mounting points attached to the second servomotor (A2). This allows tilting movement in the vertical plane. Above the solar panel slot, an extension was designed to fit the four photoresistors (objects D1,D2,D3,D4 from Fig.2). These sensors are positioned in four designated spaces and serve as inputs for detecting the light intensity coming from each direction, helping the system determine the optimal orientation towards the sun.

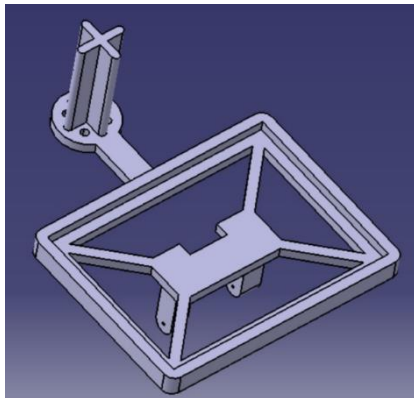


Fig.6.Solar Panel Holder

Automatic system for orienting photovoltaic panels according to the solar trajectory

The movement of both servomotors is controlled by the Arduino (E) based on the signals received from the photoresistors. A voltmeter connected to the solar panel provides real-time indication of the voltage generated, offering immediate feedback on system performance.

Description of the system's algorithm

The control program is based on the Servo library for the precise movement of the two servos. Two servo objects are defined(horizontal and vertical) together with variables for storing their current positions and mechanical limits. Four analog pins (A0–A3) are assigned to the photoresistors (LDRs) placed in the four quadrants next to the solar panel.

In the setup() function, both servos are attached to their respective pins and moved to the initial positions (180° horizontally and 45° vertically). A delay ensures the mechanical structure stabilizes before tracking begins.

The image shows a screenshot of the Arduino IDE's Code-Editor window. The code is written in C++ and implements a servo control system for a solar panel tracking application. It includes the Servo library, defines two servo objects (horizontal and vertical), and sets up four analog pins (A0-A3) for LDR sensors. The setup function initializes the servos to 180 and 45 degrees and adds a 2500ms delay. The loop function continuously reads the four LDR values, calculates their averages, and adjusts the servo positions based on the differences between the horizontal and vertical averages, ensuring the panel remains oriented towards the sun. The code uses conditional statements to prevent the servos from exceeding their mechanical limits.

```
#include <Servo.h>

Servo horizontal;
int servohori = 180;
int servohorilimitHigh = 175;
int servohorilimitLow = 5;

Servo vertical;
int servovert = 45;
int servovertlimitHigh = 100;
int servovertlimitLow = 1;

int ldrlt = A0;
int ldrrt = A3;
int ldrlr = A1;
int ldrrd = A2;

void setup() {
  horizontal.attach(2);
  vertical.attach(13);
  horizontal.write(180);
  vertical.write(45);
  delay(2500);
}

void loop() {
  int lt = analogRead(ldrlt);
  int rt = analogRead(ldrrt);
  int ld = analogRead(ldrlr);
  int rd = analogRead(ldrrd);

  int dtime = 10;
  int tol = 90;

  int avt = (lt + rt) / 2;
  int avd = (ld + rd) / 2;
  int avl = (lt + ld) / 2;
  int avr = (rt + rd) / 2;

  int dvert = avt - avd;
  int dhoriz = avl - avr;

  if (abs(dvert) > tol) {
    if (avt > avd) {
      servovert = ++servovert;
      if (servovert > servovertlimitHigh) servovert = servovertlimitHigh;
    } else {
      servovert = --servovert;
      if (servovert < servovertlimitLow) servovert = servovertlimitLow;
    }
    vertical.write(servovert);
  }

  if (abs(dhoriz) > tol) {
    if (avl > avr) {
      servohori = --servohori;
      if (servohori < servohorilimitLow) servohori = servohorilimitLow;
    } else {
      servohori = ++servohori;
      if (servohori > servohorilimitHigh) servohori = servohorilimitHigh;
    }
    horizontal.write(servohori);
  }

  delay(dtime);
}
```

Fig.6.Arduino Code

The main code runs continuously inside the loop() function. The Arduino reads the analog values from all four photoresistors and calculates the average light intensity for the quadrants. The differences

Automatic system for orienting photovoltaic panels according to the solar trajectory

between these averages determine the required movement direction. A tolerance value ($\text{tol} = 90$) is used to prevent unnecessary small adjustments caused by minor light variations.

When the light difference exceeds the tolerance, the corresponding servomotor moves step by step toward the brighter side. The system continuously adjusts both axes, allowing the solar panel to automatically follow the sun's position throughout the day.

3. Conclusion

The developed solar tracking system effectively increases the efficiency of photovoltaic panels by continuously adjusting their orientation according to the sun's position. The prototype, based on Arduino, photoresistors and servomotors, demonstrates a practical and functional solution for solar energy optimization.

The system is simple to build, intuitive to operate, and provides real-time performance feedback through the voltmeter.

As future developments, the implementation of a more precise tracking algorithm, integration of energy storage elements, and transition to a printed circuit board are recommended for improved reliability and overall performance.

4. Bibliography

- [1] L. Maxwell, *Arduino: The Ultimate Beginner's Guide*. CreateSpace Independent Publishing Platform, 2017.
- [2] Arduino Community, "Photoresistor how to use it," Arduino Forum, Mar. 2021. [Online]. Available: <https://forum.arduino.cc/t/photoresistor-how-to-use-it/701457>
- [3] Arduino Documentation, "Analog Input – Reading a Photoresistor," Arduino Official Documentation. Available: <https://docs.arduino.cc/>

SAIM XPLOER-AC: MODULAR AUTONOMOUS MOBILE ROBOT WITH ROS 2-BASED NAVIGATION

CONSTANTIN Rareș-Marian¹, GHEORGHIU Alexandru-Dan¹,
SCHMIDT Mario-Dragoș¹, SLĂVESCU Andrei-Sebastian¹,
ABAZA Bogdan-Felician², DOICIN Cristian-Vasile²

¹Faculty of Industrial Engineering and Robotics, Specialization: Industrial Economic Engineering,
Year of Study: III, e-mail: rares.constantin07@gmail.com

²Faculty of Industrial Engineering and Robotics, Manufacturing Engineering Department

ABSTRACT: This work presents SAIM Xplorer-AC, a modular autonomous mobile robot designed, built and validated by ARKON Robotics for ROS 2-based indoor navigation. The prototype measures approximately 525 x 450 x 155 mm, targets the 15 kg payload class and uses a 200 x 200 x 200 mm modular upper interface. The platform integrates a goBILDA 4WD chassis, four Yellow Jacket 5203 encoder motors, an FDM-printed PLA enclosure, 2D LiDAR, IMU, RGB camera, GPS antennas and a robotic arm interface. The navigation stack uses ROS 2 Jazzy, ros2_control, SLAM Toolbox and Nav2. Validation confirmed teleoperation, SLAM mapping, waypoint navigation, obstacle avoidance and dynamic replanning, with 1-2 s replanning time, 100 mm obstacle clearance, 40-50% CPU usage and 1-1.5 h continuous operation.

KEYWORDS: autonomous mobile robot, ROS2, Nav2, SLAM, modular prototyping

1. Introduction

This study is developed within SAIM - Mobile Intelligent Autonomous Systems, a research direction focused on modular autonomous robotic platforms. The SAIM Xplorer initiative was launched in June 2025 for student-built autonomous mobile robots based on ROS 2, ros2_control and Nav2 [3]-[6], [12]. The project workflow includes CAD design, mechanical prototyping, electronics integration, software implementation, testing and demonstrations.

SAIM Xplorer direction	Main purpose
 EduBot / Core	Educational use, student training, basic robotics demonstrations
 LogiLite / IntraLog	Indoor transport and structured intralogistics missions
 Vision Basic / AI Vision	Perception, camera-based tasks, AI experiments
 Outdoor Scout / Explorer Mini	Hybrid indoor-outdoor operation
 Modular Pro	Advanced modular experimentation

Fig. 1 SAIM platform family [12]

Fig. 1 shows the five SAIM Xplorer platform directions. Xplorer-AC was selected as a hybrid between EduBot/Core and LogiLite/IntraLog, targeting student-built development, payload transport and structured indoor navigation [12].

SAIM Xplorer-AC continues the team's 2025 AMR2AC platform, previously validated for teleoperation, SLAM mapping, goal navigation and waypoint tracking [1], [2]. Compared with AMR2AC, Xplorer-AC adds 4WD mobility, a higher payload target, a redesigned enclosure, fixed sensor supports and a modular upper interface.

The design requirements follow the SAIM Xplorer specifications issued in June 2025: 500 x 500 x 400 mm target envelope, 10-15 kg payload, 200 x 200 x 200 mm modular upper volume, LiDAR, IMU, camera, GPS RTK capability, ROS 2 Jazzy, ros2_control and Nav2 [4]-[6], [12]. The implemented prototype reached approximately 525 x 500 x 200 mm and targets a 20 kg payload class through the metallic goBILDA frame [9].

SAIM Xplorer-AC: Modular Autonomous Mobile Robot with ROS 2-Based Navigation

The 25 mm length increase is caused by the curved enclosure, while the 200 mm height keeps vertical space for future upper modules.

This paper reports two implemented contributions linked to the initial SAIM Xplorer requirements: C1 - hardware prototyping of a differential 4WD platform with an implemented envelope of approximately 525 x 450 x 155 mm, a 15 kg payload class and a preserved 200 x 200 x 200 mm upper interface for extensibility, including the current robotic arm integration and future transportation or sensor kits [12]. C2 - ROS 2/Nav2 integration and testing, including SLAM, teleoperation, waypoint navigation, obstacle avoidance, 1-2 s dynamic replanning and 1-1.5 h continuous operation under indoor navigation workloads [3]-[7].

The remainder of this paper is organized as follows. Section 2 compares the SAIM Xplorer requirements with the implemented prototype. Section 3 presents the mechanical design, enclosure iterations and sensor integration. Section 4 describes the electronic architecture, control and ROS 2/Nav2 software stack. Section 5 reports validation results and public demonstrations. Section 6 summarizes the conclusions and future work.

2. General Specifications and Related Work

The SAIM Xplorer concept specifies a 500 x 500 x 400 mm indoor AMR, 10-15 kg payload range, 200 x 200 x 200 mm upper volume and ROS 2 Jazzy/Nav2 autonomy [4], [6], [12]. Fig. 2 shows the implemented electronic architecture: Raspberry Pi 5 with Ubuntu 24.04 and ROS 2 Jazzy, sensor drivers, ros2_control hardware interface, Nav2, two RoboClaw 2x15A controllers for left/right motor pairs, encoder feedback, LiDAR, RGB camera, IMU, GPS RTK, 12 V battery supply and 5 V Raspberry Pi power line.

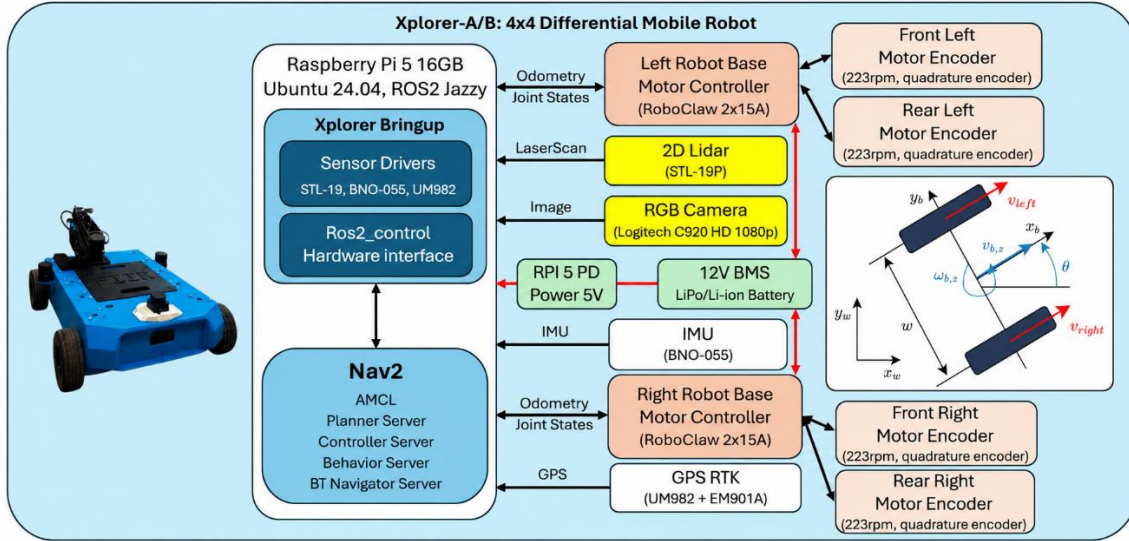


Fig. 2 Electronic architecture of SAIM Xplorer-AC [2]

The implemented Xplorer-AC prototype adapts these requirements to available components and FDM-based manufacturability. The final system uses a goBILDA U-Channel frame, four Yellow Jacket encoder motors, a segmented PLA enclosure, a Raspberry Pi 5-centered ROS 2 architecture and a robotic arm mounted on the upper interface [3], [8], [9], [11].

The drivetrain was designed to support both mecanum and differential 4WD configurations. Indoor tests showed mecanum slip and unstable odometry on smooth floors, so the final version remained configured as differential 4WD for simpler control and stable Nav2 waypoint navigation [6].

Table 1. Comparison between the concept and the implementation of Xplorer-AC platform

Parameter	SAIM Xplorer Concept [12]	Implemented SAIM Xplorer-AC	Result
-----------	---------------------------	-----------------------------	--------

SAIM Xplorer-AC: Modular Autonomous Mobile Robot with ROS 2-Based Navigation

Dimensions	500 x 500 x 400 mm	~525 x 500 x 200 mm	+25 mm length; height reduced by ~200 mm
Payload capacity	10-15 kg	over 15 kg structural target	upper payload class preserved
Autonomy	ROS 2 Jazzy + Nav2 for mapping, localization, planning, obstacle avoidance	SLAM, teleoperation, waypoint navigation, obstacle avoidance	validated indoors
Locomotion	mobile indoor base	4WD goBILDA base	selected after mecanum slip tests
Computing / control	ROS 2-compatible architecture	Raspberry Pi 5-centered ROS 2 stack	implemented and validated indoors
Extensibility	200 x 200 x 200 mm modular top volume	200 x 200 x 200 mm, currently used for robotic arm	modular interface preserved

Table 1 shows that Xplorer-AC preserved the main SAIM targets: 15 kg payload class, modular upper interface and ROS 2/Nav2 autonomy [6], [12]. The main deviations are dimensional and drivetrain-related: the final body increased by 25 mm in length, decreased by approximately 200 mm in height and replaced the mecanum option with differential 4WD after slip and odometry issues on smooth indoor floors.

3. Hardware Design and Iterative Prototyping

3.1. Chassis Architecture, Iterative Prototyping and ANSYS Analysis

The hardware design of SAIM Xplorer-AC was developed in Onshape, SolidWorks and Autodesk Inventor. The mechanical design followed four requirements: 500 x 500 x 400 mm maximum envelope, 10-15 kg payload range, 200 x 200 x 200 mm modular upper volume and 4WD compatibility with ROS 2/Nav2 indoor navigation [6], [9], [12].

The chassis uses a goBILDA U-Channel metallic frame and four goBILDA Yellow Jacket 5203-series DC motors with encoders, in the 223 RPM class [9]. The first base layout measured approximately 432 x 312 mm and used 100 mm wheels placed near the four chassis corners. This layout was kept for load distribution, constant ground contact and stable odometry on flat indoor floors.

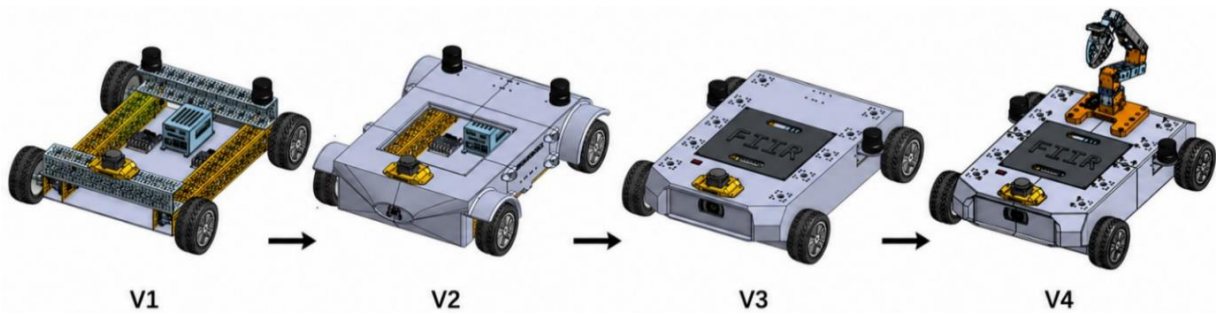


Fig. 3 Hardware evolution of Xplorer-AC from V1 to V4

The hardware evolved through four versions, shown in Fig. 3. V1 was the open goBILDA drivetrain used for motor, controller and communication tests. V2 added the first segmented PLA enclosure, with approximate dimensions of 560 x 440 x 200 mm, six FDM-printable segments, 5 mm wall thickness, 20-30% infill, M3 screw fastening, ± 0.3 mm alignment tolerance and approximately 20 mm ground clearance. V3 was a transition stage for sensor placement, adding a fixed Logitech C920/C922 camera cradle and lateral GPS antenna supports positioned approximately 159 mm from the robot middle plane. V4 integrated these changes into the final four-segment blue PLA enclosure and added the upper interface for the robotic arm module [11].

A simplified ANSYS check used a 150 kg vertical reference load applied to the aluminum-alloy chassis to identify critical areas through deformation and von Mises stress distribution. Two geometries were analyzed: the initial frame and the cut-out profile geometry adjusted to the real

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chassis mass. The initial geometry reached 0.806 mm maximum deformation and 38.52 MPa von Mises stress, while the cut-out geometry reached 3.618 mm and 140.31 MPa. Assuming linear static behavior, the resulting deformation for 10-30 kg chassis loading remains below 1 mm, so it does not affect robot architecture or component integration. The critical areas are visible in Fig. 4 in the orange-to-red zones, with the deformation scale amplified 19x for visualization. The practical payload is limited by the silent indoor wheels, tested up to 10 kg payload, together with motor torque and drivetrain revalidation requirements.

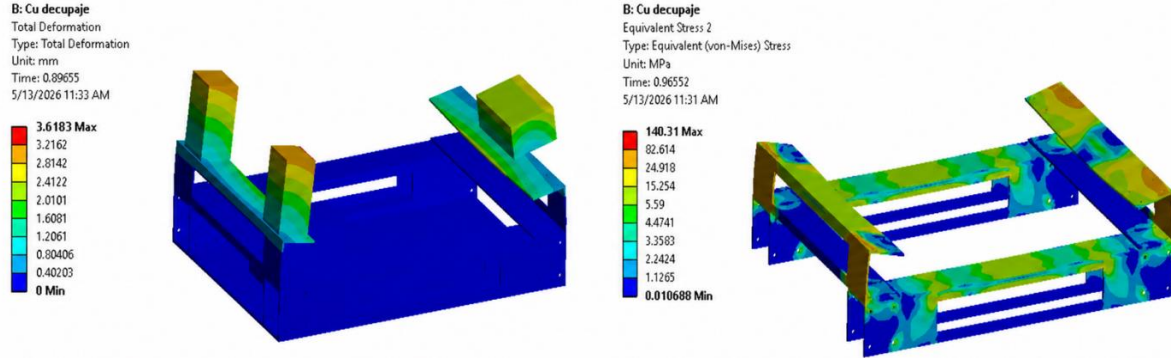


Fig. 4 ANSYS structural check of the goBILDA chassis under vertical payload

3.2. Iterative Prototyping and Final Hardware Implementation

The final implemented configuration is V4 (see Fig. 5): a four-segment blue PLA enclosure mounted on the goBILDA metallic frame [9]. The final dimensions are approximately 532 x 443 x 155 mm, below the SAIM height limit of 400 mm [12]. The internal payload kit volume is 336 x 216 x 200 mm and the top enclosure includes a 195 x 195 mm modular cutout.



Fig. 5 Real Xplorer-AC prototype

The body was FDM-printed and assembled with M3 screws. Fixed mounts were added for the 2D LiDAR, Logitech C920 RGB camera, GPS antennas, IMU, electronics and upper module. The LiDAR is placed in the upper front area on a rigid printed socket to reduce self-occlusion during SLAM. The camera uses a fixed frontal cradle. The GPS antennas are mounted on lateral rear supports, approximately 159 mm from the robot middle plane, to increase separation and reduce proximity to the drive motors.

The top module supports a ROBOTIS OpenMANIPULATOR-X / OMX-F robotic arm [11]. The arm has 5 DOF: 4 DOF for positioning and 1 DOF for the gripper, with 250 g payload, <0.2 mm repeatability and 20-75 mm gripper stroke [11]. It is mounted in the middle-rear area, with its rotation Z-axis approximately 92 mm from the rear enclosure plane. At full extension, the arm reaches approximately 400 mm, close to the 380 mm nominal reach, allowing manipulation tests without changing the mobile base (see Fig. 6) [11].

V4 closes the C1 hardware contribution by meeting the implemented platform targets: differential 4WD chassis, approximately 532 x 443 x 155 mm final body, 336 x 216 x 200 mm internal kit volume, 195 x 195 mm upper cutout, fixed LiDAR/camera/GPS mounts and robotic arm integration. The same hardware configuration was used for the ROS 2/Nav2 validation reported in the following sections [4]-[7].

4. Electronics, Control and Software Architecture

Xplorer-AC uses a Raspberry Pi 5 as the main computing unit for ROS 2 Jazzy, sensor acquisition, SLAM, Nav2 navigation, motor commands, visualization and testing [3], [4], [8]. The implemented electronic and drivetrain configuration is summarized in Table 2.

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Table 2. Xplorer-AC electronic and drivetrain configuration

Main computer	Power supply	Motor control	Motors	Drive configuration
Raspberry Pi 5; ROS 2 Jazzy, SLAM, Nav2, visualization	11.1 V 3S LiPo, 6000 mAh; 12 V-class architecture	RoboClaw 2x15A; encoder-based closed-loop control	4 x goBILDA Yellow Jacket 5203 with encoders	Differential 4WD; selected after mecanum slip

The validated sensor set includes a 2D LiDAR, IMU, wheel encoders and a front RGB camera. The LiDAR provides scan data for SLAM, obstacle detection and local costmaps. The encoders provide wheel odometry, while the IMU supports orientation estimation. The RGB camera is used for monitoring and future vision tests. GPS antennas are mechanically mounted on the robot, but they were not used in the indoor navigation results reported in this paper.

The software stack uses ROS 2 Jazzy, `ros2_control`, SLAM Toolbox and Nav2 [4]-[7]. The data flow is shown in Fig. 6: encoders and IMU generate odometry; LiDAR scans provide map and obstacle data; Nav2 uses the map, costmaps, robot footprint and velocity limits to compute motion commands; RoboClaw controllers execute the motor commands. Ordered missions are executed through waypoint navigation [6].

The local Nav2 controller is MPPI. It samples approximately 1000 control trajectories over a finite horizon and outputs the command with the lowest weighted cost [6]. On the Raspberry Pi 5, the controller was configured for approximately 10-20 Hz operation without GPU acceleration [8]. MPPI was kept because it reduced sudden `/cmd_vel` velocity-command changes during turns and improved command smoothness compared with the previous planner configuration.

The integration work included robot footprint definition, velocity-limit tuning, costmap configuration and differential 4WD parameterization. RViz was used for map inspection, TF checking, goal placement and costmap debugging [4]. Foxglove was used for telemetry, sensor topics, path visualization and demonstrations.

Voice interaction and manipulator control were tested outside the validated navigation core. Voice interaction used `whisper_ros`, Ollama and ROS 2 command interpretation. Manipulator integration used a ROBOTIS OpenMANIPULATOR-X / OMX-F-type architecture, ROS 2 teleoperation and MoveIt-oriented control [11]. These modules were not used as safety-critical navigation components.

The main integration issues were: mecanum slip on smooth floors, odometry instability before the differential 4WD configuration, USB port changes after reboot, IMU communication errors and higher CPU load when AI modules were active together with navigation. Therefore, validation was performed first on the navigation core, while voice, AI and arm control remained secondary modules.

5. Testing, Validation and Public Demonstrations

The validation started with indoor navigation conditions relevant to corridor-type operation: straight-line motion, 90° turns, waypoint tracking, obstacle response, dynamic replanning and continuous operation. The tests were performed to verify trajectory repeatability, localization stability, obstacle clearance, replanning time and battery-backed runtime. All tests used tiled and low-traction floors, the final differential 4WD configuration, fixed LiDAR mount, encoder feedback, IMU and the ROS 2/Nav2 stack [4], [6], [7].

Straight-line tests were repeated three times using the dataset stored in the project repository [10]. The completion times were 39.85 s, 34.88 s and 39.20 s, with a mean time of 37.98 s and a standard deviation of 2.69 s. The 90° turn tests showed higher lateral deviation than straight-line motion because of angular velocity and traction limits; therefore, velocity limits and MPPI control were used to reduce overshoot (see Fig. 7) [6], [10].

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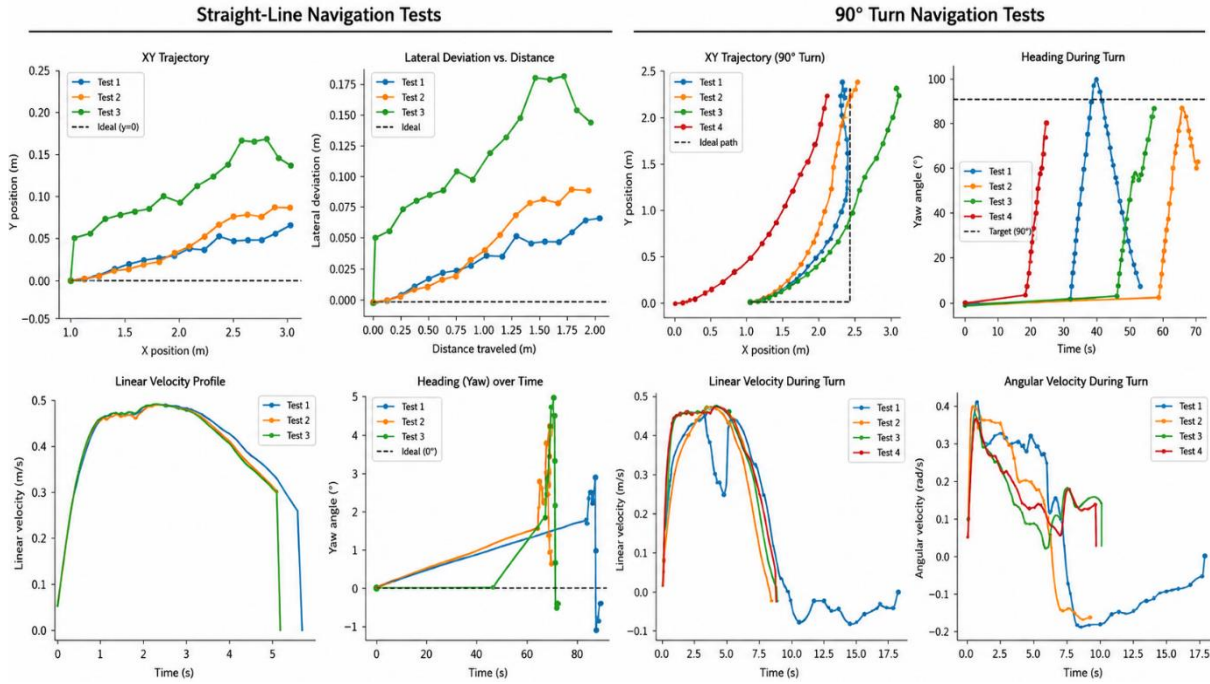


Fig. 7 Straight Line Navigation Test & 90° Turn Margin

Waypoint navigation was tested on SLAM-generated maps [10]. The robot reached predefined goals without direct control and Nav2 generated a new path in approximately 1-2 s when obstacles appeared [6], [7]. The switch from mecanum wheels to differential 4WD reduced slip-on smooth floors and improved odometry stability.

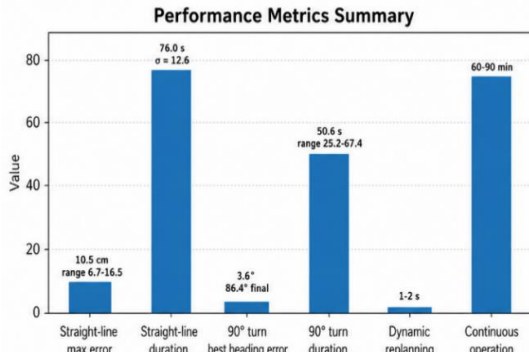


Fig. 8 Performance Metrics

Dynamic goal replanning was tested during a slalom trajectory (see Fig. 9 & 10). After a new goal was sent, the planner aborted the active path and generated a new path vector in 45 ms. Before interruption, the slalom means cross-track error was 0.07 m, with 0.12 m peak deviation at the tightest turn ($R = 0.8$ m). During the target switch, linear velocity decreased from 0.42 m/s to 0.29 m/s in 5.5 s, while angular velocity reached 0.9 rad/s.

Slalom Test Summary

Run 4* excluded from performance comparison.

Run	Replanning events (count)	Duration (s)	cmd_vel messages (count)	Status / note
Run 1	2	35.1 s	446	baseline
Run 2	6	29.5 s	289	refused obstacles
Run 3	8	37.0 s	353	completed
Run 4*	0	22.2 s	0	crashed / excluded

Fig. 9 Slalom Test Summary

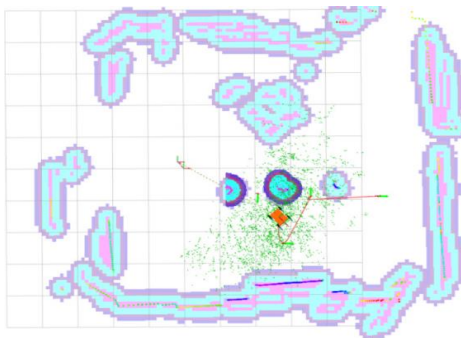


Fig. 10 Xplorer during Slalom test

The compact KPI summary is shown in Fig. 8: mean straight-line lateral error 10.5 cm, straight-line duration 76.0 s, best 90° heading error 3.6°, mean 90° turn duration 50.6 s, replanning time 1-2 s and continuous operation 60-90 min [10].

Obstacle avoidance tests showed an approximate 100 mm safety clearance. Low-profile objects below the 2D LiDAR plane remained difficult to detect. The issue was reduced by increasing the software safety radius and lowering the chassis by approximately 10 mm. Under standard navigation workloads, continuous operation was 1-1.5 h,

SAIM Xplorer-AC: Modular Autonomous Mobile Robot with ROS 2-Based Navigation

CPU usage stayed around 40-50% and no overheating was observed. The voice-command pipeline required approximately 20 s, so it remains experimental.

Public demonstrations were performed at PoliFest, RoboFEST and high school outreach activities. The robot demonstrated teleoperation, point-to-point navigation, live mapping, Foxglove monitoring, camera-assisted operation, robotic arm motion and AI-oriented experimental modules [11]. The demonstrations confirmed operation around moving visitors without major navigation failures or public collisions.

The validated functions are 4WD mobility, teleoperation, SLAM mapping, waypoint navigation, dynamic replanning, obstacle avoidance and 1-1.5 h operation. Current limits are low-object detection with a single 2D LiDAR plane, 20 s voice-command response time and experimental manipulator operation.

6. Conclusions and Future Work

This study presented SAIM Xplorer-AC, a modular autonomous mobile robot developed by ARKON Robotics from the SAIM Xplorer concept [12]. The initial requirements were a 500 x 500 x 400 mm target envelope, 10-15 kg payload range, 200 x 200 x 200 mm modular upper volume and ROS 2/Nav2-based indoor navigation [4]-[6], [12]. The implemented prototype reached approximately 525 x 500 x 200 mm, used a metallic goBILDA 4WD frame and preserved the 15 kg payload class [9].

The platform met the research objectives stated in Section 1: differential 4WD mobility, indoor autonomous navigation, extensibility through the upper interface and use as a research base for scientific student projects and bachelor-degree work. The hardware contribution was completed through V1-V4 iterations, resulting in a goBILDA U-Channel chassis, four Yellow Jacket encoder motors, segmented FDM-printed PLA enclosure, fixed LiDAR/RGB camera/GPS mounts, robotic arm integration and the replacement of mecanum motion with differential 4WD after slip and odometry issues on smooth floors [9], [11].

The software stack was validated with ROS 2 Jazzy, ros2_control, SLAM Toolbox and Nav2 [4]-[7]. The measured results include 1-2 s dynamic replanning, trajectory deviations from a few millimeters to approximately 1 cm, approximately 100 mm obstacle clearance, 40-50% CPU usage and 1-1.5 h continuous operation. Slalom testing added 45 ms replanning latency, 0.07 m mean cross-track error and 0.12 m peak deviation at the tightest turn.

SJU Vâlcea	Mihăești	Pantelimon
 Route 210 m	 Route 320 m	 Route 61.5 m
 Load 20 kg	 Load 7 kg	 Load 50 kg
 Scheduled 5 /day	 Scheduled 2 /day	 Scheduled 3 /day
 Urgent 3 /day	 Urgent 1 /day	 Urgent 3 /day

Fig. 11 Hospital requirements collected [13]

Future work will focus on integrating NXP NavQPlus as an additional embedded computing unit for workload separation, edge-AI processing, perception and sensor fusion. In parallel, the platform will be extended with modular upper subsystems, including the robotic arm, secured cargo compartments and docking hardware [11]. A hospital-oriented derivative has also been initiated through a 97-item questionnaire applied in three hospitals, targeting pharmacy-to-ward transport [13]. The collected data indicate routes up to 320 m,

medication loads in the 5-20 kg range, exceptional reported loads up to 50 kg, 2-3 compartments, scheduled and urgent delivery modes and elevator compatibility in two hospitals [13]. For the first prototype, the design target remains 25 kg nominal / 30 kg maximum, with authenticated handover at ward-level locations such as nurse stations or designated offices.

7. References

SAIM Xplorer-AC: Modular Autonomous Mobile Robot with ROS 2-Based Navigation

- [1]. Abaza, B. F. (2025), “AI-driven dynamic covariance for ROS 2 mobile robot localization”, *Sensors*, 25(10), 3026, <https://doi.org/10.3390/s25103026>, accessed on 12 May 2026.
- [2]. Abaza, B. F.; Staicu, A.-A. and Doicin, C. V. (2026), “Lightweight semantic-aware route planning on edge hardware for indoor mobile robots: Monocular camera-2D LiDAR fusion with penalty-weighted Nav2 Route Server replanning”, *Sensors*, 26(7), 2232, <https://doi.org/10.3390/s26072232>, accessed on 12 May 2026.
- [3]. Macenski, S.; Foote, T.; Gerkey, B.; Lalancette, C. and Woodall, W. (2022), “Robot Operating System 2: Design, architecture and uses in the wild”, *Science Robotics*, 7(66), eabm6074, <https://doi.org/10.1126/scirobotics.abm6074>, accessed on 12 May 2026.
- [4]. Open Robotics (2024), “ROS 2 Jazzy Jalisco release documentation”, Available online: <https://docs.ros.org/en/jazzy/>, accessed on 12 May 2026.
- [5]. ros-controls project (2026), “ros2_control documentation for ROS 2 Jazzy”, Available online: <https://control.ros.org/jazzy/>, accessed on 12 May 2026.
- [6]. Navigation2 Working Group (2026), “Nav2 documentation”, Available online: <https://docs.nav2.org/>, accessed on 12 May 2026.
- [7]. Macenski, S. and Jambrecic, I. (2021), “SLAM Toolbox: SLAM for the dynamic world”, *Journal of Open Source Software*, 6(61), 2783, <https://doi.org/10.21105/joss.02783>, accessed on 12 May 2026.
- [8]. Raspberry Pi Ltd. (2025), “Raspberry Pi 5 technical specifications”, Available online: <https://www.raspberrypi.com/products/raspberry-pi-5/>, accessed on 12 May 2026.
- [9]. goBILDA (2025), “Modular robotics build system”, Available online: <https://www.gobilda.com/>, accessed on 12 May 2026.
- [10]. ARKON Robotics (2026), “Teste_robot_saim_xplorer_2”, GitHub repository, https://github.com/Mario-Schmidt364/Teste_robot_saim_xplorer_2, accessed on 12 May 2026.
- [11]. ROBOTIS (2025), “OpenMANIPULATOR-X e-Manual and ROS 2 operation documentation”, Available online: <https://emanual.robotis.com/>, accessed on 12 May 2026.
- [12]. *** SAIM Xplorer concept specification (2025), Internal project document, coordinating team, June 2025.
- [13]. *** ARKON Robotics (2026), Preliminary hospital intralogistics requirement survey across three hospitals, Internal dataset, April 2026.

SHEILA SMART HOME

DOBRICĂ Estera-Cristina, COVERCĂ Alice-Mihaela, PRUNESCU Adelina-Nicoleta, SIMION Anamaria-Laura și SPÂNU Paulina (Conducător Științific)

Facultatea: Inginerie Industrială și Robotică, Specializarea: Industrial Engineering, Anul de studii: III, e-mail: estera.dobrica@stud.fiir.upb.ro

SUMMARY: The present paper concerns the use of automation and sensors relative to the improvement of safety, comfort and efficiency in cotidian life. Through the developing of the present project, the students intend to integrate a continuous real-time monitoring that triggers visual and sound alerts whenever imposed safety limits are passed. Given the fastened pace of life and the increase in the workload in nowadays society, the attention to crucial details regarding safety may be drawn away, especially at home, where the critical assessment of the environment drops significantly. Thus, the integrated detection and alarming system works towards preventing accidents and saving time and human resources.

KEY WORDS: prevent, sensors, automation, monitoring, safety

1. Introduction

In today's world, people are sustaining safety in their homes using smart technologies. While smart homes are convenient for everybody, they can be particularly useful for some categories of people, like people with disabilities and the elderly . Some of the technologies implemented in this project regard real time notifications in case of danger, but also day to day concerns. The system monitors the temperature and humidity inside the house, notifies the user in case of rain or fire, while also reacting automatically to needs like opening and closing the garage door when detecting movement. This project demonstrates how modern technology can make homes safer and smarter.

2. Actual stage

In the contemporary society, the main focus is developing and delivering to the customers new and captivating inputs, rather than trying to control and solve systematic errors from the past through innovation.

Considering the global accelerating increase in old age and the speedy development of technology, there is a gap forming in between the rate of acquiring necessary technology handling skills and its development and variation in terms of user-friendliness.

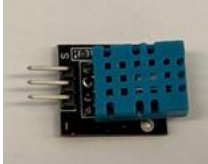
Automation at its core, has been developed to ease the human labour and reorient the focus and abilities towards a more fulfilling, but correlating activity for the individual involved. In the same manner, the automation of one's house aims to benefit the tenant in reducing the risks regarding their health in the possibility of the appearance of a life threatening interference.

3. Hardware components

Table 1. Components

Number	Name	Role in the project	Functionality
--------	------	---------------------	---------------

SHEILA SMART HOME

1	Humidity and temperature sensor DHT-11¹ 	-used to measure the climate inside	-for measuring the temperature the sensor has a thermistor that changes its resistance based on the change in temperature -for measuring the humidity the sensor has a metallic plate whose electrical properties change with the humidity -the measuring interval for the temperature is 0°-50° and for humidity 0-90%
2	Water sensor YL-83² 	-placed on the roof of the house to give a rain warning	-the sensor has metal traces, which form a series of parallel circuits, printed on its surface. When water touches the sensor it conducts electricity slightly between the traces. -more water leads to more traces covered and a higher conductivity which leads to a higher output signal
3	Flame sensor KY-026³ 	-used to detect a fire in the house	-the flame sensor works on the principle of infrared (IR) detection -the sensor has an IR receiver that detects the IR radiation emitted by flames
4	LCD display Lcd 1602 with thinned I²C module⁴ 	-used to display the temperature and the humidity inside the house	-the I²C module uses SDA (Serial Data) and SCL (Serial Clock) to communicate with the microcontroller -the I²C module sends commands and data to the LCD to tell it what characters to display and

¹

²

³

⁴

SHEILA SMART HOME

			where to place them
5	Bluetooth module 5.0 JDY-24M 6p 	- used to make the connection between the sensors and the app	-the module transmits the data read by the sensors connected to the Arduino board to the app
6	Buzzer 	-used to give a warning in case of a fire	-small electronic device that produces sound through a small vibrating plate inside when it receives an electric signal
7	Led 	-it will light up when it's raining	-the led lets current flow in only one direction from the arduino pin through the resistor and the led, ending up to the ground
8	Servomotor SG90 ⁵ 	-used to open the garage door	-the servomotor consists of three pins: Vcc (positive power supply pin), GND (ground) and PWM (pulse-width modulated) -it works at angles ranging from 0° -180°

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9	Ultrasonic sensor HC-SR04 ⁶ 	-used to detect when the car is coming close to the garage -it has two circular transducer components, a receiver and a transmitter, that resemble eyes -the transmitter emits a high frequency sound that hits an object and bounces back to the receiver
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The table above represents a list of all the components used, with the name, model and picture on the second column, the way they were implemented on the third column and their basic functionality as electronic components on the last column.

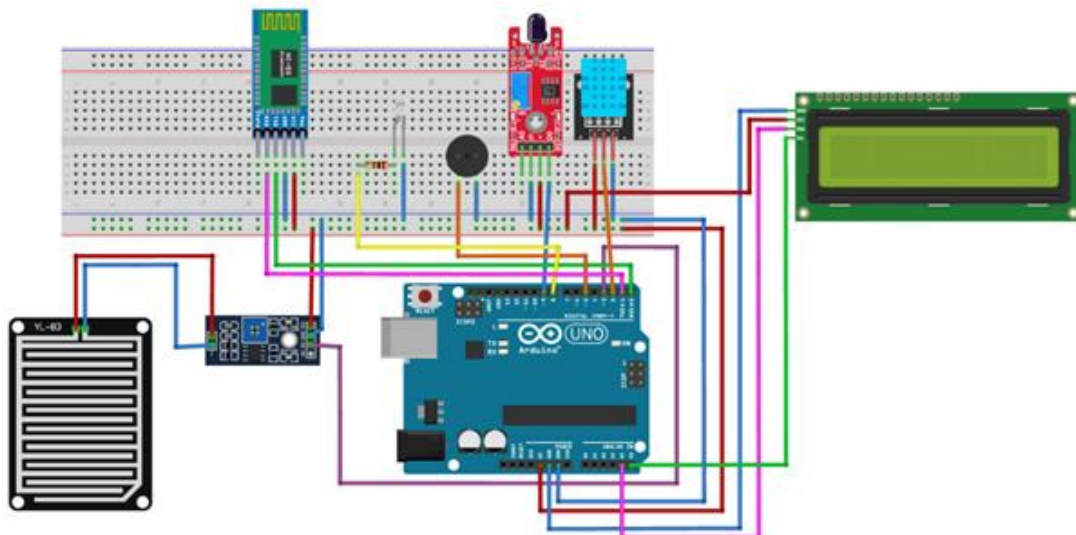


Fig. 1. Home Safety System

The diagram in Fig.1. was made in Fritzing and is based on a physical project built on a breadboard. The circuit uses an Arduino Uno and includes several sensors and components: a rain sensor (YL-83), a flame sensor (KY-026), a DHT11 temperature and humidity sensor, a white LED with a 200Ω resistor, a buzzer, a 16x2 I2C LCD display and a Bluetooth module. The DHT11 sensor reads the temperature and humidity from the environment and displays the values on the LCD screen. The rain sensor monitors weather conditions and turns on the white LED as a visual alert whenever rainfall is detected. The flame sensor is probably the most important part of this circuit. If it detects fire, the buzzer starts making noise and a 'Fire detected!' message is sent through the serial monitor. The data is also sent to a phone via Bluetooth so it can be monitored in real time without being near the device.

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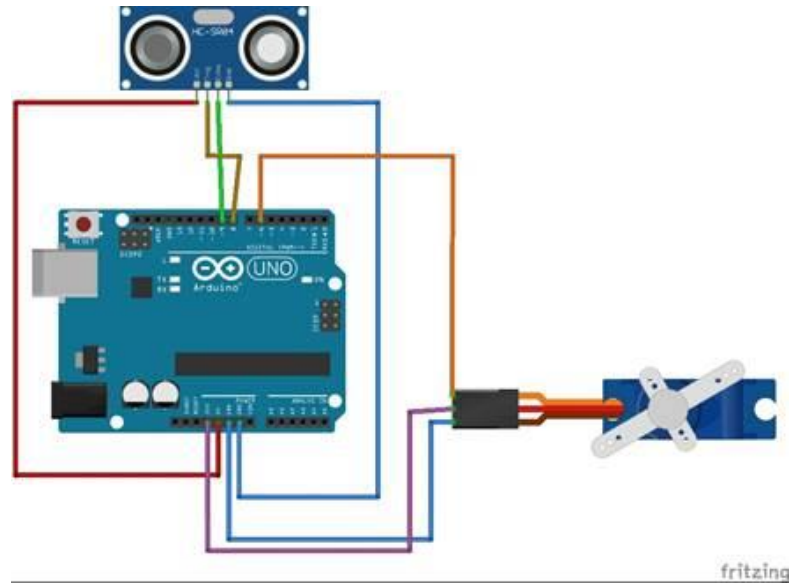


Fig. 2. Automatic garage system

The diagram in Fig. 2. represents an Arduino Uno connected to an HC-SR04 ultrasonic distance sensor and an SG90 servo motor. The ultrasonic sensor measures distances and functions as a proximity detector for automated access. When the car is detected within 20 cm proximity, it triggers the servo motor to execute an automated opening sequence. The servo rotates to the opening position, maintains it for one second, then returns to the closed position, simulating an automated garage door system.

4. Conclusions

The project highlights the efficiency of using IIoT in the development of smart home technologies. By integrating humidity, water and flame sensors together with warning elements such as display, buzzer and LED's, a system capable of monitoring and signaling different situations in real time was obtained.

In the future , the project can be developed by adding new sensors, intelligent functions, advanced control and security methods, and a system for fire extinguishing , automatic closing of windows during rain, with photovoltaic power panels.

5. Bibliography

- [1]. [DHT11 Humidity & Temperature Sensor](#)
- [2]. [Rain drop Sensor Module](#)
- [3]. [Arduino Flame Sensor KY-026 — Wiring Diagram & Code](#)
- [4]. [I2C Serial Interface 1602 LCD Module](#)
- [5]. [SG90 TowerPro Micro Servo Motor](#)
- [6]. [HC-SR04 Ultrasonic Sensor Module User Guide](#)

RESEARCH ON WIRE ELECTRICAL DISCHARGE MACHINING AND ALTERNATIVE TECHNOLOGIES

¹GRIGORESCU L. Alexandru-Mihai, ²PLEȘ M.N. Mario-Florin, ³TICĂ D. Alexandru-Mihai și

Research Advisors: Prof. Dr. Ing. Liviu Daniel GHICULESCU,

S.I. Dr. Ing. Cornel Cristian ENCIU

Faculty: Industrial Engineering and Robotics, Major: IEI, Year: 4, Email:

dandruandu@yahoo.com

ABSTRACT: *This paper presents a study on Wire Electrical Discharge Machining (WEDM) and related nonconventional technologies. The working principles of EDM and WEDM are analyzed, including the role of the plasma channel, and dielectric fluid. Key technological performance indicators are discussed: cutting speed (up to 300 mm²/min), dimensional accuracy ($\pm 1 \mu\text{m}$) and surface roughness (R_a in the μm range). Special attention is given to other alternative technologies on massive electrode EDM machine, respectively wire cutting using a special device (wire diameter 0.3 mm) and cutting with blade electrode (0.3 mm thickness).*

KEYWORDS: *WEDM, EDM, wire, blade electrode, numerical simulation.*

1. Introducere

Electrical Discharge Machining (EDM and Wire EDM) is a thermal erosion process capable of machining conductive materials regardless of their hardness. It is the most widely used unconventional technology and belongs to the group of thermal erosive machining processes because it uses thermal energy to melt, vaporize, and even boil the material of the workpiece. Although it has the disadvantage of low productivity—as it is a machining process that removes material through successive electrical discharges between the tool and the workpiece—WEDM and EDM achieve accuracies in the micrometer range and surface roughness values of $R_a=0.05 \mu\text{m}$ [1]

2. Stadiul actual

Electrical discharge machining (EDM) comes in two main forms: die-sinking EDM and wire EDM. It is a machining process that uses successive electrical discharges (sparks) to remove material from a workpiece, resulting in the complementary shape of the tool. An electric current is discharged between two electrodes in a dielectric fluid, to which voltage pulses are applied. One of these electrodes is the tool, and the other is the workpiece [2], with a positive or negative polarity assigned to the tool so that the power distributed is greater to the workpiece and less to the tool, thereby increasing productivity and reducing tool wear.

In EDM/WEDM, material is removed through melting, vaporization, and boiling, using the energy of electrical discharges that form a plasma channel with temperatures of approximately 10,000 °C. At this extreme temperature, the workpiece material melts, vaporizes locally, and even boils. During the discharge, the workpiece material is superheated to approximately 200–300 °C above its boiling point due to the high pressure generated by the discharge's plasma channel. After the discharge ends, a volume of material bounded by the boiling isotherm under normal conditions is removed; this is the primary mechanism by which material is removed from the formed microcrater [3], [4]. The major problem with the conventional process is its low efficiency: only ~10% of the material is actually removed, with the rest resolidifying due to a gas bubble that blocks the flushing of the work area. The proposed modern solution is ultrasound-assisted machining (EDM+US), which breaks this gas bubble at the end of each cycle, resulting in a 400–500%

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increase in productivity [5]. From the perspective of the theoretical operating principles, the main emphasis is placed on carefully adjusting the pulse generators and operating modes to achieve the optimal ratio between feed rate and the resulting surface area [1].

The current state of WEDM technology involves machining with a wire electrode, with mechanical tension controlled by a roller system, which is CNC-controlled to produce complex contours, eliminating the need for a predefined mating tool. Current WEDM performance includes: Productivity: Up to 300 mm²/min on 50 mm thick steel. Modern hybrid equipment combines waterjet with WEDM cutting for significantly better thermal management and automatic threading. Precision and Surface Roughness: Thanks to sapphire or diamond guides, the machines achieve a profile tolerance of $\pm 1 \mu\text{m}$, resulting in a surface roughness (Ra) of 0.006 μm [6,7].

3. Analiza SEM a suprafețelor sculelor și suprafețelor prelucrate

The cutting process for the three types of electrical discharge machining is illustrated in Figures 1–3. Each figure shows the tool (1), the clamping fixture (2), the workpiece (3), and the dielectric fluid used (4).

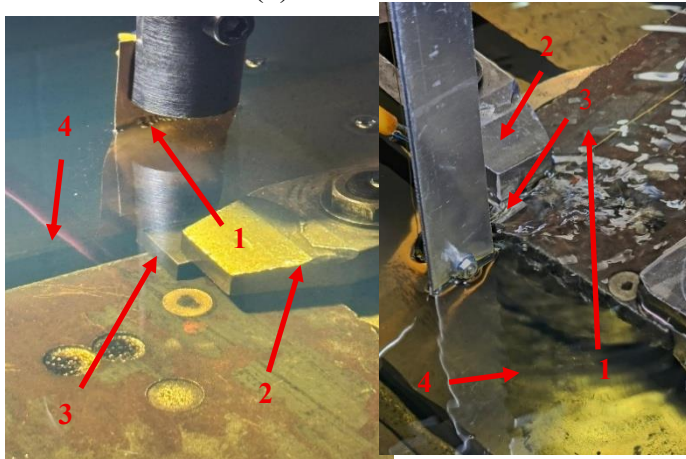


Fig. 1. The process of wire-cut EDM with lamellar electrode



Fig. 2. Wire EDM cutting process using a device mounted on the EDM machine

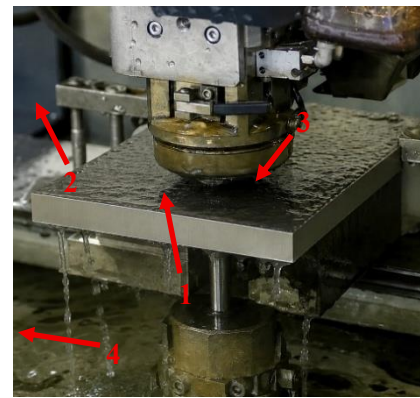


Fig. 3. The WEDM (Wire Electrical Discharge Machining) cutting process performed on a specialized CNC machine

A detailed microscopic analysis of the surfaces of the machined parts was performed to objectively assess the impact of the machining process on the tools used, which affects the achieved precision. The investigation was conducted using a scanning electron microscope (SEM), the QUANTA INSPECT F50, with a resolution of 1 nm, at the Polytechnic University of Bucharest, observing morphological changes and dimensional wear at high resolution, Figures 4–12.

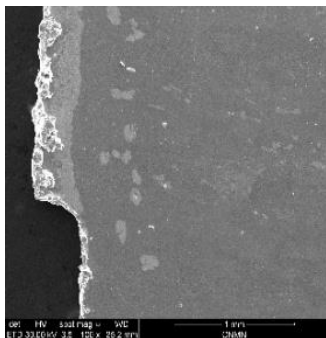


Fig. 4. The copper lamellar electrode after processing

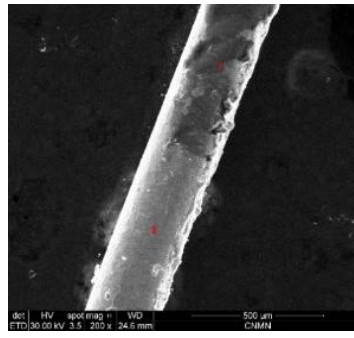


Fig. 5. The wire highlighted through the affected area 1 and the unaffected area 2

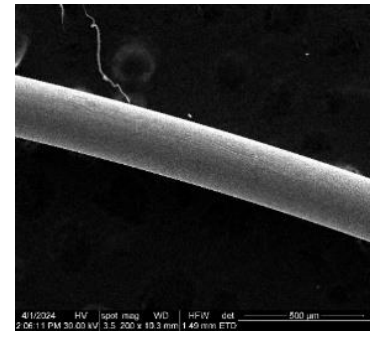


Fig. 6. Tool used for WEDM machining

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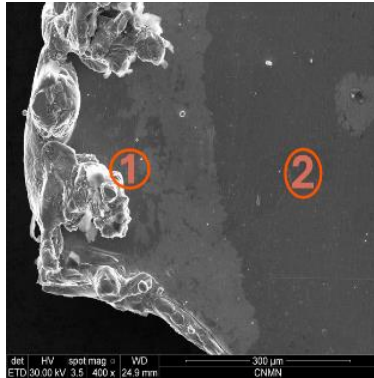


Fig. 7. 300-μm section—worn area (left) and unaffected area (right)

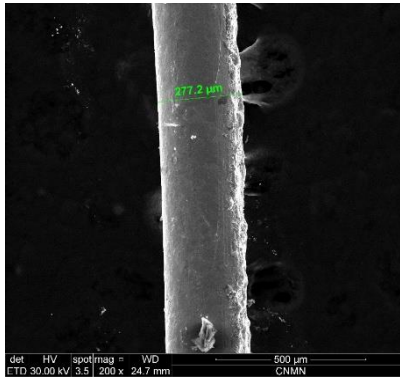


Fig. 8. Wire before processing: 277.2 μm

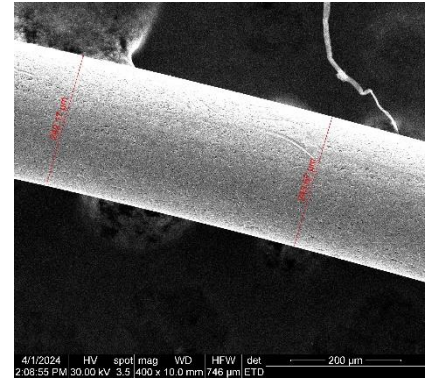


Fig. 9. Diameter of the wire used for WEDM machining

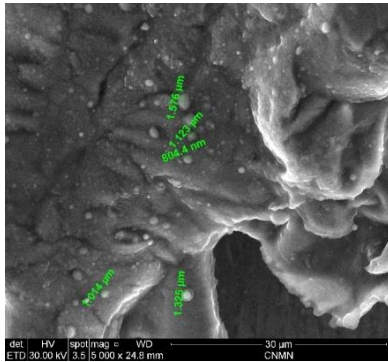


Fig. 10. 0.3 mm lamellar electrode

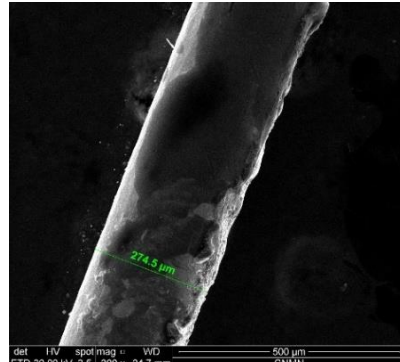


Fig. 11. The wire after processing 274.5 μm

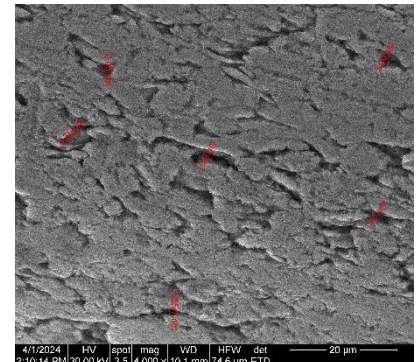


Fig. 12. Microporosity in wire WEDM

The comparative study focused on two types of tools: the copper strip electrode (used for slot machining) and the wire electrode (used in the WEDM process and static wire machining). The previous figures presented images obtained at various magnifications, showing the areas thermally affected by electrical discharges, the condition of the base material, as well as the dimensional changes resulting from machining. From the analysis of the micrographs presented, the following key observations regarding tool wear emerge: Wear of the lamellar electrode (copper): At a magnification of 400×, a clear demarcation is observed between the severely worn machining zone 1 and the unaffected base material zone 2. Detailed analysis at 5000× of the eroded area reveals microcraters and resolidified particles, with dimensions ranging from 804.4 nm to 1.576 μm. Dimensional variation of the static wire: The images show a clear decrease in the tool's volume due to vaporization. The wire diameter decreased from 277.2 μm (before machining, visible at 200× SEM) to 274.5 μm (after machining, at 300× SEM). Surface morphology of the WEDM wire: Analysis at 4000× magnification reveals the presence of “micro-imperfections” on the surface of the used wire. These micro-defects and asperities result from the intense thermal cycle of melting and rapid resolidification during electrical discharges.

The cross-sections shown in Figures 13–15 depict machined surfaces observed under an SEM.

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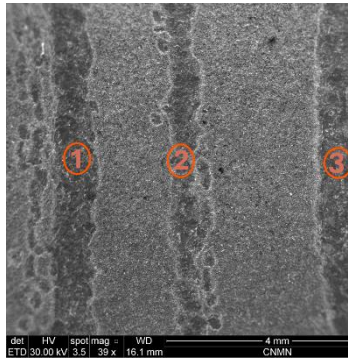


Fig. 13. Overview of the workpiece with the three cut marks made using a strip electrode under different operating conditions

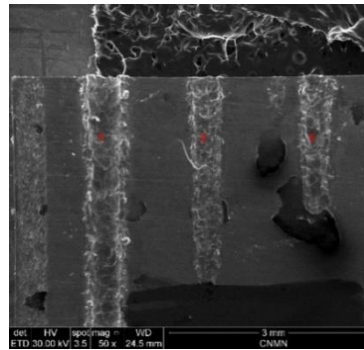


Fig. 14. The semi-finished product and the three machining operations performed under three different machining conditions

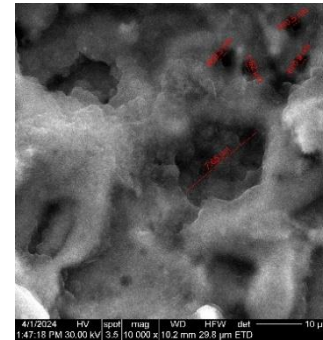


Fig. 15. Craters formed after WEDM cutting

Electro-erosion cutting using a strip electrode, as analyzed by examining the machined slot, reveals variations in geometric accuracy depending on the evolution of the applied operating conditions. In the first tested mode, a slot with widths ranging from approximately 515 μm to 726 μm is generated, exhibiting micro-craters of up to 4.5 μm at the microscopic level. The transition to the second regime leads to a slight widening of the slit, reaching maximum values of approximately 766 μm ; however, the surface topography indicates a uniformity of the micro-craters, with smaller dimensions ranging between 2 and 3.3 μm . In the third mode, the widest slot is generated, with values exceeding 823 μm , along with the largest wear craters ranging from 6.7 to 8.2 μm , indicating a considerably more severe thermal impact on the material. Mouralova et al. demonstrated that micro-EDM technology using a foil electrode allows for the creation of precision slots in thin conductive materials without generating mechanical forces on the workpiece. The same study concludes that the simultaneous optimization of the pulse current and the pulse duration (T_{on}) is essential for surface quality control [8].

Processing Mode 1
($L_v=08$, $T_{on}=210\mu\text{s}$,
 $T_{of}=03\mu\text{s}$, $\text{Gap}=80\mu$,
 $I=8\text{A}$)

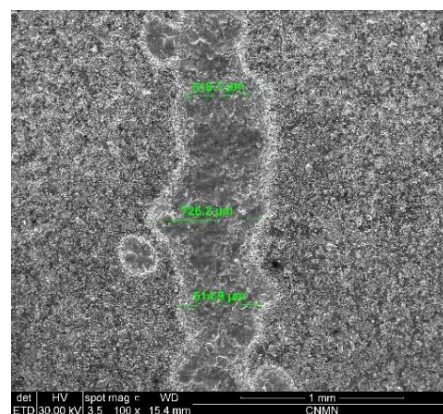


Fig. 16. 1 mm bar – Zone 1

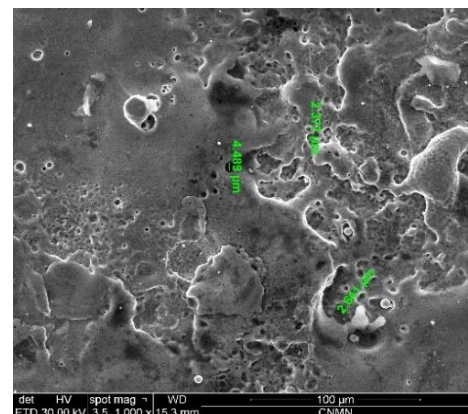


Fig. 17. 100 μm scale bar – Zone 1

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Processing Mode 2
($L_v=12$, $T_{on}=100\mu s$,
 $T_{of}=0.13\mu s$, $Gap=90\mu m$,
 $I=12A$)

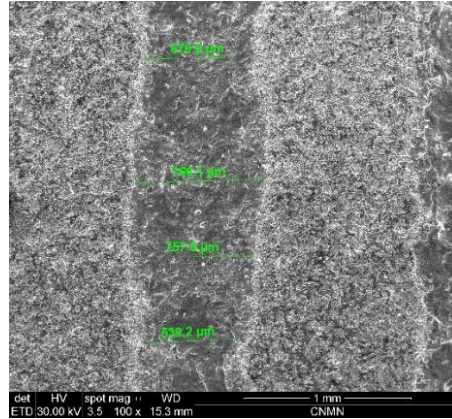


Fig. 18. 1 mm bar – Zone 2

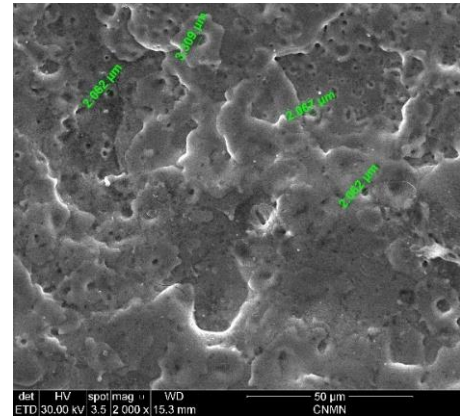


Fig. 19. 50 μm bar – Zone 2

Processing Mode 3
($L_v=10$, $T_{on}=250\mu s$,
 $T_{of}=0.3\mu s$,
 $Gap=90\mu m$, $I=10A$)

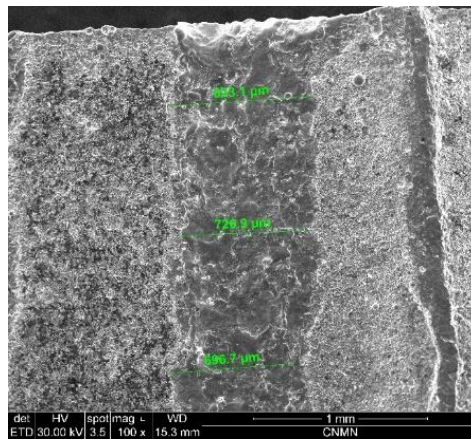


Fig. 20. 1 mm bar – Zone 3

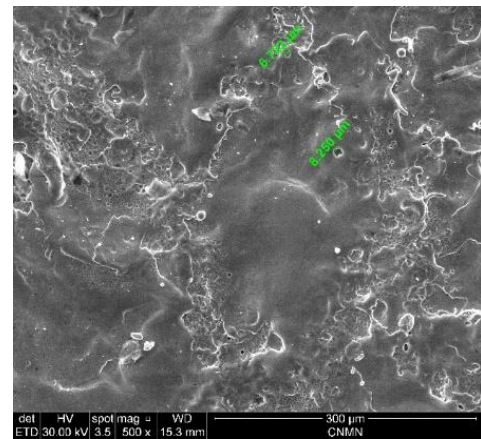


Fig. 21. 300 μm bar – Zone 3

In static wire EDM cutting, the level of precision is noticeably improved compared to the use of a wire blade. The first mode maintains the kerf width within the range of 468–576 μm , leaving behind small surface craters measuring less than 2.4 μm . With the application of the second mode, a significant narrowing and stabilization of the cut slot is observed, with widths decreasing to values between 339 μm and 398 μm , although the size of the craters resulting from vaporization increases slightly toward 4.3 μm . The third mode produces the narrowest cut of all those analyzed, with recorded widths dropping to 327–375 μm . However, although the overall contour accuracy is maximized, isolated micro-craters of the largest dimensions appear on the generated surface, exceeding 7.8 μm . Goyal and Rahman confirmed that the energy of the electrical discharge directly determines the morphology of the surface machined by WEDM, influencing both the size of the erosion craters and the thickness of the resolidified layer. The voltage applied to the electrode wire also plays a decisive role; a higher voltage reduces tool vibrations and improves process stability [9].

RESEARCH ON WIRE ELECTRICAL DISCHARGE MACHINING AND ALTERNATIVE TECHNOLOGIES

Processing Mode 1
(Lv=03,
Ton=060us,
Tof=05us,
Gap=20u, I=2 A)

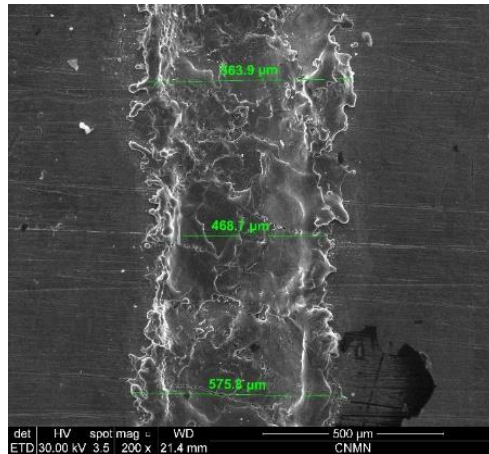


Fig. 22. 1 mm bar – Zone 1

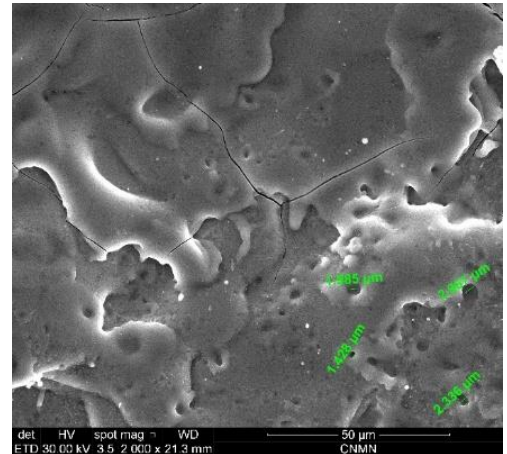


Fig. 23. 50 μm bar – Zone 1

Processing Mode 2
(Lv=04,
Ton=100us,
Tof=06us,
Gap=25u, I=3 A)

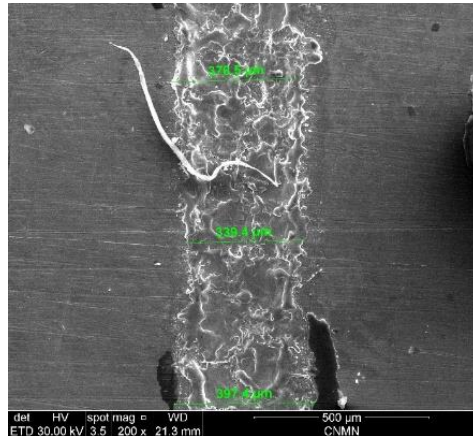


Fig. 24. 1 mm bar – Zone 2

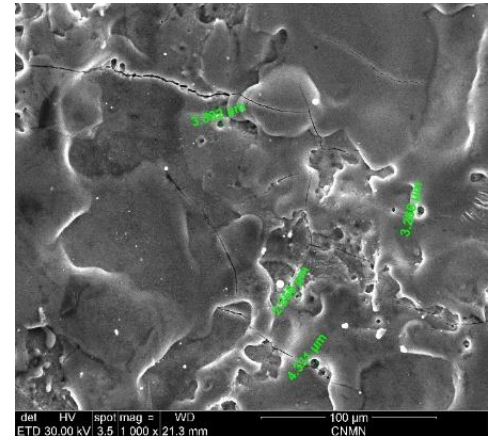


Fig. 25. 100 μm bar – Zone 2

Processing Mode 3
(Lv=02, Ton=03us,
Tof=030us,
Gap=10u, I=1.5 A)

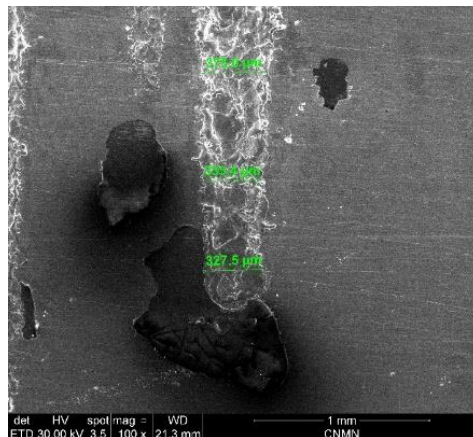


Fig. 26. 1 mm bar – Zone 3

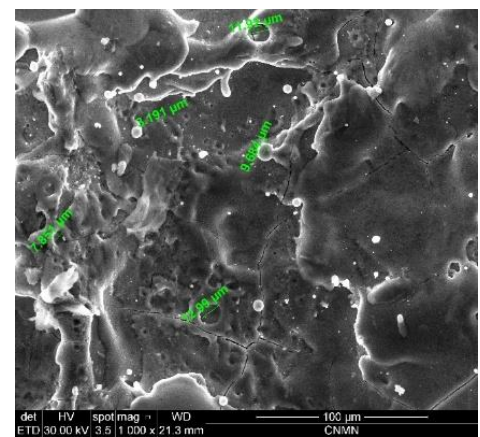


Fig. 27. 100 μm bar – Zone 3

4. Simularea numerică a prelevării materialului

For the modeling and numerical simulation of material removal in COMSOL Multiphysics 5.5 [10], the Heat Transfer in Solids module (time-dependent, 2D) was used. The model parameters are shown in Figure 28, and the part geometry was created as shown in Figure 29.

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Parameters			
Name	Expression	Value	Description
hp	4[mm]	0.004 m	inaltime piesa de proba
lp	14[mm]	0.014 m	lungimea piesei de proba
I	3	3	treapta de curent [A]
dcr	6.877e-6	6.877E-6	diametru crater initial
tif	100e-6	1E-4	timp de impuls final [us]
acr	dcr/2	3.4385E-6	raza crater initial
bcr	0.9*acr	3.0947E-6	adancime crater initial
Ra	2.648e-6	2.648E-6	Rugozitatea Ra
rms	0.2e-6	2E-7	raza material resolidificat
rbg	0.1[mm]	1E-4 m	raza bula gaz
raport	3.9947/4.43	0.90174	raport adancime / raza cr...
TfTiAlNbV	3200	3200	Temperatura de fierbere,...
TmTiAlNbV	1600	1600	Temperatura medie de to...
rcp	$1e-6 \cdot 1.3 \cdot 10^{-2} \cdot (ti \cdot 1e6)^{0.15}$	0	raza canal plasma depen...
ti	0	0	timp impuls baleiat
a	0.25e-6	2.5E-7	raza initiala canal plasma
densTiAl...	4500	4500	densitate [kg/m ³]
kTiAlNbV	20	20	conductivitate termica [...]
CpTiAlNbV	600	600	Capacitate calorica [J/kgK]
TfC120	3000	3000	Temperatura de fierbere,...
TmC120	1250	1250	Temperatura medie de to...
densC120	7650	7650	densitate [kg/m ³]
kC120	25	25	conductivitate termica [...]
CpC120	620	620	Capacitate calorica [J/kgK]

Fig.28. Parametrii utilizati pentru modelare

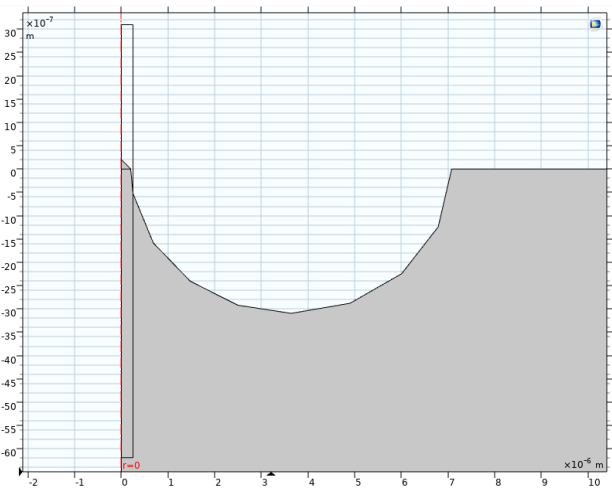


Fig. 29. Part geometry

The material was distributed as follows, Figures 30 and 31:

✓ Thermal conductivity	k_iso ; ki...	kTiAlNbV	W/(m
✓ Heat capacity at constant pressure	Cp	CpTiAlNbV	J/(kg·
✓ Density	rho	densTiAlN...	kg/m ³

Fig.30. Material TiAlNbV

✓ Thermal conductivity	k_iso ; ki...	kC120	W/(m
✓ Heat capacity at constant pressure	Cp	CpC120	J/(kg·
✓ Density	rho	densC120	kg/m

Fig.31. Material C120

The discretization is shown in Figures 32 and 33:

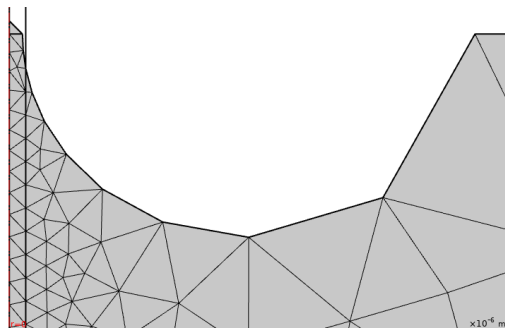


Fig. 32. Dynamic discretization (varies over the time interval ti)

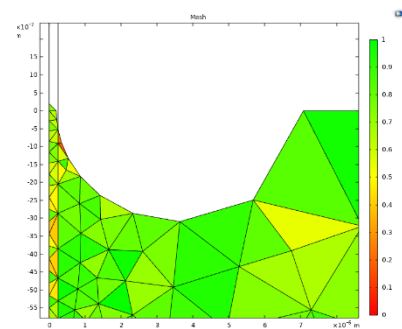


Fig. 33. Discretization quality Statistics

The results of the simulation using COMSOL Multiphysics 5.5 are shown in Figures 34, 35, and 36:

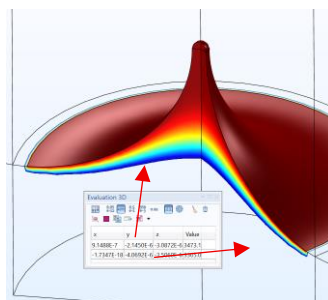


Fig. 34. Modeling of a lamellar electrode

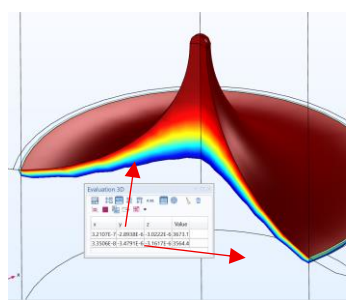


Fig. 35. Modeling for static wire

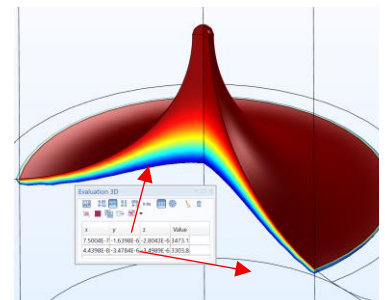


Fig. 36. Modeling for WEDM

RESEARCH ON WIRE ELECTRICAL DISCHARGE MACHINING AND ALTERNATIVE TECHNOLOGIES

5. Concluzii

The numerical simulation is consistent with the experimental data, highlighting that the primary mechanism of material removal is boiling. After the discharge is extinguished, the machining accuracy of WEDM is significantly superior, as alternative cutting technologies are affected by wire guidance and mechanical tensioning, as well as the guidance of the copper blade. The copper strip underwent deformation when using the pulsed mode (up-down), which is necessary for the evacuation of the removed particles. Additionally, during static wire machining, upon contact with the workpiece, due to a minor error, the wire underwent deformation when using the pulsed mode. Future research will focus on improving the devices used to enhance the performance of these technologies implemented on solid-electrode and wire-cut EDM machines, through the use of guiding devices for the lamellar electrode-tool, as well as wire feeding and guiding with controlled mechanical tension.

6. Bibliografie

- [1] Ghiculescu, D., Curs Tehnologii neconvenționale, UNSTPB, 2026. Disponibil la: <http://...> (moodle), accesat la: 26.03.2026.
- [2] Masini de electroeroziune de la Mitsubishi electric, disponibil la <https://www.mitsubishielectric-edm.eu/landingpages/romania/>, accesat la 08.03.2026
- [3] Ghiculescu, D. (2021), Inginerie și fabricație asistată de calculator în domeniul prelucrărilor mecanice neconvenționale. UPB.
- [4] Jameson, E.C. (2001), Electrical Discharge Machining. Society of Manufacturing Engineers, Dearborn, Michigan.
- [5] Ghiculescu, D. (2016), Contribuții la dezvoltarea și inovarea prelucrării neconvenționale asistate cu ultrasunete. Teză de abilitare, UPB
- [6] *** GF, CUT X series Extreme accuracy, simple and fast, disponibil la: <https://www.gfms.com/en-hu/machines/edm/wire-cutting/agiecharmilles-cut-x-series.html>, accesat la: 09.05.2026
- [7] *** Sodick, AP 250 L, Disponibil la: <https://ichungary.hu/wp-content/uploads/2023/06/AP250L-E-katalogus-Angol.pdf>, accesat la: 9.05.2026
- [8] Muralova și alții, Scientific Reports (Nature), 2022- disponibil la <https://www.nature.com/articles/s41598-022-08957-9>, accesat la 30.04.2026
- [9] Goyal & Rahman, Experimental studies on Wire EDM for surface roughness and kerf width for shape memory alloy, publicat în Sādhanā (Springer), 2021- disponibil la <https://link.springer.com/article/10.1007/s12046-021-01684-3>, accesat la 30.04.2026
- [10] Ghiculescu, LD, Gheorghita, V., Staicu, A-A; Constantin, Constantin, P-A, Analysis Based on Computer Vision of Machined Surfaces by Hybrid Ultrasonic and Classic Electrical Discharge Machining of CoCr Alloys, Machines, eISSN 2075-1702, Volume 14, Issue 4, DOI 10.3390/machines14040394, Departamentul de Inginerie a Producției, Universitatea Politehnică din București, România

A COMPARATIVE ANALYSIS OF TECHNOLOGIES EMPLOYED IN DIE ACTIVE COMPONENTS

CRÎNGUȘ D. Ciprian, MANTEA A. Ionica-Stelica, TONEANU V. D. Livia-Maria
Scientific Supervisor: Prof. Dr. Ing. **GHICULESCU Liviu Daniel**, Prof. Dr. Ing. **IONESCU Nicolae**

Faculty: Faculty of Industrial Engineering and Robotics, Specialization: Machine Building Technology,
Academic Year: IV, e-mail: cringusciprian@gmail.com

Abstract: The research presents a comparative study on the performance of milling, EDM (Electrical Discharge Machining), and WEDM (Wire Electrical Discharge Machining) technologies in the fabrication of high-precision cavities. The analysis focuses on evaluating surface topography and the geometric accuracy of corners through SEM (Scanning Electron Microscopy) investigations. The mechanisms of surface layer formation and the influence of operating parameters on the final micro-geometry are explored. The results provide a technical perspective on the limitations and advantages of each method.

KEYWORDS: active plates, mill, EDM, WEDM,

1. Introduction

The choice of the machining process depends on the nature and complexity of the part to be manufactured. The main objective of this research work is to compare three machining processes: end milling as a conventional method, and EDM (Electrical Discharge Machining) and WEDM (Wire Electrical Discharge Machining) as nonconventional methods. The core element of the analysis is represented by the technological limitations in generating very small internal radii; while milling is constrained by the radius of the cutting tool, erosion

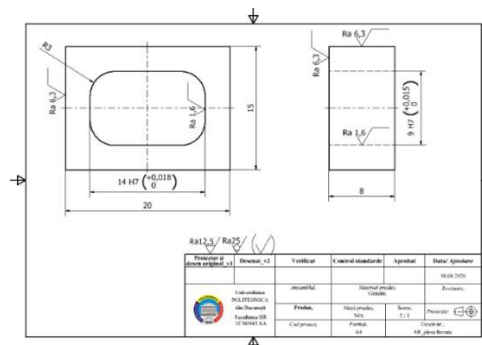


Fig. 1 Engineering drawing of the part with final dimensions

methods promise superior geometric precision. Thus, the subject of the research is a part characterized by small dimensions and a cavity with strict precision requirements at the corners, made of C10 low-carbon unalloyed steel, with the engineering drawing illustrated in Figure 1. The comparison of these methods targets essential parameters such as geometric precision, productivity, and the integrity of the resulting surface.

2. State of the Art

The comparative analysis of conventional machining methods, specifically milling, in relation to nonconventional ones, namely EDM and WEDM, represents a subject of major interest in current specialized literature used in the industry. This comparison between

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machine, the part was mounted in a universal fixing frame (U-type), and the tool is a brass wire with a diameter of 0.3 mm.

The first stage in manufacturing the part was milling, which was carried out through a roughing operation with a 3 mm allowance to remove the excess material, followed by a finishing operation. The required roughness was ensured by using a high cutting speed and a low working feed rate.

Due to the use of a 6 mm diameter end mill, the part exhibits a residual radius in the internal corners that is impossible to produce by milling. These will be subsequently machined using EDM and WEDM processes to achieve the sharp corners. This hybrid strategy ensures high productivity and increased precision for the fine details of the die plate.

The machining of the die plate began with the execution of the contour and flat faces using a Ø14 mm milling cutter, operating under a roughing regime ($v_c = 260$ m/min, $f_z = 0.08$ mm/tooth) and a finishing regime ($v_c = 350$ m/min, $f_z = 0.07$ mm/tooth) [8]. To facilitate chip evacuation in the internal cavity, a Ø8 mm relief hole was drilled ($v_c = 60$ m/min, $f_z = 0.1$ mm/tooth) [9], followed by the actual milling of the cavity with a Ø6 mm tool. The entry was performed via ramping, under a roughing regime ($v_c = 180$ m/min, $f_z = 0.02$ mm/tooth) and a wall finishing regime ($v_c = 350$ m/min, $f_z = 0.023$ mm/tooth) [8]. The process was



Fig. 4 Cavity finishing

completed by rotating the part 180° and machining the opposite face with the Ø14 mm milling cutter, thus ensuring parallelism and the final thickness dimension. The cavity finishing can be observed in Fig. 4.

Electrical discharge machining with a die-sinking electrode (EDM) was selected as a nonconventional method for manufacturing the cavity due to its high precision in copying the tool geometry. The process allows the transfer of the copper electrode shape directly into the part matrix, facilitating the attainment of internal corners with a minimal radius.

The material chosen for the solid electrode is copper. This option was selected because copper is the reference



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material in electrical discharge machining due to its high electrical and thermal conductivity, which allows superior material removal rates and enhanced stability of the electrical discharges [7]. The geometry of this electrode can be observed in Figure 5.

The EDX analysis of the copper electrode monitored composition stability and the contamination level. Initially, as detailed in Figure 6, it exhibits high purity (99.4% Cu and 0.6% Fe). Post-erosion, as detailed in Figure 7, the surface was severely contaminated through material transfer from the part and carbon depositions originating from the pyrolysis of the dielectric fluid.

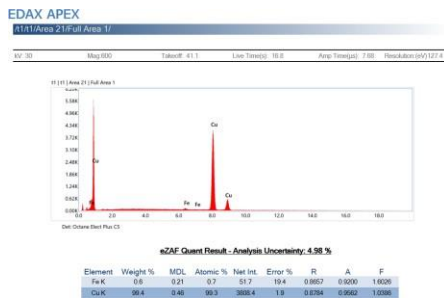


Fig. 6 EDX analysis of the electrode before EDM Fig. 7 EDX analysis of the electrode after EDM

The erosion process on the machine consisted of clamping the part and the electrode onto the EDM machining rig, Fig. 8, and machining by immersion in dielectric fluid, Fig. 9.

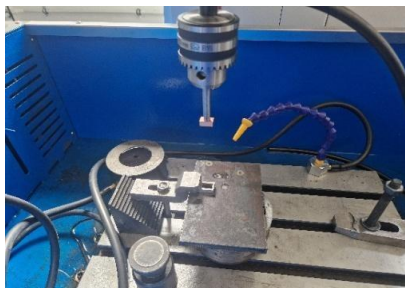
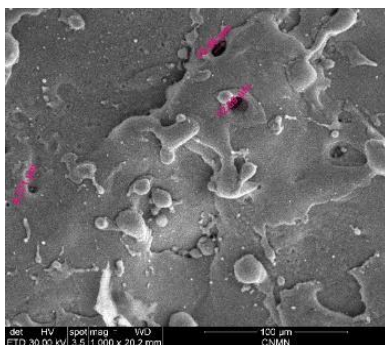


Fig. 8 EDM machining setup

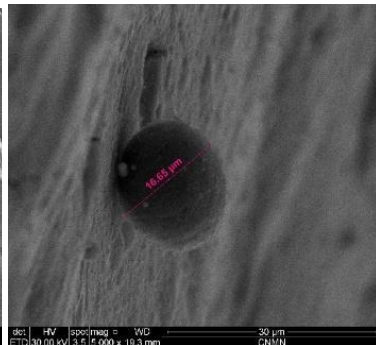


Fig. 9 EDM machining process

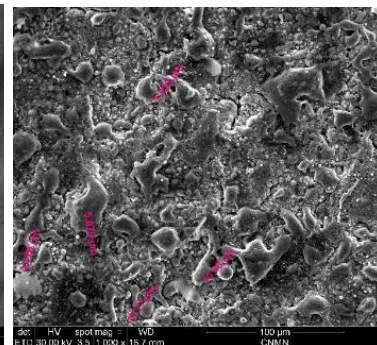
After machining, the surfaces of the part and the electrode were analyzed using scanning electron microscopy (SEM), with the aid of the QUANTA INSPECT F50, featuring a 1 nm resolution, at the National University of Science and Technology Politehnica Bucharest, in order to identify the micro-geometry details.



a. Recast layer and resolidified material



b. Spherical particle



c. Electrode with deposited C layer

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Fig. 10 SEM analysis of the EDM process

The topography is dominated by erosion craters and areas with resolidified melted material, specific to the high temperatures in the plasma channel, according to Figure 10.a. On the cavity walls, numerous spherical particles are observed, resulting from the rapid solidification of molten particles in the dielectric fluid, according to Figure 10.b. Analyzing Figure 10.c, we observe the pyrolysis of the dielectric fluid, which at sublimation temperatures (of approximately 3500°C) generates carbon depositions on the electrode. Although these indicate contamination, the carbon layer plays a protective role against electrode wear in finishing regimes [10].

The second nonconventional method used for finishing the cavity of the chosen part is wire electrical discharge machining (WEDM). The choice is justified by the ability to generate sharp corners and perfectly vertical walls, with the process utilizing a continuously renewed wire electrode that eliminates errors caused by tool wear. While in the case of the die-sinking electrode the entire shape is copied simultaneously, the WEDM process involves traversing the contour on a numerically generated toolpath, with the wire rectifying the corner geometry by removing the material allowance. The tool used was a brass wire with a diameter of 0.3 mm. The wire erosion process consisted of clamping the part on the machine table, after which the brass wire was manually inserted into the machining hole previously executed by milling. To produce the internal surface, 2 passes were performed, roughing and finishing, such that the core surface is rough, while that of the part is finished. Figure 11 highlights the wire fixing, Figure 12 shows the cutting execution, and Figure 13 displays the final result of the process.



Fig. 11 Wire clamping

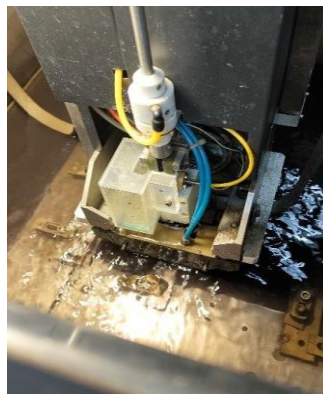


Fig. 12 Wire cutting process

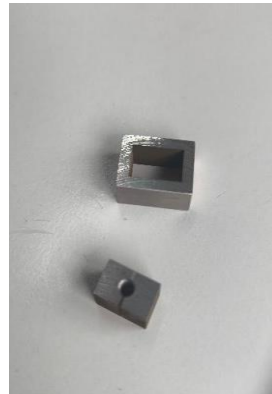


Fig. 13. Part and core

The working parameters were configured to ensure discharge stability in the deionized water dielectric: a pressure of 30 bar, a working voltage of 80 V, and a current intensity of 50 A, which define the plasma channel energy, along with a pulse-off time of 18 μ s required for the deionization of the working gap. Precision control is supported by a wire speed of 10 mm/s and a wire tension of 18 N.

The SEM analysis reveals the specific features of the wire cutting process, starting from the threading hole, where marginal melts are observed on the wire exit edge, illustrated in Fig. 14.a, resulting from incomplete cooling of the material in the corner area. According to Fig. 14.b, the formation of burrs and massive depositions of resolidified material is observed because the melted material was drawn back and accumulated at the contour closing point. In Fig. 14.c, it can be observed that in the sharp corner topography, spherical particles and irregular agglomerations appeared on the part edge.

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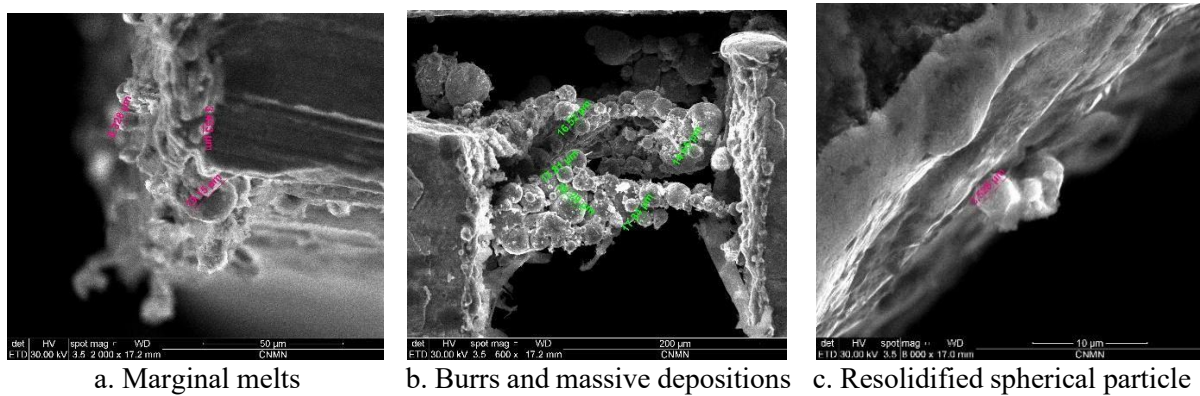
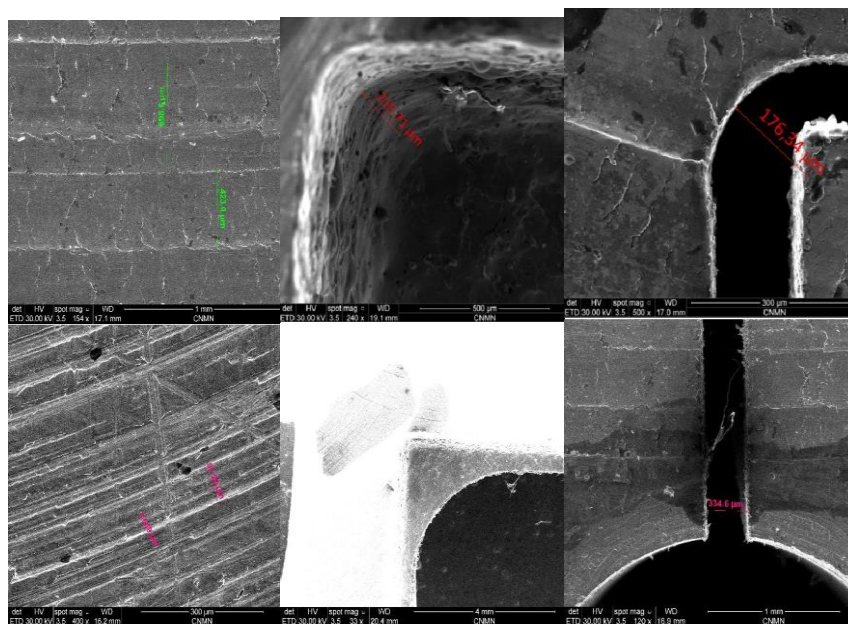


Fig. 14. SEM analysis of the WEDM process

4. Comparative Analysis

In order to comparatively evaluate the performance of the three utilized technologies, an investigation using scanning electron microscopy (SEM) was conducted. The images obtained following the SEM verification are presented in Fig. 15, allowing the identification of the specific surface formation mechanisms and the geometric precision achieved at the internal corners. From the standpoint of the micro-geometry formation mechanism, in Figure 15.a, the surface produced by milling exhibits an anisotropic texture, with parallel and well-defined cutting marks. This is the result of the mechanical action of the tool's cutting edge. Microscopic ridges and grooves caused by the tool feed rate are observed, with the surface being characterized by a geometric regularity induced by the cutting parameters. According to Figures 15.b and 15.c, the mechanism is purely thermal, based on melting, vaporization, and boiling. The texture is isotropic but with a random character, being formed of overlapping micro-craters.



a. SEM analysis of the milling process

b. SEM analysis of the EDM process

c. SEM analysis of the WEDM process

Fig. 15 Comparative analysis

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The comparative analysis of the images reveals major differences regarding geometric precision at the corners. Although in milling, the corner radius is limited by the tool radius, making it a fast method, it cannot generate perfectly sharp corners without using extremely thin tools that are prone to breakage. In EDM, a corner rounding with a radius of approximately 216 μm is observed. This phenomenon occurs due to concentrated wear at the corners of the copper electrode and lateral discharges within the working gap, which tend to erode the edges faster than flat surfaces. WEDM offers the highest precision, generating a "sharp corner". The $\varnothing 0.3$ mm wire electrode allows obtaining very small internal radii of approximately 176 μm , determined by the tool radius plus the machining gap, eliminating the error induced by the geometric wear of the solid electrode. It is also mentioned that on external surfaces, using a fish-tail toolpath, a sharp edge with a radius close to zero can be generated [11].

Following the EDM process, the surface is affected by the pyrolysis of the dielectric fluid, resulting in carbon depositions that can protect the electrode. According to Figure 4.1.b, deeper craters and a more prominent recast layer can be observed due to the high discharge energy. The WEDM process is cleaner due to the deionized water. However, at the start or end zones of the contour and at the starting holes, micro-burrs and spherical particles appear. Milling exhibits work hardening or mechanical burrs upon the tool's exit from the material.

5. Numerical Simulation of Material Removal

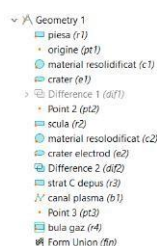
The numerical simulation of the material removal process was performed in COMSOL Multiphysics using a *2D axisymmetric spatial dimension, and the Heat Transfer in Solids, Time Dependent physics interface*. The material removal from the surface of the C10 steel part and the active surface of the 99.9% Cu tool was approached comparatively, with the following modeling stages.

The model parameterization was carried out according to Fig. 16

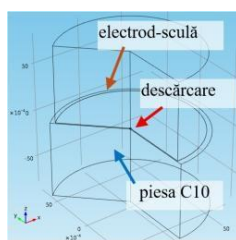
Name	Expression	Value	Description	Name	Expression	Value	Description	Name	Expression	Value	Description
hp	8[mm]	0.008 m	"inaltime piesa de proba"	densC10	7500	7500	"densitate [kg/m ³]"	acrCu	4e-6	4.0E-6	raza crater initiala pe electrod
lp	15[mm]	0.015 m	"lungimea piesei de proba"	kC10	35	35	"conductivitate termica [W/mK]"	bcrCu	3.6e-6	3.6E-6	adancime crater initiala pe electrod
I	8	8	"treapta de curent [A]"	CpC10	700	700	"Capacitate calorica [J/kgK]"	gC	10e-6	1.0E-5	strat C depus
dcr	10e-6	1.0E-5	"diametru crater initial"	ls	14[mm]	0.014 m	lungimea sculei	densCu	8900	8900	densitate Cu
tif	90e-6	9.0E-5	"timp de impuls final [us]"	hs	8[mm]	0.008 m	inaltime sculei	CpCu	450	450	caldura specifica Cu [J/kg C]
dcr/2	5.0E-6	5.0E-6	"raza crater initial"	U	17	17	tensiunea de descarcare [V]	kCu	380	380	conductivitate termica Cu [W/kg C]
bcr	0.9*acr	4.5E-6	"adancime crater initial"	P	U*I	136	puterea descarcarii [W]	CpC	1800	1800	caldura specifica C [J/kg C]
Ra	2.648E-6	2.648E-6	"Rugozitatea Ra"	Pd	P/Ad	1.602E12	densitatea de putere [W/m ²]	kC	5	5	conductivitate termica C [W/kg C]
rms	0.2e-6	2.0E-7	"raza material resolidificat"	Ad	3.14*(rms+acr)^2	8.491E-11	aria spotului EDM	densC	2000	2000	densitate C
rbg	0.1[mm]	1.0E-4 m	"raza bula gaz"	rr	0	0	raza de referinta	Ads	3.14*(rms+acrC...	5.539E-11	aria spotului EDM pe scula
raport	3.9947/4.43	0.9017	"raport adancime / raza crater"	sigma	dcr/6	1.667E-6	abaterea medie patratica	Rds	P/Ads	2.455E12	densitate de putere pe scula [W/m ²]
TfC10	2800+273.15	3073	"Temperatura de fierbere, C10[K]"	sF	80e-6	8.0E-5	interstiul frontal [um]	TsC	3600	3600	temperatura de sublimare a C
TmC10	1500+273.15	1773	"Temperatura medie de topire, C10[K]"	acrCu	4e-6	4.0E-6	raza crater initiala pe electrod				

Fig. 16. Model parameterization

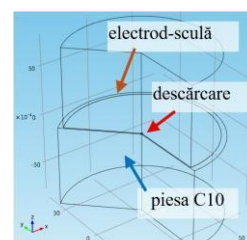
The creation of the model geometry using the built-in tools in COMSOL is presented in Fig. 17:



Used tools



3D geometry



2D geometry, discharge zone

Fig. 17. Model geometry

The material assignment was carried out according to Fig. 18:

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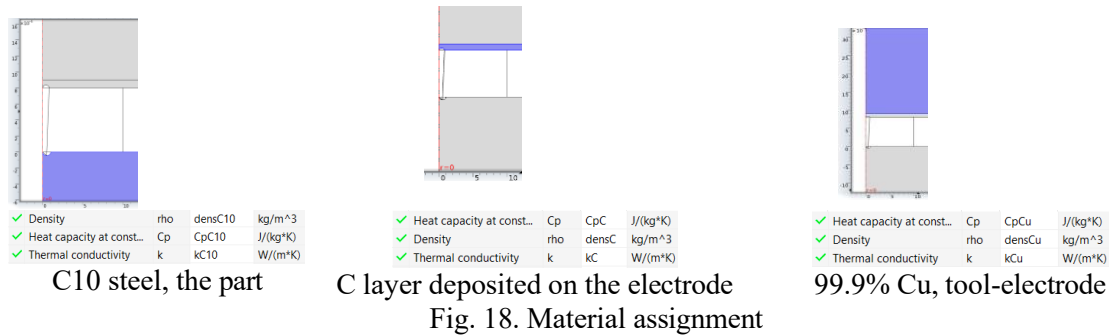


Fig. 18. Material assignment

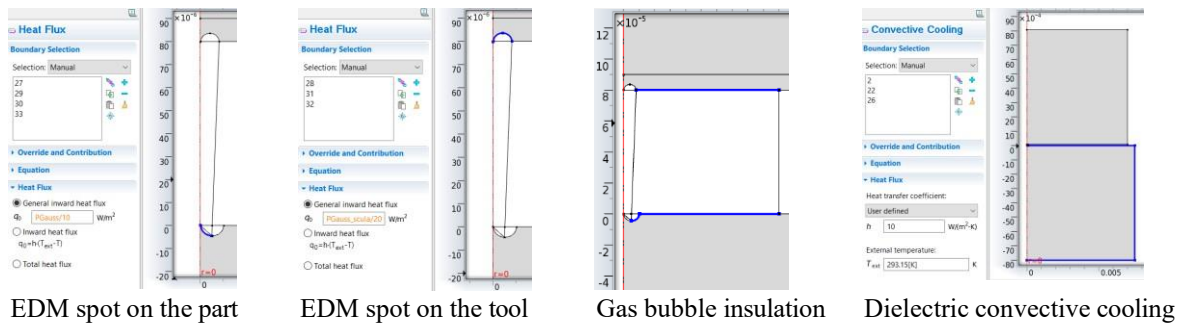


Fig. 19. Boundary conditions

The boundary conditions were introduced using the heat flux parameter with a Gaussian distribution on the surface of the machined part and the tool-electrode, the thermal insulation provided by the gas bubble around the plasma channel, and the convective cooling at 20°C through contact with the dielectric fluid, according to Fig. 19. The meshing was performed with 8175 free triangular elements of normal fineness, Fig. 20. By running the models, the radii of the craters formed by a single discharge were determined on the part surface, Fig. 21, and the tool surface, Fig. 22, in agreement with the experimental data. The discharge on the tool surface does not penetrate the superficial C layer, achieving tool protection, Fig. 22

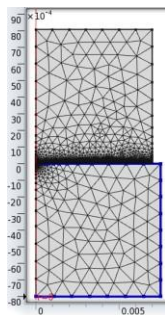


Fig. 20. Meshing

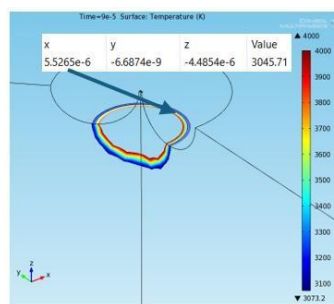


Fig. 21. Crater radius and depth on the part

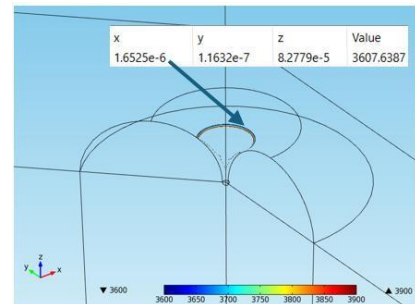


Fig. 22. Crater radius and depth on the tool-electrode

6. Conclusions

The use of C10 steel proved to be a comprehensive testing scenario, due to its ferritic structure with a high melting point, which provides superior thermal resistance, thereby validating the EDM/WEDM processes. Although efficient for the rapid removal of the allowance, milling is geometrically limited by the tool radius and can induce mechanical stresses (work hardening) in the superficial layer, being unable to generate perfectly sharp edges in deep cavities. WEDM was demonstrated to be the optimal technology for finishing cavities, generating very small internal radii, while die-sinking EDM is limited by pronounced rounding caused by electrode wear. The numerical simulation explains the material removal process from the part surface and the tool protection through C deposition on its surface.

7. References

- [1]. Sandvik Coromant (2020). *General Turning and Milling Selection Guide (Rotating Tools)*. Sandvik Tooling, Sandviken, Sweden.
- [2]. VDI 3402 Blatt 2: *Elektroerosive Bearbeitung; Verfahrensbegriffe, Beurteilung, Arbeitsbedingungen*, Verein Deutscher Ingenieure, Düsseldorf.
- [3]. Mitsubishi electric, *M800V/M80V/M800/M80 Series Instruction Manual*, Mitsubishi CNC, Technical Section: Machining Conditions for Wire EDM.
- [4]. Kalpakjian, S., & Schmid, S. R. (2014). *Manufacturing Engineering and Technology* (7th ed.). Pearson. ISBN 978-0133128741
- [5] *** GF, CUT X series Extreme accuracy, simple and fast, disponibil la: <https://www.gfms.com/en-hu/machines/edm/wire-cutting/agiecharmilles-cut-x-series.html>, accesat la: 09.05.2026
- [6] *** Sodick, AP 250 L, Disponibil la: <https://ichungary.hu/wp-content/uploads/2023/06/AP250L-E-katalogus-Angol.pdf>, Accessed:: 9.05.2026
- [7] Suci, V., & Suci, M. V. (2008). *Materials Science* (in Romanian). Fair Partners, București.
- [8] <https://guhning.com/ProductsServices/SizeDetails?EDP=9067360140000>, accesat la: 9.05.2026
- [9] <https://www.sandvik.coromant.com/en-gb>, accesat la: 9.05.2026
- [10] Ghiculescu, D. (2026) et. al., Analysis Based on Computer Vision of Machined Surfaces by Hybrid Ultrasonic and Classic Electrical Discharge Machining of CoCr Alloys, Machines, eISSN 2075-1702, Volume 14, Issue 4.
- [11] Ghiculescu, D. (2026). *Computer Aided Manufacturing Course* (in Romanian). UNSTPB. Available at: <https://curs.upb.ro/2025/course/view.php?id=7569>, Accessed: 9 May 2026.

STUDY ON MANUFACTURING BLANKS VIA LASER, PLASMA, OR WATERJET CUTTING

Stud. Andrei-Eduard GHIOCULEȚ,

Lect. Sergiu NANU, Asst. Marius LAZĂR and Prof. Sergiu TONOIU

Faculty: IIR, Specialization: IEI, 4th Year, e-mail: andreyghioculet@gmail.com

ABSTRACT: This paper examines the fundamental mechanisms, mathematical data, and performance of three essential processing technologies: laser beam cutting, plasma cutting, and abrasive waterjet machining. Within the context of modern industrial requirements, the study rigorously analyzes four major technological parameters: kerf width, maximum penetration depth, kerf taper angle, and estimated manufacturing costs. The analysis is based on material typology and part complexity, synthesizing data to provide decision support for selecting the optimal manufacturing process without conducting original experiments, relying instead on reference studies.

KEY WORDS: laser, plasma, waterjet.

1. Introduction

Among the most widely used and advanced technologies globally, which currently dominate machining processes, are laser cutting, plasma cutting, and abrasive waterjet cutting. Each of these three types of processes operates on fundamentally different physical principles, thereby generating unique advantages as well as specific limitations.

Laser and plasma cutting are predominantly thermal processes that utilize an extreme power density to melt, vaporize, or burn the material along a predetermined trajectory. The consequence of these photothermal and thermoelectric processes is the formation of a heat-affected zone (HAZ) at the cut surface, which can alter the local mechanical properties of the semi-finished product. In contrast, abrasive waterjet cutting represents a cold mechanical erosion process. This technology dislodges material particles through a transfer of momentum from a supersonic stream of water and abrasive particles, eliminating the risk of thermal distortions, edge hardening, or metallurgical alterations.[1]

The central objective of this study is to analyze four major technological components that determine the geometric quality and economic viability of any manufacturing process: the kerf width, the maximum depth at which material penetration can be achieved, the operational costs, and the profile or technological slope generated by fluid and beam dynamics.

2. State of the art

The laser cutting process utilizes a continuous laser beam focused onto the workpiece surface, achieving extreme power densities. The material absorbs the optical energy and instantaneously converts it into thermal energy, melting it, while a coaxially blown assist gas evacuates the melt. The recent transition to fiber lasers (up to 20 kW) has considerably increased efficiency, enabling cutting speeds of 100 m/min on thin steel, as well as the cutting of highly reflective materials such as aluminum or brass.[2][4]

Plasma cutting represents a thermoelectric process. The electric arc is struck between an internal electrode and the workpiece. The gas is forced through a narrow nozzle, reaching

very high velocities and temperatures of up to 30,000°C. The massive thermal energy instantaneously melts conductive metals, making this process ideal for rapid roughing operations and thick sections (50–200 mm).[5]



Fig. 1. Laser cutting [10]

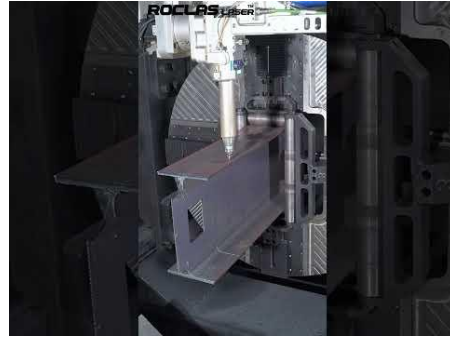


Fig. 2. Laser cutting [13]

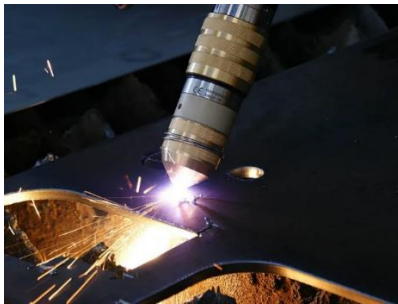


Fig. 3. Plasma cutting [11]



Fig. 4. Plasma cutting [14]

Abrasive waterjet cutting operates on a cold mechanical erosion principle. Hydrostatically pressurized water (300–600 MPa) is projected through an orifice (> 0.9 mm), entraining abrasive particles (garnet) within a mixing chamber. For an operating pressure of 400 MPa, the theoretical water velocity reaches approximately 900–1000 m/s, exceeding three times the speed of sound in air. At pressures of 600 MPa, the velocity can exceed 1200 m/s. Material removal occurs through kinetic shearing, thereby eliminating the heat-affected zone. This characteristic makes the process indispensable in the aerospace and nuclear sectors.[1][6][7][9]



Fig. 5. Waterjet cutting [12]



Fig. 6. Waterjet cutting [15]

3. Analysis of technological components

3.1. Kerf width after cutting and dimensional accuracy

The kerf width determines the degree of precision, the minimum internal radii the machine can execute, and the efficiency of automatic nesting algorithms. The extremely small beam diameter typically generates kerf widths ranging between 0.1 mm and 0.4 mm, facilitating the cutting of highly complex geometries.[6]

The waterjet produces a wider kerf (0.8 mm – 1.5 mm), physically limited by the diameter of the mixing tube, but compensates with a superior edge quality (free of dross or melted burrs).[6][8]

Plasma generates the widest kerf (1.5 mm – 4 mm); the complex fluid and thermal phenomena of the plasma jet are often investigated through empirical trials in the literature. A performance comparison of the three technologies is summarized in Table 1.

Table 1. Summary of technologies by width

Process	Minimum width (mm)	Main factors
Laser	0.1	Beam width, focal length
Waterjet	0.8	Nozzle diameter, pressure
Plasma	1.5	Electricity, material thickness

3.2. Maximum material penetration depth

As the thickness of the semi-finished product increases, maintaining the stability of the cutting process becomes a major challenge. For laser processing, at high speeds where conduction losses can be neglected, the maximum cutting depth (d) is determined by a simplified energy balance [3]:

$$d = 10,043 \times \frac{A \times P}{v \times w_k} \quad (1)$$

The equation demonstrates that the depth is directly proportional to the beam power (P) and material absorptivity (A), but inversely proportional to the kerf width (w_k) and cutting speed (v). Practically, due to thermal dissipation within the kerf walls, laser cutting is productively limited to thicknesses of 20–25 mm for steels. For carbon steel, the surface roughness ranges from Ra 0.8–1.6 μm at thicknesses under 3 mm to Ra 6.3–10.0 μm for thicknesses exceeding 12 mm. Plasma cutting was designed specifically to overcome these barriers. Due to the thermal power of the electric arc, plasma can penetrate thicknesses between 1–40 mm, while heavy industrial equipment can even reach a thickness of 160 mm. For carbon steel, Ra values increase from 3.2–6.3 μm at thicknesses below 6 mm to over 12.5 μm for thicknesses greater than 20 mm. [16][17]



Fig. 7. Surface roughness in laser cutting using air or oxygen assist gases [22]

However, abrasive waterjet cutting is the most powerful technology in terms of depth capability. The absence of molten material prevents re-welding at the base of the cut. Because the driving force is purely mechanical, a waterjet can consistently cut at depths of 100–150 mm, reaching up to 300 mm in specialized applications, limited only by the natural divergence of the abrasive particles. For small thicknesses, under 10 mm, Ra values range between 1.5–4.0 μm , whereas for thicknesses of 10–60 mm, they increase to Ra 2.5–12.5 μm . At thicknesses exceeding 60 mm, the surface roughness in the lower zone can reach Ra 25.0 μm , requiring the adjustment of process parameters to maintain surface quality within acceptable limits.[18]

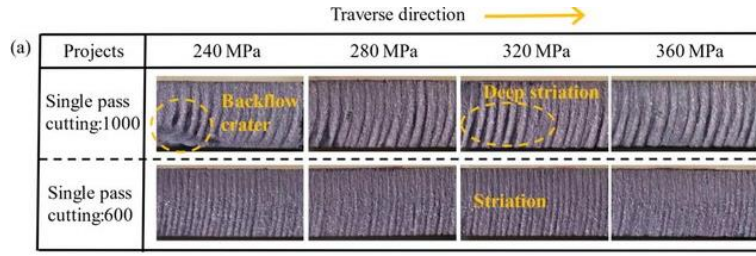


Fig. 8. Surface roughness in waterjet cutting as a function of pressure and speed [20]



Fig. 9. Surface roughness in plasma cutting [21]

The performance comparison of the three technologies is presented in Table 2.

Table 2. Summary of technologies by depth

Material	Laser (mm)	Plasma (mm)	Waterjet (mm)
Carbon steel	25	160	300
Stainless steel	10	50	200

3.3. Profile, slope, and technological tapers

No cutting process achieves a perfectly perpendicular cut. The deviation of the flanks from a cylindrical geometry is referred to as the technological slope (kerf taper). Regardless of the technology, the kerf taper angle (θ°) is geometrically determined by relating the difference between the top width (T_w) and the bottom width (B_w) to the material thickness (t):

$$\theta = \arctg\left(\frac{T_w - B_w}{2t}\right) \quad (2)$$

Laser cutting. From an optical perspective, the laser beam is not a uniform cylinder; rather, it converges through the lens toward the focal point and then diverges according to the Rayleigh length. Studies on composites show that this geometry generates a typical V-shaped kerf profile. The resulting taper angles, even under demanding conditions, do not exceed the conservative threshold of 1° (more precisely, a generalized average between 0.3° and 1°), validating laser cutting as an exceptionally perpendicular technology within its operating range.[6]

Plasma cutting. Even in the modern era of systems assisted by convergent inert gas streams that compress the electric plasma at the theoretical arc point, the asymmetric taper angle continues to fluctuate within marginal limits between 2° and 3° .[6]

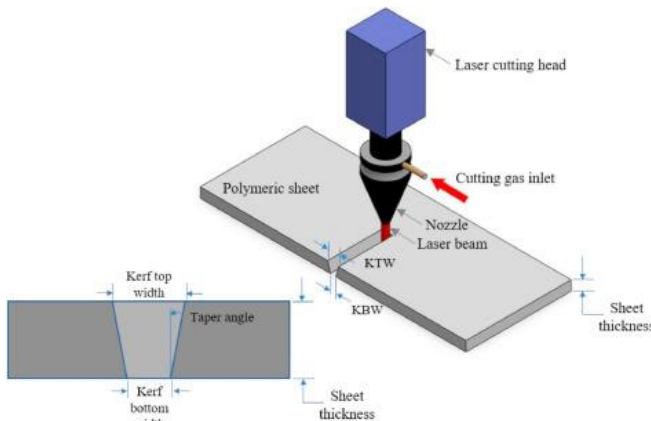


Fig. 10. Kerf profile in laser cutting [16]

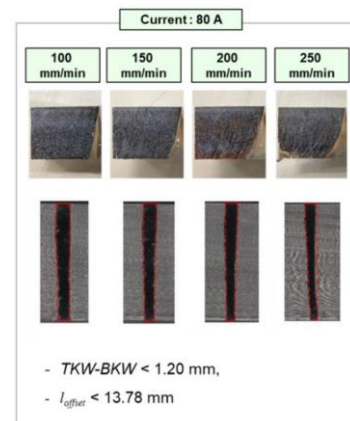


Fig. 11. Kerf profile in plasma cutting [17]

Abrasive waterjet cutting. The kinetics of the waterjet loses energy as it penetrates deeper into the material. While the jet has maximum velocity at the upper surface entry and efficiently removes material, it subsequently diverges radially, generating a V-shaped profile.

Studies confirm a high characteristic taper, typically ranging between 1.4° and 5.9° . To combat "jet lag" at corners, modern equipment utilizes dynamic cutting heads (5-axis), which automatically compensate for the taper through the CNC program. [20]

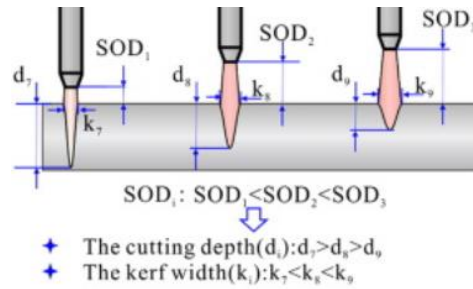


Fig. 12. Kerf profile in waterjet cutting [18]

3.4. Estimated manufacturing cost analysis

Fiber laser cutting reveals a major financial contrast: the initial investment is massive, ranging between \$250,000 and \$1,000,000 for 4 kW – 8 kW units; however, the cutting speed on thin sheets (<5 mm) ensures the best cost per part. Expenses are driven by the assist gas, varying from \$20.49/hour for oxygen (1–3 bar) up to \$86.32/hour for nitrogen (10–20 bar).[8]

Plasma cutting follows the "razor and blades" business model [4]. Although the investment in a CNC table is affordable (\$20,000 – \$90,000), the daily wear of consumables (electrodes, nozzles) adds constant costs of \$20 – \$50 per set. However, for thick and bulky components, plasma remains the only economically viable solution, featuring an average operating cost of approximately \$15/hour.[4][8]

Waterjet cutting is a demanding and expensive procedure in terms of hourly rates. Expenditure analysis shows that the mineral abrasive, which flows at a constant mass flow rate (0.3 – 0.6 kg/min), represents the largest expense, with prices ranging between \$0.50 and \$2/kg. Factoring in component maintenance at 400 MPa, the operating cost of the abrasive waterjet often sits between \$25 – \$35/hour [17]. Therefore, it must be market-targeted toward complex components that cannot withstand thermal stress or parts that would otherwise lose their aerospace integrity.[1]

Table 3. Economic analysis

Technological process	Initial investment	Major factors	Operational speed
Fiber Laser	\$250k - \$1 million	Assist gas, optical energy	Highest on thin parts (<10 mm)
Waterjet	\$150k - \$300k	Abrasive sand, hydraulic maintenance	Lowest; long cycle times per cut part
Plasma	\$20k - \$90k	Consumables (nozzles, electrodes), electricity	Moderate (ideal for parts >15 mm)

3.5. Material typology and part complexity

Waterjet cutting represents the universal process; being a "cold" cutting method, it can process any type of material: ballistic steels, titanium, glass, ceramics, wood, marble, and even composites such as carbon fiber.[2] It is widely utilized in the aerospace industry on superalloys, where the occurrence of thermal microcracks would be catastrophic.

The laser is ideal for extremely complex and detailed contours in carbon steel, stainless steel, and thin aluminum. Its limitations arise at large thicknesses and with highly reflective materials, although latest-generation fiber lasers have begun to overcome these obstacles.[1][8]

Plasma, being dependent on completing an electrical circuit, can only cut conductive materials (metals). Part complexity is limited to basic structural shapes, failing to produce small holes or fine details due to the massive kerf width.[9]

4. Case study

In order to validate the theoretical conclusions presented previously, an applied case study is subsequently conducted on a model part. From the engineering drawing, it can be observed that the thickness of the part exceeds the operating limit of the laser cutting process. The analysis aims to evaluate plasma and abrasive waterjet cutting under the conditions imposed by the geometry, dimensions, and material of the part (C15). For the execution of the cutting operations, the following characteristics were considered: machining allowances, deviations according to ISO standards, flat bar thickness, and jet diameter. CATIA V5 was used for the simulation, and AutoCAD 2026 was utilized for the cutting layout.

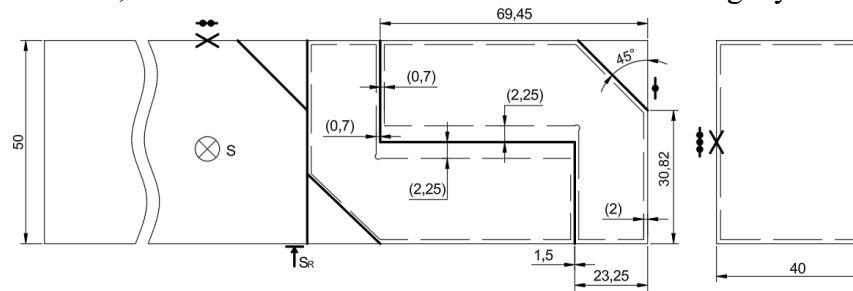


Fig. 13. Cutting layout for plasma and waterjet cutting

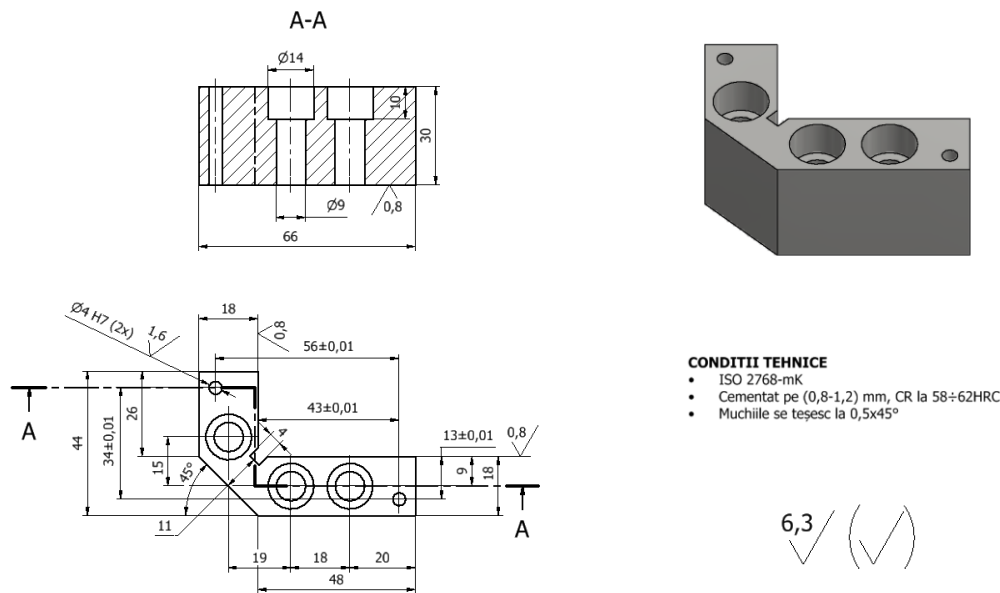


Fig. 14. Engineering drawing of part DP.00.102

4.1. Cutting simulation using CATIA V5

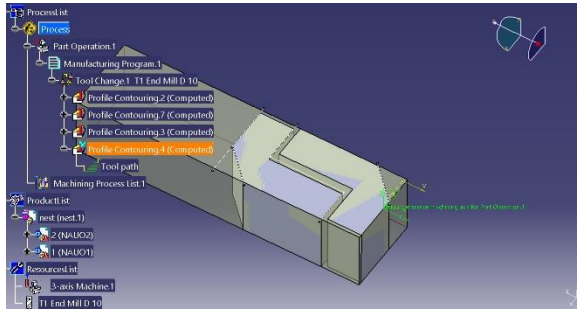


Fig. 15. Establishing the cutting toolpath

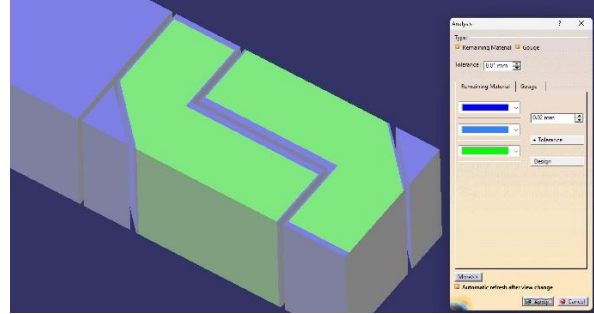


Fig. 16. Determining the machining allowance



Simulare.mov

Fig. 17. Cutting simulation

Resulted G-Code from the simulation:

```

N10 G17 G54 G71 G90
N20 M06 T01
N120 G0 X-19.56 Y27.44 Z10 M3
N130 G1 Z-40 F1000 G94
N140 X2.44 Y5.44
N150 Z10
N160 G0 X-71.45 Y27
N170 G1 Z-40
N180 Y-0.05
N190 X-24.9
N200 G2 X-23.45 Y-1.5 I0 J-1.45
N210 G1 Y-27
N220 Z10
N230 G0 X-75.34 Y-27.44
N240 G1 Z-40
N250 X-95.925 Y-6.854
N260 G2 X-96.35 Y-5.828 I1.025 J1.026
N270 G1 Y27
N280 Z10
N290 G0 Y-6.995
N300 G1 Z-40
N310 Y-27
N320 Z10
N330 M5
N340 M30
    
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5. Conclusions

The in-depth scientific analysis of the thermodynamic and kinetic processes underlying the production of semi-finished products by laser beam, plasma arc, and abrasive waterjet cutting demonstrates that there is no single, universally capable technology to meet all the demands of the contemporary industrial sector. The selection of the machining system represents a complex optimization function that balances geometric tolerance parameters,

metallurgical characteristics, and depreciation models for the operating and investment costs of the specific equipment.

Within the analyzed case study, plasma cutting represents the more affordable alternative, featuring shorter execution times and reduced operational costs. However, the resulting surface quality and dimensional accuracy are inferior to those achieved by the waterjet—characteristics that cannot be accepted for the analyzed part. Abrasive waterjet cutting ensures a cold cut with no heat-affected zone, a controlled kerf width, and superior precision, which are essential factors for complying with the specified tolerances. Consequently, based on this analysis, abrasive waterjet cutting was selected as the optimal process for this case.

6. References

- [1]. *** Ghid de debitare laser. LaserMet. Available at: <https://lasermet.ro/wp-content/uploads/2023/09/Ghid-debitare-laser-LaserMet.pdf>, accessed April 25, 2026;
- [2]. *** An Analytical Model of Metal Cutting with a Laser Beam. American Institute of Physics, *Journal of Applied Physics*. Available at: https://pubs.aip.org/aip/jap/article-pdf/79/5/2198/8805036/2198_1_online.pdf, accessed April 25, 2026;
- [3]. *** Laser vs Plasma Cost and Quality: Which Cut is Better? Arcus CNC. Available at: <https://arcuscnc.com/laser-vs-plasma-cost/>, accessed April 25, 2026;
- [4]. *** CO2 Laser Cutting Cost Estimation: Mathematical Model and Analysis. Old City Publishing, *International Journal of Laser Science*. Available at: <https://www.oldcitypublishing.com/wp-content/uploads/2019/06/IJLSv1n2p169-183Madic.pdf>, accessed April 25, 2026;
- [5]. *** Plasma Cutting vs. Laser Cutting. Hypertherm. Available at: <https://www.hypertherm.com/resources/more-resources/blogs/plasma-cutting-vs-laser-cutting/>, accessed April 25, 2026;
- [6]. *** Ask Dr. Hashish. Flow Waterjet – Flow International. Available at: <https://www.flowwaterjet.com/explore/waterjet-basics/ask-dr-hashish>, accessed April 25, 2026;
- [7]. *** Laser Cutting vs. Waterjet Cutting: Cost, Speed, Precision, and Materials. Xometry. Available at: <https://www.xometry.com/resources/sheet/laser-cutting-vs-waterjet-cutting/>, accessed April 25, 2026;
- [8]. *** So, What Is Stream Lag & Taper? FlowBlog. Available at: <https://flowwaterjetblog.com/2015/03/10/so-what-is-stream-lag-taper/>, accessed April 25, 2026;
- [9]. Momber, A.W. & Kovacevic, R. (1998) – Principles of Abrasive Water Jet Machining, Springer-Verlag London;
- [10]. *** <https://www.debitare-laser.eu/>, accessed May 03, 2026;
- [11]. *** <https://chiulan.ro/servicii/debitare-plasma/>, accessed May 03, 2026;
- [12]. *** <https://gmagarnet.ro/>, accessed May 03, 2026;
- [13]. *** https://youtube.com/shorts/AB1OjkDoQ8Q?is=qF5pe76_ItIU75AM, accessed May 03, 2026;
- [14]. *** https://youtube.com/shorts/38rFD1eJSvU?is=d-J9L1_9aNx0Qk4y, accessed May 03, 2026;
- [15]. *** https://youtube.com/shorts/4xTS7Y6SHy4?is=nNigJo_y7jI2OGJ3, accessed May 03, 2026;
- [16]. Elsheikh, A.H., Ma, N., Essa, F.A., Khedr, M., Ibrahim, A.M.M. (2025). *Kerf geometry prediction and optimization in laser cutting of basalt fiber reinforced polymer composites using decision tree and coati optimization algorithm*. Results in Engineering, Vol.

- 26, Article 105514. Available at: <https://www.sciencedirect.com/science/article/pii/S2590123025015841>, accessed May 03, 2026;
- [17]. Tuladhar, U., Ahn, S.H., Jeong, G.H., Bae, J., Kim, S., Kang, J., Cho, D.W., Ahn, S. (2024). *Numerical analysis and Schlieren visualization of gas flow dynamics inside the plasma arc cut kerf with curved cutting fronts*. International Communications in Heat and Mass Transfer, Vol. 159, Part A, Article 108075. Available at: <https://www.sciencedirect.com/science/article/pii/S0735193324008376>, accessed May 03, 2026;
- [18]. Perotti, F., Monno, M., Annoni, M. (2023). *Investigation of the influence of the AWJ-specific energy on the cutting kerf profile on aluminium 6082*. The International Journal of Advanced Manufacturing Technology, Vol. 130, Nr. 5–6, pp. 2799–2809. Springer. Available at: <https://doi.org/10.1007/s00170-023-12841-9>, accessed May 03, 2026;
- [19]. Dumitru, G., Radu, C. și Dumitru, B. (2006). *Recondiționarea pieselor în construcția de mașini*. Publisher PRINTECH, Bucharest;
- [20]. Li, Maojun & Su, Ting & Lin, Xiangchen. (2024). Improving surface striation and kerf taper of hybrid Al/CFRP stacks using dual-pass abrasive waterjet slotting strategy. The International Journal of Advanced Manufacturing Technology. 130. 1-14. 10.1007/s00170-024-13084-y. Available at: https://www.researchgate.net/publication/377722993_Improving_surface_striation_and_kerf_taper_of_hybrid_AlCFRP_stacks_using_dual-pass_abrasive_waterjet_slotting_strategy, accessed May 04, 2026;
- [21]. Matteo Busatto, Julia Meyer, Leonardo Caprio, Davide Gandolfi, Barbara Previtali, Investigating the effect of different axial oscillation waveforms in laser fusion cutting, Optics & Laser Technology, Volume 201, 2026, 115284, ISSN 0030-3992, <https://doi.org/10.1016/j.optlastec.2026.115284>;
- [22]. Kuat Kombayev, Yernat Kozhakhmetov, Dias Yerbolat, Yerkhat Dauletkhanov, Vadim Kim, Argyn Kaidar, Aibek Ishangaliyev, Fuad Khoshnaw, Influence of cutting parameters and assist gases on the laser cutting quality of 09G2S (S355J2, EN 10025-2) structural steel, Results in Surfaces and Interfaces, Volume 22, 2026, 100716, ISSN 2666-8459, <https://doi.org/10.1016/j.rsufi.2026.100716>.

7. Symbols

The following symbols are used throughout this paper:

- v = general linear cutting speed [m/s];
- d = maximum laser cutting depth [mm];
- A = material absorptivity coefficient [m^{-1}];
- P = laser beam power [W];
- w_k = laser kerf width [mm];
- θ° = kerf angle relative to the vertical axis [degrees];
- T_w = top kerf width [mm];
- B_w = bottom kerf width [mm];
- t = exact thickness of the machined part [mm].

HYBRID VOICE-CONTROLLED AUTONOMOUS NAVIGATION IN ROS 2 USING SPEECH RECOGNITION AND LLM-BASED GOAL TRANSLATION

**CHIRIȚĂ Mihail-Edward, DOICIN Cristian-Vasile, ABAZA Bogdan
Felician (Scientific Supervisor)**

**Faculty of Industrial Engineering and Robotics, Industrial Informatics
Program, Second Year, email: mihail.chirita@stud.fiir.upb.ro**

***ABSTRACT:** This work presents a voice-controlled navigation system for autonomous mobile robots, emphasizing natural human-robot interaction (HRI) through Large Language Models (LLMs). It proposes a modular, hybrid architecture that dynamically switches between local and remote inference for speech-to-text (using Whisper and Vosk) and semantic processing, optimizing latency, privacy, and computational resources. The system efficiently translates complex conversational commands into actionable Nav2 objectives and includes a web-based interface for tracking and managing Points of Interest (POIs). Additionally, the integration of lightweight object detection (MobileNet) enables semantic navigation. Future work aims to implement Text-to-Speech, agentic models, and a touchscreen user interface.*

***KEYWORDS:** Autonomous Mobile Robots, Human-Robot Interaction (HRI), Large Language Models (LLM), Speech-to-Text, Semantic Navigation*

1. Introducere

Autonomous mobile robots are increasingly being deployed in industrial, logistics, healthcare, and residential environments, where the ability to interact naturally with users has become an important requirement. In this context, voice control represents one of the most intuitive forms of human-robot interaction, as it enables users to issue commands in a natural manner without relying on complex interfaces or dedicated peripheral devices.

The integration of modern Natural Language Processing (NLP) technologies and Large Language Models (LLMs) enables the development of systems capable of understanding complex conversational commands and transforming them into executable robotic actions. However, implementing such solutions on embedded platforms introduces significant challenges related to latency, memory consumption, and the limited computational resources available.

The main contributions of this work are as follows:

- Natural-language generation of navigation commands using Large Language Models;
- A hybrid local/remote inference architecture for speech-to-text and LLM-based AI models;
- A web-based interface for managing Points of Interest (POIs) and issuing natural-language commands.

2. State of The Art

HYBRID VOICE-CONTROLLED AUTONOMOUS NAVIGATION IN ROS 2 USING SPEECH RECOGNITION AND LLM-BASED GOAL TRANSLATION

As of 2026, Human-Robot Interaction (HRI) has evolved from systems based exclusively on predefined commands and graphical user interfaces toward multimodal interactions that incorporate voice, natural language, and semantic context. Rapid advances in artificial intelligence have enabled robots to interpret user requests formulated in a manner closely resembling human language and to execute complex tasks through natural-language instructions.

A representative example of this evolution is the Gemini Robotics project developed by Google DeepMind [1], which introduces Vision-Language-Action (VLA) models capable of transforming visual information and natural-language instructions directly into robot-specific actions. Variants such as Gemini Robotics On-Device demonstrate the growing trend toward local inference, reducing latency and eliminating the need for a permanent Internet connection.

Although cloud-based services provide substantial computational capabilities for speech recognition and AI inference, their exclusive use introduces additional latency, dependency on Internet connectivity, and potential concerns regarding data privacy. Processing performed directly on the robot or on a local server within the network enables system operation even in the absence of external connectivity while ensuring that audio data and navigation-related information remain within the local infrastructure.

For these reasons, the development of a hybrid architecture capable of dynamically switching between local and remote processing depending on available resources represents an important direction for modern robotic systems.

In parallel, the development of interfaces for managing Points of Interest and interacting with robotic systems has become an essential component of modern navigation ecosystems. The adoption of web technologies and conversational interfaces enables centralized map management, Point-of-Interest definition, and the transmission of natural-language commands to robots or autonomous agents in an accessible and intuitive manner.

3. Architecture of the Voice-Controlled Navigation System

To enable natural robot control through voice or text commands, the proposed system is organized in a modular manner, with each component responsible for transforming user instructions into executable actions for the Nav2 navigation framework [2]. The overall workflow begins with audio signal acquisition through a web-based interface, continues with speech transcription and semantic interpretation, and concludes with the generation of navigation goals or autonomous actions executed by the robot. The modular architecture allows individual components to be replaced independently, facilitates latency optimization, and enables adaptation to different languages and hardware platforms.

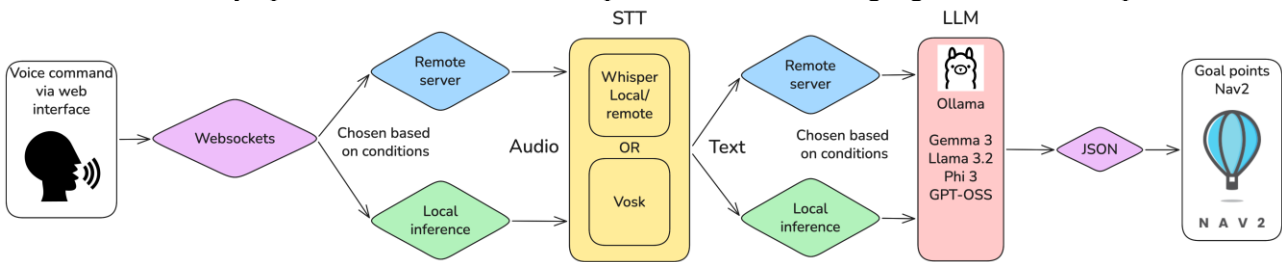


Fig. 1. System Architecture

3.1. Speech-to-Text System

3.1.1. Whisper Implementation (Local or Cloud-Based)

Several variants of the Whisper model (“base,” “small,” “medium,” and “turbo”) [3], as well as the Vosk speech recognition engine, were evaluated for the speech recognition component using both English and Romanian languages. The analysis focused on two primary criteria: transcription accuracy and inference time on the target embedded platform.

Local deployment offers the advantages of independence from Internet connectivity and a high degree of data privacy; however, it requires greater hardware resources. On the Raspberry Pi 5 platform, the absence of GPU acceleration results in increased processing times for larger models. Consequently,

HYBRID VOICE-CONTROLLED AUTONOMOUS NAVIGATION IN ROS 2 USING SPEECH RECOGNITION AND LLM-BASED GOAL TRANSLATION

model selection must be based on a trade-off between accuracy and latency.

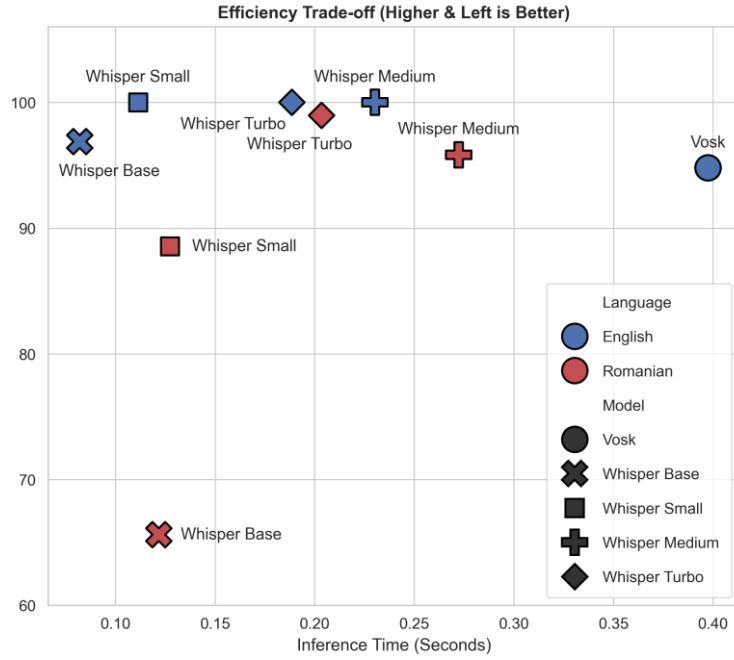


Fig. 2. Comparison of STT Models in Terms of Processing Time and Accuracy

The models were evaluated using a dataset of 97 audio recordings produced by the same speaker and containing utterances specific to the developed application. To automate the evaluation process, a Python script was used to manage the recordings together with their corresponding reference transcripts and subsequently compare the transcriptions generated by the STT models against the original texts. A result was considered correct when the generated transcription achieved a similarity score greater than 80% relative to the reference text. This threshold was chosen because it produces transcriptions sufficiently close to the original utterance, allowing downstream text interpretation methods to correctly identify the user's intent.

For English-language speech, all Whisper variants achieved very good performance. In contrast, for Romanian-language speech, the “base” model, primarily optimized for English, did not provide satisfactory accuracy. The “turbo” model delivered the best results in both languages, being an optimized version of the larger “large-v3” model. These findings indicate that smaller models are generally sufficient for English, whereas Romanian requires a larger model to achieve high transcription accuracy.

The system automatically checks for the availability of a server within the local network. When such a server is detected, the audio stream is forwarded for external processing. This approach reduces the computational load on the embedded device and enables the use of hardware acceleration on more powerful systems. In the absence of network connectivity, the robot can continue operating using local processing, thereby ensuring redundancy and operational autonomy. The inference results presented in Fig. 2 were obtained on a workstation equipped with an NVIDIA GeForce RTX 4070 GPU and an Intel Core i9 processor, simulating the scenario in which a processing server is available on the network.

3.1.2. Acceleration Using Vosk

Vosk is a speech recognition engine optimized for real-time local execution, making it particularly suitable for robotic systems with limited computational resources [4]. Its primary advantage is execution speed. The models available by default provide good performance for English, while support for Romanian is missing. As a result, Vosk is most appropriate for recognizing short and repetitive English commands.

It is important to note that Vosk operates efficiently on CPUs, unlike Whisper, which requires GPU acceleration to achieve optimal performance. Therefore, although Vosk exhibits the longest response time in Fig. 2, it maintains consistent latency even in environments lacking dedicated graphics processing hardware.

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3.2. Automatic Command Interpretation

Following speech transcription, the resulting text must be interpreted to identify the user's intent. This stage performs the conversion from natural language into the robot's internal command representation. Depending on the complexity of the request, both simple rule-based and fuzzy-matching approaches, as well as advanced language models capable of interpreting complex conversational structures, may be employed.

3.2.1. Fixed Commands Parsed With Fuzzy-Matching

For repetitive and well-defined commands, the system employs a fuzzy matching approach between the recognized text and a predefined list of valid expressions. This method tolerates minor transcription errors and variations in user phrasing. For example, expressions such as “go to the office,” “navigate to office,” or “where is the office” can all be mapped to the same internal action (navigation to the office), provided that the Point of Interest (POI) office exists in the database. The primary advantage of this method is its high execution speed and predictable behavior, making it suitable for systems with strict latency requirements. This algorithm is implemented exclusively for the Vosk-based configuration operating in English.

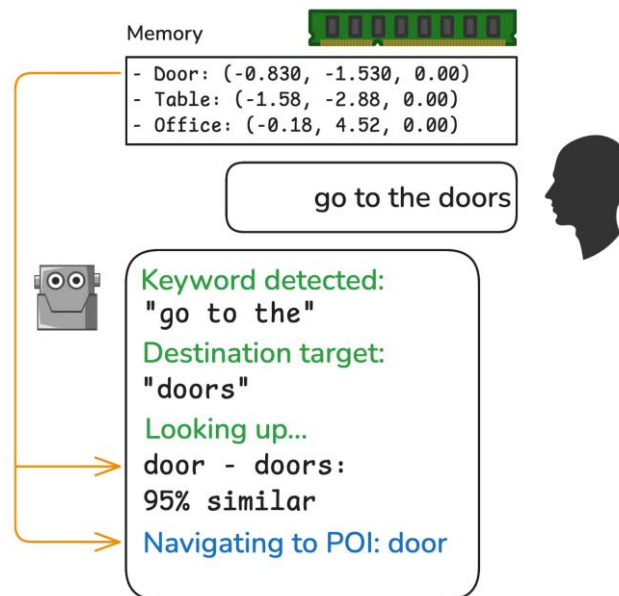


Fig. 3. Fuzzy-Matching Algorithm for POI Identification

Within this functionality, the Python library „FuzzyWuzzy” is used to calculate the similarity between the text recognized by the speech recognition system and the expressions defined in the list of valid commands. The library is based on the Levenshtein distance algorithm, which measures the minimum number of operations (insertions, deletions, or character substitutions) required to transform one string into another. Based on this calculation, a similarity score expressed as a percentage is generated, and the command with the highest score above a predefined threshold is selected as the best match.

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3.2.2. Advanced Commands Parsed by an LLM

For the interpretation of complex or conversational commands, the system can employ Large Language Models (LLMs). These models enable semantic extraction of the user's intent and identification of the parameters required to execute the requested action. The use of an LLM allows the system to understand natural requests such as “go to the laboratory first and then return to the charging station.” Compared to rule-based methods, this approach provides significantly greater flexibility; however, it introduces additional computational costs and requires validation mechanisms to prevent the execution of invalid commands.

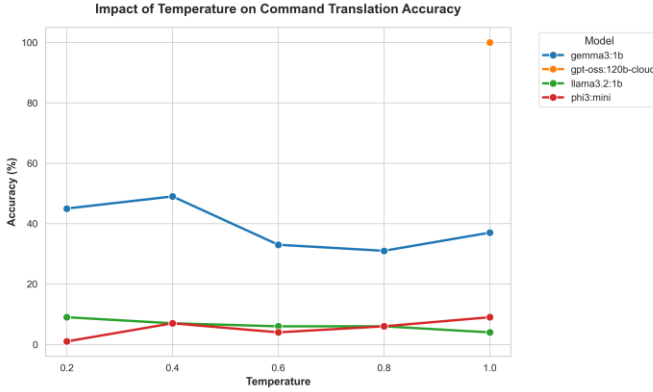


Fig. 4. Precision depending on temperature

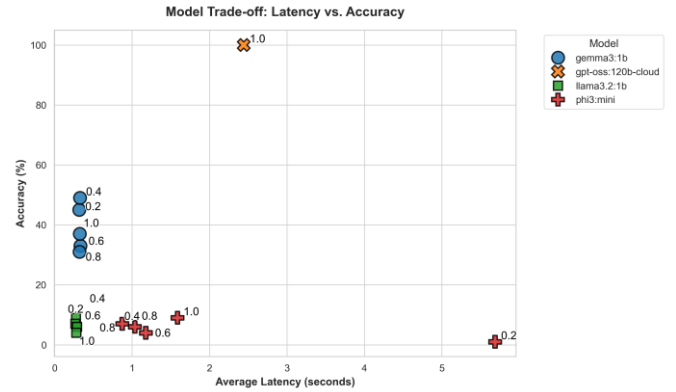


Fig. 5. Precision depending on latency

The models were evaluated using a Python script that automatically generated sets of Points of Interest with randomly assigned names and coordinates, together with queries for which the correct answers were known beforehand. The performance of each model was determined by comparing the generated responses with the expected outputs. A response was considered correct only if it fully complied with the required JSON format and contained the exact coordinates associated with the requested Point of Interest.

The evaluation results indicate that, among the locally executed models, gemma3:1b achieved the highest accuracy when using temperature values between 0.2 and 0.4. The cloud-based model gpt-oss:120b achieved 100% accuracy, benefiting from a substantially larger number of parameters and execution on cloud infrastructure. The inference results presented in Figures 4 and 5 were obtained on a workstation equipped with an NVIDIA GeForce RTX 4070 GPU and an Intel Core i9 processor, simulating the scenario in which a processing server is available within the local network.

3.2.2.1. Prompt Engineering for Converting Speech into Nav2 Goals

Constraining small-scale LLMs to generate correct coordinates based on user requests and the Points of Interest stored in memory requires a carefully optimized system prompt capable of guiding the model toward the desired output without overloading its reasoning capabilities. Smaller models are particularly sensitive to complex instructions. By applying prompt engineering techniques, the likelihood of generating ambiguous or non-executable responses can be significantly reduced.

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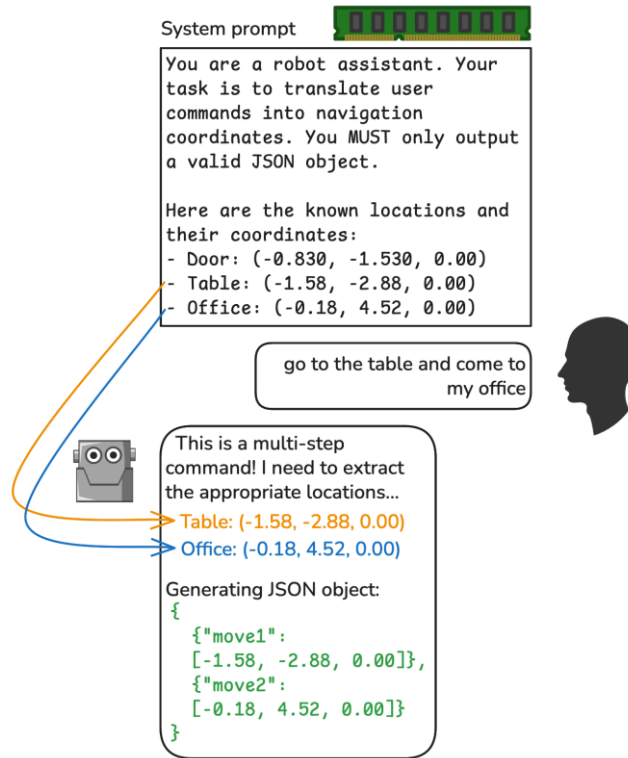


Fig. 6. LLM Architecture for Generating Navigation Coordinates from Natural-Language Commands

3.3. Command Execution

3.3.1. Navigation Commands to One or Multiple POIs

The system supports navigation toward Points of Interest (POIs) previously defined on the map. Each point is associated with a semantic identifier and spatial coordinates used by Nav2 for path planning. Users may request navigation to a single location or to a sequence of locations visited in a specified order. In the case of multiple destinations, the system automatically manages the transition between goals and monitors the completion of each stage before initiating the next navigation task.

3.3.2. Script Execution Until a Stop Command Is Received

In addition to navigation toward predefined locations, the system supports the execution of predefined autonomous scripts. Such scripts may include patrol routines, periodic inspection tasks, or repeated traversal between fixed locations. Upon receiving a start command accompanied by the script name, the robot repeatedly executes the associated sequence until a corresponding stop command is detected.

3.4. Web Communication Interface and ROS Bridge

The web interface provides real-time visualization of the robot's position and system status. Users can issue commands either by typing into a text input field or by submitting voice commands through a microphone. Communication between the interface and ROS is achieved via WebSockets using ROS Bridge, enabling low-latency bidirectional data exchange [5]. This approach facilitates integration with mobile devices and external control stations.

The interface also includes a management system for the Points of Interest used in navigation. Users can add, modify, or remove locations directly through the web application without modifying the internal ROS system files. Each POI is stored together with its name and spatial coordinates, making it subsequently available for both voice-command processing and autonomous navigation.

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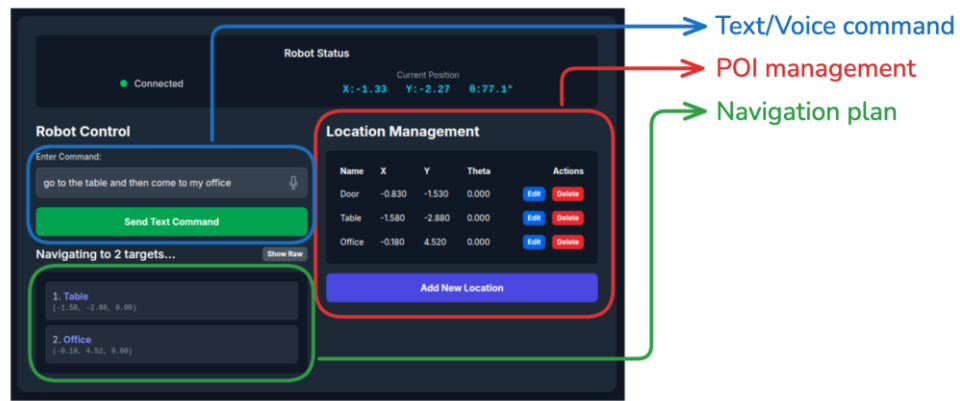


Fig. 7. Web Control Panel

4. Integration of Object Detection and Semantic Navigation on the NXP NavQPlus Platform

4.1 Performance Analysis of YOLO and MobileNet Models on NXP NavQPlus

The experimental results indicate significant differences between the two architectures. With the navigation stack active and the system in an idle state, resource utilization is approximately 40% CPU and 542 MB of RAM. During the execution of YOLO26 [6][7], resource consumption increases to approximately 65% CPU and 964 MB RAM, with an average inference time of 53.6 ms and an estimated accuracy of approximately 90%.

In comparison, MobileNet [8] utilizes approximately 60% CPU and 630 MB RAM, achieving an average inference time of 10.294 ms and an accuracy of approximately 62%. Accuracy was evaluated by positioning a known object in front of the camera and calculating the average detection confidence and object identification time.

These results highlight the trade-offs between performance and computational efficiency. YOLO26 provides superior accuracy but requires substantially greater hardware resources and introduces higher latency. MobileNet, although less accurate, offers significantly lower inference times and reduced CPU and memory utilization.

Due to its architecture optimized for embedded systems, MobileNet can operate reliably alongside the Nav2 stack and ROS 2 localization and planning nodes. For this reason, it was selected for the final implementation of the semantic navigation system.

4.2 Implementation of the Semantic Navigation Package

Semantic navigation was implemented using MobileNet object detection, and LiDAR distance fusion via the "semantic_localizer" ROS2 package [9]. The objects detected by the RGB camera are correlated with the spatial data provided by the LiDAR, resulting in semantic localization of the objects on the map. This approach allows generating navigation objectives based on the real-life description of the objects, not just on predefined static coordinates.

In the future, this system can be extended by fully integrating voice commands together with semantic navigation, such that the robot will autonomously identify objects from its environment and automatically generate Points of Interest without any interaction from the user.

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5. Discussions and Ongoing Developments

5.1 Strategy for Training a Romanian Language Corpus for Vosk

Extending automatic speech transcription for the Romanian language while preserving the speed benefits offered by Vosk requires the construction of a specialized audio corpus dedicated to robotic commands. This corpus should include diverse examples of pronunciation, tone, speaking rate, and background noise in order to ensure model robustness. An effective strategy involves collecting commands from multiple users, automatically segmenting recordings, and performing manual or automatic annotation using a larger model, thereby achieving a form of task-specific distillation. The corpus should include domain-specific expressions such as location names, rooms, or navigation targets in order to improve recognition accuracy within the application context. Additionally, the dataset can be enriched and the model's recognition coverage expanded by incorporating publicly available datasets such as Mozilla Common Voice [10].

5.2. Implementation of Agentic Models

A clear direction in recent developments of LLMs is the enhancement of agentic capabilities, namely the ability of models to use external tools to solve complex tasks. This direction is also relevant to the proposed voice-controlled navigation architecture, as an agentic model can interpret more complex instructions and coordinate more advanced action pipelines beyond simple voice command processing.

5.3. Conversational Interaction Through TTS

The addition of a Text-to-Speech (TTS) component could improve user feedback and interaction clarity by introducing a vocal response mechanism. In particular, within the context of a conversational agent, the system could request clarifications or confirm received commands. A suitable solution for this scenario is Piper TTS [11], due to its optimization for resource-constrained platforms and the small size of its models, enabling fully local speech synthesis.

5.4. Real-Time Streaming of Inference Outputs to Reduce Latency

Within the integration of the NXP NavQPlus platform, the possibility of embedding a touchscreen display into the robot chassis has been considered. This would allow users to configure system functionalities or issue voice commands without relying on an external web interface. For implementing such an interface, SDKs such as Qt, GTK, or ImGui are considered, as they enable the development of custom graphical interfaces for visualizing ROS 2 data, including maps, LiDAR data, detected obstacles, and generated Points of Interest.

5.5. Real-Time Streaming of Inference Outputs to Reduce Latency

A feature provided by most AI inference APIs and frameworks is the ability to stream outputs in real time before the model has fully completed generation. Using this approach can reduce the perceived latency between the user's command and the system's response, leading to more natural interactions in the context of Human-Robot Interaction (HRI).

6. Conclusions

This work has demonstrated the feasibility of integrating modern artificial intelligence technologies into an autonomous mobile robotic system by combining speech recognition, Large Language Models, and a ROS 2/Nav2-based navigation architecture. Through the use of a hybrid inference strategy (local/remote), the system maintains functionality even under limited computational resources or in the absence of Internet connectivity, while achieving a balanced trade-off between latency, accuracy, and resource consumption. The results obtained from STT and command interpretation experiments confirm that the selected models are capable of supporting natural and robust interaction in real-world scenarios. Overall, the proposed system provides a scalable solution for human-robot interaction through natural language, enabling intuitive control of mobile robots in applications such as logistics, industrial environments, or assistive systems. The integration of a web interface for managing Points of Interest, together with the potential extension toward semantic navigation and advanced conversational capabilities, highlights the system's potential as a foundation for future intelligent autonomous systems.

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7. References

- [1] Brohan, A., Brown, N., Carbajal, J., Chebotar, Y., Chen, X., Choromanski, K., Xia, F. et al. (2023), “RT-2: Vision-Language-Action Models Transfer Web Knowledge to Robotic Control”, arXiv preprint arXiv:2307.15818. (accessed 13.05.2026)
- [2] Navigation 2 (Nav2) Documentation, Navigation2 Project, 2026. Available at: <https://docs.nav2.org> (accessed 13.05.2026)
- [3] Radford, A., Kim, J.W., Xu, T., Brockman, G., McLeavey, C., Sutskever, I. (2023), “Robust speech recognition via large-scale weak supervision”, Proceedings of the International Conference on Machine Learning (ICML), PMLR, Honolulu. (accessed 13.05.2026)
- [4] Vosk Offline Speech Recognition API, AlphaCephei, 2026. Available at: <https://alphacephei.com/vosk/> (accessed 14.05.2026)
- [5] rosbridge_suite, RobotWebTools, GitHub Repository, 2026. Available at: https://github.com/RobotWebTools/rosbridge_suite (accessed 14.05.2026)
- [6] Sapkota, R., Cheppally, R.H., Sharda, A., Karkee, M. (2025), “YOLO26: Key Architectural Enhancements and Performance Benchmarking for Real-Time Object Detection”, arXiv preprint arXiv:2509.25164. (accessed 14.05.2026)
- [7] nav2-semantic-route-server (yolo26_cpp), GitHub Repository, Bogdan Abaza, 2026. Available at: https://github.com/bogdan-abaza/nav2-semantic-route-server/tree/main/yolo26_cpp
- [8] Howard, A.G., Zhu, M., Chen, B., Kalenichenko, D., Wang, W., Weyand, T., Andreetto, M., Adam, H. (2017), “MobileNets: Efficient Convolutional Neural Networks for Mobile Vision Applications”, arXiv preprint arXiv:1704.04861. (accessed 15.05.2026)
- [9] Abaza, B.F., Staicu, A.-A., Doicin, C.V. (2026), “Lightweight Semantic-Aware Route Planning on Edge Hardware for Indoor Mobile Robots: Monocular Camera–2D LiDAR Fusion with Penalty-Weighted Nav2 Route Server Replanning”, Sensors, 26(7), 2232.
- [10] Ardila, R., Branson, M., Davis, K., Henretty, M., Kohler, M., Meyer, J., Morais, R., Saunders, L., Tyers, F.M., Weber, G. (2020), “Common Voice: A Massively-Multilingual Speech Corpus”, Proceedings of the 12th Language Resources and Evaluation Conference (LREC), Marseille. (accessed 15.05.2026)
- [11] Piper – A Fast, Local Neural Text-to-Speech System, GitHub Repository, 2026. Available at: <https://github.com/rhasspy/piper> (accessed 15.05.2026)

DESIGN AND IMPLEMENTATION OF A SMART ETHERNET DIAGNOSIS SYSTEM

MANEA Mihai-Cătălin

Faculty of Industrial Engineering and Robotics, Specialization: Industrial Informatics, Year of Study: 2, e-mail:

mihaicsde@gmail.com

Scientific leader: Lecturer Dr. Eng. GHEORGHITĂ Vlad

ABSTRACT: This paper presents the development of an intelligent UTP/FTP cable tester designed around an ESP32 microcontroller. The device operates using a custom resistor ladder and diode network within a passive remote unit. An analog signal is injected through the RJ45 port routed to the ESP32 board, loops through the network, and returns via collector pin 1 to be processed by the master unit. A novel relative hierarchy logic was implemented, wherein each conductor's voltage level is dynamically compared with the remaining active lines. Consequently, the diagnosis remains unaffected by cable length variations or open circuits. The diagnostic outcomes are rendered graphically on an OLED display using solid rectangles for fully functional conductors, an "x" symbol for open/broken lines, and a "?" symbol for miswired/inverted pairs, providing a significantly faster and more intuitive readout compared to traditional testing devices.

KEYWORDS: Ethernet, RJ45, Network, UTP/FTP cables, Resistor ladder, ESP32, tester.

1. Introduction

The primary objective of this research is to design and implement a hardware device capable of rapidly identifying the structural integrity and wiring mapping of UTP/FTP network cables. By delivering an instant visual diagnosis on a dedicated screen and utilizing an exceptionally low-cost, passive remote unit, the proposed system yields a significantly higher testing throughput than traditional market alternatives.

2. Problem statement. Research objectives

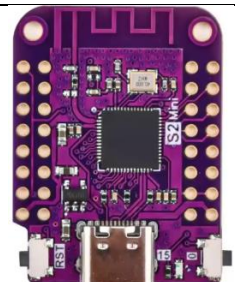
Low-cost commercial testers relying on sequential LED flashing are inherently difficult to monitor at distance, and the verification cycle is time-consuming. Conversely, professional digital cable analyzers equipped with graphic displays are prohibitively expensive for small-scale deployments, despite offering comprehensive diagnostics. To bridge this gap, the research objectives were defined as follows:

- Self calibration: Eliminating signal read errors induced by the intrinsic loop resistance of long cable runs;
- Fault detection: Accurately identifying open, broken, or floating wires;
- Graphic rendering: Designing an intuitive visual user interface for immediate fault location;
- Cost efficiency: Achieving a low production cost using off-the-shelf components.

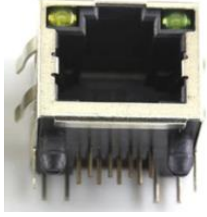
3. Proposed solution

The architecture centers around an ESP32-S2 microcontroller which sequentially applies a voltage step to each output pin. Within the passive remote terminal, each input pin is wired to a specific steering diode (ensuring signal unipolarity and preventing reverse current loops) and a unique resistor value. All paths terminate into a common return line via pin 1 of the UTP/FTP connector. The master unit samples the resulting attenuated voltage, interprets the configuration, and displays the diagnostic report on the screen (table 1).

Table 1. Components of the system

No.	Component name	Qty	Role	Component
1	ESP32-S2	1	Microcontroller running the firmware, processing connectivity logic, and driving the OLED interface	

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2	1N4148 Diode	8	Ensures signal unipolarity across channels	
3	RJ45 Socket	2	Interface ports for connecting the UTP/FTP cable under test	
4	Push button	1	User trigger to initiate the diagnostic cycle	
5	Resistor	1x1kΩ 1x2.2kΩ 1x4.7kΩ 1x10kΩ 1x22kΩ 1x47kΩ 1x100kΩ 1x10kΩ	Formulates the voltage divider network for pin identification; PULL-DOWN resistor	
6	TP4056 Charging module	1	Battery charge management and over-discharge protection	
7	li-po battery	1	System power supply ensuring device portability	
8	3 pin slide switch	1	Main hardware power On/Off toggle	
9	Oled screen	1	Graphic representation of diagnostic data.	
10	Connection wires	-	Internal point-to-point electrical connections.	

3.1. Technical implementation

The electronic core acts as an asymmetric voltage divider. In the remote node, each conductor path routes through a distinct resistor value, followed by a blocking diode, before converging onto the collector line (Pin 1). The master unit excites individual pins sequentially and performs an Analog-to-Digital Conversion (ADC) on the returning collector line. Voltage levels approaching zero are immediately flagged as broken/open connections. Inverted pairs violate the descending voltage steps and are mapped as "?" on the screen; completely missing paths are flagged with an "x", whereas fully verified, correctly mapped lines are rendered as solid rectangles.

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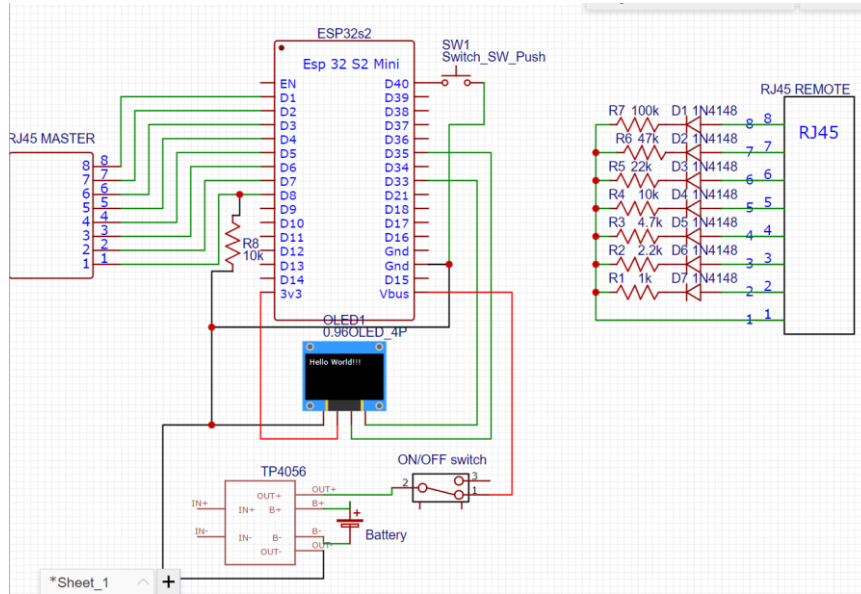


Fig. 1. System diagram

Utilizing the pinout configuration delineated in Fig. 2, the specific microcontroller GPIO pins were selected for interfacing the hardware components

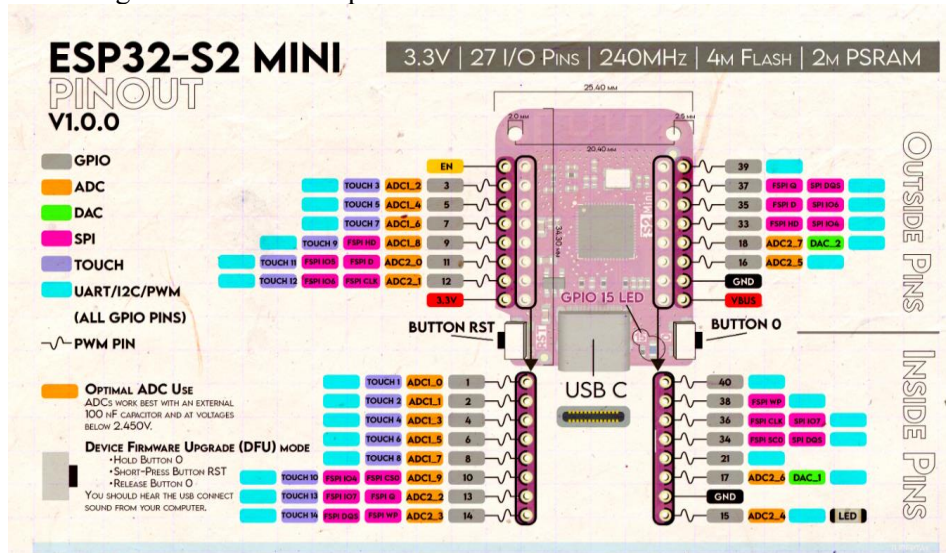


Fig. 2. ESP32 pinout map [1]

Table 2 ESP32-S2 Mini Pinout and Signal Allocation Interface

Microcontroller pin	Signal name	Signal type	Target Hardware Component	Operational Function
GPIO 33	I2C_SDA	Digital I/O	SSD1306 OLED Screen	Serial Data line for display interface
GPIO 35	I2C_SCL	Output	SSD1306 OLED Screen	Serial Clock line for bus synchronization.
GPIO 40	BTN	Input(Pull-up)	Mechanical Push button	starting test cycle .
GPIO 1	Scan_pin1	Digital Output	Remote Resistor Ladder	Sequential digital pulse output for cable 1.
GPIO 2	Scan_pin2	Digital Output	Remote Resistor Ladder	Sequential digital pulse output for cable 2.
GPIO 3	Scan_pin3	Digital Output	Remote Resistor Ladder	Sequential digital pulse output for cable 3.
GPIO 4	Scan_pin4	Digital Output	Remote Resistor Ladder	Sequential digital pulse output for cable 4.
GPIO 5	Scan_pin5	Digital Output	Remote Resistor Ladder	Sequential digital pulse output for cable 5.

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GPIO 6	Scan_pin6	Digital Output	Remote Resistor Ladder	Sequential digital pulse output for cable 6.
GPIO 7	Scan_pin7	Digital Output	Passive Remote Resistor Ladder	Sequential digital pulse output for cable 7.
GPIO 8	ADC_return	Analog input	Pull-Down Network (R_{PD}) - Master analog feedback input.	Analog input for sequential voltage feedback processing.
VCC(5V)	+5V_DC	Power	OLED Module – Main positive DC voltage power supply rail.	Analog input for sequential voltage feedback processing.
GND	GND	Power	Common Ground.	System-wide common reference potential.

3.2 Mathematical Analysis of the Resistor Ladder Network

To validate the theoretical operation of the diagnostic system prior to algorithmic implementation, a static mathematical analysis of the asymmetric voltage divider network was conducted. The master unit operates by applying a stabilized nominal digital voltage ($V_{CC}=6.6V$) sequentially to each output channel (Pins 1-7). Inside the passive remote terminal, each channel routes through a unique resistor value (R_n , where $n \in \{1,2,3,4,5,6,7\}$) and a diode (D_n). All channels converge onto the common return line (Pin 1), which is tied back to the Master unit's analog-to-digital converter (ADC Pin 8).

To prevent high-impedance floating states and filter out capacitive ambient noise, a dedicated pull-down resistor ($R_{PD} = 10k\Omega$) is permanently wired between the ADC channel and the system ground (GND).

Accounting for the standard voltage drop across the 1N4148 diodes (V_D approximately 0.7 V), the effective network source voltage (V_{net}) operating within the calculation loop is defined as:

$$V_{net} = V_{CC} - V_D = 6.6V - 0.7V = 5.9V \quad (1)$$

Since the microcontroller measures the analog voltage at the circuit node relative to the system ground (GND), the ADC senses the total potential at that junction. This potential consists of the voltage drop across the pull-down resistor combined with the fixed forward voltage offset (V_D) maintained by the active silicon diode.

By applying Kirchhoff's Voltage Law (KVL) to this series loop, the actual output voltage ($V_{out,n}$) for any active channel n is determined by adding this diode baseline directly to the standard voltage divider expression:

$$V_{out,n} = V_{net} \times \frac{R_{PD}}{R_n + R_{PD}} + V_D = 5.9V \times \frac{10k\Omega}{R_n + 10k\Omega} + 0.7V \quad (2)$$

The software then translates this voltage into the final discrete numerical domain (ADC_{calc}) via the following linear scaling expression:

$$ADC_{calc} = \frac{V_{out,n}}{6.6V} \times 8192 \quad (3)$$

3.2.1 Theoretical values versus practical values

Applying Kirchhoff's Voltage Law (KVL) and the voltage divider rule to each individual stage of the ladder network yields the following discrete ideal transfer functions:

$$R_1 = 1k\Omega$$

$$V_{out,1} = 5.9V \times \frac{10k\Omega}{1k\Omega + 10k\Omega} + 0.7V = 5.9 \times \frac{10}{11} + 0.7V \approx 6.06V$$

$$ADC_{calc,1} = \frac{6.06V}{6.6V} \times 8192 \approx 7522$$

$$R_2 = 2.2k\Omega$$

$$V_{out,2} = 5.9V \times \frac{10k\Omega}{2.2k\Omega + 10k\Omega} + 0.7V = 5.9 \times \frac{10}{12.2} + 0.7V \approx 5.53V$$

$$ADC_{calc,2} = \frac{5.53V}{6.6V} \times 8192 \approx 6864$$

$$R_3 = 4.7k\Omega$$

$$V_{out,3} = 5.9V \times \frac{10k\Omega}{4.7k\Omega + 10k\Omega} + 0.7V = 5.9 \times \frac{10}{14.7} + 0.7V \approx 4.71V$$

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$$\begin{aligned}
 \text{ADC}_{\text{calc},3} &= \frac{4.71\text{V}}{6.6\text{V}} \times 8192 \approx 5846 \\
 R_4 &= 10\text{k}\Omega \\
 V_{\text{out},4} &= 5.9\text{ V} \times \frac{10\text{k}\Omega}{10\text{k}\Omega+10\text{k}\Omega} + 0.7\text{ V} = 5.9 \times \frac{10}{20} + 0.7\text{ V} \approx 3.65\text{V} \\
 \text{ADC}_{\text{calc},4} &= \frac{3.65\text{V}}{6.6\text{V}} \times 8192 \approx 4530 \\
 R_5 &= 22\text{k}\Omega \\
 V_{\text{out},5} &= 5.9\text{ V} \times \frac{10\text{k}\Omega}{22\text{k}\Omega+10\text{k}\Omega} + 0.7\text{ V} = 5.9 \times \frac{10}{32} + 0.7\text{ V} \approx 2.54\text{V} \\
 \text{ADC}_{\text{calc},5} &= \frac{2.54\text{V}}{6.6\text{V}} \times 8192 \approx 3153 \\
 R_6 &= 47\text{k}\Omega \\
 V_{\text{out},6} &= 5.9\text{ V} \times \frac{10\text{k}\Omega}{47\text{k}\Omega+10\text{k}\Omega} + 0.7\text{ V} = 5.9 \times \frac{10}{57} + 0.7\text{ V} \approx 1.73\text{V} \\
 \text{ADC}_{\text{calc},6} &= \frac{1.73\text{V}}{6.6\text{V}} \times 8192 \approx 2147 \\
 R_7 &= 100\text{k}\Omega \\
 V_{\text{out},7} &= 5.9\text{ V} \times \frac{10\text{k}\Omega}{100\text{k}\Omega+10\text{k}\Omega} + 0.7\text{ V} = 5.9 \times \frac{10}{110} + 0.7\text{ V} \approx 1.23\text{V} \\
 \text{ADC}_{\text{calc},7} &= \frac{1.23\text{V}}{6.6\text{V}} \times 8192 \approx 1527
 \end{aligned}$$

To evaluate the mathematical model against real-world operation, the theoretical outputs were mapped directly against the experimental values captured via the system's Serial Monitor. The comparative dataset is structured in Table 3 below:

Table 3 Theoretical values versus practical values

Wire	Nominal resistor(R_n)	Theoretical voltage ($V_{\text{out},n}$)	Measured voltage (experimental)	Theoretical raw ADC value	Measured raw ADC value (experimental)
1	1 k Ω	6.06V	6.16V	7522	7638
2	2.2 k Ω	5.53V	5.60V	6864	6943
3	4.7 k Ω	4.71V	4.70V	5846	5833
4	10 k Ω	3.65V	3.48V	4530	4315
5	22 k Ω	2.54V	2.23V	3153	2765
6	47 k Ω	1.73V	1.28V	2147	1585
7	100 k Ω	1.23V	0.67V	1527	829

The empirical voltage levels closely follow the predicted mathematical curve. The minor deviations observed at higher resistance stages (wires 5, 6, 7) are thoroughly justified by the 5% component tolerances and the internal impedance of the ESP32-S2 ADC peripheral stage.

Crucially, because the firmware utilizes a relative hierarchy logic rather than fixed static templates, these deviations have zero impact on diagnostic accuracy. The physical sequence remains perfectly monotonic ($\text{ADC}_n > \text{ADC}_{n+1}$), validating the performance of the system under all testing conditions.

4. Software Implementation

Prior to physical hardware assembly, a virtual simulation environment was constructed to validate the graphic rendering layouts and debug the core processing logic. A digital DIP-switch array was integrated to simulate various wiring faults and open circuits (Fig. 3).

Following baseline prototype wiring with core modules, verification commenced via the IDE Serial Monitor to log raw ADC conversion data (Fig. 4). These empirical values established the mathematical threshold ranges for the initial revision of the firmware (Fig. 5). The structural wiring standard adhered to throughout this development is T-568B (Fig. 6).

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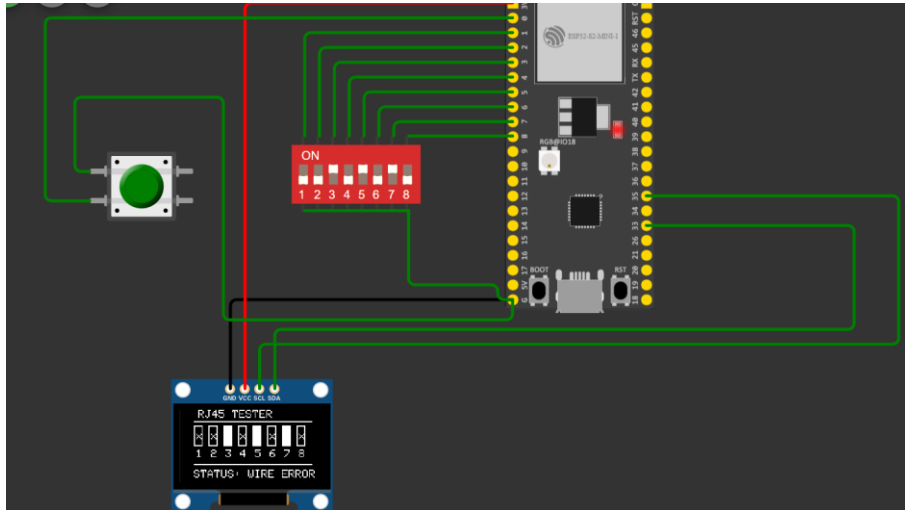


Fig. 3. Code simulation [2]

Complete source code can be found at this link: <https://pastebin.com/8Za37VCE>

```
NEW TEST CYCLE
Wire 1 (GPIO 1) -> ADC Value: 7638 | Voltage: 6.16 V
Wire 2 (GPIO 2) -> ADC Value: 6943 | Voltage: 5.60 V
Wire 3 (GPIO 3) -> ADC Value: 5833 | Voltage: 4.70 V
Wire 4 (GPIO 4) -> ADC Value: 4315 | Voltage: 3.48 V
Wire 5 (GPIO 5) -> ADC Value: 2765 | Voltage: 2.23 V
Wire 6 (GPIO 6) -> ADC Value: 1585 | Voltage: 1.28 V
Wire 7 (GPIO 7) -> ADC Value: 829 | Voltage: 0.67 V
```

Fig. 4. Raw ADC readings and calculated voltages

```
CABLE SCAN
Wire 1: OK
Wire 2: OK
Wire 3: OK
Wire 4: OK
Wire 5: OK
Wire 6: OK
Wire 7: OK
RESULT: PERFECT CABLE!

CABLE SCAN
Wire 1: [ !!! ] OPEN
Wire 2: [ !!! ] OPEN
Wire 3: [ !!! ] OPEN
Wire 4: [ !!! ] OPEN
Wire 5: [ !!! ] OPEN
Wire 6: [ !!! ] OPEN
Wire 7: [ !!! ] OPEN
RESULT: FAULTY / UNDETERMINED CABLE
```

Fig. 5. Pre-OLED diagnostics in Serial Monitor

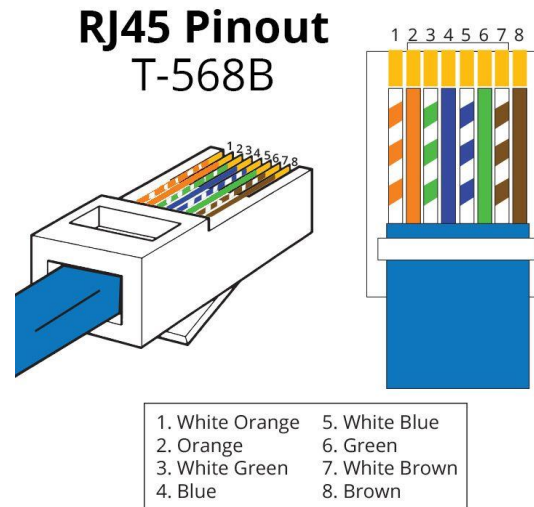


Fig. 6. RJ45 pinout standard T-568B [3]

The software architecture is decoupled into four primary sequential stages: data acquisition, digital signal filtering, relative hierarchical analysis, and graphic rendering.

4.1. Data acquisition

The firmware executes an iterative loop that sequentially drives the digital output lines (Pins 1–7) to a logical HIGH state. For each active pin, a transient stabilization delay ($\text{delay}(45)$) is introduced to dissipate any capacitive or inductive noise accumulated along the twisted pairs. Following the delay, an analog sample is acquired via ADC Pin 8 and stored into a raw data array.

4.2. Relative Hierarchy Algorithm

The primary innovation of this diagnostic tool resides within its classification algorithm. Conventional network testers evaluate incoming signals against rigid, pre-defined voltage thresholds—a technique prone to critical failure on long cable runs due to the progressive voltage drop across the copper core. This system overcomes that limitation by executing a relative hierarchy logic.

The algorithm processes data through the following pipeline:

1. **Filtering:** Any raw ADC acquisition falling below an absolute noise floor threshold of 300 units is classified as an open circuit ("broken wire"). This step safely discards stray electromagnetic interference or cross-talk from entering the analytical array.
2. **Hierarchical Validation:** For every actively verified conductor, the algorithm validates whether its voltage signature satisfies the monotonic sequence condition: the voltage on wire n must be strictly greater than that on wire $n+1$ and less than that on wire $n-1$.
3. **Fault Compensation:** If a wire is broken, the algorithm maintains its physical index within the data structure but dynamically bypasses it during subsequent array sorting. This structural approach entirely eliminates array indexing offsets that plagued earlier revisions (where an isolated open circuit would erroneously corrupt the sorting of all subsequent operational lines).

4.3. Graphic Rendering

The processed analytical matrix is mapped in real time to the OLED panel (Fig. 7) utilizing the Adafruit_SSD1306 graphic library. The visual interface is optimized for rapid, human-error-free inspection:

- **Solid rectangle:** Confirms electrical continuity and compliant pin mapping.

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- **Question mark (“?”):** Indicates an active electrical path that fails the descending voltage sequence (the line is miswired/inverted with another pair).
- **Cross (“x”):** Indicates a loss of electrical continuity.

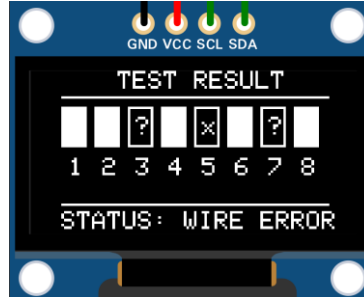


Fig. 7. Graphic interface diagnostic layout

5. Enclosure design

The physical device is split into two modular enclosures. The Master enclosure integrates dedicated cavities for the primary PCB, battery, and display; its physical layout is illustrated in Fig. 8, and the matching upper cover plate is shown in Fig. 9. The passive Remote terminal enclosure is detailed in Fig. 10; it incorporates a mechanical interlocking rail system that slides directly onto the Master housing to ensure compact storage and field portability.

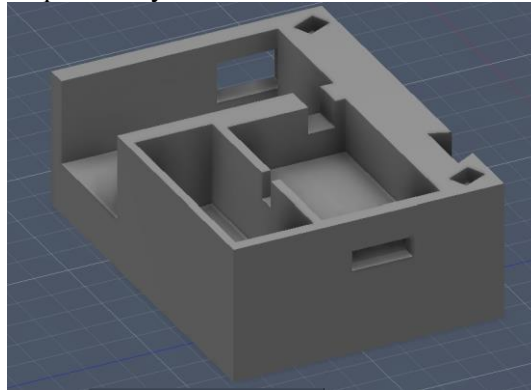


Fig. 8. Master enclosure body

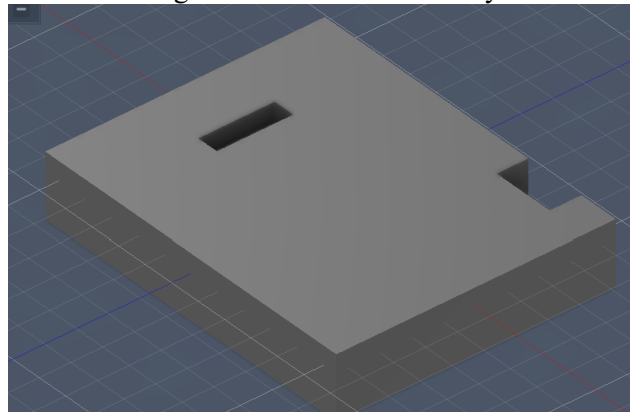


Fig. 9. Master enclosure top cover

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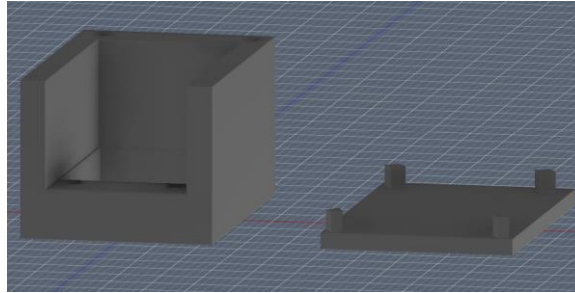


Fig. 10. Remote enclosure and top cover

6. Testing and validating

Validation involved subjecting the system to an extensive testing matrix utilizing variable cable lengths alongside specialized test cables pre-wired with intentional faults (open paths, split pairs, reversed lines). These empirical cycles refined the filtering coefficients and led directly to the implementation of the relative hierarchy algorithm.

Testing confirmed the vital necessity of the 10k Ω pull-down resistor to ground to filter out high-impedance floating states. To complement this hardware filter, a software safety mask was hardcoded to completely zero out any sampled data failing to exceed the 300 ADC unit threshold.



Fig. 11. The Prototype

7. Conclusions and future developments

This research successfully produced a portable UTP/FTP cable diagnostic instrument that transcends the operational constraints of standard market entry-level testers, providing instant, distinct diagnostic data at a minimal component cost. The transition to a relative hierarchy algorithm successfully decoupled the analysis from cable loop resistance discrepancies and resolved indexing errors caused by missing lines.

A conventional flashing LED network tester requires up to 7 seconds in slow-scan mode and 5 seconds in standard mode to complete a single diagnostic pass. These durations represent purely electronic sweep cycles, completely excluding human reading errors or the distinct likelihood of an operator missing the start of the visual blinking sequence. Conversely, the smart prototype developed in this work executes its entire acquisition, filtering, and hierarchical classification sequence in approximately 0.3 to 0.4 seconds, locking the final diagnostic output on screen until the next user-initiated test.

Through the successful execution of this project, key engineering competencies were demonstrated in analog signal processing, noise mitigation via strategic component placement, algorithmic optimization, and the complete workflow of transitioning an academic schematic into a field-ready, functional prototype.

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While the current iteration of the platform provides a robust and stable foundation, some advanced functionalities are planned for future development:

1. Battery Monitoring: Integrating a precision voltage divider tied to an auxiliary ADC line to render real-time battery charge percentages.
2. Wi-Fi Connectivity: Utilizing the native Wi-Fi stack to host a local web server, allowing technicians to view live pin mappings on a smartphone interface.
3. Wire-Map Vectoring: Upgrading the GUI to render dynamic vector lines connecting master-to-remote nodes, visually isolating crossed or miswired pins for precise troubleshooting.
4. Length Estimation: Implementing a distance approximation algorithm based on conductor resistivity constants. By measuring the progressive voltage drop across the relative hierarchy steps, the firmware will mathematically calculate the cable length.

8. Bibliography

- [1]. ESP32-S2 Hardware and Pinout Schematic,
<https://www.letscontrolit.com/forum/viewtopic.php?t=9759> [Accessed: 13th June, 2026]
- [2]. Wokwi Embedded Systems Simulator, <https://wokwi.com/> [Accessed: 13th June, 2026]
- [3]. RJ45 Pinout T-568A and T-568B Wiring Standard,
<https://www.showmecables.com/blog/post/rj45-pinout> [Accessed: 13th June, 2026]
- [4]. Wemos S2 Mini Microcontroller Hardware Specifications,
https://www.wemos.cc/en/latest/s2/s2_mini.html [Accessed: 13th June, 2026]
- [5]. Scherz, P., Monk, S., Practical Electronics for Inventors, 4th ed., McGraw-Hill Education, 2016.

DESIGN AND IMPLEMENTATION OF A NON-CONTACT VIDEO-BASED MOTION AMPLIFICATION SYSTEM FOR VIBRATION ANALYSIS

CROITORU David-Ioan și SAVU Tom (Conducător Științific)

Facultatea IIR, Specializarea IAI, Anul I, Universitatea POLITEHNICA din București

david.ioan.croitoru@stud.fir.upb.ro

Abstract. *This paper presents Video Motion Amplification (VMA) as a dense virtual sensing approach in which each pixel provides a vibration-sensitive time series. A single 960×540 frame yields approximately 518 000 simultaneous virtual measurement channels. The pipeline implements both Eulerian Video Magnification (EVM) and complex steerable pyramid phase-based processing, validated against a National Instruments DAQ accelerometer system. Validation on a rigid flange with a DC motor at 600 RPM achieved a mean relative frequency error of 0.70%. Industrial applicability and implementation challenges are also discussed.*

Keywords: video motion amplification, Eulerian video magnification, phase-based processing, NI DAQ, vibration monitoring

1. Introduction

Continuous vibration monitoring (Condition-Based Monitoring, CBM) is a foundational pillar of Industry 4.0. Mechanical defects such as rotor imbalance, incipient cracks, and structural resonances manifest as spectral shifts long before catastrophic failure [1]. Traditional methods rely on contact transducers (MEMS accelerometers, IEPE sensors, strain gauges) that deliver one-dimensional measurements at discrete points, requiring extensive cabling and installation time.

Video Motion Amplification (VMA) proposes a different measurement paradigm: each pixel provides a virtual measurement channel. The temporal series of intensity or phase at pixel (x,y) encodes the displacement of the corresponding scene point. A 10 s clip at 120 fps and 960×540 px provides ≈518 000 simultaneous channels — a non-contact sensing array deployed by pointing a camera at the structure.

This paper presents: (i) a Python VMA pipeline (EVM and phase-based) with automatic frequency detection, validated against an NI DAQ reference system; (ii) validation on a rotating flange at 10 Hz; (iii) industrial application scenarios; and (iv) implementation challenges encountered during development.

2. State of the Art

Wu et al. [2] introduced EVM as the first practical method for sub-pixel motion visualisation: temporal intensity variations of each pixel are bandpass-filtered and re-amplified in the original frame. Wadhwa et al. [3] demonstrated that phase-based processing of the complex steerable pyramid outperforms EVM by being invariant to illumination variations — a critical property in industrial environments where lighting is rarely controlled.

Chen et al. [4] identified natural modal frequencies of civil structures via VMA without any contact instrumentation. Shang et al. [5] correlated natural frequency shifts detected by VMA with stiffness degradation in concrete beams. Molina-Viedma et al. [6] compared VMA directly with Digital Image Correlation on a stiffened panel, demonstrating sub-pixel detection without

Table 1. Tabelul 1. Hardware specifications.

Equipment	Specifications
Primary	camera

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S o		ny, 120 fps, 1920×1080, ALL-I
	Test camera	Smartphone, 240 fps, H.265, rolling shutter
	Accelerometer	IEPE, magnetic, NI DAQ, $f_s = 1000$ Hz
	Drive unit	DC motor 23 mm, PWM driver 25 kHz
	Test struc- ture	Rigid metal flange, bench- mounted

physical surface markers. Yang et al. [7] performed full-field operational modal identification from video data, and Poozesh et al. [8] extended the method to rotating wind turbine blades.

3. Theoretical Foundations

3.1. Linearised displacement model (EVM)

Let $I(x, y, t)$ be pixel intensity at time t . The first-order Taylor model for small displacement $\delta(t)$:

$$I(x, y, t) \approx I(x, y, 0) + \delta(t) \frac{\partial I}{\partial x} \quad (1)$$

EVM applies a temporal bandpass filter $H(f)$ and amplifies by α :

$$\hat{I}(x, y, t) = I(x, y, t) + \alpha \cdot F^{-1}[H(f) \cdot F[I(x, y, \cdot)]] \quad (2)$$

3.2. Phase-based processing

Each frame is decomposed through a complex steerable pyramid at scales s and orientations θ [3]:

$$R_{s,\theta}(x, y, t) = A_{s,\theta}(x, y, t) \cdot e^{i\phi_{s,\theta}(x, y, t)} \quad (3)$$

Phase $\phi_{s,\theta}$ encodes local motion independently of illumination. Amplification: $\hat{\phi} = \phi + \alpha \cdot \Delta\phi$, where $\Delta\phi$ is the temporally filtered phase component.

3.3. Spectral resolution

Spectral resolution is determined by acquisition duration T :

$$\Delta f = \frac{f_s}{N} = \frac{1}{T} \quad (4)$$

At $f_s = 120$ fps and $T = 10$ s: $\Delta f = 0.1$ Hz. Sub-bin frequency estimation uses parabolic interpolation around the spectral peak bin f_k :

$$f^* = f_k + \frac{\Delta f}{2} \cdot \frac{S(f_{k-1}) - S(f_{k+1})}{S(f_{k-1}) - 2S(f_k) + S(f_{k+1}))} \quad (5)$$

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$$2 \quad S(f_{k-1}) - 2S(f_k) + S(f_{k+1})$$

yielding estimates such as 10.07 Hz versus the 10.0 Hz bin boundary. Illumination artefacts from 50 Hz mains (100 Hz flicker) alias to $|100 - 120| = 20$ Hz at 120 fps, coinciding with the $2f_0$ harmonic; these are excluded by recording under daylight or high-frequency LED.

4. Experimental System

4.1. Hardware and acquisition chain

Table 1 summarises the equipment. Fig. 1 shows the dual-chain layout and experimental setup.



Figure 1. Fig. 1. (a) Dual acquisition chain (VMA + NI DAQ). (b) Original vs. VMA-amplified frame; arrow marks detected motion on flange face. (c) LabVIEW FFT with peak at 10 Hz.

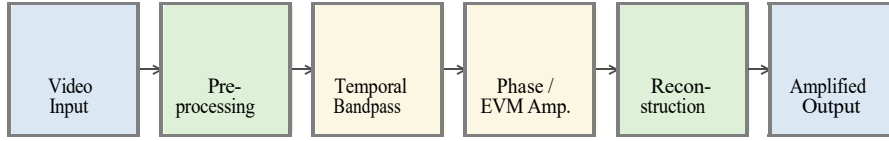


Figure 2. Fig. 2. VMA pipeline: pre-processing, bandpass (EVM or phase-based), amplification α , reconstruction.

4.2. Experimental setup

A rigid metal flange was driven by a DC motor at 600 RPM ($f_0 = 10$ Hz) via a PWM driver. An IEPE accelerometer (magnetic mount) was attached directly on the flange and connected to an NI DAQ system running LabVIEW, implementing Hann-windowed FFT acquisition at 1000 Hz ($\Delta f^{\text{DAQ}} = 0.1$ Hz). The Sony camera (ALL-I encoding) was positioned on a tripod at ≈ 40 cm, perpendicular to the vibration plane. VMA and DAQ acquisitions were started simultaneously, with an estimated offset below 0.5 s.

Smartphone recording at 240 fps proved unsuitable due to three compounding factors: rolling-shutter phase distortion ($\Delta\phi_{rs} = 2\pi f_{v} t_{rs} \approx 0.26$ rad at 10 Hz), H.265 inter-frame DCT artefacts amplified by α , and manufacturer re-encoding of slow-motion to 30 fps on export (preventing true 240 fps analysis).

5. Software Pipeline

Raw clips (HEVC 10-bit) are decoded into tensor $I \in \mathbb{R}^{N \times H \times W}$. The first 2 s are discarded (mechanical transient); analysis operates on $N = 1200$ frames ($10 \text{ s} \times 120 \text{ fps}$). Downsampling to 960×540 reduces memory from ≈ 30 GB to 1.5 GB without affecting Δf .

EVM applies a 4th-order Butterworth bandpass $H(f)$ via FFT along the temporal axis, fully vectorised across all pixels. Processing: ≈ 45 s at 960×540 , $N = 1200$. **Phase-based** decomposes each frame through the steerable pyramid ($S = 4$ scales, $K = 6$ orientations), filters and amplifies the complex phase, and reconstructs via inverse pyramid. Processing: ≈ 8 min, 3.5 GB RAM; superior sub-pixel sensitivity at $\alpha = 15\text{--}20$ vs. $\alpha = 50\text{--}100$ for EVM.

Automatic frequency detection uses a variance-weighted spectrum:

$$S(f) = \sum_{x,y} \sigma^2(x,y) \cdot |F_l[I[\cdot, x, y]](f)| \quad (6)$$

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which suppresses the static background. The dominant peak $f^* = \operatorname{argmax} S(f)$ centres the bandpass automatically.

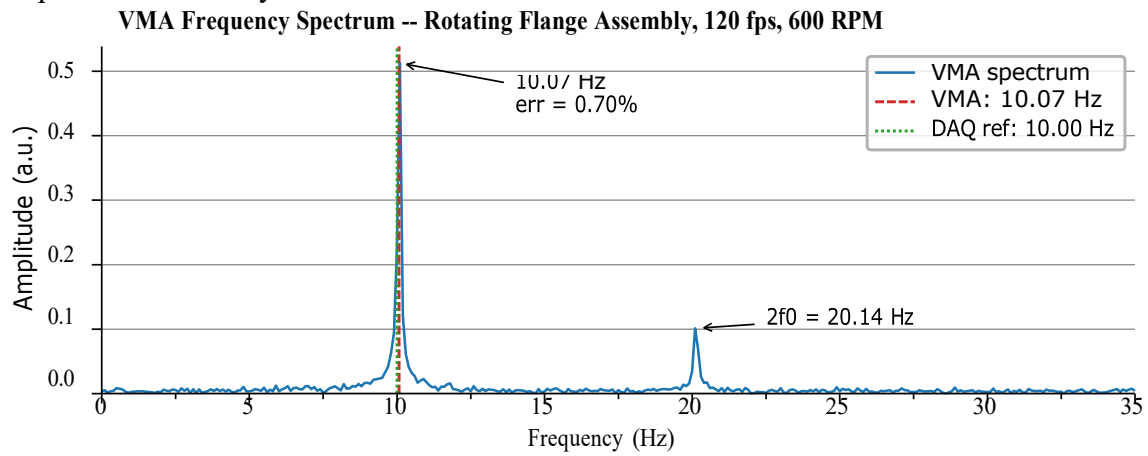


Figure 3. VMA spectrum on flange (120 fps): peak at 10.07 Hz vs. DAQ reference 10.00 Hz (0.70% error); harmonic $2f_0 = 20.14$ Hz.

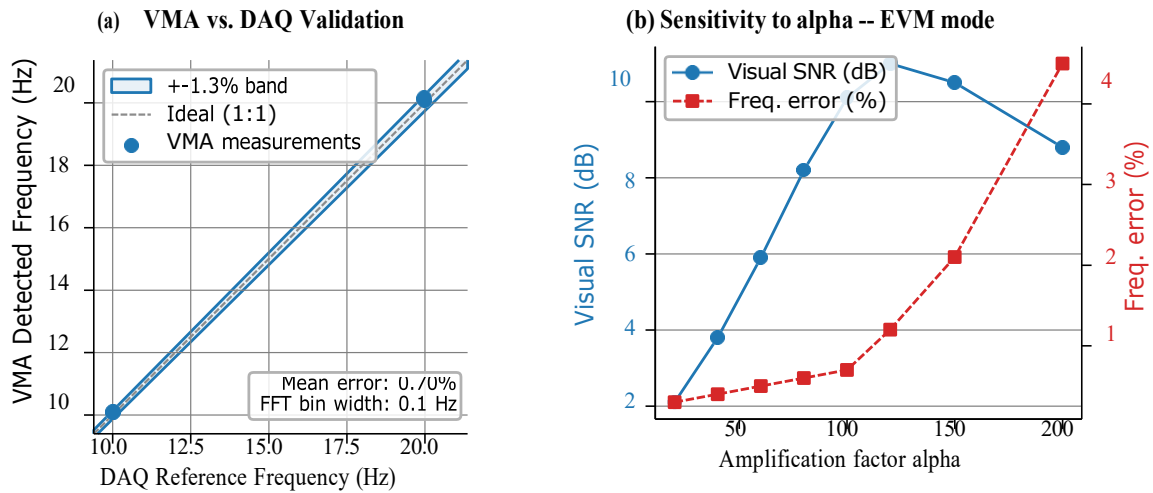


Figure 4. Fig. 4. (a) VMA vs. DAQ validation; mean error 0.70%, bounded by $\Delta f/f = 1\%$ at 10 Hz.
 (b) SNR sensitivity to α (EVM): optimal at $\alpha \in [50, 100]$.
 (c)

6. Results and Discussion

6.1. Detected frequency spectra

Fig. 3 shows the VMA spectrum on the flange. The motor at 600 RPM produces a narrow peak at 10.07 Hz (0.70% error vs. DAQ), consistent with $\Delta f/f^* = 1\%$. The 20.14 Hz component (2×10.07 Hz) confirms harmonic consistency. Dataset was recorded under daylight/LED to preclude 20 Hz illumination aliasing.

6.2. Validation and α sensitivity

Table 2 summarises frequency validation. Fig. 5 shows all VMA estimates plotted against DAQ reference values; all points fall within the $\pm 1.3\%$ band. Fig. 4(a) confirms mean error 0.70%, and Fig. 4(b) shows visual SNR peaking at $\alpha \approx 100$ and degrading above 120 through DCT artefact amplification.

6.3. EVM vs. phase-based

Table 3 compares the two methods. Virtual sensor density represents the key advantage over contact methods: $n_{\text{sensors}} = 960 \times 540 = 518400$ channels vs. 1–8 accelerometers in a classical DAQ setup.

7. Industrial Applications

VMA offers practical advantages over contact transducer networks in three scenarios: (i) *rotat-ing machinery diagnostics* — a camera surveys the full machine casing simultaneously, localising

Table 2. VMA vs. DAQ frequency validation.

Exp.	f_{DAQ}	f_{VMA}	Error	Mode
Flange	10.00 Hz	10.07 Hz	0.70%	fundamental
Flange	20.00 Hz	20.14 Hz	0.70%	harmonic $2f_0$
Mean fundamental error			0.70%	

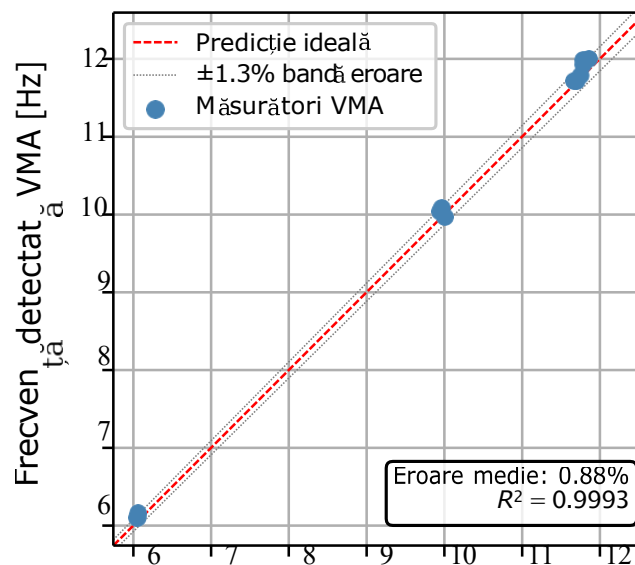


Figure 5. Fig. 5. VMA vs. DAQ scatter: all acquisitions within $\pm 1.3\%$ band (dashed). Diagonal =

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perfect agreement.

the vibrating zone without knowing the defect location in advance; (ii) *structural health monitoring* — operational modal analysis from ambient excitation without sensor attachment; and

(iii) *predictive maintenance* — periodic screening sweeps that complement continuously monitoring accelerometers.

Tables 3 and 4 summarise the comparative performance. The 518 000-channel field map replaces the need to know sensor placement a priori, and zero mass loading eliminates frequency shift on lightweight structures.

As a second qualitative validation, Fig. 6 shows the VMA spectrum on a CNC milling machine frame under operational conditions. Dominant spindle harmonics are resolved without contact instrumentation or additional calibration.

8. Implementation Challenges

Video compression. H.264/H.265 inter-frame prediction introduces DCT block discontinuities that, at $\alpha > 120$, manifest as spurious spectral peaks indistinguishable from structural vibration. Sony ALL-I (all-intra) encoding eliminates inter-frame dependencies, increasing file size $\approx 8\times$ but providing the frame independence required for phase-based VMA.

Illumination flicker. AC-powered lighting (50 Hz, European mains) produces 100 Hz intensity modulation. At 120 fps, this aliases to $|100 - 120| = 20$ Hz, coinciding with the $2f_0$ harmonic. Diagnostic check: compute $S(f)$ on a static background patch — peaks present there are electrical, not mechanical. Solution: natural light or LED driver > 10 kHz.

Camera micro-vibration. Floor-borne vibrations conducted through the tripod produce a global translational motion component that at high α is visually indistinguishable from structural motion. Global motion compensation via phase correlation of static background patches reduced the residual below 0.05 px RMS, sufficient for EVM but marginal for phase-based at $\alpha < 30$. A

Table 3. Tabelul 3. EVM vs. phase-based. contact.

Criterion	EVM	Phase
Time	~45 s	~8 min
(960×540)		
RAM	1.5 GB	3.5 GB
Light invariance	No	Yes
Sub-pixel ($\alpha=20$)	Poor	Good
Freq. error	<1.3%	<0.8%
Use case	Screening	Modal

Table 4. Tabelul 4. VMA vs.

Criterion	DAQ	VMA
Channels	1–32	~518k
Install	Hours	Seconds
Mass load	Yes	None
High-temp	Limited	Stand-off
Spatial map	No	Yes
Cost	15–50k EUR	3–4k EUR

VMA Spectrum — CNC Centre (C0031)

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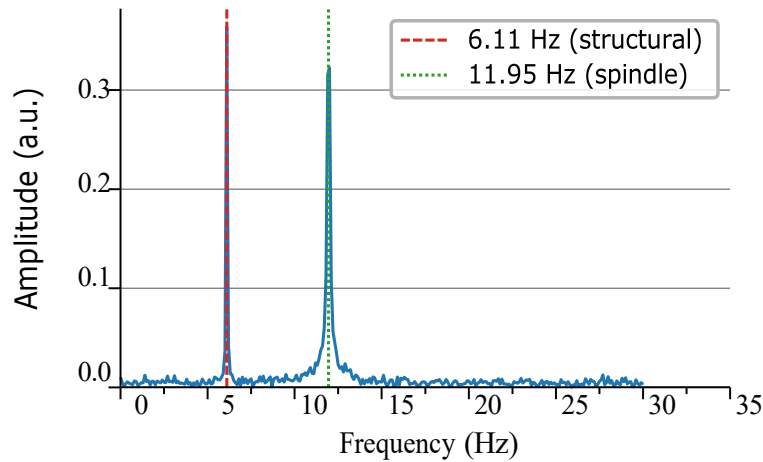


Figure 6. Fig. 6. VMA spectrum on CNC milling machine frame under operational conditions; spindle harmonics resolved without contact instrumentation.

quasi-zero-stiffness (QZS) isolation mount [9] is identified as a future hardware solution.

Computational cost. EVM processes 960×540 , 10 s clips in ≈ 45 s on a standard CPU; phase-based requires ≈ 8 min and 3.5 GB RAM. Phase-based uses 24 subbands ($S = 4$ scales, $K = 6$ orientations), each an $N \times H \times W$ complex array — approximately 1.5 GB per subband at full resolution, requiring downsampling to 960×540 for memory feasibility. GPU acceleration (CuPy) reduces EVM to ≈ 4 s per clip on a mid-range GPU, approaching real-time throughput for 120 fps acquisition.

Geometric calibration. Without pixel-to-mm calibration, the system reliably extracts vibration frequencies but not absolute displacement amplitudes. A checkerboard or known-dimension marker in the field of view provides the scale factor; this remains an open integration task for frequency-to-amplitude cross-validation against the DAQ double-integrated acceleration signal. Fig. 7 summarises the effect of the amplification factor α on detection quality for EVM mode.

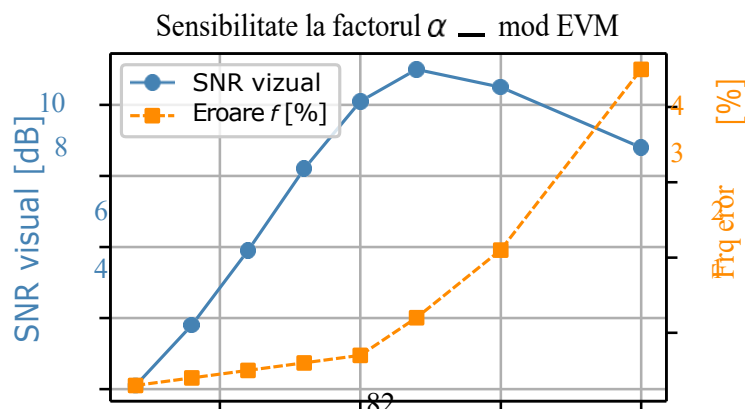
Below $\alpha = 20$ the motion is not visually discernible; above $\alpha = 120$ compression artefacts dominate. The practical operating window of $\alpha \in [50, 100]$ balances SNR against artefact level.

9. Conclusions

Video Motion Amplification transforms a standard video camera into a system with ≈ 518 000 simultaneous virtual measurement channels. Dominant frequency estimation against NI DAQ achieved a mean relative error of **0.70%**, consistent with the Fourier spectral resolution for a 10 s

acquisition window. ALL-I encoding, daylight illumination, and global motion compensation are identified as essential practical requirements.

Industrial scenarios confirm the non-contact, full-field nature of VMA offers capabilities that



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2

50 100 150 200
Amplification factor α

Figure 7. Fig. 7. Effect of amplification factor α on EVM detection quality: SNR vs. frequency error across the tested range.

contact transducer networks cannot match economically.

Future directions: (1) geometric calibration for absolute displacement amplitude validation; (2) SSI/FDD for full operational modal analysis; (3) global-shutter camera (≥ 500 fps) to extend the analysis band and eliminate rolling-shutter phase error; (4) GPU-accelerated pipeline (CuPy) to approach real-time throughput; (5) QZS isolated camera support to decouple the sensor from structure-borne floor vibration.

References

- [1] Anders Brandt. *Noise and Vibration Analysis: Signal Analysis and Experimental Procedures*. Wiley, 1st edition, 2011.
- [2] Hao-Yu Wu, Michael Rubinstein, Eugene Shih, John Guttag, Frédo Durand, and William Freeman. Eulerian video magnification for revealing subtle changes in the world. *ACM Transactions on Graphics*, 31(4):65:1–65:8, 2012.
- [3] Neal Wadhwa, Michael Rubinstein, Frédo Durand, and William T. Freeman. Phase-based video motion processing. In *ACM SIGGRAPH*, volume 32, pages 80:1–80:10, 2013.
- [4] Justin G. Chen, Neel Wadhwa, Young-Jin Cha, Frédo Durand, William T. Freeman, and Oral Buyukozturk. Modal identification of simple structures with high-speed video using motion magnification. *Journal of Sound and Vibration*, 345:58–71, 2015.
- [5] Zhong Shang, Zheng Sun, Yanfeng Zhao, and Dongmei Zhao. Structural damage detection based on video motion magnification and modal strain energy. *Engineering Structures*, 222:111085, 2020.
- [6] José-Mateo Molina-Viedma, Elias Lopez-Alba, Luis Felipe-Sesé, and Francisco Aliaga-Morillo. Comparative analysis of full-field dynamic characterization of a stiffened panel using EVM and DIC. *Experimental Mechanics*, 57:1383–1395, 2017.
- [7] Yongchao Yang, Charles Dorn, Tyler Mancini, Zachary Talken, Garrett Kenyon, Charles Farrar, and David Mascareñas. Blind identification of full-field vibration modes from video measurements with phase-based video motion magnification. *Mechanical Systems and Signal Processing*, 85:567–590, 2017.
- [8] Pooya Poozesh, Aral Baqersad, Christopher Niezrecki, Peter Avitabile, Eliot Whale, and Michael Desmond. Large-area photogrammetry based testing of wind turbine blades.

DESIGN AND IMPLEMENTATION OF A NON-CONTACT VIDEO-BASED MOTION AMPLIFICATION SYSTEM FOR VIBRATION ANALYSIS

Me-chanical Systems and Signal Processing, 86:98–115, 2017.

- [9] A. Carrella, M. J. Brennan, and T. P. Waters. Static analysis of a passive vibration isolator with quasi-zero-stiffness characteristic. *Journal of Sound and Vibration*, 301:678–689, 2007.

THE ROLE AND APPLICATIONS OF CHAOS THEORY IN COMPLEX DEVELOPMENTS

Ioana-Maria FLEACĂ¹, Marian GHEORGHE², Ronny HOPF^{2, 3}

¹Faculty of Industrial Engineering and Robotics, Specialization:

Industrial Economic Engineering, 4th study year, e-mail: ifleaca1@gmail.com

²POLITEHNICA Bucharest, Manufacturing Eng. Departament, ³Siemens AG, Germany.

ABSTRACT: This article investigates the basic principles of chaos theory, with a particular focus on its applicability to organizational management. The way complex systems react to instability and are sensitive to initial conditions is essential to understanding why they do not always evolve in a linear and predictable manner, but can react disproportionately to small changes or seemingly insignificant errors. The study explores the role of chaos theory in complex systems, explaining how certain combinations of factors can push a system toward instability, transforming small deviations into major failures. This confirms that chaos theory can explain how minor disturbances may generate significant consequences when a system is already vulnerable or unstable.

KEYWORDS: chaos theory, butterfly effect, industrial production, organizational resilience, decentralized decision-making

1. Introduction

Organizations operate in an environment where changes occur rapidly, and unforeseen circumstances can have a decisive impact on their operations. Chaos theory offers a different perspective, showing that organizations behave like complex systems, sensitive to small variations and influenced by multiple factors that can lead to unpredictable outcomes.

This paper explores how concepts such as attractors, bifurcations, the butterfly effect, and self-organization can be applied in the analysis of complex systems and industrial production. To illustrate these ideas, the Chernobyl accident and modern industrial systems are used as examples in which managerial decisions, organizational factors, and technical instability can contribute to critical outcomes. Through this approach, the paper considers that chaos theory can be a useful tool for understanding instability, uncertainty, and critical situations within complex organizational and production environments.

2. Chaos theory

Chaos theory studies deterministic nonlinear systems whose behaviour is difficult to predict and control. It demonstrates that the world does not function in a simple, linear way, but rather as a dynamic system influenced by numerous factors. Even though these systems appear disorganized, they actually contain a hidden structure and a certain type of order. Because of this complexity, it is difficult to create exact models or make precise predictions.

Examples of chaotic systems can be found in nature, such as flocks of birds, fish, or insects. Their movement may seem random, but it is based on simple rules that help maintain coordination and balance. This shows that chaos does not mean total disorder, but rather a complex form of organization that is not immediately apparent [1].

Chaos theory focuses on nonlinear systems influenced by numerous variables. These systems do not follow a predictable trajectory, and their behavior can change depending on various conditions. An important aspect is nonlinear dynamics, which shows that systems are described by complex equations that can produce very different results depending on the initial data.

1. Another key idea is that chaotic systems are extremely sensitive to initial conditions, meaning that even minor differences can strongly affect the final outcome, making long-term predictions unreliable. In addition, chaotic systems are influenced by structures called attractors, which guide their behavior and keep the system within certain bounds. At the same time, these systems can generate fractal patterns, in which similar shapes repeat at different levels, demonstrating

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the system's complexity. All these concepts are important tools used to understand chaos theory. Unlike other scientific theories, chaos theory does not have a single general formula, but uses a combination of methods and approaches to explain complex behaviors [2].

2.1. Butterfly effect

The butterfly effect is one of the most known concepts in chaos theory. It describes how a very small variation in a system can, over time, lead to major and unexpected consequences. Even an insignificant action can trigger a chain of events that amplifies through feedback and produces far-reaching effects. This idea demonstrates that complex systems are extremely sensitive and difficult to control [1].

The concept of the “butterfly effect” was introduced by Edward Lorenz in the 1960s while studying meteorological systems. He showed that very small differences in initial conditions can completely alter the final outcome of a system. This finding demonstrated that long-term predictions are unreliable for complex systems. At the same time, Lorenz demonstrated that chaotic systems do not change in a random, limitless manner, but evolve within certain boundaries. By analyzing the equations describing the movement of heated gas, he created a graphical model consisting of two oval shapes that resemble the wings of a butterfly (Fig. 1). This model, known as the Lorenz attractor, shows how two starting points that are very close together can quickly move in completely different directions, even though they begin almost identically [2, 3].

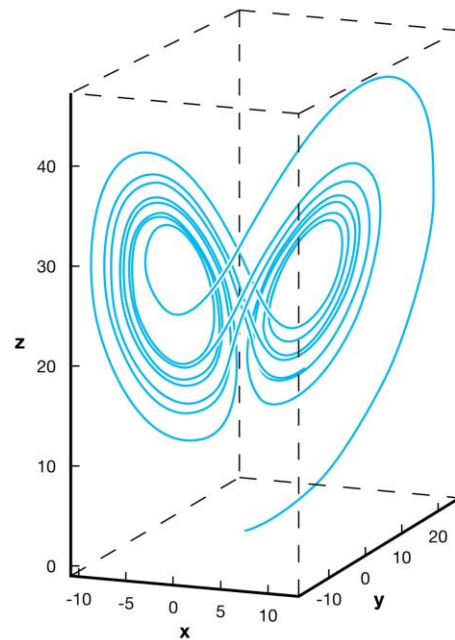


Fig. 1. The Lorenz attractor graph [3]

The butterfly effect can also be explained using examples from mathematics. In nonlinear systems, even a very small change in a value may lead to a significant difference in the result. For example, in the function:

$$F(x) = (10000)^{(100x)} \quad (1)$$

when $x = 0$, the result is: $F(0) = 1$, but when $x = 0.01$, the result becomes: $F(0.01) = 10000$.

2.

This simple mathematical example shows how a very small change in the input value can generate a very large difference in the final result. It clearly illustrates how sensitive chaotic systems are and why their behavior is difficult to predict [1].

The term “butterfly effect” also stems from the metaphor that a butterfly flapping its wings in one part of the world could eventually contribute to a major event, such as a storm, in another location. The metaphor illustrates how small actions can grow in magnitude and influence large-scale events. It also highlights the nonlinear nature of these systems, in which effects intensify over time [4].

3. Chaos theory in management and organizations

Chaos theory provides a useful sight to understanding modern organizations, as they function as nonlinear systems, as explained in Fig. 2, in which order and disorder coexist, and small changes can produce disproportionate effects. In contrast to the traditional, Newtonian-inspired paradigm, which viewed the

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organizations as a stable and predictable structures controllable through fixed rules, the nonlinear perspective shows that organizational environments are marked by instability, interdependencies, and emergent developments, rendering classical methods of planning and control insufficient [1].

Aspect	Linear System	Non-Linear System
Response to Input	Proportional and predictable	Disproportionate, may be chaotic
Relationships	Additive and separable	Interdependent and dynamic
Feedback	Often ignored or simplified	Central to system behavior
Predictability	High, if inputs are known	Low, sensitive to small changes
Control Strategy	Top-down, planned	Adaptive, decentralized
Examples	Machines, assembly lines	Ecosystems, organizations, economies

Fig. 2. Comparative overview on linear vs non-linear systems [5]

In this context, “attractors”, those internal or external influences that shape an organization’s behavior, play an important role. When an attractor becomes dominant, the organization tends to become stuck in a certain mode of operation, but the emergence of a new attractor can change the direction of the entire system [1].

A central concept of chaos theory is sensitivity to initial conditions, also known as the *butterfly effect*. In management, this means that a minor decision, a communication error, or a procedural deviation can trigger a chain of consequences that affects the entire organization [1].

The image presented in Fig. 3 illustrates this phenomenon very well. In the upper part of the image (“Chaos State I”), we can see how an initially stable system (System-A), represented by the butterfly symbol, evolves in a completely unpredictable manner (System-B) due to a small initial variation. This visual representation helps us understand that organizations are extremely sensitive to changes that are seemingly insignificant but can trigger unexpected transformations. In the lower part of the image (“Chaos State II”). Here, chaos does not arise from a small initial variation, but from the influence of internal and external attractors. System-0 represents the external factors that push the organization into a zone of instability, and System-A shows how internal dynamics begin to reorganize. The final result (System-A1) appears disordered, but it is not random; it follows a pattern determined by the system’s attractors. This part of the image illustrates that organizations may seem chaotic, but in reality they have internal structures, unwritten rules, and cultural patterns that guide their behavior [1, 6].

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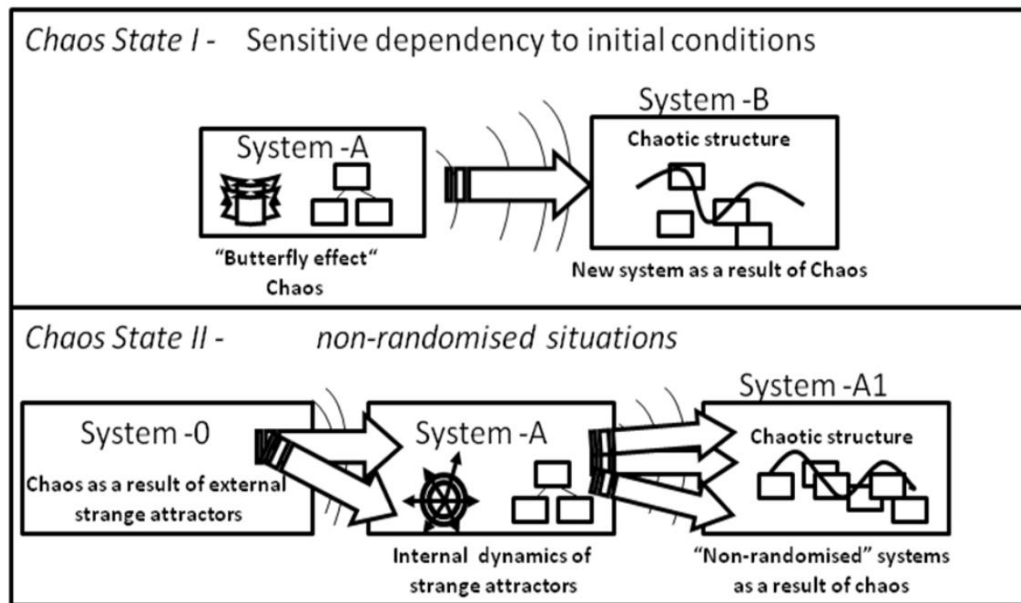


Fig. 3. Form of chaos theory in different situations [6]

Another important aspect of chaos theory is how organizations respond to unstable situations.

3. Fundamental concepts of chaos theory, such as initial conditions and attractors, that influence how an organization evolves from an unstable state to a new one, are as presented in Fig. 4, right side of the image.

4. It also illustrates the process by which an organization moves from defining a chaotic situation to analyzing it and identifying several possible response scenarios. Thus, in chaotic conditions, there is not a single possible outcome, but a wide range of scenarios, each leading to a different state of the system. This perspective is essential for management, as it shows that decisions cannot be rigidly planned, and organizations must be prepared for multiple possible outcomes [6].

5. Chaos theory suggests that organizations can self-organize when they are going through changes or unstable situations. At the same time, decision-making becomes more difficult because information is incomplete and the environment is unstable, which is why organizations must adopt flexible and adaptive decisions rather than rigid models [1].

Through chaos theory, organizations can understand the complexity of today's environment and how small changes can influence resilience and innovation [2].

In this context, leaders must provide stability within a changing system and facilitate continuous adaptation. Ultimately, success depends on the organization's ability to turn instability into opportunity [4].

6.

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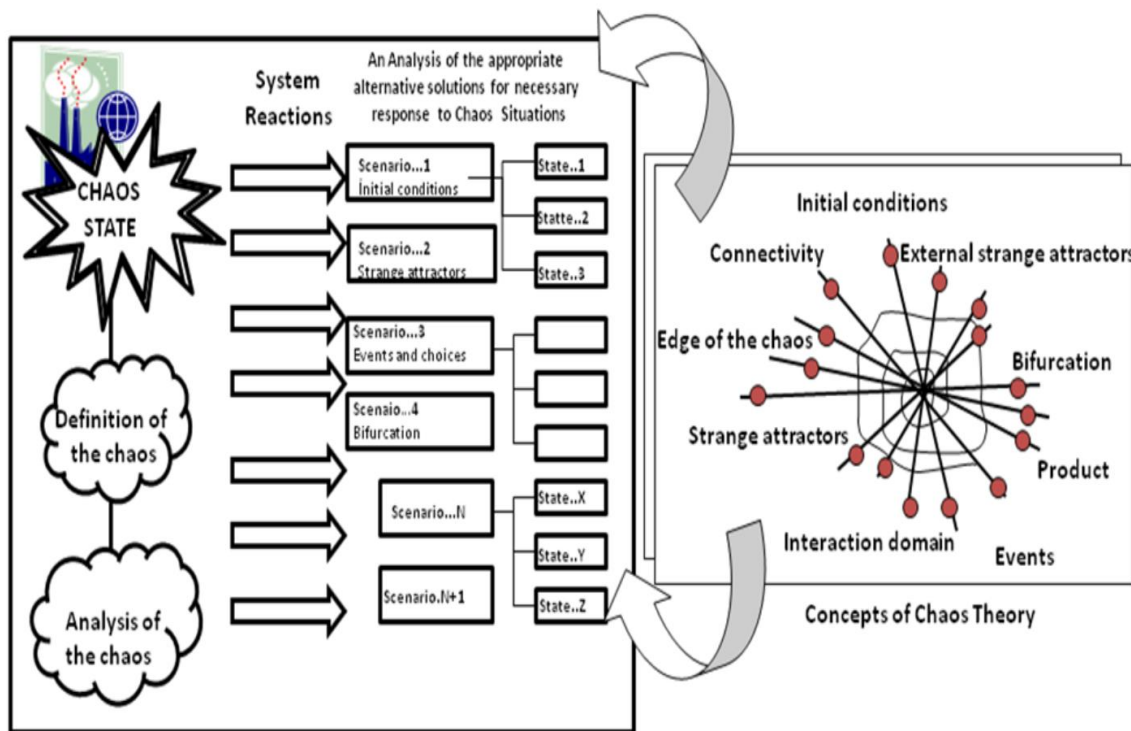


Fig. 4. Scenario analysis from the perspective of chaos theory [6]

4. Case study on Chernobyl accident through the lens of chaos theory

7. The 1986 Chernobyl accident is a prime example of how a complex system can evolve chaotically when exposed to instability, organizational pressures, and poor decision-making. In the case of Chernobyl, these elements combined in a way that pushed the system to the brink of chaos, where a small variation generated a major bifurcation.

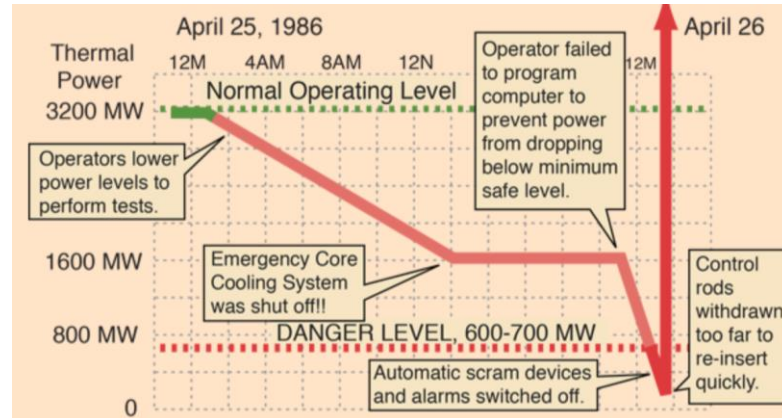
8. A fundamental cause of the accident was the rigid organizational culture, characterized by hierarchical obedience, a lack of genuine communication, and an almost militarized structure.

9. This culture functioned as a dominant attractor, hindering adaptation and blocking any attempt to halt the turbine safety test, even when technical conditions indicated danger. The test was intended to verify whether the turbine could produce enough power for the cooling pumps in the event of a power outage, but it was conducted at an inopportune time and under unstable conditions. In chaos theory, such a rigid attractor reduces the system's ability to self-organize and increases its vulnerability to collapse [7, 8]. In addition to organizational problems, a series of unstable technical conditions contributed to the system's chaotic behavior.

10. The RBMK reactor had a positive reactivity coefficient, which made it more unstable at low power levels. The sequence of events on the night of the accident was as follows:

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11. • reactor power was reduced below safety limits;
12. • several automatic systems were deactivated;
13. • operating procedures were not followed (Fig. 5).



- 14.
15. Fig. 5. Chronology of the events leading up to the explosion [9]

16. These decisions pushed the system to the “brink of chaos”. At this critical point, a small variation, namely, a sudden increase in reactivity, triggered the runaway reaction that led to the explosion.

17. The chain of errors can be understood through the butterfly effect. A series of small, seemingly insignificant decisions led to disproportionate consequences, as shown in Fig. 6 [7, 8, 10, 11].

18. Another key factor was the lack of communication between hierarchical levels. Operators did not have access to complete information about the risks associated with the RBMK reactor, and senior engineers failed to issue clear warnings. This lack of transparency prevented the system from identifying deviations and correcting them, reducing its capacity for self-organization. In chaos theory terms, a system that cannot process relevant information becomes more vulnerable to instability [7, 8].

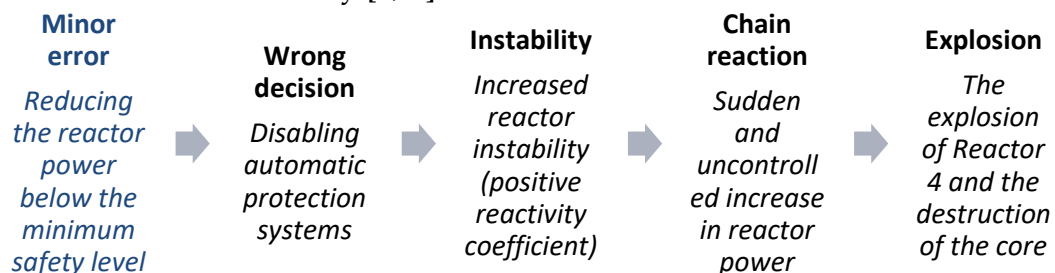


Fig. 6. Causal chain of the Chernobyl Nuclear Disaster (based on [7, 8])

5. Applications of chaos theory in industrial production

In modern industrial production, manufacturing systems are becoming increasingly complex due to automation, digitalization, and the interconnection of production processes. These systems are characterized by nonlinear relationships between machinery, operators, software, and supply chains. For this reason, even minor disruptions can have major effects on the entire production system.

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Chaos theory is applied in industry through a method known as Chaos Engineering. This method involves the controlled introduction of disruptions or errors into a system to observe how it reacts under critical conditions. The primary goal is to identify vulnerabilities and increase the resilience of industrial systems.

19. An important concept used in Chaos Engineering is the “stable state.” This represents the system’s normal operation and is defined by measurable parameters, such as cycle time, productivity, or defect rate. During experiments, it is verified whether the system maintains its operation within acceptable limits after the introduction of disturbances. If significant deviations occur, it means there are vulnerabilities that must be eliminated. Another important aspect is that the stable state must be analyzed dynamically rather than statically. Modern industrial systems operate under variable conditions, and production parameters constantly change depending on demand, equipment load, or resource availability. For this reason, the stable state must be defined as an acceptable operating range rather than a fixed value. In this regard, approaches based on chaos theory aim to identify and understand unpredictable or rare events. Thus, industrial systems become more flexible and better able to cope with unexpected disruptions [12].

20. An example of the application of chaos theory in industrial production is the burnishing process applied to an aluminum alloy, which exhibits chaotic and nonlinear characteristics. The burnishing process is influenced simultaneously by several technological parameters, such as the depth of cut, the shaft speed, and the feed rate. The interaction between these parameters results in continuous variations in system behavior and machined surface quality. For this reason, the process cannot be fully analyzed using classical linear methods.

To provide a theoretical explanation of chaotic behavior, the *logistic mapping system* is one of the best-known mathematical models in chaos theory as:

$$x_{n+1} = ux_n(1 - x_n), u \in [0, 4], x_n \in [0, 1] \quad (2)$$

21. where: x_n represents the state of the system at time n ; u - the system's control parameter.

22. The state of the logistic system changes (eq. 2) with the control parameter u ; e.g., at $u = 3.571$ the system reaches a periodic state, while at $u = 3.9$ it enters a chaotic state. The logistic model demonstrates that even very small changes in a control parameter can lead to major and unpredictable changes in the system's behavior.

Based on the experiments conducted, the researchers concluded that the burnishing depth is the parameter that most significantly influences surface roughness, followed by the feed rate and the shaft speed. By analyzing the system’s nonlinear behavior, the optimal parameter combinations were identified for obtaining a surface with low roughness and high quality [13].

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6. Conclusions

23. The chaos theory concepts, sensitivity to initial conditions, attractors, bifurcations, and the lack of self-organization, explain why complex systems can rapidly evolve toward unpredictable outcomes.

24. The case study of the Chernobyl accident confirms the applicability of the chaos theory principles: the technical instability of the RBMK reactor, poor operational decisions, a lack of communication, and a rigid organizational culture based on hierarchical obedience turned minor deviations into a major collapse, becoming one of the greatest tragedies of the 20th century.

In industrial production, chaos-oriented approaches and Chaos Engineering can support resilience by testing how systems behave under controlled disturbances. Future research should connect these technical approaches with organizational design, especially decentralized decision-making, risk awareness and risk management systems and empowered teams, because resilience depends not only on machines and software but also on how quickly people can recognize, interpret and respond to deviations and risks.

7. References

25. [1] Zohre N. (2018), The Application of Chaos Management Theories in Organization, International J. of Management Technology, Vol. 5, No. 1, pp. 39–45, European Centre for Research Training and Development UK, ISSN, www.eajournals.org.
26. [2] Murat S. (2024), Exploring Chaos Theory's Role in Management and Sustainability, Chaos, Complexity, and Sustainability in Management, IGI Global, DOI: 10.4018/979-8-3693-2125-6.ch005.
27. [3] Rauch, A. (2026), Butterfly Effect , Encyclopedia Britannica, <https://www.britannica.com/science/butterfly-effect> (accessed May 2026).
28. [4] Galacgac J., Singh A. (2016), Implications of Chaos Theory in Management Science, Chaotic Modeling and Simulation (CMSIM), Vol. 4, pp. 515–527.
29. [5] Neis P. E. (2025), Linear vs. Non-Linear Systems, LinkedIn, <https://www.linkedin.com/pulse/linear-vs-non-linear-systems-pierre-e-neis-0mt2e> (accessed May 2026).
30. [6] Özdoğan K., Halil İ. D. (2009), Application of Chaos Theory to Data Modelling Method Based on the Alternative Scenarios in Manufacturing Information Systems, Technology, Vol. 12, No. 2, pp. 107-115.
31. [7] *** (2019), Chernobyl: What Bad Management Can Cost U, PM Column, <https://www.pmcolumm.com/chernobyl-management-mistakes/> (accessed May 2026).
32. [8] ***, International Atomic Energy Agency (1992), The Chernobyl Accident: Updating of INSAG-1, INSAG-7, Safety Series No. 75-INSAG-7, IAEA, Vienna, https://www-pub.iaea.org/MTCD/publications/PDF/Pub913e_web.pdf (accessed May 2026).
33. [9] Nave R., Chernobyl, HyperPhysics, Georgia State University, <http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/cherno2.html> (accessed May 2026).
34. [10] ***, Chernobyl Disaster: The Causes Behind History's Worst Nuclear Accident, Chernobyl Nuclear Meltdown, <https://chernobylnuclearmeltdown.com/causes> (accessed May 2026).

THE ROLE AND APPLICATIONS OF CHAOS THEORY IN COMPLEX DEVELOPMENTS

35. [11] ***, OECD Nuclear Energy Agency (2002), Chernobyl: Chapter I. The site and accident sequence, OECD-NEA, https://oecd-nea.org/jcms/pl_28271/chernobyl-chapter-i-the-site-and-accident-sequence (accessed May 2026).
36. [12] Doan A. M. A., Meldt L., Bokemüller T., Pohl N., Metternich J., Weigold M. (2026), Requirement Analysis and Approach for Chaos Engineering in Industrial Production, CIRP J. of Manufacturing Science and Technology, Vol. 67, pp. 1–14, Elsevier, DOI: 10.1016/j.cirpj.2026.02.013.
37. [13] Yuan Z., Zhou Z., Jiang Z., Zhao Z., Ding C., Piao Z. (2023), Evaluation of Surface Roughness of Aluminum Alloy in Burnishing Process Based on Chaos Theory, Chinese Journal of Mechanical Engineering, Vol. 36, No. 2, pp. 1–14, Springer Nature, DOI: 10.1186/s10033-022-00828-8.

38. RESEARCH ON THE DEVELOPMENT OF A DEVICE FOR THE AUTOMATIC CHECK OF WASHING MACHINES' DRAIN PUMPS

RÎNCĂ Iuliana-Maria, DIJMĂRESCU Manuela-Roxana and NEACȘU-PAVEL Angela Miruna
Faculty of Industrial Engineering and Robotics, Specialization: Industrial Economic Engineering,
Year of study: IV, e-mail: iuliana_maria.rinca@stud.fiir.upb.ro

ABSTRACT: The paper presents the development of an automated device at Beko Romania (Ulmi) for testing drain pumps according to Industry 4.0 standards. The project replaces superficial electrical checks with a rigorous flow measurement method, calibrated for a minimum threshold of 19 l/min. The prototype, built in two weeks with a budget of 700 RON, uses a level sensor and optical signaling (green/red) to eliminate human errors and optimize logistics by testing individual parts. Implemented in the IQC department, the system ensures the quality of components, with prospects for digital integration and advanced vibration diagnosis.

KEYWORDS: pumps, control, flow, sensor, water.

1. Introduction

The work is based on the observations, data and research and development activities carried out during the internship carried out at the Beko Romania company, Ulmi branch, Dâmbovița County. **This production facility is recognized as one of the most modern facilities in Europe and the first factory in Romania aligned with "Industry 4.0" standards, integrating state-of-the-art technologies such as the Internet of Things and advanced robotics in the manufacture of washing machines [1-2].**

The integration of digital technologies within the Ulmi plant not only has the role of increasing productivity, but also of supporting a high level of control and traceability over the manufacturing processes. According to data published by Beko Romania, the factory uses IoT applications, smart equipment, interconnected devices and cooperative robotics technologies, which allows for more efficient monitoring and coordination of production operations [1]. In addition, the recognition of the factory within the Global Lighthouse Network of the World Economic Forum confirms its role as an example of the application of Industry 4.0 specific technologies in the production environment [2].

In such an industrial context, the quality control of components before they enter the assembly process becomes a critical step. The ISO 9001 standard emphasizes the importance of implementing, maintaining and continuously improving the quality management system, as well as the need to use controlled processes to ensure the compliance of products and services [3]. Thus, the activities carried out in the company's Incoming Quality Control (IQC) department have the role of preventing the introduction of non-compliant components into the manufacturing flow, which can affect both the quality of the finished product and the efficiency of the assembly line.

Within this department, where the purchased components are rigorously checked before entering the assembly lines, an opportunity to optimize the control process was identified. This is aimed at checking the exhaust pumps, for which the current method only confirms the electrical operation of the motor, without allowing the evaluation of the actual flow of water pumped. Under these conditions, there could be a risk of accepting components that started electrically but did not provide the hydraulic performance necessary for the proper operation of the washing machine.

Thus, the existing situation was analyzed, and it was proposed to implement an automated device that measures the water flow in a predetermined range, using a level sensor (float switch) to provide instant visual feedback to operators. This solution not only improves the accuracy of checks, but also directly contributes to maintaining the high-quality standards of Beko finished products.

The following are the main stages of development of the automated device intended for the functional verification of the exhaust pumps.

2. Current state of the exhaust pumps verification process

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Within the IQC department, component quality control is an essential step in ensuring the conformity of the final product to international quality management standards [3-7].

In the past, the verification of the exhaust pumps was carried out through a simplified functional control, a live start test (230V) that only confirmed whether the pump motor is rotating. This method did not provide information about the actual pumping capacity of the water underload. A pump can operate electrically, but it can have insufficient flow due to internal manufacturing defects of the rotor, lack of damaged components or parts in the pump assembly, which would lead to exhaust errors at the final product (the washing machine).

The motivation for the development of the automated device for the functional verification of the exhaust pumps started from the following important aspects observed in the workflow:

- Limitation of current methods: the functional check of the exhaust pumps boils down to a simple power supply test, confirming only that the engine has been started.
- Lack of load parameters: the current method did not allow the evaluation of the actual flow of pumped water, which could lead to infiltration of hydraulically inefficient parts on the assembly line.
- The need to increase efficiency: The aim was to develop a device that would provide a clear result ("OK/NOK") through a rapid signaling system, eliminating human errors of interpretation and reducing testing time.

In the case of exhaust pumps, a simple check of engine start is not sufficient to confirm the proper functioning of the component. A pump can be electrically powered and started, but its functional performance must be correlated with hydraulic parameters, especially the flow of water discharged within a certain time frame. The ISO 9906 standard on testing the hydraulic performance of pumps highlights that the evaluation of pumps must be carried out in relation to measurable performance, such as flow rate and operating conditions [5]. For this reason, the introduction of an automated device for checking the water flow allows the control to be transformed from an empirical check into an objective functional test, with a clear result for the operator.

The developed device is mounted as an optimal variant between a simple electrical test and a complex industrial test bench. It was selected following a decision matrix that demonstrated that the level switch-based solution offers the best ratio between portability, minimal realization costs and the ability to assess water flow.

By implementing this prototype, the transition from a purely qualitative check (starts/does not start) to a quantitative one (compliant/non-compliant flow) is achieved, thus ensuring a much more effective quality barrier before the final assembly of the washing machines.

3. Conceptual development

The development process involved transforming functional requirements into concrete technical solutions through the use of integrated product engineering methodologies [8]. This stage found in transforming functional requirements into concrete technical solutions, using systematic design tools to ensure that the final product meets the real needs of operators in the IQC department.

The process began by interviewing technicians on to turn observed operational problems into measurable technical specifications. The identified needs were ranked on a scale from 1 to 5, where grade 5 is a decisive requirement for the operation of the device, and grade 1 is a requirement of low importance. The results of this assessment are presented in Table 1.

Table 1. Attribution of relative importance

No.	Identified needs	Relative importance
1	The device can be used daily	5
2	The device is small in size	3
3	The device should be electrically safe	5
4	The device should have interchangeable parts	2
5	The device should be light weight	2

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6	The device should have a clear display	4
7	The device should not use a lot of water	3
8	The device should be easy to use	4
9	The device is easy to clean	2

The relative importance analysis highlighted that the most important requirements are the daily use of the device and electrical safety, both of which are rated with a grade of 5. These requirements directly influenced the choice of the construction solution, as the device must withstand repeated use, be stable in operation and pose no risk to the operator. Also, the clear display of the result and ease of use were considered important requirements, as the purpose of the device is to provide a quick and easy-to-interpret response within the IQC control process.

In order to perform the general function of checking the flow, it was broken down into main functions, for which several technical solutions were generated. The function tree is as follows:

FG. Check the flow rate at the outlet.

F1. Allow for quick mounting/dismounting of pumps.

F2. To show a clear result.

F3. Be easy to use.

F4. To be environmentally friendly.

F5. Be stable on a flat surface.

F6. Have a flow verification system.

For each function associated with the device, several variants of possible technical solutions were identified, and after combining them, also taking into account the possibility of realization and compatibility between them, 3 possible concepts related to the device to be realized were developed. These are presented below.

3.1. Concept 1

Concept 1 (see Table 2 and Figure 1) proposes a fixed assembly, consisting of a water tank, pipe routes, pump clamping system and measuring and display elements. The pump is mounted at the bottom of the device and the water is directed through the test circuit to allow verification of its operation under controlled conditions. The working parameters are tracked using the LCD display system and digital flow meter, which allows the operator to observe the behavior of the pump during the test and determine whether it meets the operating requirements.

Table 2. Concept 1

F1	F2	F3	F4	F5	F6
Pump clamping system	Display system	Complexity	Economic	Surface Laying System	Flow Check
Spring clamps	LCD	With preset settings (time, sensor fixation)	Connected to a water source	Rubber feet	Graduated Industrial Flow Meter
No clamping	Signal column	No settings	Have a reuse circuit	Directly on the skeleton	Level switch
Plastic necklace				With wheels	Digital Flow Meter

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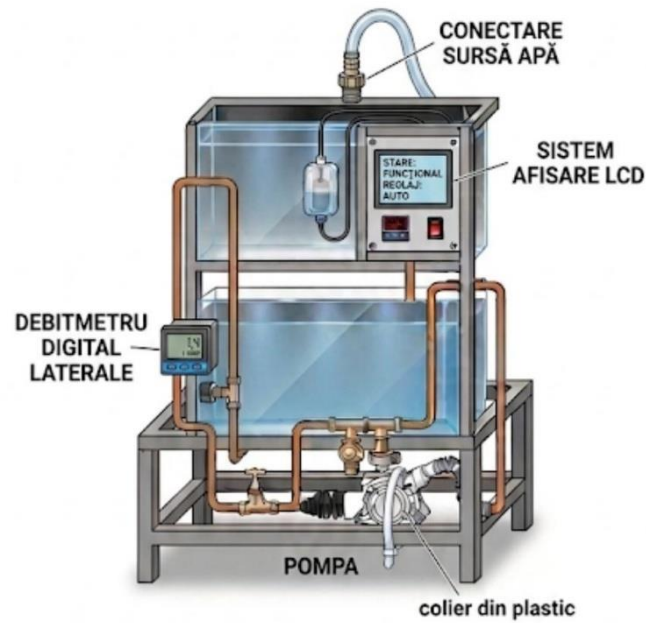


Figure 1. Concept 1

3.2. Concept 2

Concept 2 (see Table 3 and Figure 2) proposes a simplified and efficient solution for performing a rapid test, in which the pump is fixed in the working position and the volume of discharged water is checked by means of a level switch. The operating principle consists of tracking the achievement of a predetermined water level within a certain period of time, which allows the conformity of the pump to be established in terms of flow. The test result is transmitted to the operator via a signal column, providing a clear visual response of the OK/NOK type. The solution is geared towards current use in the IQC department, where fast, easy-to-interpret and repeatable checks are required.

Table 3. Concept 2

F1	F2	F3	F4	F5	F6
Pump clamping system	Display system	Complexity	Economic	Surface Laying System	Flow Check
Spring clamps	LCD	With preset settings (time, sensor fixation)	Connected to a water source	Rubber feet	Graduated Industrial Flow Meter
No clamping	Signal column	No settings	Have a reuse circuit	Directly on the skeleton	Level switch
Plastic necklace				With wheels	Digital Flow Meter

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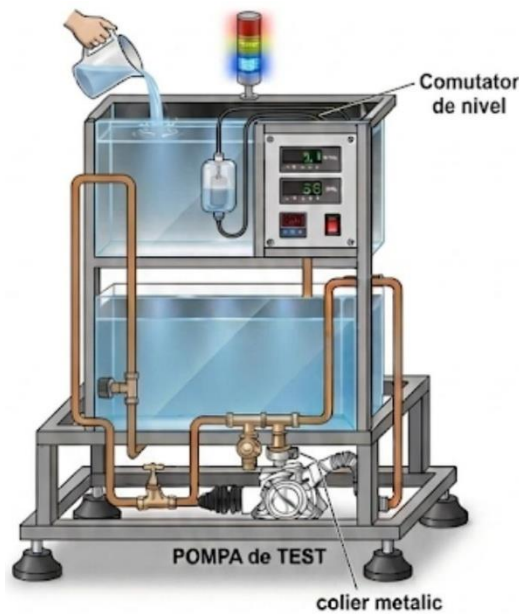


Figure 2. Concept 2

3.3. Concept 3

Concept 3 (see Table 4 and Figure 3) is developed as a mobile assembly with tank, piping system, test pump and flow measuring elements. The device allows verification to be carried out in different work areas, thanks to the wheel-mounted structure, and the hydraulic circuit allows recirculation or controlled water supply during testing. The result of the check is transmitted via a signaling system and the flow rate can be tracked using the integrated measuring element. The concept aims to ensure a functional check of the pump, by correlating the electrical operation with the hydraulic performance observed during the test.

Table 4. Concept 3

F1	F2	F3	F4	F5	F6
Pump clamping system	Display system	Complexity	Economic	Surface Laying System	Flow Check
Spring clamps	LCD	With preset settings (time, sensor fixation)	Connected to a water source	Rubber feet	Graduated Industrial Flow Meter
No clamping	Signal column	No settings	Have a reuse circuit	Directly on the skeleton	Level switch
Plastic necklace				With wheels	Digital Flow Meter

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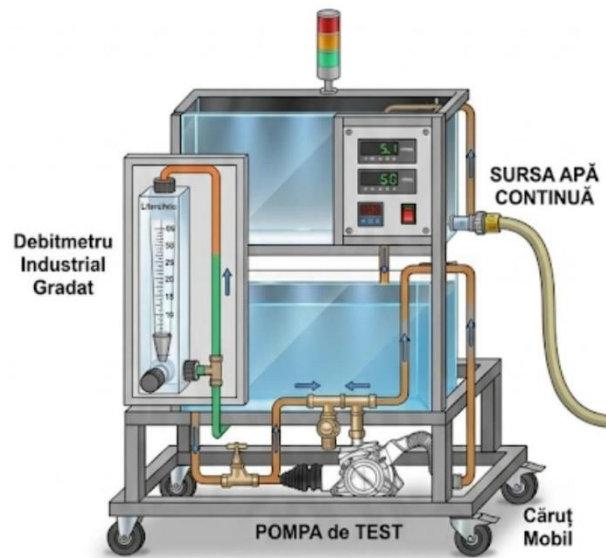


Figure 3. Concept 3

In order to choose the concept that best satisfies the imposed restrictions, a decision matrix was used (see Table 5), comparing the proposed product with the current verification bench in the company.

Table 5. Decision matrix

Evaluation criterion	Test bench	Concept 1	Concept 2	Concept 3
Clear LED Signaling	0	-	+	+
Actual Flow Assessment	0	+	+	+
Simplicity of use	0	+	+	-
Minimum cost of implementation	0	0	+	-
Net Score	0	1	4	0
Rank		2	1	3

The symbol "+" was used for performance above the reference, "-" for the lower and "0" for equal.

Following the analysis, concept 2 (device with level switch and signal column) was selected. It achieved the highest net score (4) and rank 1, demonstrating that it offers the best balance between technical innovation (evaluation of real parameters) and practical utility (low costs and intuitive operation).

4. Analysis of production costs

In the realization of the device, the aim was to obtain a low-cost, but extremely reliable solution, capable of withstanding the intense work regime in a cargo reception department. The total budget allocated for the prototype was 700 RON. This amount includes only the purchase of raw materials and electronic components necessary for operation, without including labour costs, as the execution was carried out in-house over two weeks with the help of workers from the maintenance department [9].

Table 6. Purchased components

Component	Description / Role	Estimated cost
Transparent boxes	Container for collecting water and visualizing the level.	700 Lei
Level sensor	It detects the amount of water to provide automatic feedback.	

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Faucets	Control of the flow of water in the hydraulic circuit.	
Extension cord	Ensuring the power supply to system components.	
Insulating tape	Securing electrical connections for safety.	
Stud with nut and gasket	Tight fastening of components to the device structure.	
Automatic safety with differential protection	Guarantees the electrical safety of the operator and equipment.	
Pipe fixing clamp	Supporting the hydraulic circuit on the metal skeleton.	
Screws	Mechanical assembly of the whole assembly	
Control button	Manually triggering the testing process.	
Electrical panel	Hosting control and protection components.	

The metal frame, hoses, bellows, signal column and test pumps were reused from the scrap yard.

5. Execution and implementation in the laboratory

The system was configured by mounting the sealing elements and the electrical panel equipped with automatic fuse with differential protection to guarantee the integrity of the operator. The device's architecture makes it easy to test pumps without mounting them in complete equipment, simplifying the logistics flow.

The validation of the prototype was carried out in the electrical test laboratory, the process focusing on calibrating the system in relation to the technical requirements of the exhaust pumps. According to the data sheets, the pumps must provide a nominal flow rate of 20 ± 1 l/min, which is why the level sensor level sensor has been strategically positioned to validate the conformity of the part only when a minimum performance threshold of 19 l/min has been reached. This precise calibration ensures the strict correlation between the volume of water discharged within a predetermined time frame and the optical signaling system, guaranteeing the activation of the green indicator exclusively for components that meet the minimum standard of hydraulic efficiency. Through this procedure, the device's ability to trigger the red indicator for any non-compliant part was confirmed, eliminating the risk of inefficient pumps ending up on the washing machine assembly line.

6. Conclusions

In conclusion, an automated device for checking the exhaust pumps was made at Beko Romania, transforming the quality control from a simple electrical sample into an accurate measurement of the hydraulic flow. One of the main contributions is the calibration of the system to validate components only when the minimum threshold of 19 l/min is reached, ensuring compliance with the technical standard of 20 ± 1 l/min by means of a level sensor and an optical signal column. This solution eliminates operator subjectivity and provides a major logistical advantage through the possibility of individual testing of parts before final assembly.

The implementation was completed in two weeks, with a budget of 700 RON, including technical validation in the electrical test laboratory and training of IQC staff. The efficiency of the device is demonstrated by reducing control time and human error, using affordable components such as the differential protection fuse and the electrical panel for safe operation. As future directions, it is proposed to integrate the system into Industry 4.0 networks for real-time data monitoring and to add sensors for vibration and noise diagnosis.

7. Bibliography

- [1].*** Beko Romania, <https://www.beko.com/ro-ro/compania-beko-romania>, accessed on 10.05.2026.

RESEARCH ON THE DEVELOPMENT OF A DEVICE FOR THE AUTOMATIC CHECK OF WASHING MACHINES' DRAIN PUMPS

- [2]. World Economic Forum (2019), "Scaling Intelligent Manufacturing: 10 Factories Leading the Way in Innovation", Press Release, Geneva, 3 July 2019.
- [3]. ***SR EN ISO 9001:2015 standard. *Quality Management Systems*
- [4]. Paraschivescu, A.O. (2020). *Quality management*. Technopress Publishing House, ISBN 978-6066874373, Bucharest.
- [5]. ***Standard SR EN ISO 9906:2012 - Rhododynamic pumps. Hydraulic operating tests for reception. Grades 1, 2 and 3
- [6]. ISO/IEC 17000:2020 - Conformity assessment. Vocabulary and general principles.
- [7]. *** ISO 10012:2026 - Quality Management. Measurement management systems. Requirements for measuring processes and measuring equipment.
- [8]. Drăghici, G. (1999). *Integrated product engineering*. Eurobit Publishing House, Timișoara, ISBN 973-96065-7-1.
- [9]. Groover, M. P. (2020). *Automation, Production Systems, and Computer-Integrated Manufacturing*. Pearson.

8. Notations

The following notations are used in the paper:

FG = general function

F = function

IQC = Incoming Quality Control

LCD = Liquid Crystal Display

OPERATIONAL RISK MANAGEMENT IN SUPPLY FLOWS DEPENDENT ON CRITICAL NETWORKS

Alexa-Eugenia DĂNILĂ¹, Marian GHEORGHE², Anant WADHWA²

¹Faculty of Industrial Engineering and Robotics, Specialization: Industrial Economic Engineering, 4th study year, e-mail: eugeniaa214@gmail.com

²POLITEHNICA Buharest, TCM Department

ABSTRACT: *This paper investigates operational risk management within global supply flows dependent on critical networks. By defining the strait as a primary Critical Node Set (CNS), the study evaluates how throughput contractions propagate across the supply chain, thereby disrupting industrial production scheduling. The research applies the Global Supply Chain Stress Index (GSCSI) framework and Agent-Based Modeling (ABM) methodology to evaluate operational latency. The results highlight a direct correlation between maritime volatility and the desynchronisation of the Master Production Schedule (MPS), quantifying the impact of delayed capacity on new manufacturing flows and the resulting erosion of economic performance. Circular economy financing and the implementation of strategic safety stocks are proposed mechanisms to mitigate these risks by integrating Secondary Raw Materials (SRMs).*

KEYWORDS: *Critical Node Set (CNS), Agent-Based Modeling (ABM), Master Production Schedule (MPS), Safety stock, Circular Economy Financing.*

1. Introduction

39. This paper aims to explore general mechanisms for identifying Critical Node Sets (CNS) and analyze energy flow vulnerability through a case study of the Strait of Hormuz.

40. These objectives are met through the use of the GSCSI-M stress index based on AIS data, Agent-Based Modeling, ABM, simulations for LNG trade, and the application of inventory optimization and circularity financing algorithms under uncertainty, as well as by evaluating the stability of new manufacturing flows by determining the delayed capacity and safety stocks required to ensure operational continuity under transport network volatility.

41. 2. General considerations

42. In global supply flows, management dependency on critical networks represents a primary vulnerability where disruptions trigger cascading effects, and a critical node or checkpoint propagates rapidly, leading to operational paralysis and massive financial losses [1]. Strait of Hormuz is defined as a singular operational corridor due to the absence of maritime alternatives [3]. Specifically, the study evaluates how throughput contraction induces operational latency, affecting the Master Production Schedule, MPS, and industrial working capital requirements [1, 3, 5].

Supply flows in complex systems are highly dependent on the stability of critical networks. Management of operational risk in these environments requires a proactive approach to identify nodes whose failure could trigger systemic collapse. The resilience of such a network is often dictated by capacity of its components to absorb sudden shifts in load [6, 7].

Network dynamics on Critical Node Sets

Supply chains are modeled as complex systems where key nodes play a vital role in maintaining flow

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connectivity. To achieve the objective of identifying the Critical Node Set, CNS, the load-capacity model is utilized. In this model, a node fails if its redistributed load exceeds its maximum capacity, C_i , is calculated using the relationship defined in Eq. (1) [7]:

$$C_i = (1 + \gamma) \times F_i \quad (1)$$

where: C_i is the maximum carrying capacity of the node; F_i — the initial load or flow of the node; γ is the tolerance parameter that determines the capacity margin.

The failure of a critical node triggers a redistribution process that can lead to cascading failures across the network, as illustrated in Fig. 1 [6].

Mechanics of flow redistribution and systemic stress

To quantify the operational impact of a network disruption, it is essential to analyze the mechanism of flow redistribution.

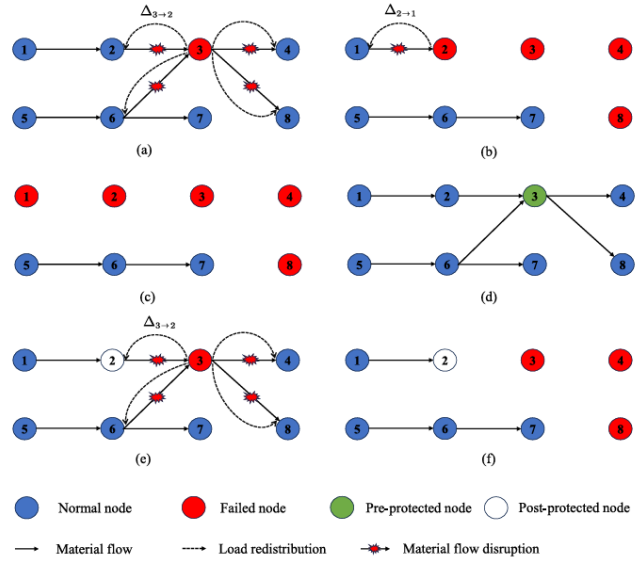


Fig. 1. Diagram of risk propagation process [6]

43. When a critical node “i” fails, the initial routes are interrupted, forcing the system to seek alternative paths to maintain connectivity. This process generates systemic stress by increasing the load on the remaining functional nodes. If this redistributed load exceeds the nodes maximum capacity (c_i), cascading failures may occur throughout the network, is schematically represented in Fig. 2 [7].

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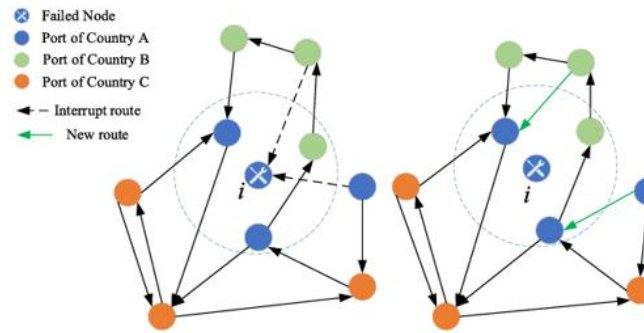


Fig. 2. Schematic diagram of inflow load redistribution [7]

The magnitude of this stress is quantified through the delayed capacity metric, based on a mathematical model adapted to the specifics of the present research, which establishes the link between physical disruptions and the financial losses mentioned in the objectives, as quantified in Eq. (2) [1]:

$$D_c = \frac{F_i}{\Delta t} \times D_t \quad (2)$$

46.

where: F_i is the initial load or flow of the node; Δt - horizontal timeline of the manufacturing flow; D_t

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- the additional delay duration relative to the normal delivery term.

To mitigate these risks, inventory optimization models are integrated to absorb fluctuations. Under uncertainty, a safety stock, SS , is calculated to ensure flow continuity even network efficiency is compromised. Also, the mathematical notation associated with the model was adapted in accordance with the analytical structure adopted in the present research, as detailed in Eq. (3) [5]:

$$SS = k \times \sigma \times \sqrt{\Delta t} \quad (3)$$

47.

48. where: σ is customer demand standard deviation; Δt – the horizontal timeline of the manufacturing flow; k – safety factor.

3. Case study

The present case study refers to a techno-financial evaluation of industrial production under Hormuz flow constraints.

Topological significance and strategic resource exposure

The Strait of Hormuz is identified as a primary Critical Node Set (CNS), acting as a critical maritime corridor and can be an operational bottleneck that facilitates 21 million barrels per day and 25% of the global Liquefied natural gas (LNG) trade. Its topological significance is absolute due to the lack of maritime alternatives for these volumes. To assess the stability of Master Production Schedule (MPS) inputs, it is quantified the geographical concentration of strategic materials within jurisdictions where governance indicators may induce supply volatility, as mapped in Fig. 3 [3].

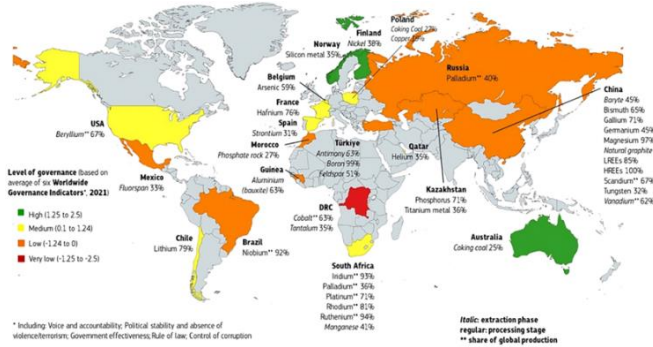


Fig. 3. Global Sourcing Vulnerability and Governance Mapping for Strategic Inputs [3]

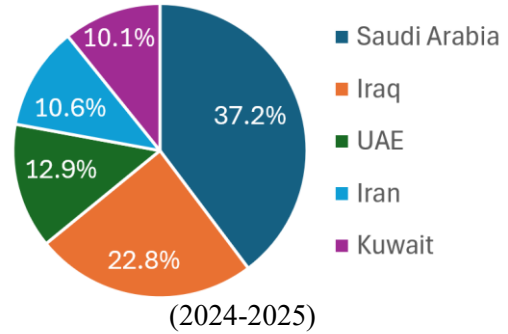


Fig. 4. Crude oil exports through the Strait of Hormuz by exporting country (based on [10])

49.

50. Main exporting countries heavily depend on the strait are presented in Fig. 4.

51. Although alternative export routes exist, their capacity is limited, combined spare capacity of 3.5-5.5 million barrels per/day. This makes the Strait of Hormuz a critical vulnerability, especially for LNG from Qatar and the UAE.

Dynamics of industrial supply latency

52. The evaluation of maritime disruption propagation toward the manufacturing system is conducted through an Agent-Based Modeling architecture, as conceptualized in Fig. 4.

53. This framework conceptualizes the global Liquefied Natural Gas (LNG) trade – defined as natural gas cooled to a temperature of -162°C to be converted into a liquid, allowing for large-scale maritime transport between regions not connected by gas pipelines, marked by simulating the stochastic interactions between exporter and importer agents, characterized by their operational capacities and fluctuating demand patterns. The model integrates global selling

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mechanisms, including contract-based and cost-driven geographical supply strategies, which dictate the redistribution logic when the primary route is restricted. In disruption scenarios simulated by the ABM framework, the restriction of passage capacities forces the rerouting of flows. Alternative maritime routes fail to fully compensate for the load, because the redistributed volume exceeds the maximum capacity of the remaining functional nodes (according to the load-capacity model). This process generates systemic stress and operational latency, materialized by increasing delivery times.

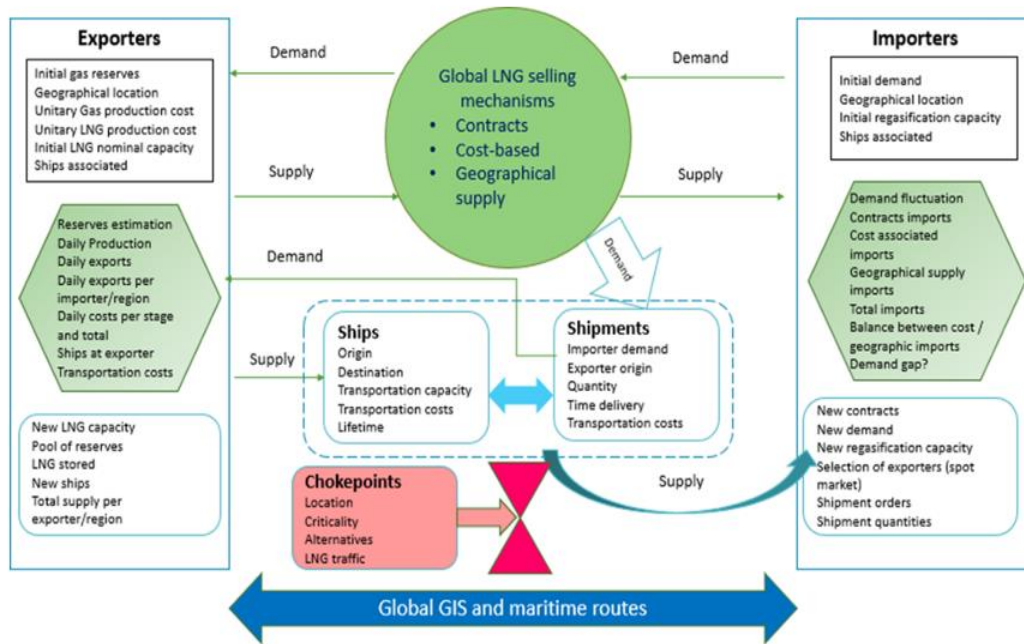


Fig. 5. Conceptual Agent-Based Logic for Supply-Demand Connectivity [4]

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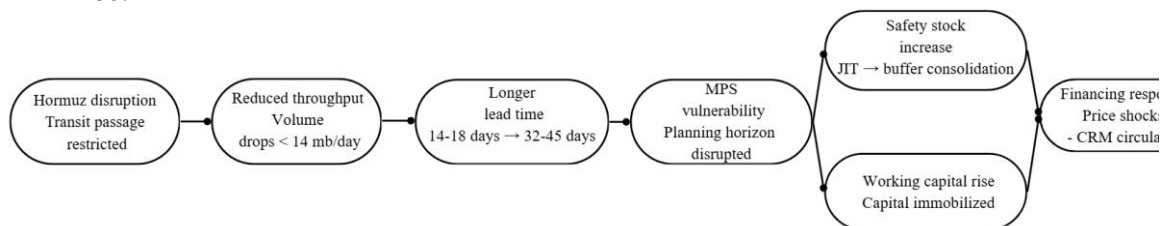
55. The direct consequence is the desynchronization of the Master Production Schedule (MPS) through the instability of the planning horizon and the appearance of demand gaps for raw materials [4].

56.

57. The disruption propagates through a clear causal chain, as shown in Fig.

5.

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59.

60. Fig. 6. Chain of disruption propagation from Strait of Hormuz to manufacturing MPS Horizon and working capital

The economic impact analysis highlights a direct correlation between the maritime throughput degradation and the stability of the Master Production Schedule (MPS) planning horizon. The increase in delivery

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time (L) to 45 days forces a transition from JIT strategies to reserve consolidation, leading to working capital immobilization, as quantified in Table 1.

61. Table 1. Technical-economic impact: correlating Hormuz flow constraints with production scheduling [9, 10, 11]

62. Operational indicator	63. Nominal Regime (Stable flow)	64. Volatile Regime (Transit restrictions)	65. Industrial consequence (Factory level)
66. Daily volume transit	67. 21 million barrels/day	68. 14million barrels/d	69. Raw material scarcity
70. Lead time (L)	71. 14-18 days	72. 32-45 days	73. MPS horizon instability
74. GSCSI-M index	75. 0.15	76. 0.85	77. Systemic flow interruption
78. Inventory strategy	79. Lean/ JIT	80. Buffer consolidation	81. Working capital surge
82.			

Longitudinal resilience

Long-term industrial stability requires a strategic shift from linear supply chains based on imports of critical raw materials (CRMs) to circular models integrating secondary raw materials (SRMs). As the longitudinal expansion of the CRM list demonstrates an increasing systemic dependence on remote and vulnerable nodes, manufacturers should implement circularity financing to support localized material recovery, as reflected in the temporal depicted in Fig. 5.

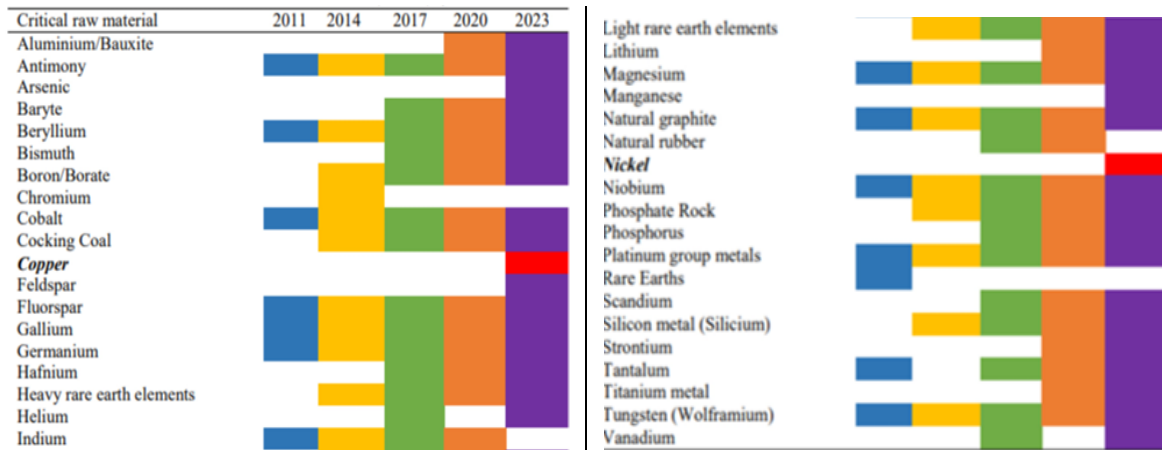


Fig. 7. Temporal Expansion of Strategic Resource Constraints (2011-2023) [4]

Reorganizing production inputs by replacing primary CRMs with recycled SRMs ensures that the Master Production Schedule (MPS) remains protected from the stochastic risks of maritime bottlenecks, thereby enhancing overall supply chain resilience [2, 4].

4. Impact of critical networks on economy development

83. Supply flow stability serves as the foundation of industrial efficiency, directly conditioning production capacity through operational cost control.

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84. Transport infrastructures contribute differently to economic competitiveness. Port infrastructure has the largest share (4.2%), followed by rail infrastructure (3.3%), air transport (2.5%), inland waterways (1.9%) and road networks (0.1%), where the basic factors of competitiveness contribution is 88% [8].

85.

86. *The impact of logistical instability on technological flows*

87.

88. In industrial systems, the operation of production flows depends on the constant supply of essential raw materials and auxiliary consumables as metal bars required for processing, the technological flow requires a steady intake of lubricants, cooling emulsions, and heat treatment media, including quenching oils, or technical gases: nitrogen and argon, used for controlled atmospheres.

89. In manufacturing processes, transport delays directly affect the sequence of technological operations performed on CNC or conventional machinery. Consequently, bottlenecks in critical transport networks can lead to shifts in the Master Production Schedule (MPS), increased waiting times, and ultimately higher production costs due to the underutilization of installed capacities [8].

90.

91.

92.

Financial loss quantification via reactive cost modeling

93.

94. The financial impact generated by network volatility on industrial flow is evaluated using the post-disruption cost model, as formulated in Equation (4) [6]:

95.

$$c_{ik}^{post} = \alpha * c_i^{pre} + \beta * (L_i^0 - l_{ik}), \forall i \in I, \alpha \geq 1, \beta \geq 1 \quad (4)$$

where: α is the penalty coefficient for reactive measures; c_i^{pre} - proactive investment in protective measures; β - ripple effect coefficient representing the loss propagation across the industrial assembly; L_i^0 - nominal production flow planned under stable conditions; l_{ik} - actual production flow realized following the logistical disruption.

5. Application concerning a technical - economic modeling of the critical networks impact on new production flows

The application is carried out on the following products: Valve RV.10.100, Pneumatic Motor PM.10.000, Prismatic Part Device PD.00.100 and Lifting Hook LH.10.000.

The analysis is based on the equations previously mentioned in § 2 and 4 [7, 1, 5, 6]:

- the nominal flow of components required to reach production objectives, F_i , $F_i = 10000$ parts/year;

- the tolerance parameter defining the excess capacity available to the node to absorb fluctuations, γ , $\gamma = 0.15$;

- the horizontal timeline of the manufacturing flow, Δt , $\Delta t = 90$ days;

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- the additional delay duration relative to the normal delivery term, $D_t, D_t = 14$ days;
- the safety factor correlated with the probability of not experiencing stockout, $k, k = 1.65$;
- the estimated daily variation of the part flow under the influence of perturbation, $\sigma, \sigma = 150$;
- the penalty coefficient reflecting the increase cost of processes due to emergency logistics, $\alpha, \alpha = 1.2$;
- the cost initially allocated for risk prevention in manufacturing process, $c_i^{pre}, c_i^{pre} = 5000$;
- the intensity factor indicating how lack of materials translates into financial losses on the line, $\beta, \beta = 1.05$;
- the number of units that did not arrive on time, serving as the direct source of additional cost, $L_i^0 - l_{ik}, L_i^0 - l_{ik} = 1556$.

Resilience evaluation of the critical node set (CNS)

The rigorous dimensioning of the logistics network is imperative to prevent flow blockages under the pressure of material demand, guaranteeing a capacity reserve necessary for the fluidization of component transport, as dimensioned through Eq. (1):

$$C_i = (1 + \gamma) \times F_i = (1 + 0.15) \times 10000 = 11500 \text{ units}$$

The result indicates that the network must be able to sustain 11500 units to allow the transit of the 10000 parts without bottlenecks. From a practical standpoint, if this 15% reserve is compromised due to congestion, the factory can no longer receive the parts necessary for assembling the prismatic devices and pneumatic actuators, leading to a halt in assembly regardless of active demand volume.

Quantifying the magnitude of stress through delayed capacity

The impact of critical networks is determined by the immobilization of an inventory volume that no longer reaches its destination within the established time window, causing a fracture between supply and production requirements, which is evaluated using the delayed capacity Eq. (2) :

$$D_c = \frac{F_i}{\Delta t} \times D_t = \frac{10000}{90} \times 14 = 1555, (5) \approx 1556 \text{ units}$$

The value of 1556 units defines the delayed capacity, representing the volume of material resources blocked in the network exactly at the moment the technological process required their entry onto the line. This deficit makes it impossible to complete the valve and lifting assemblies according to plan, as the physical lack of components forces a desynchronization of the entire assembly flow.

Determination of safety stock for assembly protection

To protect the manufacturing flow from delivery uncertainty, it is necessary to establish a safety stock, SS, that takes over the production load during periods when supply is interrupted as following calculated by Eq. (3):

$$SS = k \times \sigma \times \sqrt{\Delta t} = 1.65 \times 150 \times \sqrt{90} = 2348 \text{ units}$$

The 2348 units form the reserve that allows the factory to maintain activity during the 14 days of delay. This stock guarantees that the assembly of mechanical and hydraulic units is

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not suspended, substituting delayed parts with existing inventory, thus avoiding forced factory inactivity periods.

Financial impact evaluation through the post-disruption cost model

The analysis concludes by calculating the additional financial effort the factory must undertake to compensate for losses caused by transport network blockages, quantified according to the post-disruption cost model using Equation (4):.

$$c_{ik}^{post} = \alpha \times c_i^{pre} + \beta \times (L_i^0 - l_{ik}), \forall i \in I, \alpha \geq 1, \beta \geq 1,$$

$$c_{ik}^{post} = 1.2 \times 5000 + 1.05 \times 1556 = 7634 m. u.$$

The final sum of 7634 m.u. reflects a 53% increase in expenses compared to initial estimates. This represents the direct correlation between transport issues and the economic impact on the factory: to recover 1556 parts and honor delivery deadlines for the four assemblies, additional funds are required for reactive measures aimed at stabilizing production.

The system (5) of the determined elements represents an overall characteristic of the considered technical - economic analysis model.

$$\left\{ \begin{array}{l} C_i = 11500 \text{ units} \\ D_c \approx 1556 \text{ units} \\ SS = 2348 \text{ units} \\ c_{ik}^{post} = 7634 m. u. \end{array} \right\} \quad (5)$$

6. Conclusions

96. Ensuring supply flow stability constitutes a foundational requirement for the operational integrity of manufacturing systems within critical networks.

97. Under volatile transit conditions, delivery lead times can increase around 150% , e.g., from 14 - 18 to 32 - 45 days, forcing a transition from lean JIT strategies to buffer consolidation and generating significant working capital immobilization at factory level.

98. Long-term resilience requires a strategic transition from linear supply chains dependent on primary Critical Raw Materials (CRMs), to circular models integrating Secondary Raw Materials (SRMs), supported by circularity financing mechanisms.

99. Nowadays, it is to note, e.g., that the Strait of Hormuz, as the main operational corridor, whose flow contraction induces a systemic demand deficit, desynchronizes the Master Production Schedule (MPS) and increases the volume of blocked working capital.

100. The quality of transport infrastructure proves to be a decisive factor of economic competitiveness, with port infrastructure holding the highest contribution (4,2%), while logistical disruptions in critical networks directly translate into production cost increases.

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101. From an industrial perspective the techno-financial analysis demonstrates that a delayed capacity deficit of 1556 units requires the constitution of safety stock of 2348 units, while the post-disruption cost of 7634 m.u. reflects a 53% increase over initial estimates, highlighting the direct financial impact of critical transport network bottlenecks on industrial production flow.

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7. References

103. [1] Arvis, J.-F., A metric of global maritime supply chain disruptions: The Global Supply Chain Stress Index - Maritime (GSCSI-M), *J. of Transport Geography*, vol. 131, Amsterdam, 2026.
104. [2] Reisdorf, A. R., Critical raw material supply chain risks and resilience: Discrepancies of perspectives - An SLR approach, *Sustainable Futures*, vol. 11, Amsterdam, 2026.
105. [3] Meza, A., Disruption of maritime trade chokepoints and global LNG trade: An agent-based modeling approach, *Maritime Transport Research*, vol. 3, Amsterdam, 2022.
106. [4] Xie, K., Financing circularity strategies in critical raw materials supply chains: Towards a novel blended framework, *Resources Policy*, vol. 112, Amsterdam, 2026.
107. [5] Siriruk, P., Order quantity optimization model for perishable products under continuous review (Q, r) inventory policy with stochastic demand and positive lead time, *Omega*, vol. 138, Amsterdam, 2026.
108. [6] Hou, B., Identifying critical node set in supply chain network considering hybrid operational risk management, *International J. of Production Economics*, vol. 291, Amsterdam, 2026.
109. [7] Xu, K., Vulnerability analysis of liner shipping networks under cascading failures based on improved map lattice, *Chaos, Solitons and Fractals*, vol. 208, Amsterdam, 2026.
110. [8] Teclean, C., The impact of the quality of transport network on economic competitiveness in the European Union, *CES Working Papers*, vol. XIV (2), Iași, 2022.
111. [9] ***, UNCTAD, *Maritime Transport Review 2025*, United Nations Publications, Geneva, 2025, <https://unctad.org/publication/review-maritime-transport-2025> (accessed May 2026).
112. [10] ***, International Energy Agency (IEA), *The Strait of Hormuz - Oil Security and Emergency Response*, IEA Reports, Paris, 2024, <https://www.iea.org/about/oil-security-and-emergency-response/strait-of-hormuz> (accessed May 2026)..
- 113.**[11] ***, U.S. Energy Information Administration (EIA), *World oil transit checkpoints, Analyze EIA, Washington D.C., 2023*, https://www.eia.gov/international/analysis/specialtopics/World_Oil_Transit_Chokepoints (accessed May 2026).

RESEARCH ON THE OPTIMIZATION OF THE LOGISTICS CHAIN OF AN INDUSTRIAL COMPANY

MIHAI Ioana-Diana and DIJMĂRESCU Manuela-Roxana (Scientific Coordinator)

Faculty of Industrial Engineering and Robotics, Specialization: Industrial Economic Engineering,
Year of study: IV, e-mail: ioana_diana.mihai@stud.fiir.upb.ro

***ABSTRACT:** The paper presents an analysis of a general logistics process encountered within industrial companies and proposes an optimized version of the logistics chain, aiming to reduce operating times, logistics costs and activities that do not add value to the process. The study identified the primary issues generated and problems created through temporary storage, repetitive handling and management of non-compliant materials. The paper is putting forward a set of proposals aiming at the simplification of the flow of materials and increasing operational efficiency within an industrial company. The optimized solution developed by the study, if implemented, will result in a more efficient use of resources as well as the overall improvement of the structural organization of logistics activities.*

***KEYWORDS:** logistics chain, optimization, logistics flow, warehousing.*

1. Introduction

The research paper underlines the impact and significance carried by logistics within the scope of efficient conduct of industrial activities as well as the impact logistics have on operating costs and time and the material flow organization in an industrial company. Logistics represents one of the main support functions of industrial companies, ensuring the movement, storage and control of materials from the procurement stage to their use in production activities. Therefore, logistics is not limited to transport, but also includes unloading, handling, reception, internal distribution, quality control, inventory management and storage activities [1-2]. The way in which these activities are organized influences the continuity of production, the use of resources and the ability of a company to respond to operational requirements.

Given the existing pressure exercised towards ever increasing operational efficiency and implicitly cost reduction and rational use of resources, the optimization of the logistics processes has gained paramount importance in the overall performance of companies within the industrial sector. Within this frame, the supply chain management, involving the coordination of the flows of materials, information and resources, plays a crucial role in ensuring products arrive at the correct place and time while maintaining the lowest possible operational cost [1-5]. Consequently, a logistics flow that is organized and well managed helps reduce not only waiting times but also unnecessary handling with their implicit costs and plays a vital role in avoiding bottlenecks in storage and reception areas [6].

Among the issues facing day-to-day operations, companies are frequently confronted with warehouse crowding, the need to use temporary storage spaces, often for extended periods, repeated unnecessary handling of material and additional internal transport operations as well as the restart of certain process steps in the event of non-conformities. By their very nature, these activities not only do not add any value to the end-product, but they increase operational costs by consuming time, human and technical resources, and through the extra utilization of logistical equipment and space. From a logistics management perspective, the identification, streamlining or elimination of issues which generate activities that do not contribute to value creation is a crucial condition for increasing operational efficiency [3, 7].

In addition to direct cost increases, temporary storage in outdoor spaces such as containers or industrial tents, a method frequently employed out of operational necessity, carries the risk of exposing sensitive materials to adverse environmental factors including increased humidity, temperature variation, dust or corrosion, which can cause damage to components necessitating additional resources

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allocated for verification, repackaging or, in some instances, re-submission to the supplier. These factors transform efficient storage organization and the subsequent reduction of repeat handling of materials as well as connected operations into key elements of logistics activities [6-7].

Given the outlined elements and their potential impact, the primary objective of the paper is to analyze an existing logistics chain within an industrial company and to determine and propose an optimized solution that can contribute towards reducing operating times, reducing logistics costs and improving the organization of internal activities.

2. Actual logistic chain

Pursuant to the general analysis of the logistics chains employed in industrial companies as well as studies carried out within university activities, a primary determination was made that current logistics processes too frequently include additional unnecessary steps or activities which do not add value to the operational flow [1] and lead to increased time working time, bottlenecks in storage as well as inefficient use of resources and available space. Based on these observations, the main problems encountered in the existing logistics flow within the production company subject to this study were analyzed (see figure 1), and optimization solutions aimed at simplifying the process and improving operational efficiency were subsequently identified and compared.



Fig. 1. Initial supply chain

Within the company analyzed, the flow begins with the unloading of components and their handling to a temporary storage area, followed by reception and quality control. Compliant components are handled and transferred to an external temporary storage area before final storage. In the case of non-compliant materials, they are repacked, handled and temporarily stored, and then transported back to suppliers to identify and remedy the problems found. After carrying out the checks at the suppliers, the materials are retransmitted to the company, where the process of handling, reception and quality control is resumed until the final acceptance of the components. This logistics flow involves a high number of steps and repeated handling, which leads to increased operating time and inefficient use of space and logistics resources.

Analyzing the existing logistics process, it was observed that it contains numerous stages of handling, storage and verification, which leads to a slowdown in the operational flow and an increase in working time. Repeated handling and temporary storage of materials contribute to the congestion of logistics spaces and the increased risk of damage to components, especially when they are stored in external spaces, such as industrial containers or tents, where they may be exposed to moisture, temperature variations, dust or corrosion. Also, the management of non-compliant materials involves additional transport and the resumption of the reception and quality control stages, which causes high logistics costs and affects the overall efficiency of the process.

3. Proposal for optimization of the logistics chain

RESEARCH ON THE OPTIMIZATION OF THE LOGISTICS CHAIN OF AN INDUSTRIAL COMPANY

Based on the problems identified in the existing logistics process, a simplified logistics flow was proposed (see figure 2), consisting of the following steps: unloading of components from suppliers, their handling, reception, quality control and final storage.

Eliminating the additional steps of repacking, temporary storage and resending of non-compliant materials is possible by carrying out preventive checks directly at suppliers, with the help of staff from the company's quality department. Thus, the components are checked before delivery, significantly reducing the risk of non-conformities within the company. The new logistics flow helps to reduce operating time, reduce logistics costs, use storage space more efficiently and limit the risk of damage to components during the logistics process.



Fig. 2. Optimized supply chain

4. Benefits of implementing the solution

The implementation of the optimized logistics chain contributes to reducing the number of operations and the time required to carry out the logistics process, leading to increased operational efficiency and more efficient use of the company's resources. In line with this, eliminating supplementary temporary storage and the associated logistics steps generates an efficiency increase across the entire chain by lowering the need to use external storage spaces such as containers and industrial tents which implicitly cuts the costs generated by their purchase, rental and maintenance while simultaneously reducing the exposure and implicit downsides of exposure of components to adverse environmental conditions.

In parallel, optimizing the logistics flow allows for a decrease in repetitive and inefficient activities and subsequently the redistribution of existing assigned personnel to other operations, while a decrease in local handling and transport as part of the logistics operations contributes to a more efficient use of equipment such as electric forklifts with additional key downstream positive effects including lower indirect operating and maintenance costs and lower energy consumption. Additionally, a degree of simplification and streamlining of the process leads to a decrease in bottlenecks and implicitly an improvement in the efficiency of the reception and quality control activities.

5. Conclusions

The optimization of the logistics chain is a primary factor in any drive to increase a company's operational efficiency and decrease existing costs generated by logistics operations. The analysis performed within this study outlined the existence of potentially superfluous stages of handling storage and transport which carried a direct increase in working times and cause a degree of inefficiency in the use and deployment of available resources and equipment.

The simplified logistics flow eliminates operations that do not generate added value, by reducing the number of handling activities and the use of temporary storage, while preventive checks

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carried out at the supplier's level contribute to preventing the inclusion of non-compliant materials, consequently eliminating the costs associated with performing corrective operations and additional unnecessary logistical stages.

Overall, the proposed solution generates a direct and indirect reduction in logistics costs, a more efficient use of existing storage space, a reduction in the risk of damage to components and a general improvement in efficiency. Consequently, the results outlined in the current research highlight the importance of optimizing logistics chains in organized industrial processes.

6. Bibliography

- [1]. Abaza B., *Course Notes of the Logistics discipline*, 2025-2026.
- [2]. Chopra, S., "*Supply Chain Management: Strategy, Planning, and Operation*", 7th Edition, Pearson Education Limited, ISBN 978-0134731889, 2019.
- [3]. Christopher, M., *Logistics & Supply Chain Management*, 5th Edition, Pearson Education, ISBN 978-1292083797, 2016.
- [4]. Yalcin, H., Daim, T. U., "Logistics, supply chain management and technology research: An analysis on the axis of technology mining", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 168, 2022, 102943, doi: 10.1016/j.tre.2022.102943.
- [5]. Li, M., Lee, G., "Supply Chain Management: The Impact of Shared Meaning, Inter-Organization Coordination, and Leadership", *SAGE Open*, Vol. 15, Issue 3, 2025, doi: 10.1177/21582440251363827.
- [6]. Ballou, R. H., "*Business Logistics/Supply Chain Management: Planning, Organizing, and Controlling the Supply Chain*", 5th Edition, Pearson/Prentice Hall, 2004.
- [7]. Rushton, A., Croucher, P., Baker, P., "*The Handbook of Logistics and Distribution Management: Understanding the Supply Chain*", 7th Edition, Kogan Page, 2022.

STUDY OF SOME COMPLEX SURFACES WASHING AT EDM FINISHING

BARBU George Cătălin, LUPEI Iustin, OLTEANU Emilia

Faculty: Industrial Engineering and Robotics, Specialization: TCM, Academic year: 3,
e-mail: catalinbarbu496@gmail.com

Scientific Advisor: Prof. Dr. Ing. Liviu Daniel GHICULESCU

ABSTRACT: This paper presents the optimization of flushing methods in electrical discharge machining (EDM) of some complex surfaces to enhance process stability and surface quality. Flushing is critical for debris removal, electrode cooling and dielectric restoration. The study analyzes the laminar flow and velocity of dielectric fluid in the work gap which is crucial for surface finish. Proper flushing prevents the accumulation of eroded particles thereby reducing the risk of harmful arcing and short-circuits. Furthermore, the research details the technical requirements for dielectric fluids, focusing on viscosity and multi-stage filtration. Optimized flushing strategies demonstrate a significant increase in the material removal rate and superior surface finish in precision EDM applications.

KEYWORDS: EDM, Gap flushing, Debris evacuation, Laminar flow, Pulsatory regime

1. Introduction

Electrical discharge machining (EDM) technologies represent the optimal solution for processing high-hardness materials and are in continuous evolution regarding modeling and sustainability [1]. The process is based on the transformation of electrical energy into thermal energy, a phenomenon that occurs through repetitive electrical discharges [2]. The efficiency of this method depends critically on the optimization techniques used to maintain discharge stability [3]. Currently, the EDM industry places special emphasis on integrating solutions that allow a high material removal rate without compromising the geometric precision of the parts [4].

2. Current State

In EDM flushing, the dielectric liquid fulfills 3 vital functions in processing:

- It determines, through its own movement, the removal of molten material from the working area.
- It contributes to the cooling of the workpiece and the tool.
- It is essential for the electrical insulation between the tool and the workpiece, in order to concentrate the electrical energy in a single point.

Thus, it can be understood why any improvement in the flushing process in the working area has a direct impact on the quality of the machined surface and on carrying out the processing under ideal conditions.

Maintaining the machining gap through efficient flushing methods is essential for the evacuation of residues and the prevention of short-circuits [5]. EDM processing of blind holes has been a difficult task due to the inherent difficulties of removing debris from the discharge space, a factor directly dependent on the flushing process [6]. For this reason, innovative gap flushing methods have emerged, such as electrode rotation with internal flushing during processing, for better productivity and quality of the machined surface [7].

The accumulation of particles in the working areas leads to the need for filtration and recirculation of the dielectric liquid through filters that capture the eroded material, a phenomenon that is especially

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critical in deep hole drilling [8].

The main flushing methods analyzed in the specialized literature include: injection flushing, suction flushing, and lateral flushing.

In the case of injection flushing, the dielectric is injected under pressure through the internal channels of the tool-electrode or through the workpiece. It is the most used method for processing deep cavities, although it can generate stagnation zones at the base of the tool-electrode [9].

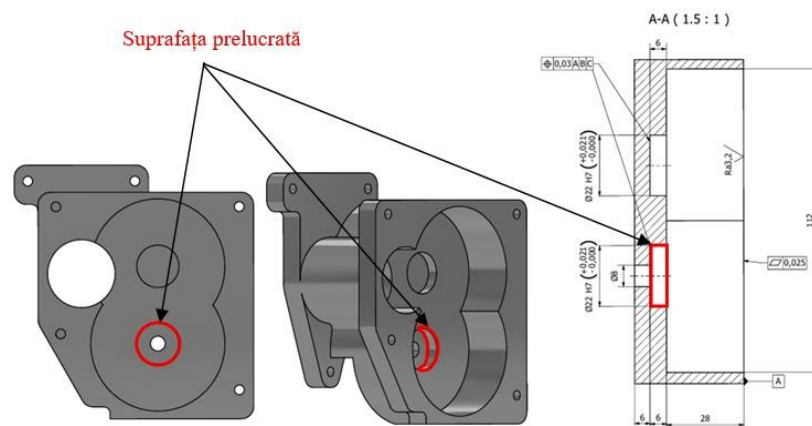
Regarding suction flushing, the liquid is aspirated through the machining gap. This method offers superior process stability and high geometric precision, eliminating the risk of residue deposition on the lateral walls of the cavity [2].

Lateral flushing is used when the electrode geometry does not allow the processing of internal channels. The dielectric jet is directed from the outside towards the working area. This type of flushing is efficient for processing external surfaces, but less productive for deep hole processing [10].

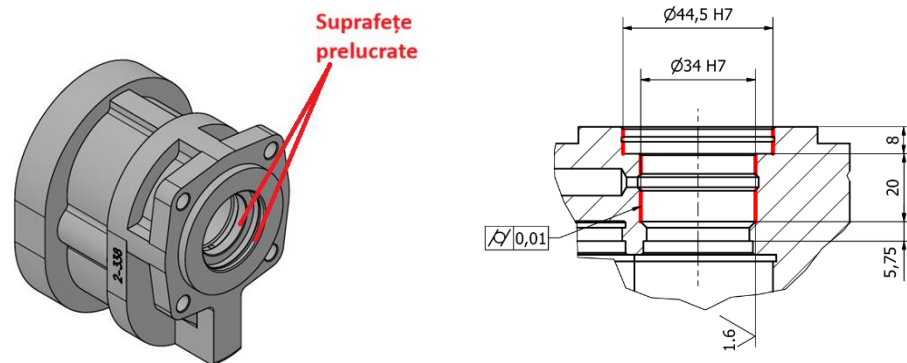
3. Workpieces and machined surfaces

In the current paper, the efficiency of injection flushing is studied in the case of machining precise bores. The analyzed surfaces belong to the 3 studied workpieces highlighted in Fig.1.

Workpiece 1



Workpiece 2



Workpiece 3

STUDY OF SOME COMPLEX SURFACES WASHING AT EDM FINISHING

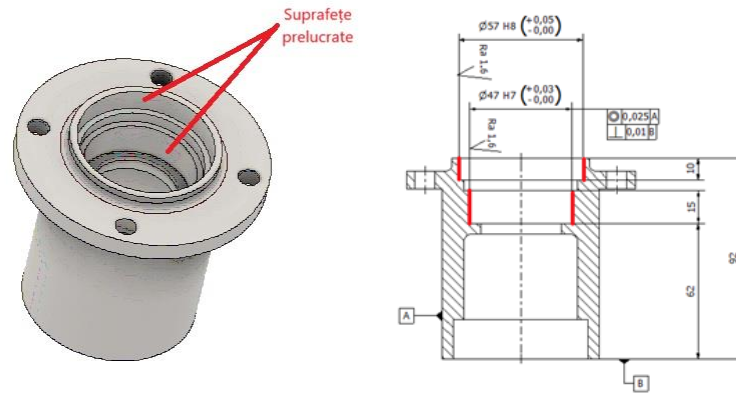


Fig. 1. Machined surfaces

4. Modeling of Dielectric Fluid Flow in the Machining Interstice

To study the efficiency of the dielectric fluid flow through the machining interstice, the comsol multiphysics software was used.

The model was built in the 2d axisymmetric workspace, using simple geometric shapes to generate the form of the machined part and the electrode used, highlighting the work interstice.

THE PARAMETERS OF THE MODEL ARE PRESENTED IN FIG. 2.

Parameters			
Name	Expression	Value	Description
sL	0.020	0.02	Lățimea interstițiului
dens	780	780	kg/m3
vd	0.0014	0.0014	Vâscozitate dinamică
viam	0.2[m/s]	0.2 m/s	viteza de curgere laminara
pin	121590	121600.0	presiunea la intrare masurata [Pa]
pout	101325[Pa]	101300.0	zero! Se ia diferenta de presiune
dia1	44.5	44.5	Diametrul primului tronson
lp1	8	8	Lungimea primului tronson
r1	dia1/2	22.25	Raza primului tronson
dia2	34	34	Diametrul tronson 2
r2	dia2/2	17	Raza tronson 2
lp2	20	20	Lungimea tronson2
dia3	30.5	30.5	Diametrul tronson 3

Parameters			
Name	Expression	Value	Description
sL	0.02	0.02	interstițiu lateral
dia	57	57	diametrul primului tronson de prelucrat
dia1	52	52	diametrul degajării
dia2	47	47	diametrul tronsonului 2 de prelucrat
dia3	37	37	diametrul intrare lichid
rp	dia/2	28.5	raza primului tronson de prelucrat
rp1	dia1/2	26	raza degajare
rp2	dia2/2	23.5	raza tronson 2 de prelucrat
rp3	dia3/2	18.5	raza intrare lichid
lp	10	10	lungimea primului tronson de prelucrat
lp1	5	5	lungime degajare
lp2	15	15	lungime tronson 2 de prelucrat
lp3	5	5	lungime intrare lichid

rs	rp-sL	28.48	raza sculă
rs1	rp2-sL	23.48	rază sculă tronson 2
ls	lp-sL	9.98	lungime sculă tronson 1 de prelucrat
ls1	lp2-sL	14.98	lungime sculă tronson 2 de prelucrat
dens	780	780	densitatea kg/m3
vd	0.004	0.004	Paș
viam	0.02[m/s]	0.02 m/s	viteza de curgere laminara
pin	121590	121600.0	presiunea la intrare masurata [Pa]

FIG. 2 PARAMETERS OF THE 3 MODELS

To build the geometry (Fig. 3), the profile of the bore was first constructed with all the chamfers and channels provided in the execution drawing, after which the area to be occupied by a two-step electrode for internal machining was removed.

STUDY OF SOME COMPLEX SURFACES WASHING AT EDM FINISHING

Also, for a better representation and discretization of the laminar flow, the interstice was divided into four equal parts.

Another particularly important step was defining the inlet zone (inlet - Fig. 3) and outlet zone (outlet – Fig. 4) of the fluid from the work area, as well as setting the parameters, namely the inlet pressure, which was measured on the laboratory machine, and the outlet pressure, which we considered to be zero.

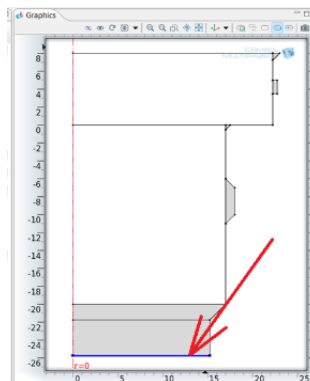


Fig.3 Inlet

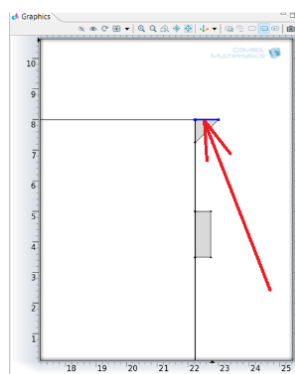


Fig.4 Outlet

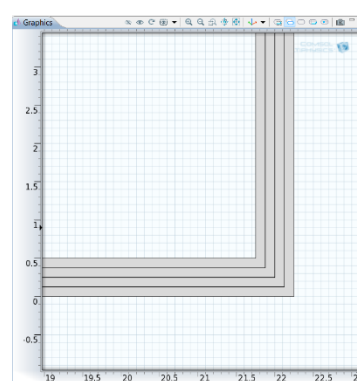


Fig.5 Work gap

To highlight the behavior of the dielectric fluid, it was allocated as a material on the geometry representing the work interstice, as can be observed in Fig.5.

The next step was defining a laminar flow for the dielectric fluid, after verifying by calculation whether, at the considered parameters, the laminar flow condition is met, meaning that the Reynolds number (4.1) is less than 2100-2300 (Table 1).

Both the boundaries defining the fluid path and its inlet and outlet through the part were selected, as can be seen in Fig. 6.

The final step to complete the geometry of the interstice was its discretization (Fig. 7) using small triangular elements for the highest possible machining accuracy.

$$Re = \frac{\rho \cdot \omega \cdot l}{\mu} \quad (4.1)$$

Table 1

Lichid	Cut-Max SE2	
ρ	780	kg/m ³
w	0,2	m/s
l	0,0045	m
μ (vascozitate dinamica la 20°C)	0,0019	Pa·s
Re	369,47	
Concluzie:	Numar Reynolds < 2000 Curgere laminara	

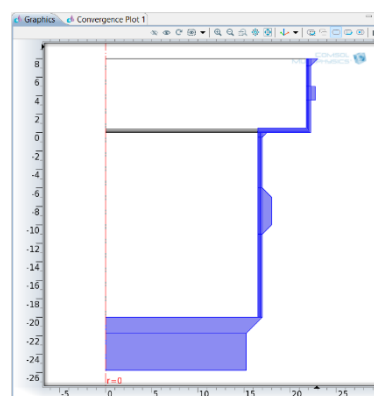


Fig.6 Flow zone

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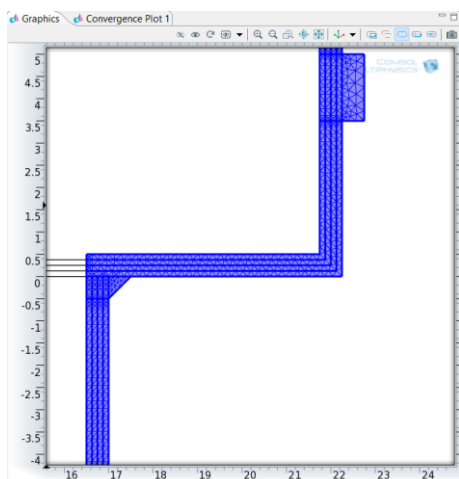


Fig.7 Discretization of the gap

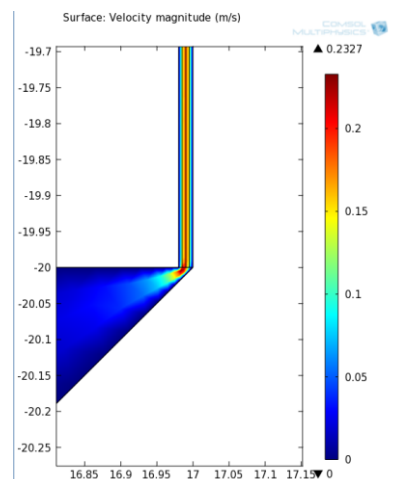


Fig 8. Visualization of laminar flow

Following the discretization, the following values were obtained for defining the mesh in the case of each workpiece.

Triangular elements: 65129
Edge elements: 12566
Vertex elements: 35
Domain element statistics
Number of elements: 65129
Minimum element quality: 0.8189
Average element quality: 0.9426
Element area ratio: 7.995E-4
Mesh area: 48.34 mm²

Piesa 1

Triangular elements: 59098
Edge elements: 24491
Vertex elements: 70
Domain element statistics
Number of elements: 59098
Minimum element quality: 0.5678
Average element quality: 0.8847
Element area ratio: 1.81E-5
Mesh area: 95.04 mm²

Piesa 2

Triangular elements: 89049
Edge elements: 36752
Vertex elements: 61
Domain element statistics
Number of elements: 89049
Minimum element quality: 0.6373
Average element quality: 0.8927
Element area ratio: 6.231E-6
Mesh area: 106.3 mm²

Piesa 3

5. Results

The model was run adopting different values of the work interstice to highlight the evolution of the velocity in the transverse plane, considering the effect of pressure variation along with the size of the interstice.

Following the run, a graphical simulation of the laminar flow in the interstice was also obtained for an initial process verification step (Fig.8). The graph corresponding to this variation is highlighted in Fig 8.

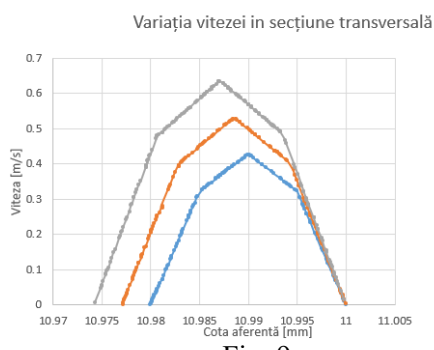


Fig. 9

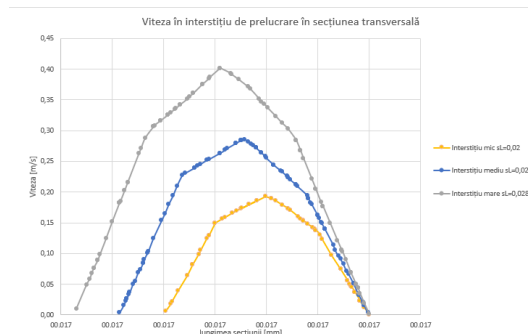


Fig. 10

STUDY OF SOME COMPLEX SURFACES WASHING AT EDM FINISHING

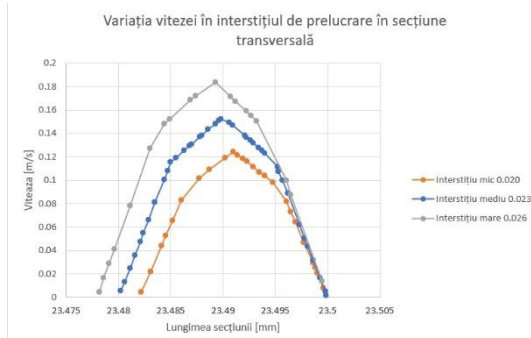


Fig. 11

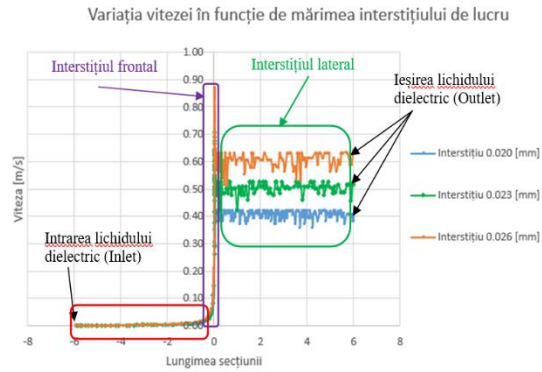


Fig. 12 Workpiece 1

Additionally, a velocity variation in the longitudinal plane can be observed due to pressure variation in different areas of the part, as highlighted in graphs 4-6.

In the relief zone, the velocity decreases considerably because the distance between the tool and the part increases, machining not being necessary.

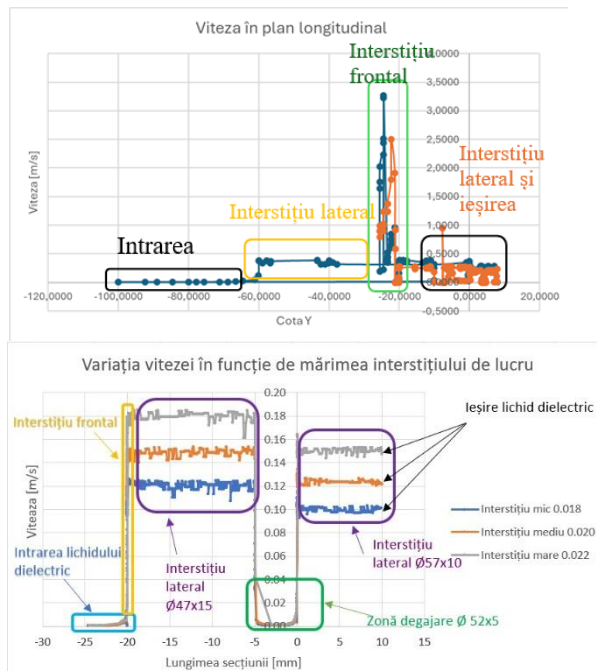


Fig 13. Workpiece 2

Fig 14. Workpiece 3

From the study of flow in this type of interstice, as a complex shape, it can be concluded that there will be no areas where flushing is suboptimal, as flow velocity exists across the entire machined surface within the machining interstice.

In addition, data were obtained through process simulation that allow for a better understanding of the process itself and offer optimal parameters for the chosen machining regime.

Thus, the role of the study is fulfilled, which is to prevent situations where the electrode geometry and the chosen machining method might not be suitable for the real-world case.

For the experimental case (Figs. 15-18), a real-world verification of the operation mode predicted in the simulation was performed using the laboratory EDM machine, going through all the machining steps: mounting the workpiece, mounting the tool-electrode, starting the machine, starting the dielectric fluid flow through the part, setting parameters, testing the machining, stopping the machine, and detaching the workpiece.

Thus, we ensured that the theoretical part agrees with the real situation.

STUDY OF SOME COMPLEX SURFACES WASHING AT EDM FINISHING



Fig15. Mounting Fig16. Setting parameters Fig17. Starting dielectric
Fig18. Machining

Regarding future research directions, although the analysis performed is highly important for a precise understanding of the flushing process during machining and for preventing faulty operation in the real case, the paper is very little developed compared to the true potential of this study.

The importance of dielectric flushing for EDM makes it necessary to verify other flow models on complex surfaces, observe and analyze the machined surface based on varying different parameters of the flow regime or pressure, as well as adopt different modes of flushing the interstice.

STUDY OF SOME COMPLEX SURFACES WASHING AT EDM FINISHING

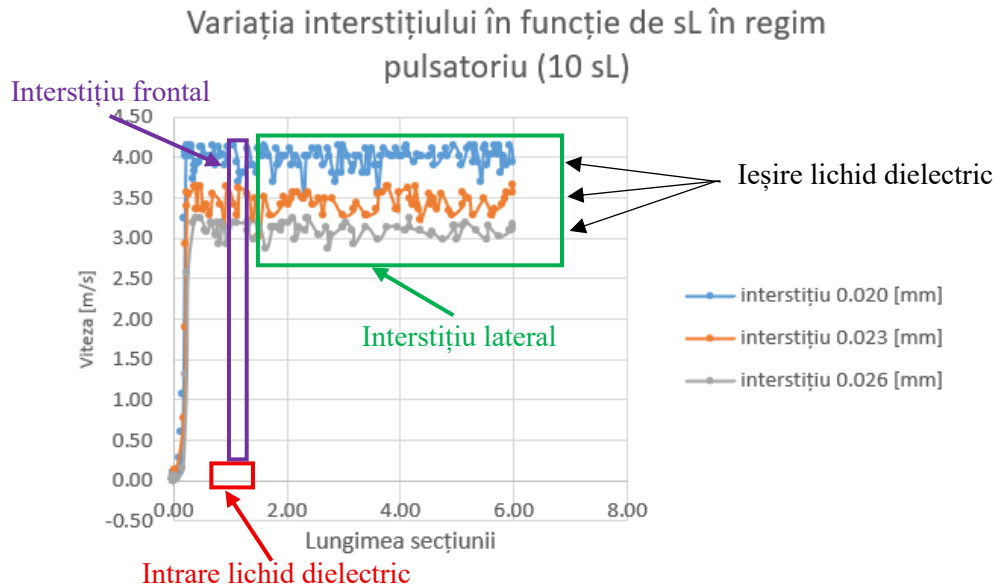


Fig. 19 Pulsatory regime for sL 10mm

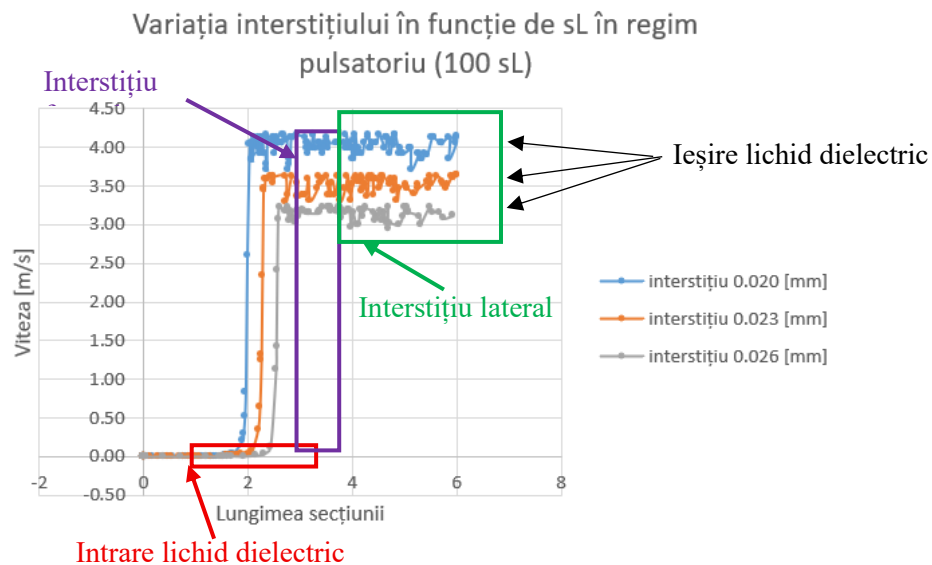


Fig. 20 Pulsatory regime for sL 100mm

The pulsatory regime in EDM represents a process stabilization strategy through the alternating lifting and lowering motion of the tool-electrode.

This dynamic generates a hydraulic pumping effect that facilitates the forced evacuation of eroded particles from the interstice, preventing the formation of short-circuits and continuous electric arcing.

The graphs illustrate the direct correlation between tool retraction and the replenishment of the dielectric medium, thereby ensuring discharge continuity and optimizing volumetric productivity (V_w) in deep cavities.

6.Conclusion

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The results obtained confirm the effectiveness of the flushing method through the workpiece, demonstrating that the use of a cassette-type injection device, combined with the mechanical blocking of secondary holes, forces the dielectric fluid to transit exclusively through the machining interstice. This technological configuration optimizes the evacuation of erosion products by maintaining an active flow profile, preventing fluid stagnation zones and ensuring the stability of electrical discharges throughout the entire EDM process.

7. Bibliography

- [1]. Ulhakim, M.T.; Sukarman (2025), **Electrical discharge machining: Recent advances and future trends in modeling, optimization and sustainability**, vol. 8, p. 495-511.
- [2]. Ghiculescu, D. (2025), „Advanced Electrochemical Discharge Machining Methods”, Course in Romanian, Production Engineering Dept., University Politehnica from Bucharest, Romania.
- [3]. Kumar, S.; Gupta, T. (2023), A review of electrical discharge machining (EDM) and its optimization techniques, *Materials Today Proceedings*, <https://doi.org/10.1016/j.matpr.2023.02.186> (accesat la 08.05.2026)
- [4]. Kamenskikh, A.; Muratov, K. (2023), Recent Trends and Developments in the Electrical Discharge Machining Industry: A Review, în: S. Alborz and D. François, (eds.), *J. Manuf. Mater. Process.* 2023, 7(6), 204
- [5]. Gao, M.; Liu, M. (2023), Investigation of Machining Characteristics in Electrical Discharge Machining Using a Slotted Electrode with Internal Flushing, în: F. Irene and M. Francesco (eds.), *Micromachines* 2023, 14(11), 1989
- [6]. Mao, X., Wu, G., Tran, M. et al. Electrical discharge drilling of blind holes with injection flushing dielectric and stepped electrodes. *Int J Adv Manuf Technol* 132, 495–511 (2024). <https://doi.org/10.1007/s00170-024-13396-z> (accesat la 08.05.2026)
- [7]. Jamkamon, K., & Chuvaree, S. (2022). A Study of Electrical Discharge Machining Performance by Applied Rotating Electrode with Dielectric Flushing through the Axis of Electrode. *Recent Science and Technology*, 14(1), 16–30. retrieved from <https://li01.tci-thaijo.org/index.php/rmutsvrj/article/view/248067?utm.com> (accesat la 08.05.2026)
- [8]. Kliuev, M.; Baumgart, C. (2018), Flushing Velocity Observations and Analysis during EDM Drilling, vol. 77, p. 590-593
- [9]. Boban, J.; Ahmed, A. (2021), Effect of recirculation zone on debris evacuation during EDM deep hole drilling, vol. 102, p. 393-398
- [10]. Ablyaz, T.; Shlykov, E. (2023), Modeling of EDM Process Flushing Mechanisms, *Materials* 2023, 16(11), 4158

DEVELOPMENT OF A SMART GLOVE-BASED SYSTEM FOR REAL-TIME ASL ALPHABET RECOGNITION AND VOICE SYNTHESIS

CÎRSTEA Adrian-Florin, DOICIN Cristian Vasile

Faculty: F.I.I.R, Specialization: Industrial Informatics, Year of Study: IV, email: adrianflorin.cirstea@gmail.com

ABSTRACT: This paper presents the development of a wearable smart system designed for real-time recognition of the American Sign Language alphabet and conversion of the recognized signs into speech. The proposed prototype uses flex sensors to capture finger bending angles and an MPU6050 sensor to acquire hand orientation and motion data. The signals are processed by an ESP32 microcontroller and transmitted to a Raspberry Pi 5 single-board computer via MQTT [1] protocol, where a XGBoost [2] classifier performs gesture recognition. The recognized letter is then converted into audio output using a local text-to-speech engine. Experimental tests performed on the 26 letters of the ASL alphabet indicate a recognition accuracy above 85%, confirming the feasibility of the proposed low-cost, portable and cloud-independent solution.

KEYWORDS: smart glove, sign language, wearable device, communication

1. Introduction

Currently the deaf-mute community accounts for approximately 5% of the global population. At the moment of the research, this percentage corresponds to close to 466 million people out of the total population. Hearing-impaired individuals communicate through sign language; this language is helping to express themselves easily to other people, except the fact that not everyone knows this type of communication. [3]

These hurdles imposed by hearing-impairment are a major obstacle in the fulfillment of one of the most fundamental human need, namely communication.

Implementing, designing, testing and prototyping an intelligent gesture recognition system presents a challenge due to the multitude of variables that must be accounted. These variables include: user comfort over extended periods of time through a day; high accuracy in detecting and recognition of user's gestures; lowest possible response time; and maximizing the system's battery life.

The proposed solution aims to provide a portable, user-friendly alternative that is affordable compared to other currently available smart systems, thereby improving the quality-of-life for people with interactional difficulties and reducing the communication barrier with those unfamiliar with sign language.

The main contribution consists of integration of a functional system of flex sensors, IMU sensor (MPU6050), ESP32 microcontroller, Raspberry Pi 5, a XGBoost classifier and Text-To-Speech model running onboard.

2. The current state of the analyzed situation

This difficulty in expressing with someone unfamiliar with sign language has given a new challenge for engineers; thus, the first category of solutions for interpreting this language consists of systems based on real-time image processing. This technology is using cameras and computer vision algorithms in order to detect the fingers and hands position for gesture classification. Although it is an accessible solution, this opens the field to new limitations related to illumination conditions and background noise.

A second category include systems based on wearable sensors (flex sensors, accelerometers/gyroscopes) which are more reliable than a camera based system because the limitation factors are limited within the signal transmission/acquisition, the latency of data processing and computational power of the microcontroller(s) or SBC(s) used. Hybrid and AI-based systems represent a third, and last category for sign language interpretation. These systems are based on the fusion of sensors and deep learning architecture, achieving an average recognition rate of 99.44% via LSTM RNN and K-NN. [4]

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Systems that fall into the third category achieve state-of-the-art accuracy and typically require cloud connectivity or GPU-equipped hardware, which are not compatible with the offline operation, affordability or embedded constraints of the present work.

One system was designed by two University of Washington undergraduates called SignAloud [5]. This system was developed to recognize various hand gestures used in ASL and translate them into audio feedback, in real time. The system is based on two gloves, each one uses sensors to record hand movement and fingers position, sending the data via Bluetooth wireless technology to a computer in order to process these signals using statistical regressions, similar to a CNN.

Table 1. Comparative overview across systems categories			
Solution Type	Advantages	Limitations	Relevance for this work
Computer Vision	No physical device attached to the user	Background and lighting sensitivity Affected by camera angle and requires GPU for real-time models	Analyzed alternative
	Real data provided by direct finger bending	Requires wearing a device	
Sensor Gloves	Environment-independent	Sensor calibration needed	Chosen path
	Lower latency	Flex sensors degrade over time	
	Offline availability	Limited comfort for extended use	
	State-of-the-art accuracy	Requires large datasets	
Hybrid and AI-based	Robustness across gesture types	GPU or cloud dependency	Partially adopted
	High compute power need	High inference latency on embedded hardware	

3. Experimental Methodology

This section outlines the process framework employed to collect, process and classify hand gestures for real-time sign language recognition. The pipeline transitions from raw physical movements of the hand to digital text and vocal synthesis through five distinct stages.

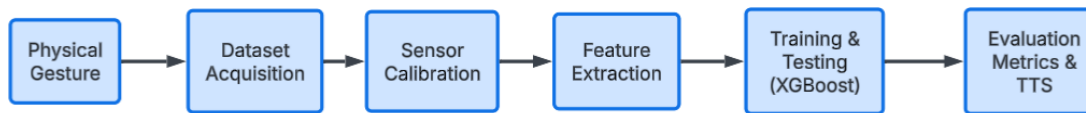


Figure 1. Block diagram of the experimental methodology and data processing pipeline

3.1 Dataset Acquisition

The dataset was acquired using a single subject equipped with the smart glove performing the 26 letters of the ASL alphabet.

To introduce structural variety and capture the natural deviations in human activity, each gesture was repeated under varying hand orientations. With that said, for every letter were recorded around 40 different hand and fingers positions, yielding a total dataset of 1040 samples (26 signs x 40 samples), close to the actual sign but expressing real world usage in everyday life. The samples were recorded from one user wearing the glove and the dataset was split in 80% training data and 20% validation data. All sensors were sending information at a sampling frequency of 50 Hz (every 20 ms), which complies to the Nyquist-Shannon theorem [6].

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3.2 Sensor Calibration

Raw sensor signals are sensitive to noise, fluctuating battery voltage or other external factors. Therefore, a calibration was executed before data was recorded:

- Flex sensors: The 12-bit raw Analog-to-Digital Converter (ADC) of the ESP32 can output raw values ranging from 0 to 4095. A Moving Average Filter (MAV) was implemented in order to smoothen values from sensors.
- MPU6050 IMU: The inertial sensor did not need any calibration due to factory calibration being suited for this project

3.3 Feature Extraction

For each sample, an one-dimensional vector of 7 numerical features were transmitted to Raspberry Pi for the XGBoost classifier:

- 5 features from the flex sensors, containing the normalized resistance values corresponding to each finger curvature;
- 2 features from the MPU6050 IMU, representing the filtered calculations of the triaxial acceleration and triaxial angular velocity.

3.4 Training and Testing

The classification task was executed on the Raspberry Pi 5 using the XGBoost Classifier. To evaluate the model's training, a Holdout Validation strategy was used, the dataset was split into an 80/20 train/test ratio. After the training and testing phase, it was found that the model has an approximately 85% accuracy after the validation tests were concluded.

3.5. Evaluation Metrics

The smart glove system was evaluated based on two criteria: classification performance of the XGBoost model and real-time execution time.

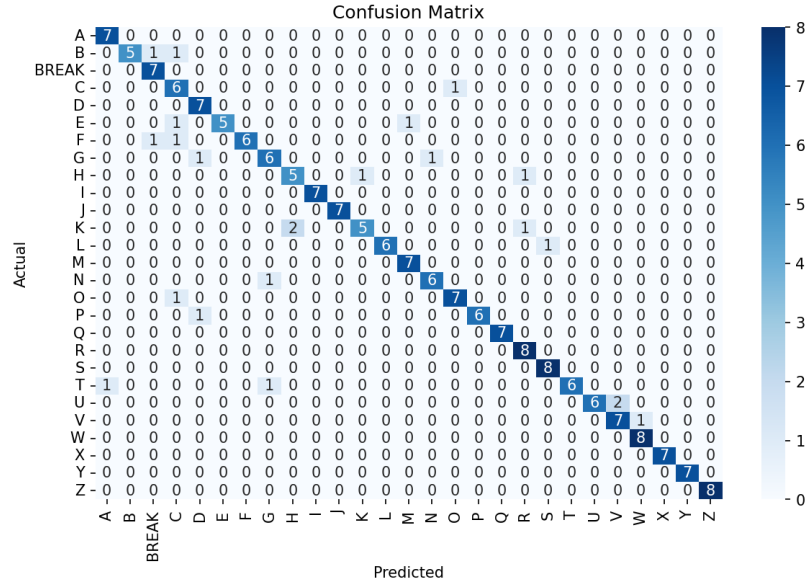


Figure 2. Confusion Matrix

The system achieved a final validation accuracy exceeding 85%, proving a highly dependable translation capability. Based on the confusion matrix in Figure 2, most letters show a true-positive count of 6, 7 or 8. Variations like 5 or 6 indicate that some samples were misclassified in validation. The gestures for I, J, R, S, W and Z all score a perfect score with zero diagonal noise, which means that the MPU6050 gyroscope data provided unique features that XGBoost could easily isolate.

System's Real-Time viability ensures natural fast communication with typical peers, latency was measured across the entire pipeline and total response time averaged ~400ms:

- Transport Latency: ~30ms for ESP32 data delivery over MQTT.
- Inference Latency: ~200ms for the XGBoost model to process the 7 features on the Raspberry Pi 5.
- Text-To-Speech Latency: ~170ms for PiperTTS [7] engine to generate and stream the audio buffer.

4. Hardware implementation

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For housing, it was designed a case strapped to the forearm which contain 1xRaspberry PI 5, 1xESP32, 1xPCB, 1xSpeaker, wires and one powerbank. As a choice of material, the final prototype is using ABS because it handles heat and impact much better than PLA, and because the heat is a considerable factor during the run-time of the Raspberry PI. [8] The necessary components were designed in SolidWorks 2022 CAD software.

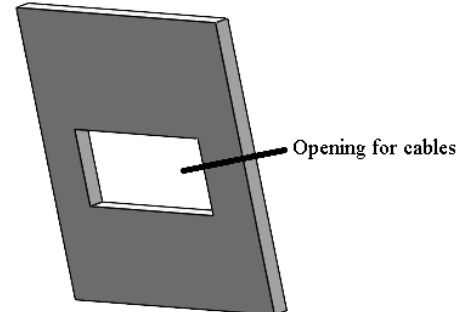
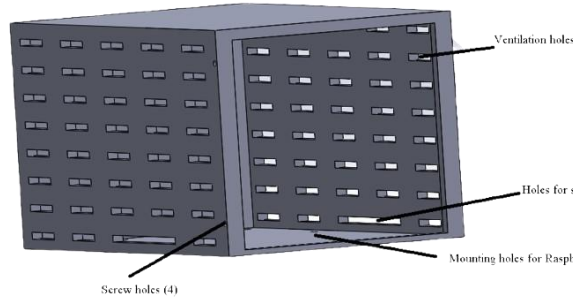


Figure 3. Main housing design

Figure 4. Closing lid design

The system is composed of a ESP32 Microcontroller, one RPI5 PD Power connected to a battery module. The system uses a Bluetooth chipset to communicate the data processed and filtered by ESP32

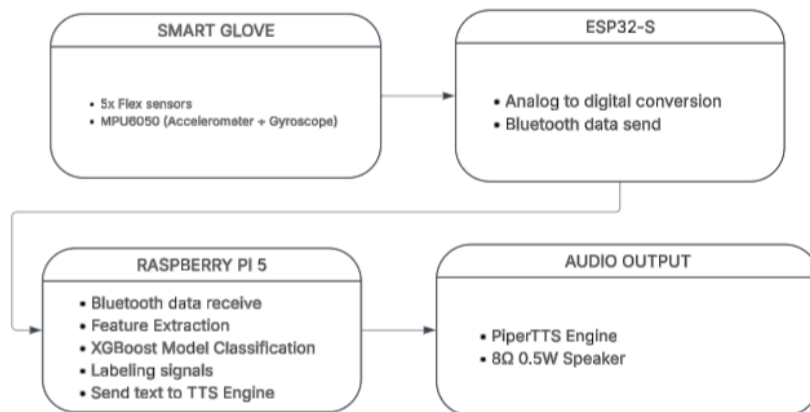


Figure 3. Overall system architecture

In figure 3 is pictured the system's electrical wiring diagram, containing the sensors pinouts and power sources.

MCU/Sensor	Pin Number	Pin Name	Table 2. Pinout configuration of the system	
			Description	
	1	3.3V	Provides power for other components	
	5	GPIO 34	Flex sensor used for data received from pinky finger	
	9	GPIO 25	Flex sensor used for data received from ring finger	
	10	GPIO 26	Flex sensor used for data received from middle finger	
	11	GPIO 27	Flex sensor used for data received from index finger	
	12	GPIO 14	Flex sensor used for data received from thumb finger	

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ESP32 MCU	14,38,32	GND	Connected to ground of the system
	19	VIN 5V	Provides power for ESP32 from RPI5 module
	36	GPIO 22	Pin used for providing clock pulse for I2C Communication
	33	GPIO 21	Pin used for data received from MPU6050 through I2C Communication
	1	VCC	Provides power for the module
MPU6050	2	GND	Connected to MCU ground system
	3	SCL	Pin used for providing clock pulse for I2C Communication
	4	SDA	Pin used for data received from MPU6050 through I2C Communication

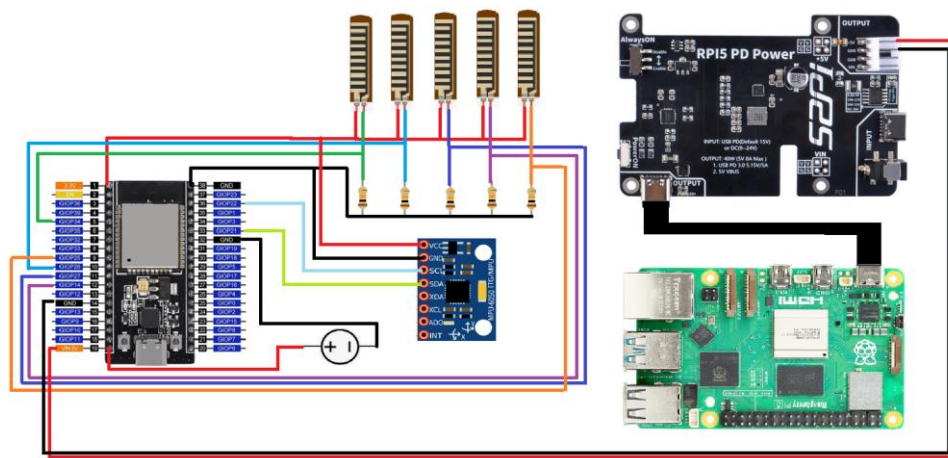


Figure 5. System electrical wiring diagram

5. Software implementation

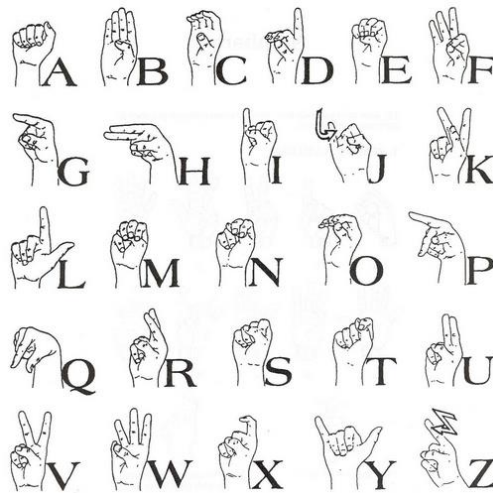


Figure 6. American Sign Language (ASL) [9]

To record, process and filter the MPU6050 accelerometer and gyroscope data, a complementary filter [10] has been implemented. This filter combines the estimated gyroscope angle with accelerometer's angle (which comes with a lot of noise). The complementary filter has been chosen instead of the Kalman's because it does not require a large amount of computing power, despite the Kalman filter being more advanced, but for this use case the choice made is perfect because it is not computational

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heavy for ESP32's processor and it does its job quite precisely.

On the other part of this software implementation, the data is training a XGBoost (a machine learning algorithm based on gradient-boosted decision trees [11]). Despite there being other deep learning approaches, the XGBoost classifier does not require a GPU, it is not computational demanding, does not require large training or validation datasets, making it appropriate for usage on a SBC such as the Raspberry Pi 5.

```
model = XGBClassifier(
    n_estimators=500,
    learning_rate=0.1,
    subsample=0.8,
    colsample_bytree=0.8,
    eval_metric="mlogloss",
    objective='multi:softprob',
    random_state=42,
    n_jobs=-1,
)
```

Figure 7. Hyperparameter configuration for XGBoost classifier

Figure 7 showcases the required configuration for the XGBoost classifier. These hyperparameters were established based on the actual data in the dataset and in order to prevent overfitting or underfitting to ensure reliable performance.

Table 3. Interpretation of hyperparameters for XGBoost classifier [12]

Hyperparameter	Description	Default	Value
n_estimators	Number of boosting rounds (decision trees count)	-	500
learning_rate	Boosting learning rate	0.3	0.1
subsample	Subsample ratio of the training process	1	0.8
colsample_bytree	Subsample ratio of columns during tree construction	1	0.8
eval_metric	Metric used to evaluate model performance during training	-	"mlogloss"
objective	Learning task and the corresponding learning objective	"binary:logistic"	"multi:softprob"
random_state	Random seed number	-	42
n_jobs	Number of parallel threads used to run xgboost	-	-1

6. Conclusions

The developed prototype demonstrates that a low-cost wearable system combining flex sensors, inertial measurement data and machine learning can successfully recognize ASL alphabet gestures and generate real-time voice output. The integration of the ESP32 microcontroller with a Raspberry Pi 5 enables local processing, reducing cloud platforms dependency or external mobile applications. The achieved recognition accuracy above 85% confirms the feasibility of the proposed approach, although several limitations remain, especially regarding user-dependent calibration, similar hand configurations and the current restriction to alphabet-level recognition. Future work will focus on increasing the dataset size, testing the system with multiple users, improving classification accuracy and extending the system from isolated letters to words and dynamic gestures.

7. Bibliography

DEVELOPMENT OF A SMART GLOVE-BASED SYSTEM FOR REAL-TIME ASL ALPHABET RECOGNITION AND VOICE SYNTHESIS

- [1 OpenMQTTGateway, «OpenMQTTGateway,» [En ligne]. Available: github.com/1technophile/OpenMQTTGateway.]
- [2 A. C. G. M.-M. Candice Bentéjac, «[1911.01914] A Comparative Analysis of XGBoost».]
- [3 H. S. Anupama, B. A. Usha, S. Madhushankar, V. Vivek et Y. Kulkarni, «Automated Sign Language Interpreter Using Data Gloves,» chez *2021 International Conference on Artificial Intelligence and Smart Systems (ICAIS)*, Coimbatore, India, 2021.
- [4 A. I. A. M. A. Abdullah Baihan, «Sign language recognition using modified deep learning network and hybrid optimization: a hybrid optimizer (HO) based optimized CNNs-LSTM approach,» *Scientific Reports*, vol. 14, n° 126111, p. 22, 2024.
- [5 E. Taggart, «These Gloves Instantly Translate Sign Language into Speech,» 09 07 2024. [En ligne]. Available: <https://mymodernmet.com/sign-language-gloves-signaloud/>. [Accès le 10 05 2026].]
- [6 GeekForGeeks, «Nyquist Sampling Theorem - GeekForGeeks,» [En ligne]. Available: <https://www.geeksforgeeks.org/electronics-engineering/nyquist-sampling-theorem/>.]
- [7 OHF-Voice, «OHF-Voice/piper1-gpl: Fast and local neural text-to-speech engine,» [En ligne]. Available: <https://github.com/OHF-Voice/piper1-gpl>. [Accès le 12 05 2026].]
- [8 Charles, «PLA Vs ABS: Which 3D Printing Filament Is Better In 2026?,» [En ligne]. Available: <https://www.3dtechvalley.com/pla-vs-abs/>. [Accès le 11 05 2026].]
- [9 O. Chand, «Alphabet Asl Chart / Asl sign language alphabet chart • asl abcs sign language abcs • asl printable. - Bill C. Blackwell Blog,» [En ligne]. Available: <https://powershotsx710hs.blogspot.com/2022/05/alphabet-asl-chart-asl-sign-language.html>. [Accès le 12 05 2026].]
- [1 N. H. Z. M. A. S. Z. I. & A. M. Y. Juwita Mohd Sultana, «Analysis of Inertial Measurement Accuracy using Complementary Filter for MPU6050,» [En ligne]. Available: https://www.researchgate.net/profile/Azdiana-Yusop/publication/366490923_Analysis_of_Inertial_Measurement_Accuracy_using_Complementary_Filter_for_MPU6050_Sensor/links/682570398a76251f22e1e11c/Analysis-of-Inertial-Measurement-Accuracy-using-Complementary-F.
- [1 GeeksforGeeks, «XGBoost - GeeksforGeeks,» [En ligne]. Available: <https://www.geeksforgeeks.org/machine-learning/xgboost/>. [Accès le 13 05 2026].]
- [1 P. A. Reference, «Python API Reference — xgboost 3.3.0-dev documentation,» [En ligne]. 2] Available: https://xgboost.readthedocs.io/en/latest/python/python_api.html#xgboost.XGBClassifier. [Accès le 13 05 2026].]

8. Notations

Next symbols are used in writing this paper:

SBC = Single-board Computer

MQTT = Message Queuing Telemetry Transport

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TTS = Text-To-Speech

IMU = Inertial Measurement Unit

ASL = American Sign Language

SLR = Sign Language Recognition

CNN = Convolutional Neural Network

ABS = Acrylonitrile Butadiene Styrene

PLA = Polylactic Acid

MCU = Microcontroller Unit

Research on Optimizing the Production Process of Electrical Switchboard Assemblies

ROMAN Marciana-Nicoleta și DIJMĂRESCU Manuela-Roxana (Scientific coordintaor)

Faculty of Industrial engineering and Robotics, Specialization: Industrial Economic Engineering,

Year of study: IV, e-mail: marcianaroman10@gmail.com

***ABSTRACT:** This research paper presents an analysis of the production process for switchboard assemblies at EUROSIC SA, highlighting the main issues in the current workflow, such as unnecessary movement, component search times, uneven resource utilization, and the risk of assembly errors. Based on an analysis of the workspace and storage areas, an optimization solution is proposed that involves reorganization the production flow, separating logistics activities from production activities, and introducing a kitting system. The proposed measures aim to reduce waiting times, increase productivity and improve the quality of the products manufactured by the company.*

***KEYWORDS:** switchboards, process optimization, production flow, Kitting*

1. Introduction

Low-voltage switchboards are essential components of modern industrial installations, playing a key role in the distribution of electrical power, circuit protection, equipment control and the integration of automation functions. Their importance is also highlighted by the requirements set forth in the IEC 61439 series of standards, which establishes the general conditions, design requirements, technical characteristics and necessary tests for low-voltage switchboard assemblies [1-2]. In industrial applications, switchboards must ensure not only the power supply to consumers, but also operational safety and the reduction of risks caused by overloads, short circuits or connection errors.

During the most recent period, the development of industrial systems has been influenced by concepts associated with Industry 4.0, which promote equipment interconnectivity, information transparency, technical support and data-driven decision-making [3-4]. In this context, switchboards can no longer be viewed merely as physical products but must be regarded as elements integrated into a complex industrial system, where the quality of design, execution and final verification directly influences the reliability of the processes they serve. Solutions such as the Okken and PrismaSeT panels are developed for power distribution and motor control in industrial applications, being used in systems where safety, modularity and power continuity are critical requirements [5-6].

Although products in this field have evolved technically, the manufacturing process for them remains, in many cases, dependent on manual labor, operator experience and the organization of the internal material flow. Made-to-order production, characterized by high variety of low volumes, creates additional challenges in planning and carrying out production activities. Each switchboard may have its own configuration, specific wiring diagram, different components and particular assembly requirements, which increases the risk of search times, unnecessary movements, identification errors and non-conformities. In the technical literature, these activities are classified as waste or non-value-added activities, which must be reduced by applying Lean Manufacturing principles [7].

An important approach to improving assembly processes involves optimizing the supply of materials to workstations. In this regard, the Kitting method involves preparing in advance the components required for an order, a product or an assembly stage, so that operators receive the correct materials at their workstations, in the necessary quantities and at the right time. Studies on the selection of assembly line supply policies show that kitting systems can reduce the time lost in identifying and handling components, contributing to better organization of the material flow [8-9]. For the manufacture of switchboards, this approach is relevant because the large number of devices, cables, connectors, pins, screws, labels and auxiliary components can lead to errors and delays if materials are not prepared and checked before assembly begins.

Production process optimization can also be supported by the use of digital tools. The concept of a

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Digital Twin enables the virtual representation of a physical system and can be used to analyze, monitor and improve industrial processes [10]. At the same time, discrete-event simulation offers the actual process. Software such as Tecnomatrix Plant Simulation is used for modeling, simulating and optimizing production systems, material flows and resource utilization [11]. Therefore, comparing a model of the current state with an optimized model can highlight the impact of flow reorganization on total manufacturing time, resource utilization and the reduction of bottlenecks.

The main objective of the research presented in this paper is to analyze and optimize the production process for specific switchboard assemblies within a specialized company – Eurosic SA – by identifying existing issues in the current flow and proposing improvement solutions based on material reorganization, reducing unnecessary movements, standardizing activities and preparing components by project. The steps to achieve this objective consist of describing the current technological workflow, identifying the main source of time loss and errors and proposing an optimized process organization which can be further validated through modeling and simulation in Tecnomatrix Plant Simulation.

2. EUROSIC S.A. and manufactured products

EUROSIC S.A. is a long-established Romanian company based in Bucharest, whose core business lies in the manufacture of electrical distribution and control equipment. Founded in 1994, the company has established itself on the domestic and international markets through its expertise in the design, manufacture, and marketing of complex low-voltage electrical equipment [12]. Its object of activity covers the provision of integrated solutions for critical sectors, directly targeting heavy and light industry (for the automation of technological installations), critical infrastructure (water treatment plants, airports, ports), electricity transmission, as well as the residential and commercial building market. The company acts as a key technology integrator, with the role of transforming theoretical design schematics into safe physical equipment, indispensable for the operation and protection of any modern facility [12].

EUROSIC's production portfolio focuses exclusively on custom-made low-voltage switchboards, strictly tailored to the technical requirements of each individual project. Among the company's top products are power distribution switchboards and complex motor control centers. A significant portion of its manufacturing activity consists of modular systems produced under licenses from world-leading manufacturers. Notable among these are the Okken series panels (manufactured under license from Schneider Electric), which are recognized in the industry for their high level of safety, ability to withstand high short-circuit currents, and excellent adaptability in operation. At the same time, the portfolio also includes modular structures from the Prisma range, designed for both general power distribution and advanced automation applications. Each finished product is thus a unique engineering solution, ergonomically designed to withstand demanding working environments and ensure absolute continuity of the power supply [12].

Due to the high variability of incoming orders, the company's production operates on a made-to-order basis (High-Mix, Low-Volume), organized as a production line with fixed assembly stations. From an administrative and technological standpoint, operations are structured into deeply interconnected departments. The process begins in the engineering and design department, where documentation is processed using specialized software (such as EPLAN), after which the information is transferred to the logistics sector, responsible for managing components in on-site warehouses.

On the production hall platform, the organization is strategically divided to handle the technical complexity. Primary mechanical processing, which includes precision cutting and drilling of copper bars, is isolated in the CNC section. The main assembly work takes place at fixed workstations and is divided among teams specialized by the type of panel being manufactured: one team focused primarily on complex mechanical structures of the Prisma type and another team dedicated to power electrical assemblies and wiring from the Okken range. Cable preparation operations on the automatic crimping machine (Crimp) and printing on industrial label printers (Phoenix) are shared resources that serve both teams simultaneously. To ensure product safety, the process concludes with the intervention of the Technical Quality Control (TQC) department, where inspectors verify compliance of the panel with

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single-line diagrams and safety standards directly at the assembly bench, immediately prior to packaging and delivery.

3. Current state of the production process for switchboards

The spatial layout of the production hall follows a "fixed-position" model, in which the main product remains stationary, and all necessary resources are brought to the workstation. This layout is divided into several critical zones, whose geographical arrangement directly influences process efficiency. Storage is decentralized, consisting of an outdoor warehouse for bulky items such as the metal frames of the panels, support bars, and outer covers, and an indoor warehouse (on-site storage), where specific devices, relays, and other small components are stored.

The central area of the hall is occupied by the assembly stations, subdivided for the Prisma and Okken teams. Peripherally, the technological support stations are located: the CNC section for processing copper bars and the technical corner equipped with the automatic crimping machine (Crimp) and Phoenix printers for labeling. This spatial fragmentation, visible in the layout diagram created in the simulation environment, necessitates heavy traffic of materials and personnel between the storage and processing areas.

Figure 1 shows the layout of the main functional areas in the production hall. It highlights the positioning of the indoor warehouse, the outdoor warehouse, the workbenches, the panel assembly area, as well as the auxiliary equipment used in the process, namely the milling-drilling machine, the crimping machine, and the label printer.

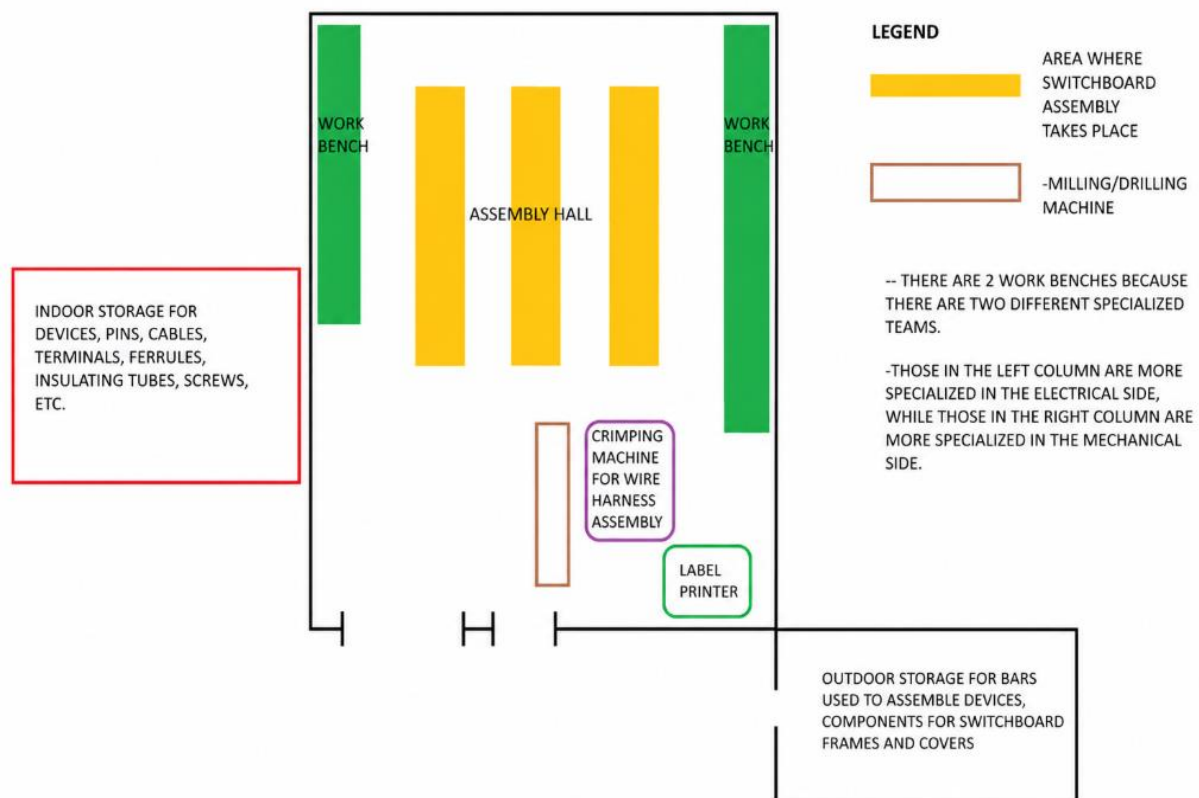


Fig. 1. Layout of the work and storage areas in the production hall

The actual manufacturing process follows a linear sequence from a logical standpoint, but it proves to be complex in terms of the physical movements carried out in the workshop. The process begins with initial logistical preparation, which involves retrieving structural components and support bars from the outdoor warehouse. Immediately after these are brought to the workstation, primary mechanical assembly takes place, consisting of securing the switchboard's base structure. Next comes the stage of identifying and sorting the equipment, a step that requires the team leader to go to the indoor warehouse

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to identify and retrieve the components according to the single-line diagram. Once these components are secured, the process continues with the actual installation of the equipment on DIN rails or back panels.

The workflow then proceeds to the copper busbar processing phase, a step that requires cutting and drilling them in the CNC section, followed by their transport back to the assembly table. This step allows for the completion of the power electrical assembly by integrating the busbar systems inside the panel. A critical step is the preparation of the wiring system, which includes labeling the components and crimping the cables. This operation is handled differently, being performed either automatically on the crimping machine by one team or manually directly at the workbench by the other. With the materials thus prepared, the actual electrical wiring begins, with final connections made according to the EPLAN schematics.

Toward the end of the production cycle, the switchboard undergoes technical quality control, a rigorous inspection performed by technical control staff directly at the workstation. After receiving quality approval, the mechanical assembly is finalized. This phase causes another interruption, forcing staff to make a second trip to the outdoor warehouse to retrieve and install the outer covers. Finally, the process concludes with the preparation for delivery stage, which involves packaging the finished product and transporting it to the shipping holding area.

The analysis of the production flow revealed a series of critical inefficiencies that profoundly affect total manufacturing time and labor productivity, falling directly into the categories of waste specific to the Lean philosophy. First and foremost, there are significant search and identification times, caused by workers' reliance on team leaders to identify components in the warehouse. The lack of a kitting system makes this logistical stage not only repetitive but also a constant source of downtime. This situation is greatly exacerbated by unnecessary travel. Production staff spend a significant portion of their workday covering considerable distances between workstations, storage areas, and shared processing stations, such as the crimping machine or label printers. A major inefficiency in this regard is the need to make two separate trips to the external warehouse – one initially to retrieve the frame and another at the end to bring the covers – a direct consequence of space constraints at the workstation.

Second, the current process is extremely vulnerable to identification errors and non-conformities. Manual part tracking and fragmented labeling frequently lead to assembly errors that are only detected during the final inspection phase. This late detection necessitates rework, increasing operational costs and jeopardizing delivery deadlines. Last but not least, the workflow suffers from recurring delays and bottlenecks at the assembly stations. Since quality testing is performed exclusively at the assembly site, the station remains blocked for the entire duration of the inspection conducted by technical control personnel, preventing the initiation of a new order. Coupled with the lack of digital synchronization between the logistics and production departments, which means that materials do not always arrive at the right time, this procedure generates unplanned waiting periods. Taken together, all these fundamental issues demonstrate that the current system, while operational, has reached a critical efficiency threshold, requiring a profound digital and logistical transformation to ensure the sustainability of production.

4. Optimization proposal for the switchboards production process

In order to address the inefficiencies identified the switchboards production process, this study sets as its primary objective the restructuring of the assembly process through the systematic elimination of activities that do not add value to the finished product. The primary goal is to reduce the total time cycle by eliminating unnecessary movements within the production hall and by minimizing waiting times, factors that currently diminish the efficiency of direct production personnel.

From a quality management perspective, the initiative aims to eliminate assembly errors resulting from manual part identification and fragmented wiring preparation, proposing rigorous standardization of the on-station supply process. At the same time, a major objective is to increase overall productivity and ensure compliance with delivery deadlines. This goal will be achieved by maximizing the utilization rate of fixed workstations, ensuring an environment where specialized personnel can focus their efforts

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exclusively on technological execution operations, being completely relieved of logistical or material handling tasks.

To achieve these objectives, a complete reorganization of the production hall is proposed, based on the principle of continuous flow and the strict separation of logistical tasks from production tasks (see Figure 2). The spatial reconfiguration aims to group the support units – namely the central indoor warehouse, the labeling station, the crimping machine, and the CNC machining center – within a peripheral perimeter dedicated to material preparation. This reorganization frees up a central logistics corridor, designed as a main transit artery, which facilitates a direct and rapid connection between the parts preparation area and the Okken and Prisma final assembly cells. By dividing the workspace in this way, the necessary conditions are created for implementing a kitting supply system, where a staff member dedicated exclusively to transport (the kitter operator) ensures a constant flow of materials to the assembly tables.

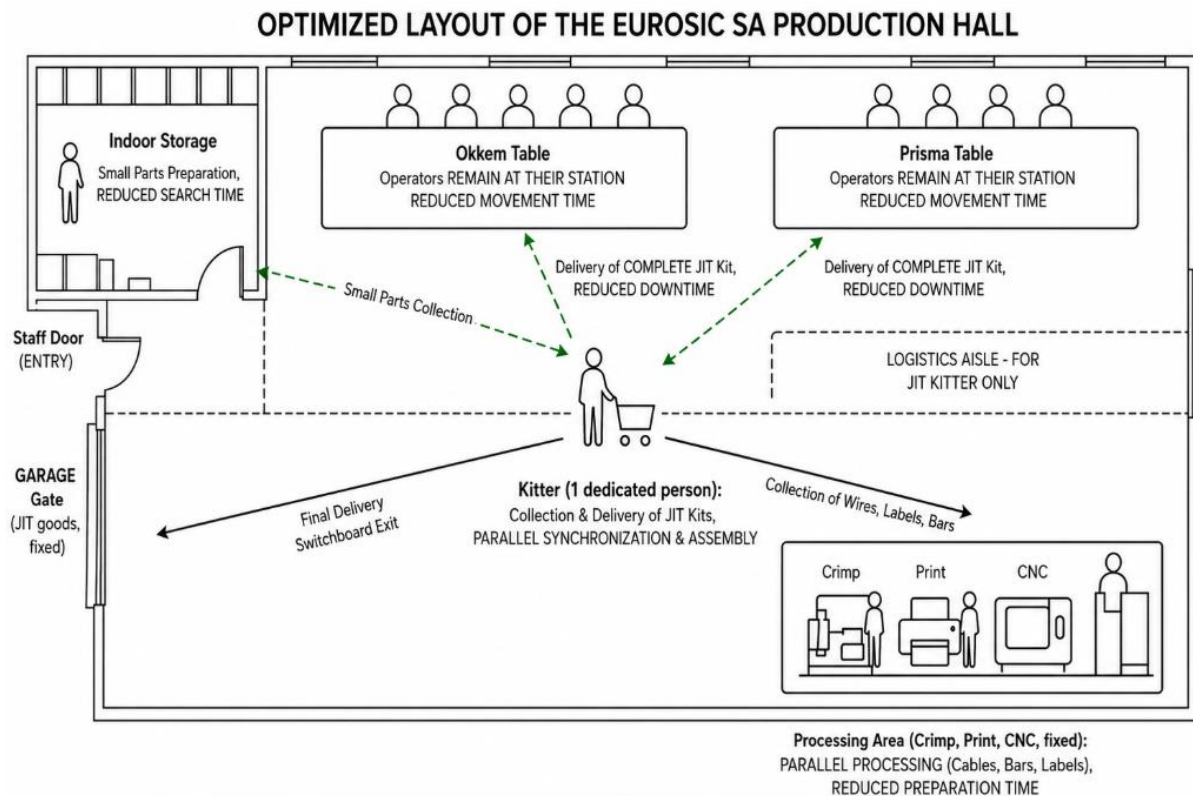


Fig. 2. Proposed optimization of the production work areas

The efficiency of this physical structure is enhanced by the introduction of a real-time digital communication system, based on the use of tablets at each workstation. This technological solution eliminates uncertainty and waiting times, transforming the supply process from a reactive one into a proactive one, guided by the actual demand of the assembly workers. In this model, operators at the assembly stations signal their component needs directly through the digital interface, and the request becomes instantly visible to warehouse and machine personnel. Thus, the processing of wires, labels, or copper bars begins well before the transport operator arrives at the respective station, ensuring that the materials are prepared and consolidated into complete kits before the delivery request is made to the workstation.

This proposed synchronization offers a major advantage in eliminating device identification errors, as the information transmitted to tablets is extracted directly from the project's technical documentation. At the same time, this decouples the processes: while warehouse staff and machine operators can organize their work in advance, assemblers remain at their stations, confident that all necessary

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resources will be made available to them without having to leave the work area or verbally communicate their requirements. In conclusion, this hybrid architecture, which combines spatial optimization with the digitization of communication, provides the necessary foundation for stabilizing production time at the standard of four hours per column, ensuring a sustainable increase in operational efficiency at Eurosic SA.

To verify the effectiveness of the proposed solution, the reorganization of the production flow can subsequently be transposed into a simulation model created in Tecnomatix Plant Simulation. This model will represent the main functional areas of the hall, workstations, shared equipment, travel routes, and the flow of materials between the warehouse, the preparation area, and the assembly tables. The simulation will allow for a comparison of the current state with the optimized variant by tracking indicators such as total manufacturing time, travel time, waiting time, resource utilization, and the occurrence of bottlenecks in the flow. Thus, the optimization proposal will not remain merely conceptual but can be quantitatively validated, providing an objective basis for decisions regarding the reorganization of the production process.

5. Conclusions

The objective of this paper was to analyze the production process for switchboard assemblies and to identify optimization solutions tailored to the specific characteristics of made-to-order production, which is characterized by a wide variety of products, complex technological flows, and significant dependence on internal material flow management. The study conducted on the manufacturing process of EUROSIC SA highlighted that operational efficiency is influenced not only by technical equipment or staff competence, but also by how the workspace, storage areas, movement routes, and communication between operators are organized.

The analysis of the current state identified several inefficiencies that affect total manufacturing time and process quality. These include repeated trips between workstations and storage areas, long search and identification times for components, operators' reliance on team leaders for part identification, fragmented use of shared resources such as the crimping machine and label printers, as well as the risk of assembly or wiring errors. These issues generate non-value-added activities, delays, and the potential for non-conformities that can only be identified during the final inspection stage.

The proposed solution aims to reorganize the manufacturing flow by separating logistics activities from production activities, introducing a kitting-style supply system, and assigning a dedicated operator to transport materials to workstations. Furthermore, reconfiguring the production space and grouping the technical support areas within a dedicated perimeter can help reduce unnecessary movement and improve synchronization between material preparation and assembly operations. The use of tablets at workstations would allow for the rapid transmission of requests and their correlation with the project's technical documentation, thereby reducing the risk of identification errors and facilitating the correct preparation of components.

The proposed measures aim to increase productivity, reduce waiting times, improve material traceability, and enhance the quality of electrical panel assemblies. An important contribution of this work is highlighting the fact that process optimization does not necessarily require major investments in new equipment but can start with the intelligent reorganization of existing resources, the standardization of activities, and improved communication between logistics and production.

Future research will focus on modeling and simulating the proposed production process in Tecnomatix Plant Simulation. To this end, a comparative model will be developed between the current state and the optimized variant, tracking indicators such as total manufacturing time, travel time, waiting time, utilization rates of workstations and shared equipment, as well as the impact of the kitting system on reducing errors and bottlenecks in the flow. The simulation results will enable quantitative validation of the proposed solution and provide an objective basis for its subsequent implementation within the actual production process.

6. References

RESEARCH ON OPTIMIZING THE PRODUCTION PROCESS OF ELECTRICAL SWITCHBOARD ASSEMBLIES

- [1]. IEC. (2020). IEC 61439-1:2020 - Low-voltage switchgear and controlgear assemblies – Part 1: General rules. International Electrotechnical Commission.
- [2]. IEC. (2020). IEC 61439-2:2020 - Low-voltage switchgear and controlgear assemblies – Part 2: Power switchgear and controlgear assemblies. International Electrotechnical Commission.
- [3]. Kagermann, H., Wahlster, W. & Helbig, J. (2013). Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final report of the Industrie 4.0 Working Group. acatech - National Academy of Science and Engineering.
- [4]. Hermann, M., Pentek, T. & Otto, B. (2016). Design Principles for Industrie 4.0 Scenarios. Proceedings of the 49th Hawaii International Conference on System Sciences, 3928–3937. DOI: 10.1109/HICSS.2016.488.
- [5]. Schneider Electric. Okken - Low voltage switchboards for power distribution and motor control up to 7300 A.
- [6]. Schneider Electric. PrismaSeT P - Tablouri electrice modulare pentru distribuția energiei, până la 4000 A.
- [7]. Womack, J. P. & Jones, D. T. (1996). Lean Thinking: Banish Waste and Create Wealth in Your Corporation. Simon & Schuster.
- [8]. Bozer, Y. A. & McGinnis, L. F. (1992). Kitting versus line stocking: A conceptual framework and a descriptive model. International Journal of Production Economics, 28(1), 1-19.
- [9]. Caputo, A. C., Pelagagge, P. M. & Salini, P. (2015). A decision model for selecting parts feeding policies in assembly lines. Industrial Management & Data Systems, 115(6), 974-1003.
- [10]. Tao, F., Zhang, H., Liu, A. & Nee, A. Y. C. (2019). Digital Twin in Industry: State-of-the-Art. IEEE Transactions on Industrial Informatics, 15(4), 2405-2415. DOI: 10.1109/TII.2018.2873186.
- [11]. Siemens Digital Industries Software. Tecnomatix Plant Simulation software. Siemens, <https://www.siemens.com/en-us/products/tecnomatix/plant-simulation>, accessed on May 12, 2026
- [12]. <https://www.eurosic.ro/>, accessed on May 14, 2026

RESEARCH AND DEVELOPMENT ON THE CHARACTERISTICS OF TECHNOLOGICAL OPERATIONS FOR ADVANCED INDUSTRIAL SYSTEMS

FLEACĂ Ioana-Maria¹, DĂNILĂ Alexa-Eugenia¹, SIMION Ana-Maria-Nicoleta¹,
LASCU Ellen¹, ANDREI Atina-Mihaela¹, DUMITRACHE Andrei-Cristian¹,
GRUIA David-Alexandru¹, GHEORGHE Marian², ILIESCU Dragoș^{2, 3},
POLOVȚEV Nicolae⁴, GANNAM Nasim^{2, 4}, DUMITRACHE Ionuț-Alin^{2, 5}

¹Faculty of Industrial Engineering and Robotics, Specialization:
Industrial Economic Engineering, 4th study year, e-mail: ifleacal@gmail.com
²POLITEHNICA Bucharest, Manufacturing Eng. Departament (TCM),
³S.C. Nuclear NDT, ⁴SC Dr. Köcher SRL, ⁵INCDT COMOTI

ABSTRACT: The machining, heat treatment and control operations are representative components of manufacturing technological processes. Based on defining data and industrial conditions, technological systems, phases, working parameters, system programming and simulation are developed, within appropriate case studies, as relevant elements related to technological operations. Experimental researches are carried out, including conformity assessment of specific experimentally manufactured products.

KEYWORDS: *technological operation, machining, heat treatment, control, technological system, technological phase, simulation.*

1. Introduction

114. Technological operations represent the fundamental structural parts of technological processes for product manufacturing.

115. Technological operations reveal important technical and economical characteristics which refer to operation sketches, process diagrams, associated technological systems, component phases, etc.

116. The main objective of this paper is to expand and present certain common features associated with the design and industrial implementation of technological systems, technological phases/ stages, working parameters, programming of CNC and CMM systems, simulation, as well as the conformity assessment of certain specific experimentally manufactured products.

117. Based on defining data and industrial conditions, the present paper analyses and develops a series of elements concerning the structural characteristics of different technological operations, through relevant case studies on machining, heat treatment and control operations for advanced systems.

2. General considerations

118. Numerous different precision functional engineering products, in the form of parts and assemblies, are manufactured by machining in industrial

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sectors such as aerospace, automotive, energy, medical implants, consumer goods, etc. [1].

119. Depending on the nature of the predominant main activities, the technological operations can be of: semi-manufacturing, machining, heat treatment, control, etc. [2].

CNC machining can create highly complex and precision parts in a single setup. It is possible to apply a configuration of 3 - Axis or multi-axis, e.g., as 4 - Axis or 5 - Axis [2 - 6].

The topic of metallic materials classification is of a large interest for engineering domain. Among the classification factors, chemical composition and the mechanical and physical characteristics are of real impact [7]. Alloying elements are major factor for classification [8]. There are classes of heat-resistant steel [9] or steels to be processed by heat treatment [10, 11].

120. Advanced geometric control systems, such as those including coordinate measuring machines (CMMs), contribute significantly to the assessment of the actual machined product features and manufacturing quality assurance within modern industrial environments [12 - 14].

121. The elements related to technological operations, i.e. technological systems, phases, working parameters, CNC programming, etc., are determined according to specific methodologies [2].

122. Thus, for the machining operations, for instance, the cutting parameters cutting depth, a , feed, f , and cutting speed, v , are determined function of restrictions imposed by material characteristics, surface prescribed quality, machining allowance, tool life, etc. [2].

123. Also, for heat treatment operations, the so-called critical temperatures/ points are essential for establishing the heat treatment process parameters. Thus, the critical temperatures A_{c1} and A_{c3} at which the steel microstructure begins and ends the transformation process from ferrite and pearlite to austenite, respectively, the austenitizing temperature, T_A , etc. can be determined by using, for example, specific equations [15, 16], the corresponding Continuous Cooling Transformation (CCT) diagrams [16] or **hardness – temperature diagrams** [17, 18], as appropriate.

3. Case studies on technological machining operations for CNC centres

124. Case 3.1

125. *Product:* Block DP.00.105, material GE200 (1.0420).

126. *Operation:* 20. Complex machining.

127. *Technological System:*

CNC Machining Centre: HAAS VM-2	•
Fixture:	Vise • Tools:
Bull nose end mill Ø10 R0.5,	End mill Ø10, Centering drill Ø5, Drill Ø10, Countersink 10 x 45°
• Cutting fluid: Emulsion Zubora 50 Universal	• Verifiers: Integrated control equipment, Digital calliper.

Technological phases: as presented in Table 1.

Cutting parameters: as presented in Table 1.

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It should be noted that: the parameters a , f and v are determined (see § 2) according to the specific methodology and industrial conditions [4]: parameters n and F are calculated as:

$$n = 1000v/\pi d, \quad F = fn \quad (1)$$

where d , in mm, is the tool diameter.

128.

129. Table 1. Technological phases and cutting parameters

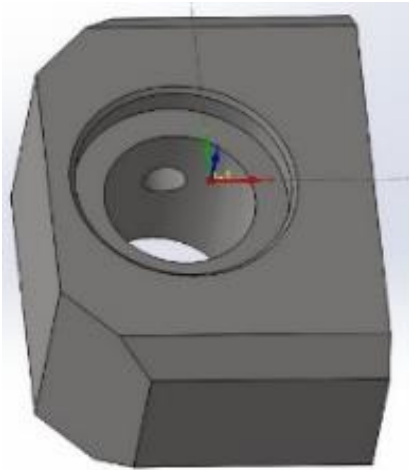
130. Technological phases	131. Cutting depth, a , 139. mm	132. Feed d , 133. f , 140. mm/rev	134. Cutting speed, v , 141. m/min	135. Rotational speed, n , 142. rpm	136. Feed speed, F , 143. mm/min
137. • 138. Part holding					
144. • 145. Rough milling to 40.1 x 30.1	146. 0.3	147. 0.27	148. 113	149. 3597	150. 971
151. • 152. Finish milling to 40 x 30	153. 0 - 0.3	154. 0.25	155. 125.6	156. 3998	157. 999
158. • 159. Centering to A5 x 5 DIN 332	160. 2.5	161. 0.1	162. 15.7	163. 999	164. 100
165. • 166. Drilling to Ø 10	167. 5	168. 0.04	169. 21.3	170. 678	171. 27
172. • 173. Rough milling to Ø13.7 – Ø 19.8	174. 0.3	175. 0.27	176. 113	177. 3597	178. 971
179. • 180. Finish milling to Ø13.9 H9 – Ø 20	181. 0.15	182. 0.25	183. 125.6	184. 3998	185. 999
186. • 187. Countersinking to 2.1 x 45°	188. 0.15	189. 0.27	190. 113	191. 3597	192. 971
193. • 194. Part release and deposition	195.	196.	197.	198.	199.

202. *Positioning scheme of XYZ axes system:*

as presented in Fig.1.

203. The origin (W) of XYZ is placed on the upper surface of the part and symmetrically with respect to the vertical boundary surfaces of the part, so that the considered surfaces have their coordinates, in mm:

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200.

Fig.1. The positioning scheme of XYZ axes system

$$\left. \begin{array}{l} 204. \quad Z_{\min} = -20, Z_{\max} = 0 \\ 205. \quad x_{\min} = -15, x_{\max} = 15 \\ 206. \quad y_{\min} = -20, y_{\max} = 20 \end{array} \right\} \begin{array}{l} 207. \\ 208. \end{array} (2)$$

209. *Sequences of the CNC program*

210. *Simulation of phase Rough milling to 40.1 x 30.1*

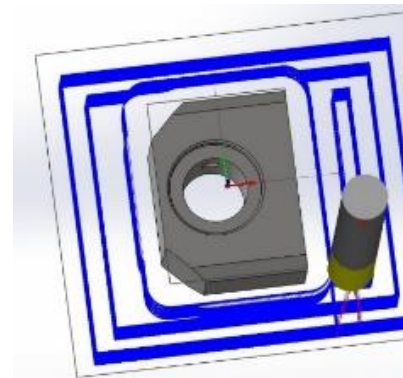
211. ; REPER:
3_BLOCK
212. ;(IA_NUME
PROGRAM :
3DR_TARGET.
MPF)
213. ; (pre_processor
cam: SIN810D)
214. ;(15-MAY-
2026time,
16:11:49)
215. N1; T1 BULL
NOSE MILL
D10. R0.5
216. N2 G17
217. N3 R1=2000
R2=1000
R3=15000
218. N4 G00 G40 G90
M7 M85 M8 M25
219. N5 G641 G0
Z100.
220. N6 G54
221. N7 G0 G90
X23.976 Y-18.135
S4000 M3

223.



Block_Sim.mp4

224.



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222. N8 X23.976 Y-
18.135 Z60.

225. Case 3.2

226. *Product*: Support_MP.10.016, material GE300 (1.0558).

227. *Operation*: 10. Complex machining.

228. *Technological System*: • CNC Machining Centre: HAAS VM-2 •
Fixture: Vise • Tools: Bull nose end mill Ø10 R0.5, End mill Ø10, Centering drill
Ø5, Drill Ø10, Drill Ø26, T-slot milling cutter Ø30 x 2, Countersink 10 x 45° •
Cutting fluid: Emulsion Zubora 50 Universal • Verifiers: Integrated control
equipment, Digital calliper, Roughness etalon sample.

Technological phases: as presented in Table 2.

Cutting parameters: as presented in Table 2.

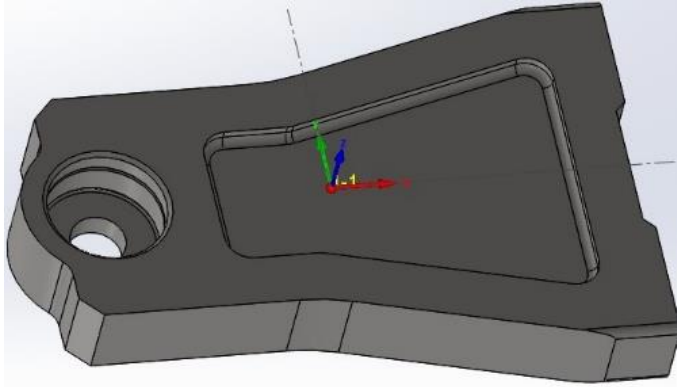
It should be noted that: the parameters a , f and v are determined (see § 2) according to the specific methodology and industrial conditions [4]: parameters n and F are calculated based on eq. (1).

229. Table 2. Technological phases and cutting parameters

230. Technological phases	231. Cutting depth, a ,	232. Feed, f ,	234. Cutting speed, v ,	235. Rotational speed, n ,	236. Feed speed, F ,
237. • 238. Part holding	239. mm	240. mm/rev	241. m/min	242. rpm	243. mm/min
244. • 245. Rough milling to 7.8	246. 0.3	247. 0.27	248. 113	249. 3597	250. 971
251. • 252. Finish milling to 8	253. 0-0.3	254. 0.25	255. 125.6	256. 3998	257. 999
258. • 259. Centering to A5 x 5 DIN 332	260. 2.5	261. 0.1	262. 15.7	263. 999	264. 100
265. • 266. Drilling to Ø 10	267. 5	268. 0.04	269. 21.3	270. 678	271. 27
272. • 273. Machining to Ø 26	274. 6.5	275. 0.08	276. 24.5	277. 300	278. 24
279. • 280. Rough milling to Ø 55.6 x 27.6	281. 0.3	282. 0.27	283. 113	284. 3597	285. 971
286. • 287. Finish milling to 55.8 H9 x 27.2	288. 0.15	289. 0.25	290. 125.6	291. 3998	292. 999
293. • 294. Finish milling to 2.15	295. 0.1	296. 0.5	297. 188	298. 1994	299. 997
300. • 301. Countersinking to 2.1 x 45 °	302. 0.15	303. 0.27	304. 113	305. 3597	306. 971
307. • 308. Part release and deposition	309.	310.	311.	312.	313.

314.

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315.

316. Fig. 2. The positioning scheme of XYZ axes system

317. Positioning scheme of XYZ axes system: as presented in Fig. 2.

318. The origin (W) of XYZ is placed on the upper surface of the part and symmetrically with respect to the vertical boundary surfaces of the part, so that the considered surfaces have their coordinates, in mm:

$$\left\{ \begin{array}{l} 319. \quad Z_{\min} = -40, \quad Z_{\max} \\ = 0 \\ 320. \quad X_{\min} = -145, \quad X_{\max} \\ = 145 \end{array} \right. \quad (3)$$

$$321. \quad y_{\min} = -92, \\ y_{\max} = 92$$

322.

*Sequences of the
CNC program*

324. N10 G0 G90
X65.973 Y-
3.881 S4000
M3
325. N11 X65.973
Y-3.881 Z60
326. N12 Z1.
327. G1 X65.933
Y-3.33 Z0.952
F=R2
328. X65.817 Y-
2.789 Z0.903
329. X65.628 Y-
2.27 Z0.855

332.

333. Case 3.3

334. *Product:* Nut CR.10.008, material X5CrNi18-10 (1.4301).

335. *Operation:* 30. Channels electroerosion.

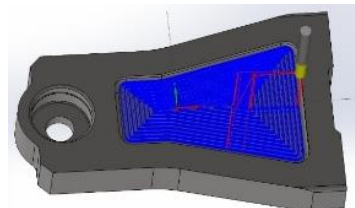
336. *Technological System:* • CNC Machining Centre: Sodick A350 Wire Cutting Machine

323. *Simulation of phase Rough milling to 7.8*



Support_Sim.mp4

330.



331.

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337. • Fixture: Special • Tool: CuZn.37 Wire Ø 0.25 • Cutting fluid: Dielectric fluid • Verifier: Caliber.

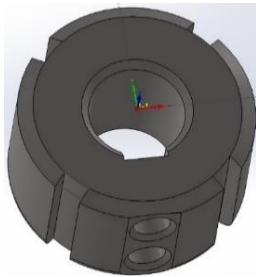
338. *Technological phases and machining parameters: as presented in Table 3.*

339.

340. Table 3. Technological phases and machining parameters

341. Technological phases	342. Voltage, U, V	343. Current, I, A	344. Pulse-on time, Ton, µs	345. Feed speed, F, mm/min
346. • 347. Part holding				
348. • 349. Rough cutting to 3.9	350. 100	351. 6	352. 12	353. 3
354. • 355. Finish cutting to 4	356. 80	357. 5	358. 8	359. 4
360. • 361. Rough cutting to 5.9	362. 100	363. 6	364. 12	365. 3
366. • 367. Finish cutting to 6	368. 80	369. 3	370. 8	371. 4
372. • 373. Part release and deposition	374.	375.	376.	377.

378.



379. Fig. 3. The positioning scheme of XYZ axes system

381. *Positioning scheme of XYZ axes system: as presented in Fig. 3.*

382. The origin (W) of XYZ is the intersection of the upper surface and the bore symmetry axis of the part, such that the horizontal surfaces and the outer cylindrical surface of the part have their coordinates, in mm:

$$\left. \begin{aligned} 383. Z_{\min} &= -18, Z_{\max} = 0 \\ 384. X_{\min} &= -16, X_{\max} = 16 \\ 385. Y_{\min} &= -16, Y_{\max} = 16 \end{aligned} \right\} 386. (4)$$

387. *Sequences of the CNC program*

388. N0001(W1 NORMAL FORWARD	391. ...	397. ...
);	392. X-8.574 Y-11.225	398. N0038T85;
N0002(TP = 0.00 TN = 0.00)	393. X-9.302 Y-10.63	(N0039T90);
N0003C000;	394. X-9.988 Y-9.988	N0041M02;
N0004H001;	395. X-10.63 Y-9.301	%%;
389. N0005G90;	X-11.225 Y-8.574	
N0006G54;	396. ...	
390. N0007G29;		

4. Case studies on technological heat treatment operations for advanced systems

399. Case 4.1

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400. *Product:* Bush 2 CR 10.004, material C45 (1.0503) SR EN ISO 683-1:2018.

Operation: 30. Heat treatment of quenching and tempering, *Hardness:* 40 - 43 HRC.

401. *Temperatures A_{c3} and T_A*

402. A_{c3} is calculated (see § 2) based on eq. (5) [15]:

$$403. A_{c3} = 925 - 219\sqrt{C} - 7Mn + 39Si - 16\text{ } \exists + 13Mo + 97V, \text{ in } ^\circ\text{C} \quad 404. (5)$$

where C , Mn , etc. represent the mass concentration, in %, of the correspondent chemical elements.

405. T_A is calculated based on eq. (6) (adapted from [16]),

406.

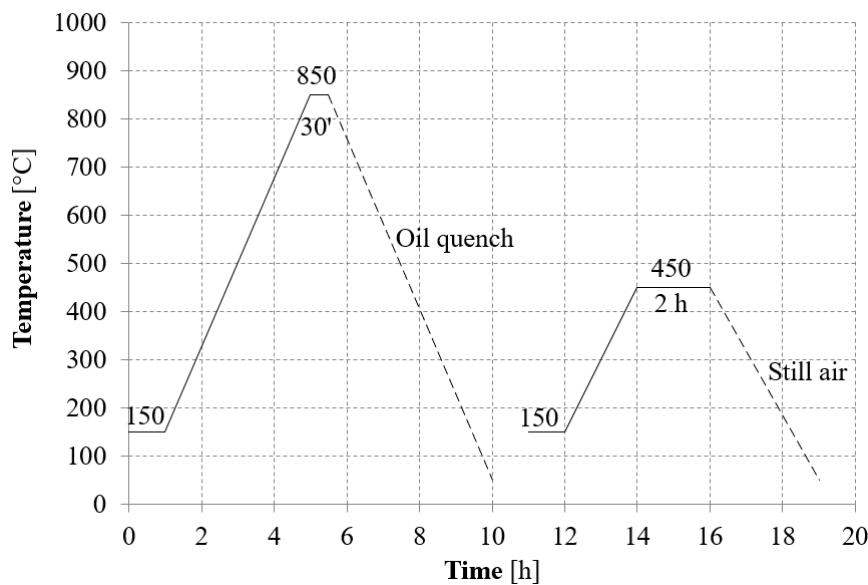
$$407. T_A = A_{c3} + k(30 - 50), k = 1-4 \quad 408. (6)$$

409. where the coefficient k depends of the actual steel, equipment, 410.
etc.

411. Thus, for the considered material (C45): $A_{c3} = 794 ^\circ\text{C}$; $T_A = 794 + 1 \cdot 50$, $T_A \approx 850 ^\circ\text{C}$.

412. *Time - Temperature Diagram:* as presented in Fig. 4.

413.



414.

415.

416. Fig. 4. Quenching and tempering cycle diagram for the C45 steel grade (adapted from [19])

417. *Technological system:*

- Heat treatment installation - molten salt bath equipment (one for 850 °C and a second for 450 °C) as heating and anti-oxidizing environment; quenching oil tank
- Fixture - basket-type, size for 20 parts, manual/ automatic handling
- Health

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and Safety - protective equipment against temperature and toxic vapours •
Verifiers: Integrated control/ surveillance equipment of heat treatment parameters; portable Rockwell hardness tester by Ultrasonic Contact Impedance, UCI, method.

418. *Technological stages*: • Batch preparation, i.e., visual examination of the parts and placement in baskets • Batch drying, i.e., heating to 150 - 350 °C in conventional oven • Batch loading, i.e., placing the baskets with parts into treatment facility • Heating and soaking (holding), with temperature and duration, respectively, as control parameters • Rapid cooling, in the quenching medium. • Batch drying • Batch loading in tempering facility • Heating and soaking, with temperature and duration, respectively, as control parameters • Cooling in still air • Hardness measurement • Part release and deposition.

419. Case 4.2

420. *Product*: Housing MP.10.003, material GX30CrSi7 (1.4710) EN 10295:2002.

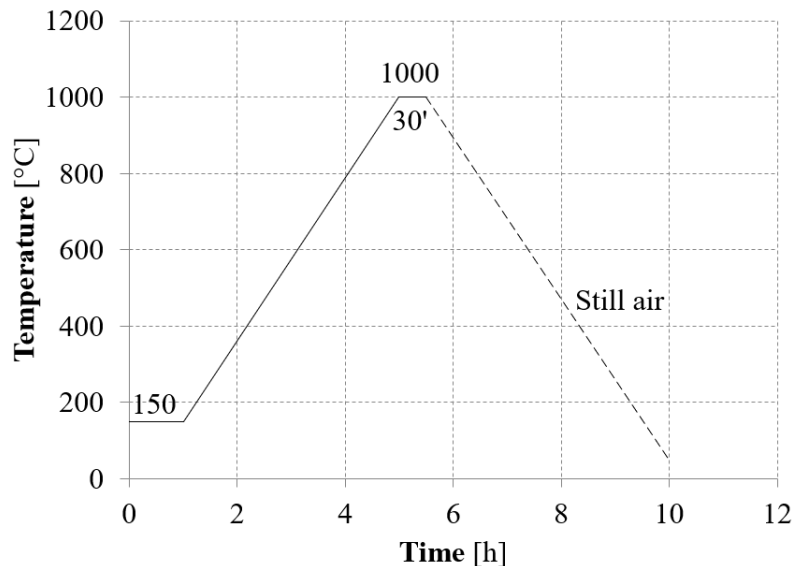
Operation: 30. Normalising heat treatment, *Hardness*: 250 - 320 HB.

421. *Temperatures A_{c1} and T_A*

422. A_{c1} is determined (see § 2) based on CCT diagram [15], and T_A – based on eq. similar to (6),

423. Thus, for the considered material (GX30CrSi7): $A_{c1} = 805\text{ °C}$; $T_A = 805 + 4 \cdot 50$, $T_A \approx 1000\text{ °C}$.

424. *Time - Temperature Diagram*: as presented in Fig. 5.



425.

426. Fig. 5. Normalising diagram for the GX30CrSi7 stainless steel grade (adapted from [19])

427.

428. *Technological system* • Heat treatment installation – gas fired furnace; forced air facility

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ADVANCED INDUSTRIAL SYSTEMS**

• Fixture – basket-type, size for 20 parts, manual handling • Health and Safety - protective equipment against temperature • Verifiers: Integrated control/surveillance equipment of heat treatment parameters; portable Brinell hardness tester (UCI method).

429. *Technological stages:* • Batch preparation, i.e., visual examination of the parts and placement in baskets • Batch loading, i.e., placing the baskets with parts into treatment facility • Stabilize temperature • Heating and soaking (holding), with temperature and duration, respectively, as control parameters • Air cooling, in the forced air equipment • Hardness measurement • Part release and deposition.

430. Case 4.3

431. *Product:* Special cover RV.10.105, material X6Cr13 (1.4000) ISO 15510:2014.

432. *Operation:* 30. Normalising and tempering heat treatment, *Hardness:* 270 - 320 HV.

433. *Temperatures Ac_3 and T_A*

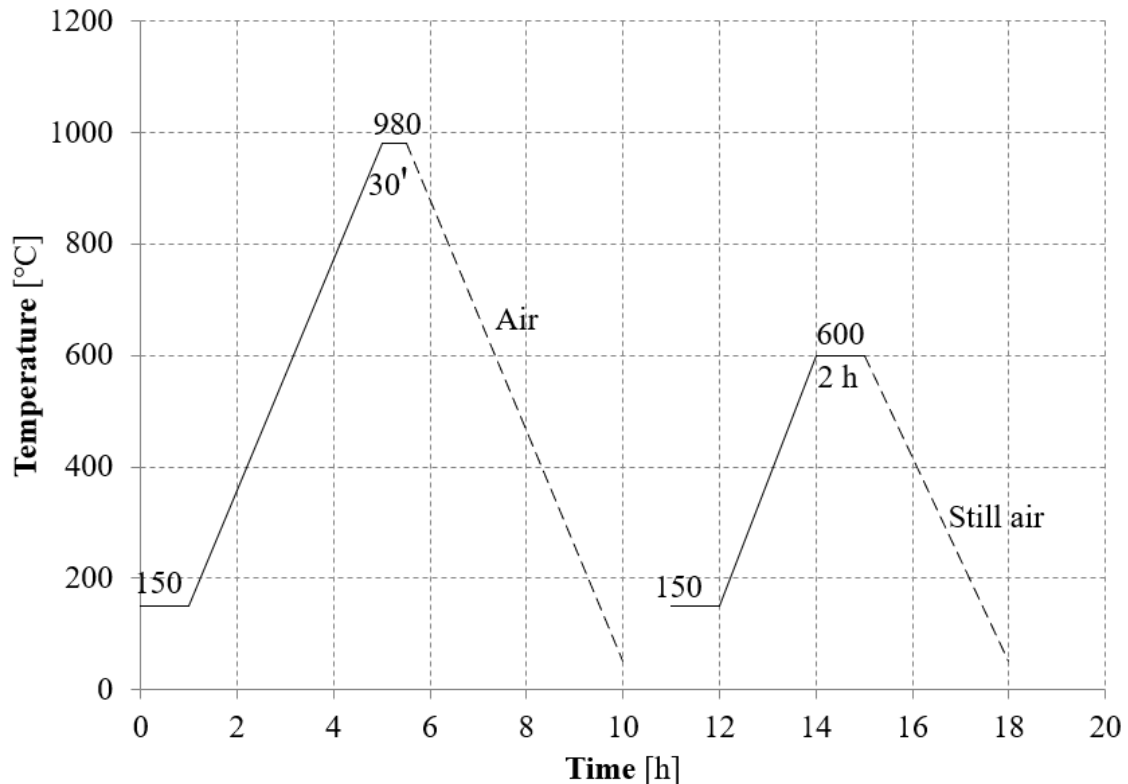
434. Ac_3 and T_A are determined (see § 2) based on CCT diagram [15], and on eq. (6), respectively.

435. Thus, for the considered material (X6Cr13): $Ac_3 = 840\text{ °C}$; $T_A = 840 + 2.75 \cdot 50$, $T_A \approx 980\text{ °C}$.

436. *Time - Temperature Diagram:* as presented in Fig. 6.

437.

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438.

439. Fig. 6. Normalising and tempering diagram for the X6Cr13 stainless steel grade (adapted from [19])

440. *Technological system:* • Heat treatment installation – gas fired furnace; air-cooling facility
• Fixture – basket-type, size for 20 parts, manual/ automatic handling • Health and Safety - protective equipment against temperature • Verifiers: Integrated control/ surveillance equipment of heat treatment parameters; portable Vickers hardness tester (UCI method).

441. *Technological stages:* • Batch preparation, i.e., visual examination of the parts and placement in baskets • Batch loading, i.e., placing the baskets with parts into treatment facility • Stabilize temperature • Heating and soaking (holding), with temperature and duration, respectively, as control parameters • Air cooling, in the air-cooling equipment. • Stabilize temperature • Heating and soaking (holding), with temperature and duration, respectively, as control parameters • Hardness measurement • Part release and deposition.

5. Case studies on technological control operations for advanced systems

442. Case 5.1

443. *Product:* Block DP.00.105, material GE200 (1.0420).

Operation: 45. Complex control.

444. *Technological System:* • Nikon Altera 10.10.8 Coordinate Measuring Machine equipped with PH10M indexing probe head • Probe: sapphire ball stylus, Ø5 mm, effective length 21 mm • Fixture: precision vise for

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- part positioning and clamping • Calibration standard: calibrated sphere Ø10 mm
- Software: integrated CMM software and digital inspection report.

445. *Technological phases:* as presented in Table 4.

446. Table 4. Technological phases

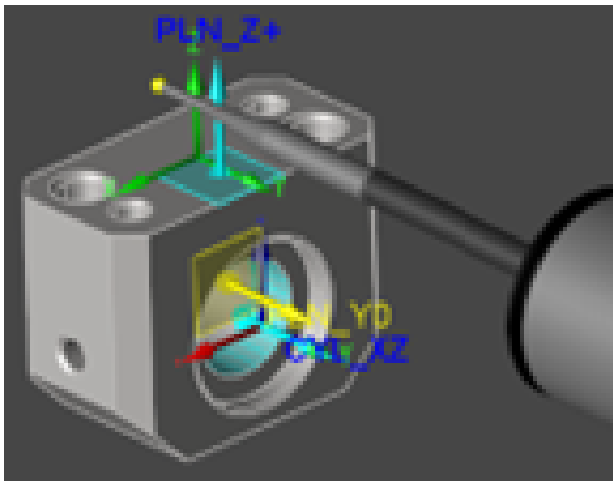
447. Technological phases	
448. • 449. Part holding	450. • 451. Measuring cylinder CYL_14
452. • 453. Probe calibration	454. • 455. Measuring plane PLN_D
456. • 457. Measuring reference plane D	458. • 459. Measuring plane PLN_E
460. • 461. Measuring reference plane E	462. • 463. Report generation and validation
464. • 465. Measuring reference cylinder	466. • 467. Part release and deposition

468.

469.

470. *Positioning schemes of XYZ axes system:*
as presented in Fig. 7.

471.



472.

473. Fig. 7. The positioning scheme of XYZ axes system

474.

475. *Sequences of the CMM program*

476.

477. ; REPER: BLOCK DP.00.105
; OPERATION: 45 CONTROL
; CMM: NIKON ALTERA 10.10.8

...

RECALL/SA(A0.0_B0.0_M3_2x2
1)
SNSLCT/SA(A0.0_B0.0_M3_2x21
)

...

478. ; Measurement of controlled
cylinder CYL_14
F(CYL_14)=FEAT/CYLNDR,INN
ER,
CART,0,-3,0,0,1,0,14,-6
MEAS/CYLNDR,F(CYL_14),6
ENDMES

479. ...

480. *Simulation*

481.



BLOCK.mp4

482.

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483. Case 5.2

484. *Product*: Connecting rod MP.00.019, material X6Cr17 (1.4026)

485. *Operation*: 55. Control

486. *Technological System*: • Nikon Altera 10.10.8 Coordinate Measuring Machine equipped with PH10M indexing probe head • Probe: sapphire ball stylus, Ø5 mm, effective length 21 mm • Fixture: 3-jaw universal chuck for part positioning and clamping • Calibration standard: calibrated sphere Ø10 mm • Software: integrated CMM software and digital inspection report.

487. *Technological phases*: as presented in Table 5.

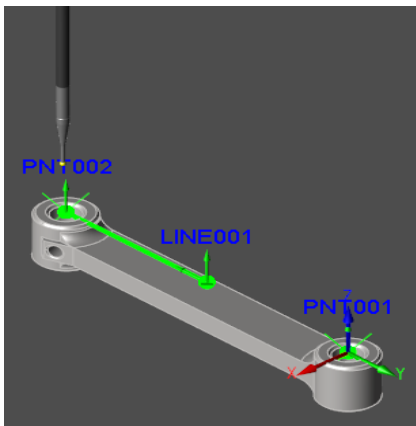
488. Table 5. Technological phases

489. Technological phases	
490. • 491. Part holding	492. • 493. Measuring bore CYL_10_1
494. • 495. Probe calibration	496. • 497. Measuring bore CYL_10_2
498. • 499. Measuring reference plane BASE_A	500. • 501. Measuring distance CYL_10_2 – CYL_10_1
502. • 503. Alignment of Z axis	504. • 505. Report generation and validation
506. • 507. Alignment of Y axis	508. • 509. Part release and deposition

510.

511. *Positioning schemes of XYZ axes system*:
as presented in Fig. 8.

512.



513.

514. Fig. 8. The positioning scheme of XYZ axes system

515.

516. *Sequences of the CMM program*

517.

```
518. ; REPER: CONNECTING ROD
MP.00.019
; OPERATION: 55 CONTROL
; CMM: NIKON ALTERA 10.10.8
...
RECALL/SA(A0.0_B0.0_M3_2x21)
SNSLCT/SA(A0.0_B0.0_M3_2x21)
; Measurement of base plane
F(PLN001)=FEAT/PLANE,CART,-
0.5821,-6.9856,0,0,0,1
MEAS/PLANE,F(PLN001),3
ENDMES
```

519. ...

520. *Simulation*



CONNECTING
ROD.mp4

521.

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522.

523. 6. Conformity assessment of specific experimentally manufactured products

524. The cases which were experimentally developed are as presented in Table 6, where:

- 525. • the prescribed characteristics (2) are from technical drawings of considered products;
- 526. • with respect to the range defined by the prescribed lower deviation, EI, and the upper deviation, ES, if the experimental (actual) deviations from nominal, δ_e , satisfy the condition:

$$527. \delta_e \in [EI, ES] \quad (7)$$

528. then the verified characteristic is compliant ($\checkmark$).

529. Table 6. Prescribed and experimental (actual) characteristics

530. (1): Product; (2): Prescribed characteristics, in mm; (3): General technological conditions; (4): Surfaces generated by: 3D printing, S-P, electroerosion, S-E, milling S-M, as applicable [...]; (5): Characteristic control, CC [...]; (6): Experimental (actual) deviations from nominal, in mm; (7): Conformity

531. (1)	532. (2)	533. (3)	534. (4)	535. (5)	536. (6)	537. (7)
538. Nut	540. 4 (± 0.1)	541. Similar to cases 3.3 and 5.1	542. S-E [4]	543. CC [4]	544. 0.007	545. $\checkmark$
CR.10.008, material	546. 6 (± 0.1)				547. 0.009	548. $\checkmark$
X37CrMoV 5-1	549. T ($\parallel$ - C): 0.016				550. 0.009	551. $\checkmark$
539. (44 - 46 HRC)						
	553. $\emptyset 14H7(^{+0.018}_0)$				557. - 0.044	558.
	559. T ($\parallel$ - D): 0.05				560. 0.016	561. $\checkmark$
	562. T ($\perp$ - E): 0.08				563. 0.199	564.
	565. 40 (± 0.3)	554. Similar to cases 3.1 and 5.1	555. S-P	556. CC [4]	566. - 0.029	567. $\checkmark$
552. Block	568. 30 (± 0.2)				569. 0.037	570. $\checkmark$
DP.00.105, material	571. 30 (± 0.2)				572. - 0.038	573. $\checkmark$
PLA	574. $\emptyset 14.4H7(^{+0.018}_0)$				577. 0.006	578. $\checkmark$
	579. T ($\parallel$ - D): 0.05		575. S-M [4]	576. CC [4]	580. 0.012	581. $\checkmark$
	582. T ($\perp$ - E): 0.08				583. 0.011	584. $\checkmark$
	585. 29.9 (± 0.2)				586. 0.004	587. $\checkmark$
	588. 19.8 (± 0.2)				589. 0.020	590. $\checkmark$
	592. $\emptyset 56H7(^{+0.030}_0)$				596. 0.018	597. $\checkmark$

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591. Support MP.00.016, material PLA	598. T (// - A): 0.03	593. Simil ar to cases 3.2 and 5.1	594. S- P	595. C C [4]	599. 0.250	600.
	601. T ($\perp$ - C): 0.05				602. 0.310	603.
	604. T ($\square$ - A): 0.03				605. 0.070	606.
	607. 40 ($\pm$ 0.3)				608. - 0.023	609. $\checkmark$
	610. 250 ($\pm$ 0.03)	614. Simil ar to cases 3.2 and 5.1	615. S- M [4]	616. C C [4]	611. - 0.267	612. $\checkmark$
	613. $\emptyset 56.8H7(+0.030)$				617. 0.007	618. $\checkmark$
	619. T (// - A): 0.03				620. 0.021	621. $\checkmark$
	622. T ($\perp$ - C): 0.05				623. 0.018	624. $\checkmark$
	625. T ($\square$ - A): 0.03				626. 0.016	627. $\checkmark$
	628. 39.7 ($\pm$ 0.3)				629. - 0.040	630. $\checkmark$
	631. 249.8 ($\pm$ 0.03)				632. - 0.012	633. $\checkmark$
	635. $\emptyset 14H7(+0.018)$				639. - 0.036	640. 1
634. Block DP.00.105, material PLA	641.	636. Simil ar to case 5.1	637. S- P [14]	638. C C [14]	642.	643.
	644. T ($\perp$ - E): 0.08				645. 0.027 5	646. $\checkmark$
	647. T (// - D): 0.05				648. 0.008 3	649. $\checkmark$
	650. T ($\perp$ - D): 0.05				651. 0.067 9	652.
	654. $\emptyset 10H7(+0.018)$	655. Simil ar to case 5.2	656. S- P	657. C C [14]	658. - 0.170	659. 6
653. Connecting rod MP.00.019, material PLA	660. T ($\perp$ - A): 0.02				661. 0.019 4	662. $\checkmark$
	663. $\emptyset 10H7(+0.018)$				664. - 0.204	665.
	666. T ($\perp$ - A): 0.02				667. 0.076 4	668.
	669. 120 $\pm$ 0.05				670. 0.020 6	671. $\checkmark$

7. Conclusions

672. The machining, heat treatment and control operations developed are representative within a group of technologies for the manufacture of a series of new products.

673. The technological operations which have been structured reveal some similar, but also different characteristics.

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674. Future intensive research and development activities can contribute to the creation of specific databases on technological operations for advanced systems.

8. References

675. [1] Shokrani A., et al., Sustainable machining: Recent technological advances, *CIRP Annals - Manufacturing Technology*, 73 (2024) 483-508, DOI: 10.1016/j.cirp.2024.06.001
676. [2] Gheorghe M., Engineering and management of production processes 1 (in Romanian), Course notes, UNSTB, 2024 – 2025.
677. [3] Willson D., 5-Axis CNC Machining: Precision Capabilities for Complex Parts, <https://www.fictiv.com/articles/articles-5-axis-cnc-machining> (accessed March 2026).
678. [4] ***, Technological systems, SC Dr. Kocher, 2025.
679. [5] ***, SolidCAM 2025, <https://solidcam.com/highlights/why-solidcam/>
680. [6] Gannam N., Industrial CNC manufacturing, Technology strategy, Course notes, UNSTPB, 2024 -2025.
681. [7] Iliescu D., Design and testing of advanced materials, Technology strategy, Course notes, UNSTPB, 2024 – 2025.
682. [8] ***, (2013), Handbook of stainless steels, Outokumpu Stainless AB, Outokumpu Oy, Finland.
683. [9] ***, (2002), EN 10295, Heat resistant steel castings, CEN, Belgium.
684. [10] ***, (2018), EN ISO 683-1, Heat treatable steels, alloy steels and free cutting steels,
Part 1 - Non-alloy steels for quenching and tempering, ISO, Switzerland.
685. [11] ***, (2015), EN 10293, Steel castings for general engineering uses, CEN, Belgium.
686. [12] Dumitrache I.-A., Manolache D.S., Nanu S., (2025), Study on geometric advanced control of actual machined product features, *U.P.B. Scientific Bulletin, Series D, Vol. 87, Iss. 2*, pp. 185–194, ISSN 1454-2358.
687. [13] ***, Nikon Metrology, (2025), Altera CMM Series – Bridge Coordinate Measuring Machines, <https://topmetrology.ro/en/product/masina-de-masurat-in-coordonate-3d-lk-metrology-altera-cmm/> (accessed May 2026).
688. [14] ***, Three-Dimensional Metrology Laboratory, COMOTI – Romanian Research & Development Institute for Gas Turbines, 2026.
689. [15] Trzaska J., (2016), Calculation of critical temperatures by empirical formulae, *Arch. Metall. Mater.*, Vol. 61, No 2B, pp. 981–986, DOI: 10.1515/amm-2016-0167.
690. [16] ***, Firgelli Automations, <https://www.firgelliauto.com/blogs/calculators/heat-treatment-austenitizing-calculator?srsId=AfmBOoryf4a9fH9pXPs-QucFnleo3q4LuikWulhZBBv4A0SQHmrnptyK#equations> (accessed March 2026).
691. [17] ***, <https://steelselector.sij.si/steels/PK1.html> (accessed March 2026).

**RESEARCH AND DEVELOPMENT ON THE CHARACTERISTICS
OF TECHNOLOGICAL OPERATIONS FOR
ADVANCED INDUSTRIAL SYSTEMS**

692. [18] ***, <https://steelselector.sij.si/mobile/steels/PK4EX.html> (accessed March 2026).
693. [19] ***, (1997), Industrial projects, IMGB, Bucharest.

DEVELOPING A MODEL FOR THE EVALUATION OF LEARNING OUTCOMES IN ROMANIAN ENGINEERING PROGRAMMES

GHENOIU Alexandra-Elena and DOICIN Cristian

Faculty: Facultatea de Inginerie Industrială și Robotică, Specialization:IEI, Year of studies:IV,
e-mail:alexandra.e.ghenoiu@gmail.com

This paper presents a model for evaluating and improving learning outcomes for three Romanian engineering study programmes: Industrial Economic Engineering, Machine Manufacturing Technology and Applied Informatics in Industrial Engineering. The model starts from the competences found in academic documents, compares their frequency, reformulates them in a clearer way and links them with the disciplines that can develop them. The paper also discusses how artificial intelligence can be introduced without changing the identity of each programme. The aim is not to make the programmes identical, but to make their competences easier to understand, compare and evaluate.

KEYWORDS:*learning outcomes, competences, engineering education, curriculum, artificial intelligence*

1. Introduction

Engineering degree programs can no longer be viewed as just a list of disciplines. In practice, a graduate is not evaluated only after coursework has gone through, but after he knows how to do when he arrives in a real professional context. This is where learning outcomes and skills come in.

The learning outcomes show what the student knows, understands and can do at the end of the training. [1] In the European Qualifications Framework, they are linked to three main areas: knowledge, skills, responsibility and autonomy. For a work of this type, this division is important because it helps formulate skills that do not remain only at the theoretical level. The work starts from a simple but difficult problem to solve in practice: many skills appear differently formulated from one program to another, even if they describe close activities. Some are too long, some are too general, and some are hard to measure. On this basis, we proposed an approach that includes gathering, comparing, selecting, reformulating and combining skills with the disciplines that support it.

The analysis covers three study plans: Industrial Economic Engineering and Machine Building Technology. We chose them because they are all related to industrial engineering, but they have different directions. IEI is closer to the technical-economic area, TCM is more applied to design and manufacturing, and IAII has a clearer orientation towards computer science and digital systems.

Another element pursued is the integration of artificial intelligence. We have not treated AI as a fashion to be introduced everywhere, but as a tool to be put where it makes sense. For IEI, AI can support analysis and decision. For TCM, it can help in design, simulation and quality control. For IAII, AI is much closer to the center of the program because it works directly with applications, data, and information systems.

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2. Current state

In recent years, university education has changed a lot. Now, there is more emphasis on results than on teaching. [4, 5] That is, it is no longer enough to say what subjects exist in a study program. We need to explain what skills these subjects provide to students.

In Europe, this change is supported by the European Qualifications Framework. It uses learning outcomes to make qualifications clearer and easier to compare between countries and institutions. At European level, key competences for lifelong learning are also identified. These include digital, scientific and engineering skills, but also entrepreneurship, communication skills and the ability to learn continuously. [9] These directions are already reflected in the engineering programs that we are analyzing.

A relatively recent shift is related to the use of artificial intelligence. The European regulation on artificial intelligence provides for artificial intelligence literacy requirements for those who use or manage AI systems. [7, 8] In the context of higher education, this means that artificial intelligence should not be seen only as a technical tool. It is a competence that includes understanding, critical verification, responsibility and traceability.

In this context, the paper proposes a working method that tries to link three things: the skills already existing in the program documents, the specifics of each program and the current requirements related to digitization and AI.

3. Method of work

The proposed model has six stages. It's not a complicated model, but it's useful because it puts order in a skill set that otherwise can be hard to compare.

Stage 1. Competency collection. The professional and cross-cutting skills identified in the documents of the programmes analysed were taken into account. [3]

Stage 2. Selection of relevant skills. The primary criterion was frequency. The skills that appear several times have been treated as more important for the graduate profile. For IEI and TCM, the higher-frequency marked competencies were considered part of the specific core. For IAII, where the programme appears in fewer sources, the principle has been applied proportionately.

Stage 3. Reformulating. Skills have been rewritten so that they are clearer, shorter and easier to assess. [6] Good competence must have a verb of action, a clear object and a professional context. For example „uses technical drawing software” can become „uses digital tools for drawing and technical design”. The second formulation is broader and closer to the current reality.

Stage 4. Separation of specific and general competences. Not all skills need to be raised to a specific core level. Some are important, but they occur in many areas and do not clearly differentiate one program from another. These may remain complementary skills.

Stage 5. Correlation with disciplines. A competence is not only valuable because it is written in a document. It must be supported by disciplines, projects, practical activities or internships.

Stage 6. Optimising. The last step is to identify overlaps, gaps and areas to be updated. This is where the AI component comes in, but only where it logically completes the program profile.

Results and discussion

4.1. Comparison of IEI, TCM and IAII

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The three programs have a common core, but do not have the same profile. They all use digital tools, work with data, demand analytical capacity and require professional communication. The difference arises in the direction in which these skills are used.

IEI combines the technical side with the economic side. The graduate must be able to analyze industrial processes, interpret technical and economic data, plan production activities and make reasoned decisions. This is where the link between efficiency, cost, quality and resources matters a lot.

TCM is closer to design, technical documentation, manufacturing and prototyping. The graduate must understand technical drawings, use CAD/CAE tools, participate in the design and improvement of products and work with concrete technical requirements.

IAII is geared towards applied informatics in the industry. The graduate must be able to work with software applications, databases, industrial information systems, modeling, simulation and digital solutions for process management.

Table 1. Overall profile of the programmes analysed

Program	Main direction	Dominant competence
IEI	Technical-economic	process analysis, planning, production management, optimization, technical-economic decision
TCM	Technological and applicative	technical drawing, design, CAD/CAE, technical documentation, prototyping, manufacturing
IAII	Digital-industrial	software applications, industrial information systems, data, modeling, intelligent systems

This comparison shows that the model should not bring the programmes together. On the contrary, the goal is to make them clearer by keeping the differences between them.

4.2. Reformulation of competences

Reformulation of skills was necessary because many initial formulations are either too operational or too general. If a competence is too narrow, it describes only one specific activity. If it is too general, it can no longer be clearly assessed.

In this paper, the rewording followed a few simple rules: the close skills were grouped, the strictly operational formulations were raised to a more general level, and the software-related skills were formulated through the professional work they support.

Table 2. Examples of reformulation of powers

Formulare inițială	Formulare propusă
Use technical drawing software	Uses digital tools for drawing and technical design
Analyze production processes to improve	Analyzes and improves production processes
Provides technical documentation	Develop and submit technical documentation
Find solutions to problems	Identify technical solutions for engineering problems
Team work	Collaborates effectively in technical and multidisciplinary teams
Uses intelligent computer applications for process management	Uses intelligent computer applications for industrial process management

With this rewording, skills become easier to use in an evaluation model. Their meaning does not change, but ambiguity is reduced.

4.3. Specific and complementary skills

An important point of the model is the delineation of specific skills from

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complementary ones. A low-frequency competence is not necessarily useless. Often, it can be important in a particular professional route, but it does not define the profile of the program itself.

For IEI, the specific core is related to the analysis and optimization of industrial processes, production planning, resource coordination, production management, and integration of the economic dimension into engineering work. Skills such as budget management, drafting technical reports or consulting for efficiency are useful, but they are more supportive.

For TCM, the specific kernel is formed around design, technical drawing, documentation, CAE systems, prototyping and manufacturing. Skills related to maintenance, troubleshooting or project management can be developed, but do not best describe the central identity of the program.

For IAII, the core is built around industrial information systems, software applications, digital technologies and smart systems. Here digital skills are no longer just support, but part of the main profile.

4.4. Correlation with disciplines

Skills cannot be properly assessed if they are separated from the disciplines that develop them. [2] The model therefore proposes that each competence be linked to one or more disciplines.

At IEI, skills are supported by disciplines such as mathematics, applied informatics, technical drawing, computer-aided graphics, assisted design, economics, production management, quality management, cost analysis and specialized practice.

At TCM, the relevant disciplines are technical drawing, CAD, CAE, CAM, material strength, machine organs, manufacturing technologies, dimensional tolerance and control, quality management and technological practice.

At IAII, the thing is this: skills are based on simple things, such as computer programming, databases, data structures, industrial information systems, computer networks, automation, data analysis, modeling and simulation, integrated production systems and, of course, information security.

This stage is important because it shows us whether a competence is truly realistic. If it is not supported by any applicable discipline or activity, then only a paper formulation remains.

5. Integration of the AI component

Artificial intelligence must be introduced differently in the three programs. Not all have the same relationship with AI, and an identical approach would be forced. [10]

For IEI, AI can support technical-economic analysis, process optimization, documentation, and decision-making. However, the final decision must remain based on technical and economic reasoning, not only on an automatically generated result.

For TCM, AI can help in design, simulation, prototyping and quality control. At the same time, the results generated must be carefully checked, as a design error can produce real technical costs or problems.

For IAII, AI is part of the natural direction of the program. Here it is not only a support tool, but a component that can directly enter into the development of software applications, data analysis and integration of smart systems.

Table 3. Proposed AI skills for the three programmes

Program	Proposed AI skills
IEI	uses AI for technical and economic analysis, critically evaluates the results generated, uses data analysis to optimize processes, complies with ethical

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	and traceability requirements
TCM	uses AI for technical design, checks the generated solutions, applies AI in simulation and optimization of manufacturing, uses data for quality control
IAII	apply AI methods in industrial information systems, develop applications with intelligent functions, integrate AI solutions in technological and logistic processes, evaluate the boundaries of AI systems

This integration is also justified by European requirements on AI literacy, which emphasise users' ability to understand and use AI systems according to context, preparedness and responsibility.

6. The proposed model

The evaluation and optimization model can be synthesized as follows:

Skills collection → frequency selection → reformulation → specific delimitation/general → correlation with disciplines → optimization and AI integration

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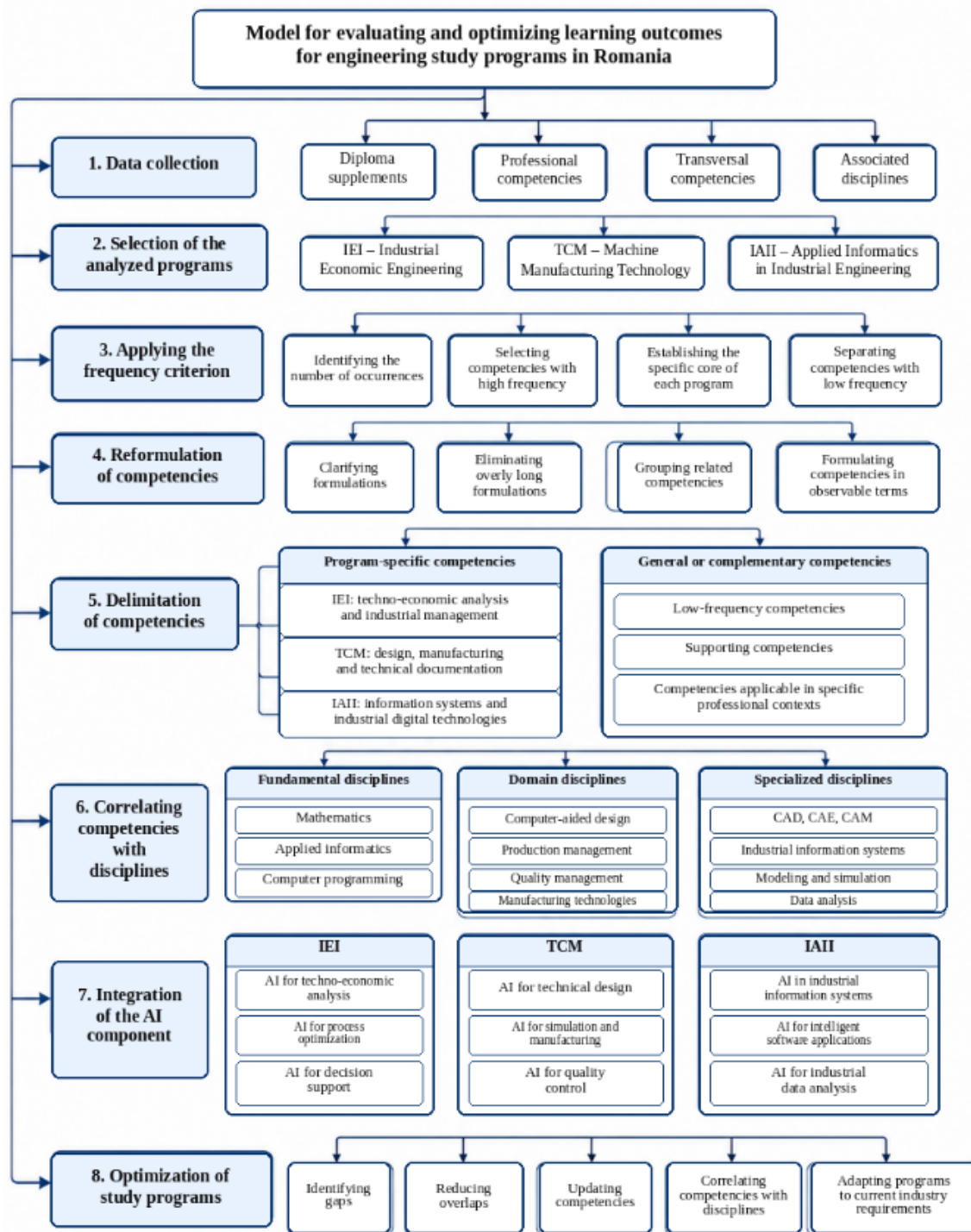


Fig. 1. The model for assessment and optimization of learning outcomes

The model starts with existing documents and comes to a clearer variant of skills. Instead of mechanically adding new skills, he first checks what exists, what is repeated, what is relevant, and what can be supported through the curriculum.

The main advantage is that the model can be applied to different programs without making them identical. IEI, TCM and IAI remain programs with their own identity, but can be analyzed according to the same logic..

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7. Conclusions

The paper proposed a model of evaluation and optimization of learning outcomes for three engineering studies programs in Romania: IEI, TCM and IAII. The model starts with existing skills, uses frequency as the first selection criterion, reformulates skills to make them clearer and correlates them with disciplines that can develop them.

The analysis shows that the three programmes have common competences but different profiles. IEI is built around the technical-economic decision and the management of industrial processes. TCM is oriented towards design, technical documentation and manufacturing. IAII is geared towards applied informatics, data, software applications and intelligent systems.

An important result is the separation of specific and complementary skills. Part-time skills should not be removed, but should not be treated automatically as central elements of the programme. They can support the graduate profile without directly defining it.

The AI component should be introduced carefully. For IEI and TCM, AI is mainly supportive. For IAII, AI can become a central part of your professional profile. In all cases, the use of AI must be linked to critical verification, accountability, ethics and traceability.

In conclusion, the proposed model can help clarify skills and update engineering degree programs. He does not solve all curricular problems alone, but offers a simple and applicable method to see what skills are important, where there are overlaps and what areas need to be developed.\.

8. Bibliografie

[1] Autoritatea Națională pentru Calificări, **Ghid metodologic privind scrierea rezultatelor învățării**, proiect POCA „Creșterea capacității administrative a ANC și MMJS prin sistematizare și simplificare legislativă în domeniul calificărilor”, disponibil la: <https://www.anc.edu.ro/upload/anc/rnc/Ghid-privind-scrierea-rezultatelor-%C3%AEnv%C4%83%C8%9B%C4%83rii.pdf> Accesat: 15.05.2026.

[2] ARACIS, **Anexa 2. Rezultatele învățării. Domeniul fundamental 2: Științe ingineresti**, 2025, disponibil la: https://www.aracis.ro/wp-content/uploads/2025/03/Anexa-2_Domeniul-fundamental-2_Stiinte-ingineresti.pdf Accesat: 15.05.2026.

[3] Autoritatea Națională pentru Calificări, **Registrul Național al Calificărilor din Învățământul Superior**, RNCIS, disponibil la: <https://www.anc.edu.ro/rnc/rncis> Accesat: 15.05.2026.

[4] Parlamentul României, **Legea învățământului superior nr. 199/2023**, Monitorul Oficial al României, nr. 614/05.07.2023, disponibil la: https://edu.ro/sites/default/files/fi%C8%99iere/Minister/2023/Legi_educatie_Romania_educata/legi_monitor/Legea_invatamantului_superior_nr_199.pdf Accesat: 15.05.2026.

[5] Cedefop, **Defining, writing and applying learning outcomes. A European handbook**, Publications Office of the European Union, 2017, disponibil la: <https://www.cedefop.europa.eu/en/publications/4156> Accesat: 15.05.2026.

[6] Cedefop, **Defining, writing and applying learning outcomes. A European handbook, second edition**, Publications Office of the European Union, 2022, disponibil la: <https://www.cedefop.europa.eu/en/publications/4209> Accesat: 15.05.2026.

DEVELOPING A MODEL FOR THE EVALUATION OF LEARNING OUTCOMES IN ROMANIAN ENGINEERING PROGRAMMES

[7] European Commission, **AI Literacy: Questions & Answers**, disponibil la: <https://digital-strategy.ec.europa.eu/en/faqs/ai-literacy-questions-answers> Accesat: 15.05.2026.

[8] European Parliament and Council of the European Union, **Regulation (EU) 2024/1689 laying down harmonised rules on artificial intelligence, Artificial Intelligence Act**, Official Journal of the European Union, 2024, disponibil la: <https://eur-lex.europa.eu/eli/reg/2024/1689/oj> Accesat: 15.05.2026.

[9] Vuorikari, R., Kluzer, S., Punie, Y., **DigComp 2.2: The Digital Competence Framework for Citizens**, Publications Office of the European Union, 2022, disponibil la: <https://publications.jrc.ec.europa.eu/repository/handle/JRC128415> Accesat: 15.05.2026.

[10] UNESCO, **AI Competency Framework for Students**, 2024, disponibil la: <https://www.unesco.org/en/articles/ai-competency-framework-students> Accesat: 15.05.2026.

9. Notations

AI = inteligență artificială

CAD = proiectare asistată de calculator

CAE = analiză inginerescă asistată de calculator

CAM = fabricație asistată de calculator

IEI = Inginerie Economică Industrială

TCM = Tehnologia Construcțiilor de Mașini

IAII = Informatică Aplicată în Inginerie Industrială

RESEARCH ON THE STUDY AND MODELING OF SMART DEVICES FOR POSTURE CORRECTION AND OFFICE ASSISTANCE

DUMITRU Mirela, MINA Mihai, NEDELEA Irina, STROE Laura and
DUGĂEȘESCU Ileana

Faculty: Industrial Engineering and Robotics, Specialization: IEMA, Year of study: 1
e-mail:mirela.seceleanu@gmail.com

SUMMARY: This study evaluates the feasibility of developing and implementing two innovative products for the modern workspace: a smart posture Corrector and an intelligent desk assistant. Quantitative research validates a distinct need for ergonomic correction and workflow optimization. The posture corrector provides real-time monitoring to foster healthier habits, while the Smart desk assistant manages environmental factors and productivity through integrated digital functions. Despite high market interest, the low adoption rate of existing solutions suggests significant growth potential. Both concepts address occupational health challenges by enhancing user interaction with their professional environment.

KEY WORDS: research, concept, posture corrector, smart desk assistant.

1. Introduction

In the actual context of accelerated digitalization and the transition toward office-based and remote work, people are spending increasing amounts of time in front of computers. This sedentary lifestyle has led to frequent health issues such as incorrect posture, back and neck pain, fatigue, and decreased productivity.

The ergonomics of the workplace is an important factor in preventing these issues, while traditional solutions currently available on the market are often limited. In this context, smart technologies and the Internet of Things (IoT) provide opportunities for the development of systems capable of monitoring user behavior and delivering personalized recommendations in real time.

2. Current state

Sedentary lifestyles have led to an increase in spinal health problems, and posture correctors have become commonly used tools. Medical issues caused by poor posture often result in healthcare professionals recommending the use of such products. Specialists can determine whether a person requires temporary external support or whether the condition can be corrected solely through specific exercise programs and lifestyle changes, such as maintaining an optimal body weight, wearing appropriate footwear, and adopting healthier daily habits. [1].

The use of a Smart Desk Assistant, an intelligent workplace assistant, aims to optimize productivity, manage repetitive tasks, and improve workspace organization through software solutions (applications, artificial intelligence, etc.) or physical robotic devices. [2].

3. Market research – identification of customers needs

This chapter presents the objectives for developing two concepts: a Smart Posture Corrector and a Smart Desk Assistant. Customer needs are identified and analyzed through the application of two questionnaires, one for each product.

The primary user profile is the **office worker**. This type of user spends many hours in static positions, frequently forgets to take breaks, and has the financial means to purchase such devices.

3.1. Smart Posture Corrector

Specific Research Objectives for the Smart Posture Corrector [3]:

- O1:** Identify the prevalence of postural problems and back pain among the target audience;
- O2:** Evaluate the extent to which existing solutions (traditional posture correctors) are used

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and identify their limitations;

O3: Determine the level of interest in smart features (such as vibration alerts and app-based monitoring) and assess users' willingness to pay for them;

O4: Define the demographic and occupational profile of the ideal consumer.

To identify the needs and preferences of potential users of the Smart Posture Corrector, a questionnaire consisting of 16 questions was developed: 2 introductory questions to identify the type of respondents, 2 demographic questions, 4 product validation questions, 3 questions for existing users, 3 questions for non-users, and 2 questions related to behavior and lifestyle.

A total of **76 respondents** participated in the survey, of whom 43.4% were between 18 and 25 years old, and 21.1% were between 35 and 45 years old (Fig. 1.a). Although the responses indicate a significant need for such a product, the adoption rate remains very low: 94.7% of respondents do not currently use such a device (Fig. 1.b).

Most of the 76 respondents experience postural discomfort: 55.3% suffer from frequent back pain, while 23.7% report occasional back pain (Fig. 1.c). In practice, nearly 80% of the sample experiences real discomfort, confirming the need for a posture correction product.

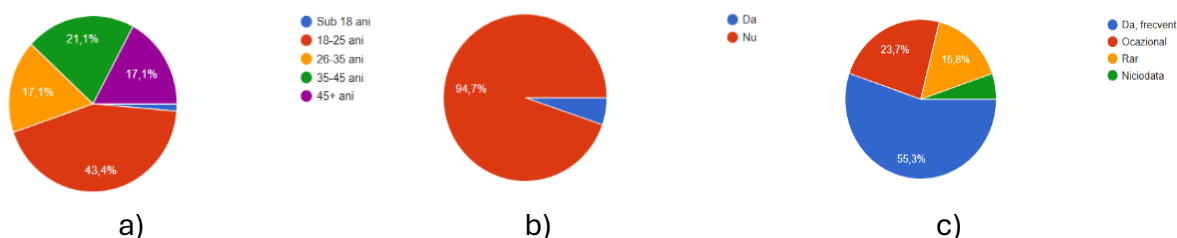


Fig. 1. Questionnaires Questions: a) Question 1, b) Question 2, c) Question 3

All respondents who use a posture corrector stated that the products they have used so far become uncomfortable after a certain period of time and gradually lose their effectiveness, highlighting the need for better materials and higher-performance sensors.

Comfort and effectiveness in maintaining proper posture are considered essential. Easy adjustment and ease of wearing are also important priorities, while price is less relevant for users who already use such a product.

The majority of respondents are office workers (71.1%), followed by pupils and students (15.8%) (Fig. 2.a). The primary context of use is screen-based activities: 55.6% would like to use the device while working on a computer, and 26.4% would use it at home while relaxing.

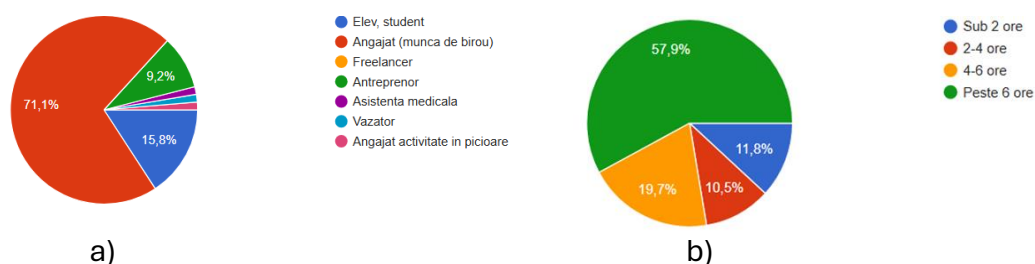


Fig. 2. Questionnaire questions: a) Question 4, b) Question 5

Based on the responses received (Fig. 2.b), it was observed that the surveyed group leads a predominantly sedentary lifestyle: 57.9% spend more than 6 hours sitting each day. Combined with the 19.7% who spend between 4 and 6 hours seated, it can be concluded that

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approximately 80% of respondents are frequently exposed to posture-related problems.

The analysis of the responses also reveals a strong openness toward technology: 40.3% of respondents clearly answered “Yes” regarding the use of this type of product, while 41.7% selected “Maybe.” Only 18.1% rejected the idea, suggesting that an effective and well-targeted marketing campaign could convince more than 80% of this sample to consider using the product.

The strongest purchasing drivers are medical recommendations (70.8%) and affordable pricing (61.1%). Reviews and design are also important (approximately 38%), but medical validation is the decisive factor for consumer trust (67%).

The market is oriented toward the following predefined budget segments included in the questionnaire: 44.7% of respondents would be willing to pay between 100 and 200 RON, while 42.1% would pay between 200 and 400 RON. Only a small proportion of respondents (7.9%) would be willing to exceed the 400 RON threshold.

3.2. Smart desk assistant

The specific research objectives regarding the Smart Desk Assistant are [4]:

- O1:** Identify current work habits and the level of use of smart devices in the workplace;
- O2:** Evaluate productivity and health-related issues, such as loss of concentration and feeling overwhelmed by work tasks;
- O3:** Validate the product concept by identifying the desired functionalities and the preferred mode of operation (automatic versus manual);
- O4:** Establish the demographic profile of potential users and determine the acceptable price range for purchasing the device.

To identify the needs and preferences of potential users of the Smart Desk Assistant, a questionnaire consisting of 19 questions was developed: 3 demographic questions, 4 concept validation questions, 2 questions addressed to individuals who already use such a product, 3 questions addressed to non-users of smart devices, 4 questions related to work routine and working style, and 2 introductory questions.

The majority of respondents (64.6%) work in an office environment on a daily basis. When combined with the segment of respondents who work in an office several days per week (15.4%), a total of 80% of the sample is characterized by a stable office-work routine (Fig. 3.a).

The largest age group is represented by respondents aged 18–25 years (41.5%), followed by those aged 26–35 years (21.5%) and 35–45 years (23.1%) (Fig. 3.b).

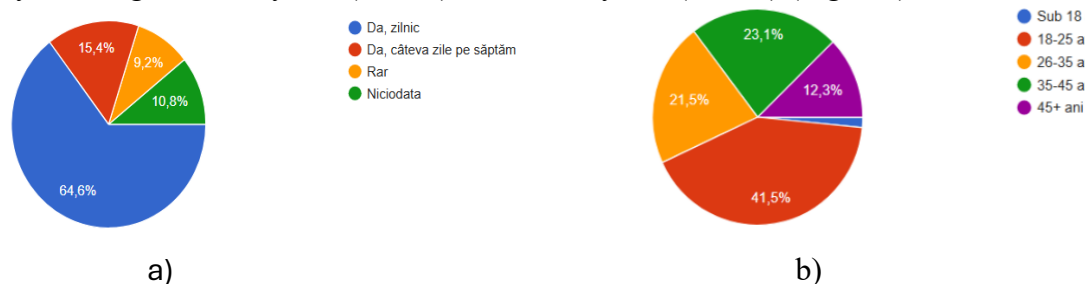


Fig. 3. Questionnaire questions: a) Question 1, b) Question 2

Interest in the analyzed product is high among individuals who do not currently use a Smart Desk Assistant: 38.8% clearly answered "Yes," while 49% were undecided and selected "Maybe." Only a small percentage of respondents (12.2%) rejected the idea of using such a device (Fig. 4.b).

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Respondents would like the product to include various features such as a digital organizer and reminders (34.7%), environmental monitoring (22.4%), and ambient light detection (16.3%) (Fig. 4.a).

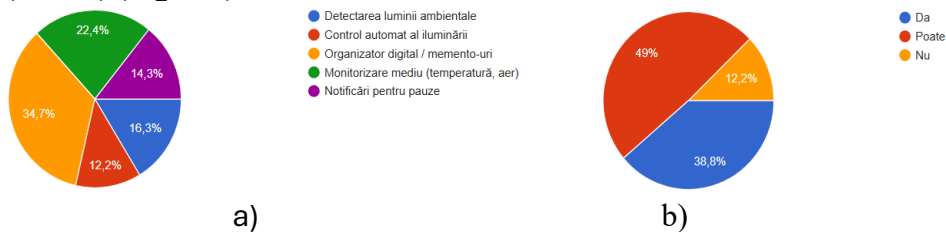


Fig. 4. Questionnaire questions: a) Question 3, b) Question 4

The number of current users is relatively low, with only 24.6% (16 respondents) already using such technologies. The majority (75.4%) do not own these types of devices, suggesting either a lack of awareness or an opportunity to introduce such a product into an underserved market.

The main issue identified by current users is the limited functionalities of the existing products (56.3%), followed by poor integration with other devices (43.8%). These represent key areas where a new product could provide significant improvements.

Price remains the most important factor for 76.9% of the 65 respondents. Compatibility with other devices is the second most important factor (55.4%) (Fig. 5).

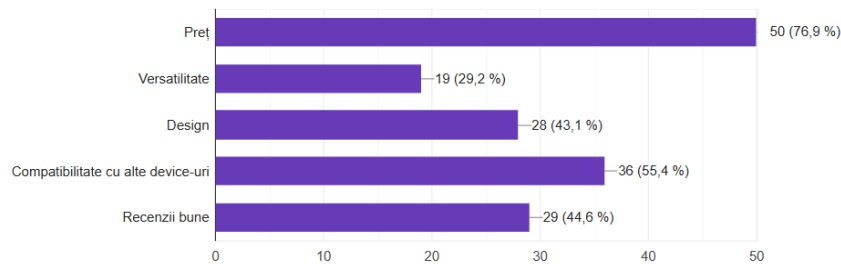


Fig. 5. Question 5

Four price ranges were considered in the survey. The most frequently selected ranges were 150–250 RON (38.5%) and 250–450 RON (38.5%). A price point of approximately 250 RON could be an attractive option for maximizing sales.

4. Concept Development

Three concepts were developed for each of the two products mentioned previously.

4.1. Smart posture corrector

Based on the analysis of the needs and objectives identified among the respondents, three concepts were developed for the intelligent posture correction device.

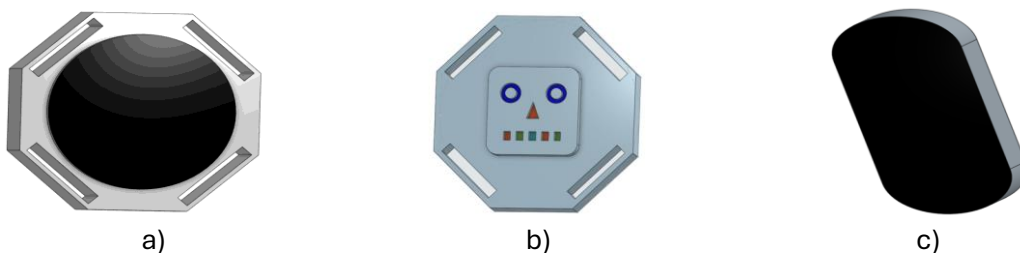


Fig. 6. Concepts for the Smart posture corrector

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The first concept (Fig. 6.a) is equipped with a digital display used to present information about the surrounding environment and user-related data. The model includes special openings for mounting the straps, which serve both to secure the device to the user's back and to support proper posture.

The second concept (Fig. 6.b) features a more complex design, with an octagonal shape and additional extruded elements that create a robot-like appearance. The increased manufacturing complexity resulted in a reduction of the space available for the digital display, thereby limiting some of the functionalities offered by the first concept.

The third concept (Fig. 6.c) retains most of the functions of the first model. Its main advantage is its compact size; however, this creates challenges in selecting electronic components and designing the attachment system for the user.

An ESP32 microcontroller can be used for the posture corrector due to its wireless communication capabilities via Bluetooth and Wi-Fi. These features enable data transmission and communication with other smart devices, facilitating the monitoring and analysis of information collected by the system [5].

To provide feedback to the user, the system integrates a vibration module, which is used to alert the user whenever an incorrect back position is detected. The vibrations serve as reminders to encourage posture correction [6].

The posture support and correction mechanism is implemented using an SG90 servo motor, selected because of its compact dimensions and sufficient torque to tension the straps used to pull the shoulders into a correct position.

To detect body position and identify improper posture, the MPU-6050 GY-521 gyroscope sensor can be used [7]. This sensor allows the measurement of the user's inclination and movements, with the collected data subsequently processed by the microcontroller to determine the correct back position.

The display of the information related to both the user and the surrounding environment can be achieved using a screen display [8], which can present data such as the number of incorrect posture events detected, posture status, and environmental information, including temperature and humidity.

4.2. Smart desk assistant

Within this subsection, several concept variants for the Smart Desk Assistant were developed and analyzed, each featuring different characteristics and functionalities aimed at intelligent interaction with the user.

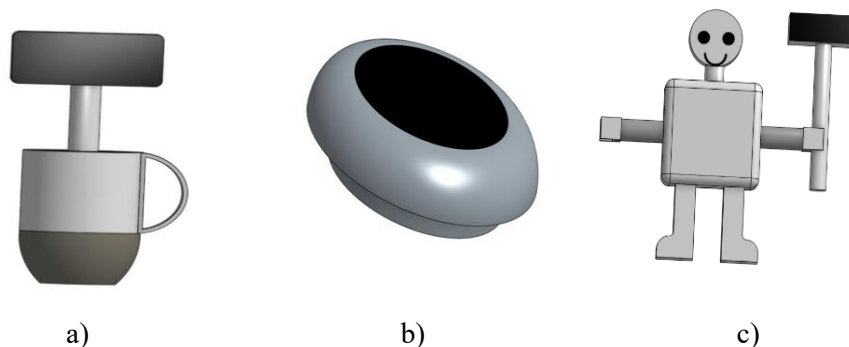


Fig. 7. Concepts for the Smart desk assistant

The first concept (Fig. 7.a) is a simple model whose design incorporates a display screen positioned on the upper part of the device. The dimensions will be selected to

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accommodate the electronic components while taking ergonomics and aesthetics into consideration, in line with the current trend toward the miniaturization of smart devices.

The second concept (Fig. 7.b) features a simpler and more compact design, with a touchscreen located on the top of the device for activating and controlling specific functions. The model also allows the integration of an RGB LED strip, which can be used to indicate the noise level in the work environment by changing the intensity or color of the emitted light.

The third concept (Fig. 7.c) represents a more complex and interactive version, capable of directly interacting with the user. The device can adapt its behavior and functions according to the user's preferences and activities, providing a personalized experience.

In this case as well, the selected microcontroller can be the ESP32 [5]. To enable the product's movements, servo motors may be used. These can be controlled directly by the microcontroller and allow precise movements, contributing to the interactive nature of the device.

The display of information and visual interaction with the user can be achieved through a display screen [8] on which different system statuses and relevant information can be presented.

The detection of the user's presence near the device can be achieved using a motion sensor [9]. This sensor can enable the automatic activation of the product when the user is within the operating area and switch the system to standby mode when the user's presence is no longer detected, thereby helping to optimize energy consumption.

5. Conclusions

All data used in this research were extracted from a series of responses collected through two questionnaires distributed online. The analysis conducted in this study highlights that both proposed product concepts have a high potential for implementation and market development, as they are supported by real needs identified among users.

Furthermore, based on the responses collected through the two questionnaires, three concepts were developed for each of the analyzed products: the Smart Posture Corrector and the Smart Desk Assistant. These concepts will be validated in the next stage of the research.

BIBLIOGRAPHY

- [1] <https://www.kinetic.ro/articole/totul-despre-postura-de-ce-este-importanta-postura-corecta/> .
- [2] <https://www.irjet.net/archives/V12/i5/IRJET-V12I595.pdf> .
- [3] <https://forms.gle/mDF1xkFKJM3Uv6bn7> .
- [4] <https://forms.gle/vQ1otMw8aDfCVZyX8>.
- [5] <https://www.emag.ro/placa-dezvoltare-esp32-s3-devkitc-1-elektroweb-16mb-flash-wifi-bluetooth-57x28x5mm-f-122/pd/DMXKML3BM/>.
- [6] <https://www.emag.ro/servomotor-sg90-180-de-grade-ai156-s297/pd/D33V1GMBM/>.
- [7] <https://www.emag.ro/modul-giroscop-mpu-6050-gy-521-accelerometru-arduino-3-axe-2-1-cm-x-1-1-cm-x-0-3-cm-albastru-c7/pd/DL3G1QYBM/>.
- [8] <https://www.emag.ro/display-tft-lcd-rotund-1-28-240x240-rgb-spi-driver-gc9a01-pentru-arduino-k0286-0415-015/pd/DBX6XSYBM/>.
- [9] <https://www.emag.ro/modul-de-masurare-a-distantei-hc-sr04-senzori-compatibil-masurare-46-mm-x-21-mm-x-15-mm-albastru-g6/pd/DY3G1QYBM/>.

DESIGN, DEVELOPMENT AND VALIDATION OF AN INTELLIGENT TRAIN DRIVER ASSISTANCE SYSTEM USING COMPUTER VISION AND POSITIONING DATA

TRANDAFIR Andrei-Alexandru și Conf. dr. ing. ABAZA Bogdan-Felician
Facultatea de Inginerie Industrială și Robotică, Specializarea: Informatică Industrială, Anul: IV, e-mail:
andrei.tren10@gmail.com

ABSTRACT: This paper presents the current development status for a train-driver assistance system that relies on pre-learned route data and computer vision techniques to retrieve track-status information using positioning data. The system is developed within the context of active railway modernization in Romania where many delays occur during implementation, adversely affecting the population. The system is based on current European regulations and addresses several key assistance needs for train drivers.

KEYWORDS: Software development, computer vision, YOLO, ERA Standards

1. Introduction

In the context of railway modernization in Romania, both infrastructure works [1] and railway rolling stock [2] are largely concentrated on specific railway corridors, such as Pan-European Corridor IV from Dresden towards Constanța. In this situation, an open market has emerged for small-scale improvement systems on routes that are not slated for modernization in the foreseeable future, e.g. the Cluj – Vatra Dornei – Suceava route, the Mărășești – Adjud – Comănești – Miercurea Ciuc route, the Ploiești Sud – Suceava route, and many others. To address this, a train-driver assistance system is proposed in order to help develop and improve railway safety on these routes, but also for the rolling stock that will operate here.

2. Objectives

To ensure that the proposed system can be integrated safely into railway operations, it must be developed and evaluated according to a rigorous development cycle. The project will strictly adhere to the following requirements:

- Standards: EN 50126, EN 50128, EN 50129
- Regulations: All directives issued by *European Union Agency for Railway* and *Compania Națională Căile Ferate Române SA* directives and instructions must be respected
- Operational rules: The rules of the national railway operator *CFR Călători* must be applied

The principal goal of the project is to deliver a proof-of-work artefact and to establish a framework that will guide future development and enhancement system. Because computer-vision techniques introduce inherent risks in safety-critical railway environments, the system cannot be proven safe within a short timeframe. Consequently, a comprehensive set of constraints must be identified and addressed during development. This paper addresses the next contributions:

C1 - Design a system architecture that resolves systematic issues: In a digital era where everything is on a screen, train drivers still use pen and paper in their everyday work. Additionally, all existing systems or systems under development are not designed to help the human factor.

C2 - Implement a practical solution for degraded usage scenarios: Ideally, computer vision and GPS positioning data shall be used at any time for real train-tracking and monitoring, but in the case that they do not work at specified limits, the human factor should not be impacted.

C3 - Develop railway-ready computer vision: Analyze the Romanian railway and implement a fast, accurate digital-twin like solution, integrating existing train protection systems in it.

C4 - Experimental validation of the proposed system: Realize dynamic tests in real-time scenarios with

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strongly defined testing methodologies, rapid development and error correction.

3. Current Status

While most of the railway industry is currently focused on large-scale digitalization initiatives [3], [4], their implementation in Romania remains costly and difficult to generalize across the entire railway network. Infrastructure rehabilitation costs can vary, from 3 to 40 million RON per kilometer [1], but also high costs for modernized railway stock, where adapting a locomotive can go higher than 1 million RON. Consequently, such solutions are usually concentrated on selected corridors or specific modernization projects, leaving many secondary or non-prioritized routes without short- or medium-term digital support.

Existing AI implementations in the railway field are mainly focused on object-detection tasks and do not provide an integrated assistance framework based on route knowledge, positioning data, degraded operating scenarios, and human-factor requirements. Digital-twin concepts exist in controlled environments such as simulators, but are not designed for real-time mainline assistance. These gaps directly motivate Contributions C1, C2, and C3.

The need for such a system is further supported by the current operational practices in Romania. Train drivers still rely on printed documents for speed-limit acknowledgement, safety-related information, train-control data, track information, and even route information. In several reported incidents, failure to correctly process or comply with such information contributed to unsafe situations, including cases involving speed-limit violations [5]. These incidents highlight a common issue: the human factor. Therefore, the proposed system does not aim to replace existing safety systems, but to support the train driver by reducing cognitive load, improving access to relevant route information, and validating the concept through real-time dynamic tests, as addressed in Contribution C4.

4. System Description

The system is defined in 4 different layers with 9 main subsystems composing it. The system flow diagram can be found below:

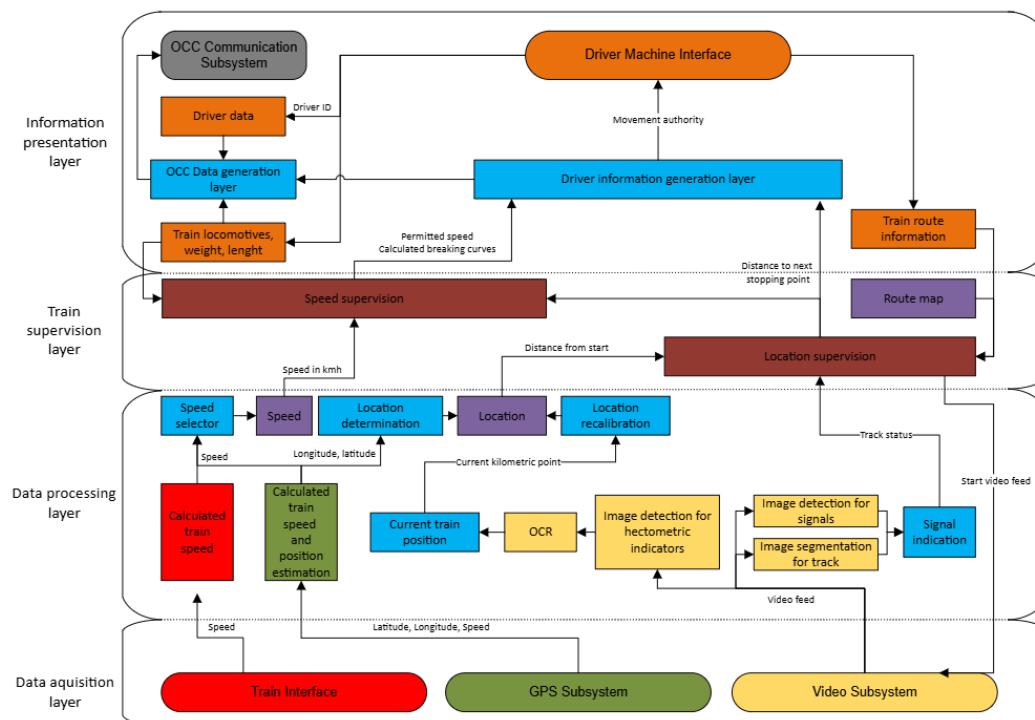


Fig. 1. System flow diagram

The description of each subsystem can be found in the table below:

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Table 1. Role of subsystems

Subsystem	Role
Central Logic Computer (CLC)	The main logic orchestrator between all subsystems integrates CFR SA operational rules, the main role is the creation of Movement Authorities and Train Supervision. Those features are implemented based on data from the Train Interface (red), GPS Subsystem (green) and Computer Vision Subsystem (yellow). The data is processed in diverse methods (light blue) and it is officialized in main input (purple) based on secondary-recalibration methods (speed and location generated from two different sources, track status generated at command). Those inputs are then used the main functions: speed supervision and location supervision (bright red), which, based on driver introduced data in the system (orange) movement authorities are generated and transmitted to the driver. Continuous speed and location supervision is realized even in the case of subsystem defects.
S-HMI Server DMI	The server that runs the logic for the Driver Machine Interface (DMI) The interface with the train driver where human inputs are inserted, and system outputs are displayed.
Train Interface	The safety-related subsystem which is designed to take information from the rolling stock (e.g. train speed). This subsystem is designed for future implementations as linking the system with the actual main train computer can represent a safety risk.
GPS Subsystem	This subsystem retrieves positional data for the train. It is also used as a placeholder for speed calculation for the Train Interface.
Vision Subsystem	This subsystem is the main orchestrator for computer-vision and is responsible for detecting objects when CLC orders it.
Video Subsystem	This subsystem retrieves video information from the cameras and sends it to the Vision Subsystem based on CLC commands.
OCC Communication Subsystem	This subsystem represents the link of the off-line system networking with an external, online system, with remote access from a possible Operations and Control Centre.
Simulators	Because of the complexity of the system and usage of GPS data, simulators need to be developed to test, verify and validate the system functionalities.

5. Hardware Design

From a system architecture point of view, the proposed solution is mainly software-oriented. The hardware components are considered only as functional interfaces required by the system: perception sensors, GPS equipment, onboard processing units, and networking interfaces. The perception sensors provide visual information from the railway environment, while the GPS Subsystem provides positioning data used by the supervision logic. These components are integrated at software level in a modular architecture.

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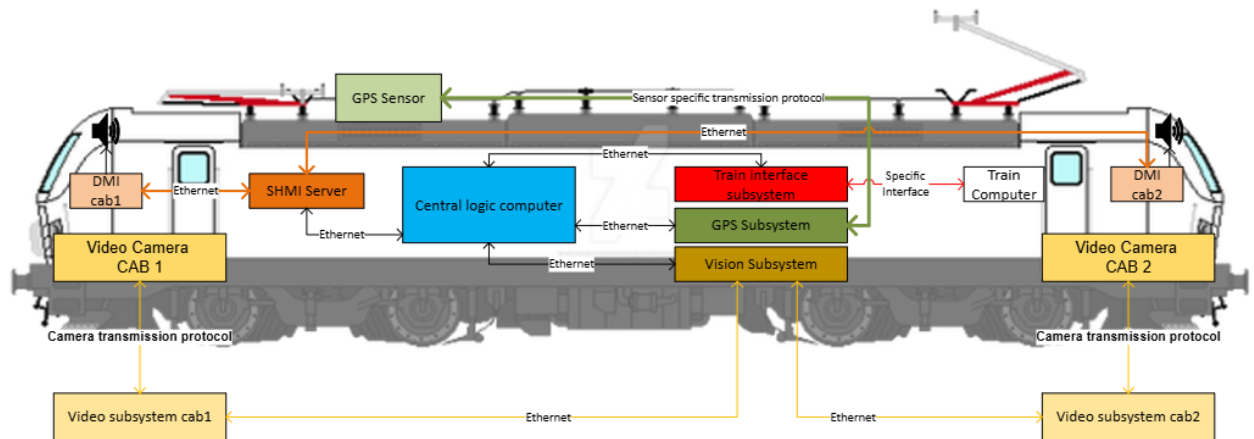


Fig. 2. Hardware placement of equipment

From a hardware design perspective, all onboard equipment must comply with railway standards for rolling-stock-mounted electronic equipment, such as EN 50155, EN 50121-3-2, and EN 61373. Since the system is still under development, specific certified hardware components cannot yet be defined. Moreover, as Siemens presents, each railway vehicle has its own structural and technical characteristics, meaning that a universal installation solution cannot be proposed [6]. However, a theoretical placement of equipments should happen in 19inch racks, including networking equipment. Some subsystems would need external placement (e.g. GPS antennas on roof, cameras in front of the train). The placement of the equipments can be seen in the figure 2.

The architecture supports both distributed and centralized processing. In a distributed configuration, the perception, GPS, supervision, and driver-interface modules may run on separate processing units connected through Ethernet. For testing purposes, the system can also run on a single machine.

6. Software Design

For each subsystem, custom software was developed and is presented in the table below:

Table 2 - Software description of subsystems

Subsystem	Description
Central Logic Computer (CLC)	CLC is a .NET 8 service (C#) featuring UDP custom packet communication, GPS-based train position and speed computation, legal data recorder for log generation, volatile/non-volatile memory state management, Movement Authority generation and train supervision systems.
S-HMI Server	S-HMI Server is a .NET 8 backend runtime handling UDP packet exchange with CLC, legal data recorder for log generation, volatile/non-volatile memory state management, diagnostics generation, API exposure for DMI, runs the logic for the human input from the DMI and sends it to CLC if applicable.
DMI	DMI is a React/Vite interface that displays real-time train-speed, displays movement authorities and speed supervision warnings. It has implemented an on-screen multi-tap keyboard for operational data entry fields.
Train Interface	Currently developed as software for testing purposes. In real production, this subsystem would be exchanged for PLC data exchange with proper language programming.
GPS Subsystem	GPS Subsystem is a Java mobile application that contains a network scanner for CLC network handshake, then continuously sends GPS position data towards CLC for runtime processing and supervision. It also has a legal data recorder integrated.
Vision Subsystem	A series of machine learning and deep learning algorithms trained on custom datasets with the role of identification of signals and kilometric markers for

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	Movement Authority generation. It is based on custom YOLO, OCR and Image segmentation models.
Video Subsystem	Currently implemented as a Java mobile application, it is remotely controlled by the Vision subsystem and sends video data over network. It integrates the same network handshake as GPS-CLC.
OCC Communication Subsystem	Not currently implemented. It will be a Java mobile application that integrates cybersecurity standards and send train data over internet.
Simulators	A series of Python scripts with multiple purposes. Currently, main simulators include but are not limited to GPS simulators, Train Interface simulators, Video data simulators

Development follows a V-Cycle approach across phased implementations. GitHub is used for version control of all subsystems; the source code is maintained in a private repository.

7. System Behavior

The systems follow the ERA UNISIG SUBSET Specifications [7], specifically ERA_ERTMS_015560 for the DMI visual specifications and SUBSET-026 for the system requirements specification. The system includes the next train modes:

1. Not-Supervised modes

In several operating modes, the system supervises only train speed while the movement authority is not monitored. These are: Standby (0 km/h, system start), Staff Responsible (20 km/h, entered after driver inputs train data such as ID, number, length and weight), Shunting (30 km/h), Non-Leading (max constructive speed, when the locomotive provides traction but is not leading), and National System (max constructive speed, when movement supervision is handled outside the assistance system).

2. Unfitted for driving mode

It is a degraded mode for supervised movement of the train. It uses a manual acknowledgment system, so the driver receives a movement authority from one station to another when operational conditions are met. It is implemented to show the train driver the maximum train speed for a section of track. The train enters in this mode when the GPS Subsystem and Vision Subsystem are not running (either not configured for the specific track segment or it is malfunctioning).

3. Limited supervision

It is also a degraded mode, but it's more advanced than Unfitted. In this case, the GPS Subsystem is up, but the Vision subsystem is not running (either not configured for the specific track segment or it is malfunctioning). In this mode, the GPS Subsystem supervises the movement and automatically sends new movement authorizations with a maximum length of 6600m to the DMI. The Movement Authority is also dynamically shown on the DMI.

4. Full Supervision

Full Supervision is the main operational mode, active when no degraded scenario is detected. It uses a preconfigured route map to determine train position via GPS and display upcoming railway elements on the DMI, similarly to ETCS. The Vision Subsystem determines track status and transmits it to the CLC. A degraded ON-SIGHT variant is also included for specific operational scenarios. This mode is still under development, with several proof-of-concept scripts already implemented.

Since the system is modular, the speed and location supervision routines from Limited Supervision are reused. Movement authorities are generated based on signal aspect rather than fixed distance, while the route map is built through a processing pipeline correlating images with GPS positions.

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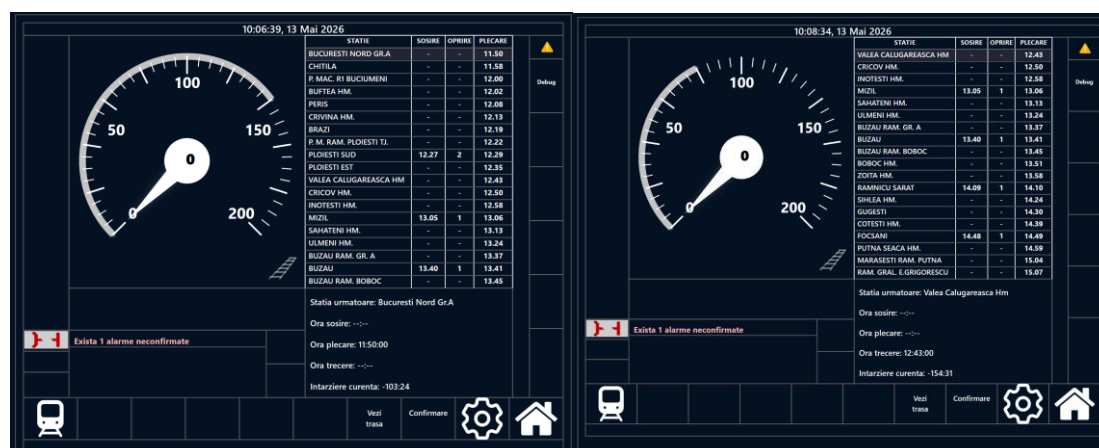


Fig. 3. UNFITTED train interface for train IR1661 Bucharest – Iasi in two different stations. Interface is designed according to ERA ERTMS015560 v400 standards [7]

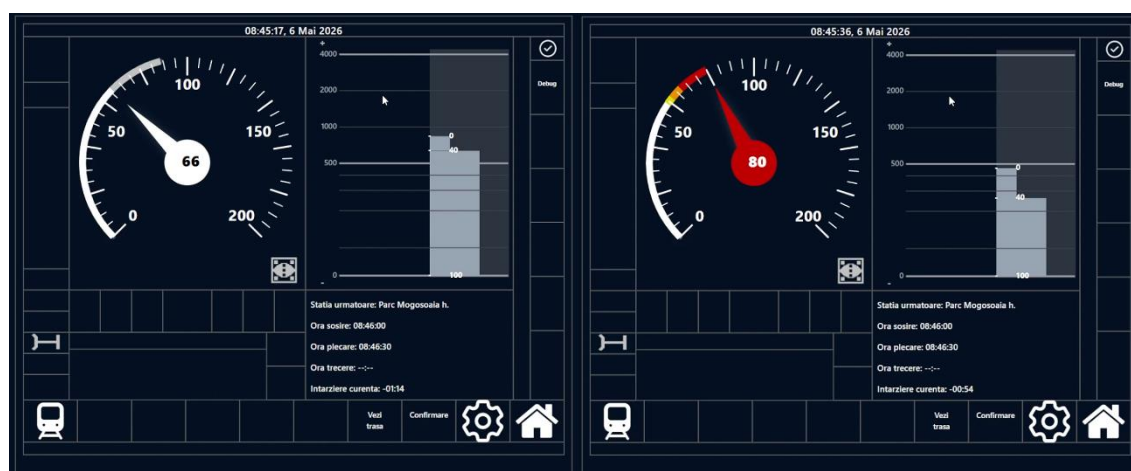


Fig. 4. LIMITED SUPERVISION train interface for train RM7915 Aeroport Henri Coandă – București nord from dynamic testing of the mode (up) and GPS Subsystem Interface – right

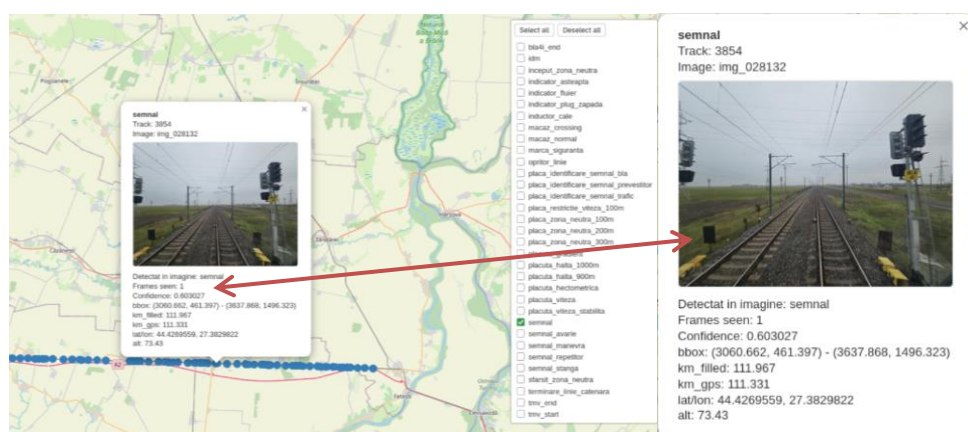


Fig. 5. Routemap of Bucharest – Fetesti route. A signal is selected on the routemap

8. System Test and Validation

Static testing has been performed for *UNFITTED* mode, while dynamic testing has been performed for *Limited Supervision* mode on the București Nord – Aeroport Henri Coandă route. Full Supervision mode has not yet been dynamically tested, but several computer-vision experiments and proof-of-concept scripts have been developed. On 4 April 2026 (trains RM7941 outbound / RM7944

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return) was the first real integration test of the GPS Subsystem with the running CLC. 32,375 GPS points were recorded over 1h 11min at 7.5 Hz, max speed 95.4 km/h. Two signal loss events (~4 min total) were identified on the return trip near Chitila. On 5 May 2026 (RM7941 / RM7944) and 6 May 2026 (RM7915 / RM7918) validated *Limited Supervision* mode. The 5 May session recorded 19,189 points over 42 min (one loss event, ~1m 43s). The 6 May final validation session recorded 33,333 points over 1h 13min, max speed 95.6 km/h, with no signal loss events outside the station area.

Across all three sessions, a recurring signal loss was identified near the tunnel (~50 m length), followed by road overpasses. This caused GPS interruption in both travel directions, confirming infrastructure as the cause rather than device or software issues.

A fourth session on 24 May 2026 tested GPS performance on the longer Focșani – București Nord Gr. A segment (train IR1654, Bacău – București Nord). The GPS Subsystem

recorded 90,993 points over 3h 7min at 8.1 Hz (123 ms interval), max speed 144.6 km/h. Ten signal loss events (cumulative ~17 min) were recorded: events 1–2 (Gugești–Sihlea) due to dense vegetation and deep track profile; events 3–7 (Râmnicu Sărat, Buzău area) in open-field conditions suggesting adverse satellite geometry; events 8–10 (Ploiești) consistent with urban multipath. In all cases, the system maintained last known position until reacquisition, demonstrating the C2 fallback behavior.

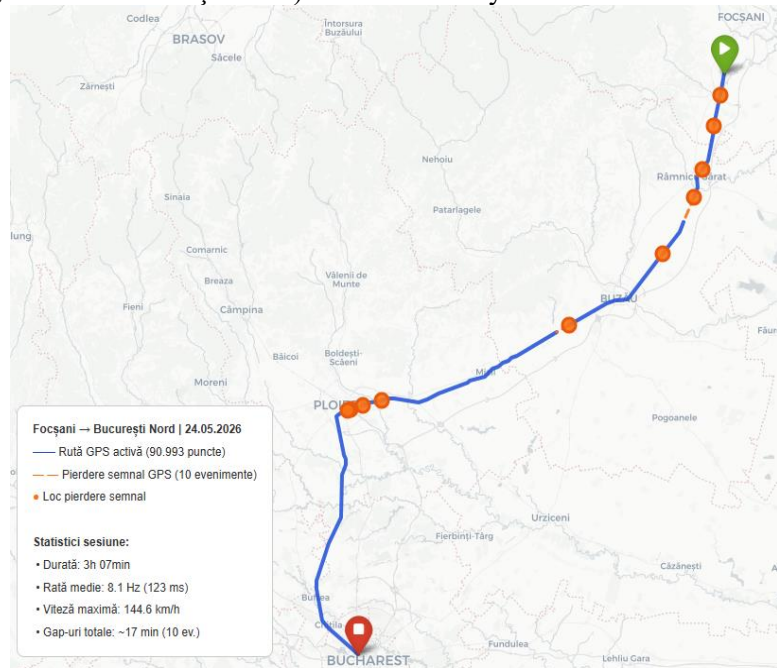


Fig. 6. GPS Route coverage for Focșani – Bucharest test

9. Results

The GPS Subsystem was expected to maintain a stable positioning update rate sufficient for real-time train supervision, with reliable data delivery to the CLC under dynamic operating conditions. Across all four dynamic sessions, the average update rate remained stable at 7.5–8.1 Hz (123–133 ms interval), consistently above the 5 Hz minimum considered sufficient for the speeds encountered on the tested routes.

Signal loss events were the main source of positioning interruption. Infrastructure-induced losses (tunnel, overpasses on the Bucharest–Airport route) were fully reproducible and predictable. Open-field losses on the Focșani–Bucharest segment suggest occasional adverse satellite geometry rather than systematic issues. In all cases, the system correctly maintained the last known position until signal reacquisition, confirming the robustness of the fallback logic. The 6 May 2026 session demonstrated the best overall GPS performance, with zero signal loss events outside the station area across a complete round trip, confirming that under favorable conditions the subsystem operates without interruption throughout the entire route.

10. Limitations and conclusions

At the current stage of development and testing, contributions C1, C2, and C3 have been demonstrated through the implemented system architecture, degraded operating modes, and preliminary computer-vision integration. The system has been validated in static and dynamic testing scenarios for UNFITTED and Limited Supervision modes. Contribution C4 is still under development, together with

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the Full Supervision mode and further YOLO model refinement.

Dynamic testing confirmed that GPS-based positioning is viable for a proof-of-concept assistance system, maintaining stable update rates of 7.5–8.1 Hz across all sessions. However, the recorded signal loss events highlight the limitations of GPS as a sole positioning source. Future development should integrate odometric data from the Train Interface as the primary speed and position source, with GPS used for periodic recalibration — mirroring the role of Eurobalises in ETCS Level 2 [7]. This evolution would significantly improve supervision reliability and bring the system closer to operational readiness on non-modernized Romanian railway lines.

12. Bibliography

- [1] Compania Națională de Căi Ferate "CFR" – SA, «PROIECTE ÎN EXECUȚIE, FAZA LUCRĂRI / PROIECT TEHNIC ȘI LUCRĂRI - MARTIE 2026,» [Online]. Available: <https://cfr.ro/wp-content/uploads/2026/04/Stadiu-proiecte-CFR-Martie-Aprilie-2026-1.pdf>. Accessed: 12 May 2026.
- [2] CFR Călători, «PNRR: Fonduri pentru România modernă și reformată!,» [Online]. Available: <https://www.cfrcalatori.ro/pnrr-fonduri-pentru-romania-moderna-si-reformata/>. Accessed: 12 May 2026.
- [3] ERTMS.NET, «ERTMS in brief,» [Online]. Available: <https://www.ertms.net/about-ertms/ertms-in-brief/>. Accessed: 12 May 2026.
- [4] Alstom, «DB and Alstom test remote driving for commuter trains in a depot environment,» [Online]. Available: <https://www.alstom.com/press-releases-news/2024/9/alstom-pioneers-automated-regional-trains>. Accessed: 12 May 2026.
- [5] AGENȚIA DE INVESTIGARE FERROVIARĂ ROMÂNĂ, «Investigații și rapoarte privind siguranța transportului feroviar,» [Online]. Available: <https://www.agifer.ro/index.php/ro/investigatii/rapoarte-investigare-finale>. Accessed: 14 May 2026.
- [6] Siemens, «ETCS Retrofit – The future of rail transport available for retrofitting,» [Online]. Available: <https://assets.new.siemens.com/siemens/assets/api/uuid:0777b0c4-4cbf-480d-b39e-ef8fce9fca65/trainguard-onboard-eng.pdf>. Accessed: 12 May 2026.
- [7] European Union Agency for Railways, «CCS TSI Appendix A – Mandatory specifications (ETCS B4 R1, RMR: GSM-R B1 MR1 + FRMCS B0, ATO B1 R1),» [Online]. Available: <https://www.era.europa.eu/era-folder/1-ccs-tsi-appendix-mandatory-specifications-etcs-b4-r1-rmr-gsm-r-b1-mr1-frmcs-b0-ato-b1>. Accessed: 12 May 2026.

Development and Experimental Evaluation of a Modular Mobile Manipulation Platform Using ROS 2, Gazebo and MoveIt 2

NICA Daniel-Rareş, ANDREI Patrick Cristian, ODOROAGĂ Vlad-Ionuţ, PUFU Andrei Florin and
Assoc. Prof. Dr. Eng. Bogdan Felician ABAZA, Prof. Dr. Eng. Cristian DOICIN
Faculty: Industrial Engineering and Robotics, Specialisation: Industrial Informatics, Year of Study: 3,
e-mail: pufuandreiflorin@gmail.com

This paper presents Xplorer Mini, a modular ROS 2-based platform addressing the critical gap between virtual simulation and physical robotic operation. Featuring a robust chassis and a 6-DOF manipulator, the system unifies autonomous navigation with an AI-driven gesture interface for touchless control. The methodology employs high-fidelity Gazebo simulations within modeled environments, followed by rigorous physical experimentation. Results demonstrate a 73.6% success rate in complex manipulation tasks while quantifying structural deflections caused by gravitational forces. This work contributes a versatile research architecture, validated simulation-to-reality workflows, and a comprehensive analysis of performance discrepancies, providing a solid foundation for future developments in autonomous mobile manipulation.

1. Introduction

In the modern industrial context, Intelligent Mobile Autonomous Systems (SAIM) represent critical technological solutions for streamlining logistics flows through automation and digitalisation. The SAIM project has evolved incrementally, from basic educational platforms towards complex systems, the current stage being embodied by the Xplorer Mini. It is designed as an integrated system that unifies a hybrid mobile base, an articulated robotic arm and a gesture-based control interface driven by artificial intelligence. This paper addresses the challenge of designing a modular platform capable of acting as a bridge between high-fidelity virtual simulation and physical deployment across varied terrain conditions. The central technical problem addressed by this study concerns the integration of these heterogeneous subsystems into a unified ROS 2-based architecture capable of ensuring precise manipulation. The relevance of the research lies in the capacity to identify and quantify the practical limitations of integrated robotic systems, from the mechanical constraints of the 3D-printed enclosure to the kinematic discrepancies induced by gravitational forces during real manipulation tasks. The main contributions of this paper are the development of a modular ROS 2-based mobile robotic platform, designed for research and education, that integrates a robust chassis with sensory units specific to autonomous navigation (LiDAR, IMU), the integration and simulation-based validation of a complete mobile manipulation system in a realistic outdoor environment, using Gazebo and MoveIt 2 for workspace and trajectory optimisation and the experimental evaluation of practical limitations and control interfaces, including a statistical analysis of operational success and the implementation of an AI gesture-recognition interface as a proof of concept for teleoperation in sterile or industrial environments.

2. Xplorer Mini Platform Architecture

The Xplorer Mini platform must comply with a system architecture proposed by the coordinating professors (Fig. 1); it must also have a maximum footprint of 500×500×400 mm and support a payload of up to 15 kg, thereby enabling industrial intralogistics simulations.

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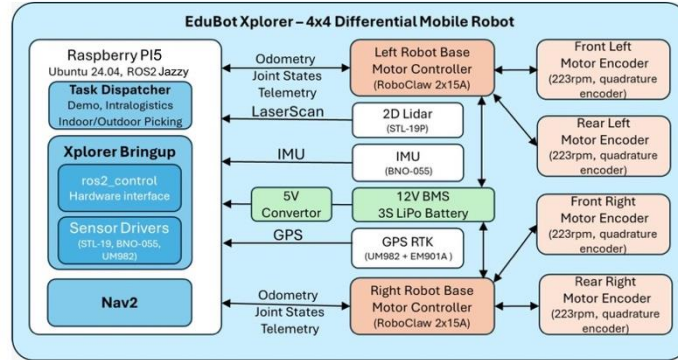


Fig. 1 System Architecture Diagram

A critical design requirement is modularity, the platform providing support for expansion kits of 200×200×200 mm, such as robotic arms or computer vision modules. System performance depends on real-time localisation and path-planning capabilities, using data streams from LiDAR sensors and inertial measurement units.

The robot's hardware architecture is based on a chassis built from GoBilda 1120 Series U-Channel profiles (Fig. 2) and is designed to deliver performance and reliability in autonomous indoor and outdoor applications.

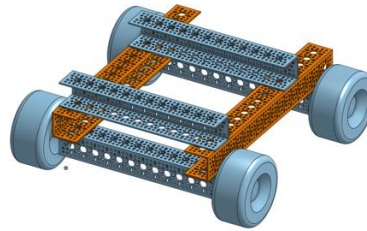


Fig. 2 Numerical model of the frame structure

Locomotion is provided by a 4WD "direct-drive" system with GoBilda 5203 Yellow Jacket 223 RPM motors with integrated encoders, chosen for high grip on varied surfaces, precise speed control and improved odometry, essential for autonomous navigation. Control is handled by RoboClaw 2x15A controllers, which drive two motors per unit, provide encoder feedback, implement hardware PID regulation of speed and position, and monitor current and voltage, contributing to system protection and stability. The processing unit is a Raspberry Pi 5 with 16 GB RAM, chosen for the computing power required to run ROS 2 nodes and real-time perception algorithms. The perception system integrates a BNO055 IMU for orientation estimation, an LDROBOT D800 LiDAR for mapping and autonomous navigation including outdoors under variable lighting conditions, thanks to its ambient-light resistance and 25 m detection range, and a Logitech C920 camera for detection and recognition of objects. Power is supplied by a 3S LiPo battery of 11.1 V and 6000 mAh, chosen for its favourable weight-to-discharge-capacity ratio, sufficient to sustain the high currents drawn by the motors and on-board electronics (Fig. 2).

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A modern-design enclosure was developed for this structure. Sensor integration imposed significant constraints: the GPS antennas require a minimum separation of 300 mm (Fig. 3), while the LiDAR must have a detection range completely unobstructed (Fig. 4). To satisfy both conditions, the LiDAR was placed above the GPS antennas, a solution that required a specific "protrusion" in the enclosure design. The design also pre-emptively included a cut-out for a front camera.

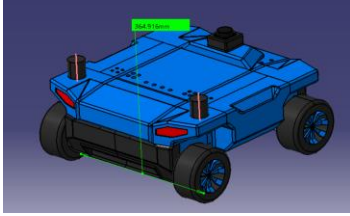


Fig. 3 Distance between the GPS antennas

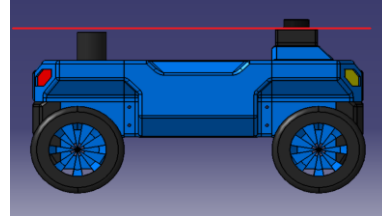


Fig. 4 LiDAR detection plane

Subsequently, the ROS 2 stack was configured to correlate data from the LiDAR and IMU sensors with the actuation units. This software-calibration stage enabled practical verification of the localisation and autonomous-navigation functions in real environments. The physical build of the system involved the use of an Ultimaker Cura S5 printer for the fabrication of custom parts and their integration onto the GoBilda chassis. The enclosure elements were produced by 3D printing. To fit within the working volume of standard printers, the larger elements were divided into sub-assemblies.

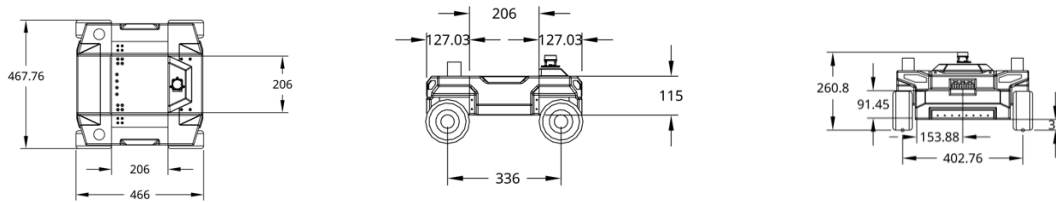


Fig. 5 Enclosure overall dimensions and enclosure sub-assemblies.

The wheel positioning approaches a "square" configuration, i.e. the wheels are laid out symmetrically, with roughly equal front-rear and left-right distances, forming an imaginary rectangle whose length and width are very close in value (Fig. 5), improving the robot's stability and manoeuvrability. This arrangement ensures a uniform distribution of mass and ground-contact forces, reducing the risk of imbalance in turns or on uneven terrain. The symmetrical geometry also allows more efficient turning, since friction forces are balanced, facilitating controlled pivoting around the robot's centre and a more precise, predictable steering.

3. Integration and simulation-based validation of a mobile manipulation system in a realistic outdoor-inspired environment, using ROS 2, Gazebo and MoveIt 2

The transition from conceptual design to physical implementation of the Xplorer Mini platform requires rigorous validation in ROS 2 and Gazebo, targeting the integration of the mobile base with the OMX-F arm. The objective is to test pick-and-place planning algorithms and inverse kinematics in a safe virtual environment, eliminating the risk of damaging the real equipment during development.

3.1. Kinematic and Structural Modelling of the System in URDF and Xacro

The physical properties of the components — masses and moments of inertia — were obtained

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by direct export from the Onshape CAD platform. Optimising the chassis topology involved structuring it into a minimal number of distinct geometric entities in order to make efficient use of computational resources.

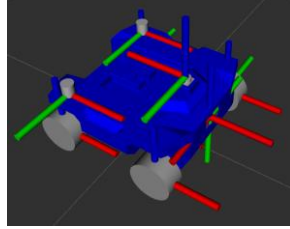


Fig. 6 Numerical model of the integrated system in RVIZ: visualisation of the reference-frame hierarchy (TF)

The system integrates the articulated OMX-F platform, an arm-type manipulator configured with 5 degrees of freedom (DoF) and a gripper, optimised for research through full compatibility with the ROS 2 ecosystem. Kinematically, it offers a maximum operating radius of 380 mm and can handle a payload of 250 g, with performance supported by DYNAMIXEL XM430 actuators.



Fig. 7 Integration of the OpenManipulator-X onto the mobile platform

Table 1. Manipulator positioning parameters

Reference element	X coordinate [m]	Y coordinate [m]	Z coordinate [m]
Manipulator base offset	-0,158	0,000	0,114

Analysis of the grasping capability indicates a maximum reach of 200 mm from the edge of the mobile platform and an angular opening of 75° when the gripper is oriented normal to the working plane (downward orientation).

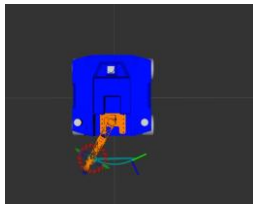


Fig. 8 Top view of the reach

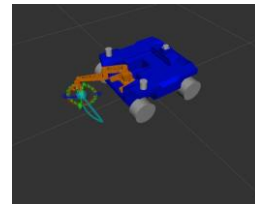


Fig. 9 Isometric view of the reach

3.3. Software Integration and Motion-Planning Configuration

Trajectory management was set up using MoveIt Setup Assistant, defining the kinematic constraints and the system's collision matrix. Motion planning is performed through the RVIZ MoveIt 2 interface, using the OMPL library to generate optimal trajectories via probabilistic sampling.

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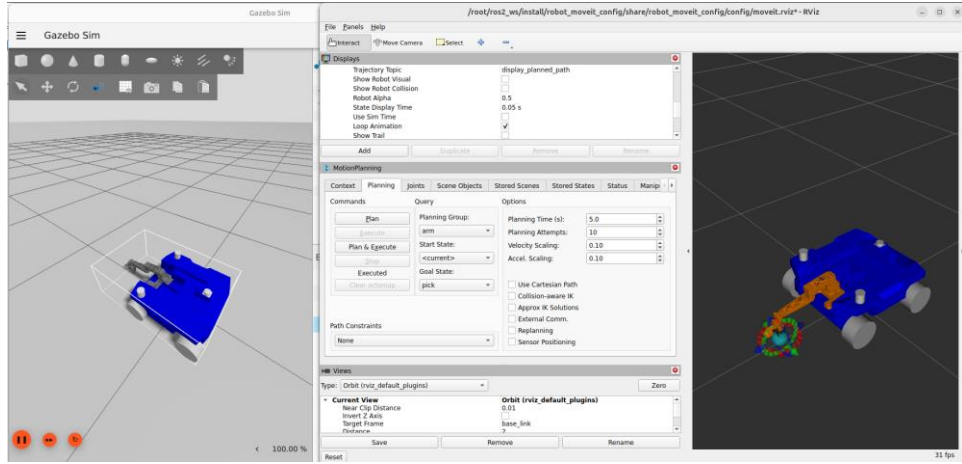


Fig. 10 Synchronisation of simulator (Gazebo) and planner (MoveIt 2).

3.4. Validation of the Manipulation Process (Pick-and-Place)

The simulator-based validation targeted the assessment of kinematic behaviour in sequential manipulation tasks, using the *MoveIt Task Constructor* framework. This approach allows the operation to be decomposed into logical sub-stages, ensuring smooth transitions between global planning in state space and the precise movements required near the object.



Fig. 11 Pick stage

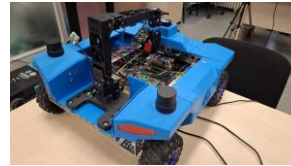


Fig. 12 Place stage

3.5. Implementation of the Virtual World

In order to replicate an operational scenario faithful to reality, a section of Crângași Park was modelled using Blender, including terrain irregularities (earth surfaces, kerbs) and static urban obstacles. The model was integrated into the Gazebo simulator and augmented with entities from the native library to generate a complex experimental context. This framework facilitated the evaluation of the platform's mobility on rough terrain and the validation of the robotic arm's interaction with adjacent objects.



Fig. 13 Google Maps reference

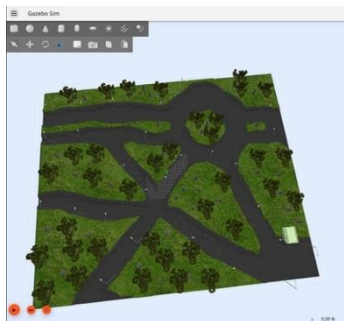


Fig. 14 Top-down view

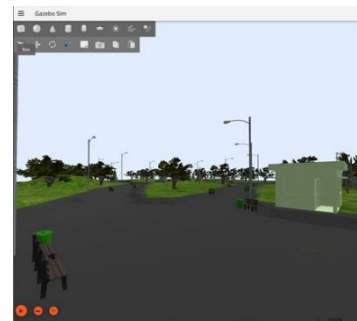


Fig. 15 3D perspective

4. Experimental results and practical limitations

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4.1. Analysis of discrepancies between virtual and physical environments

Experimental evaluation revealed a discrepancy of 20-30 mm in the vertical direction between the planned and actual trajectories, caused by mechanical imprecisions of the actuation units; consequently, the collision volumes were reconfigured by applying a safety factor.

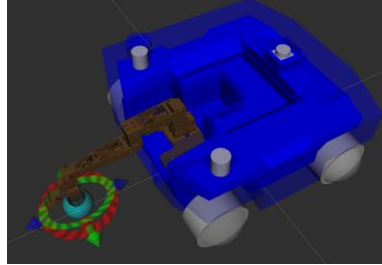


Fig. 16 Collision volumes

4.2. Experimental methodology and performance analysis

The test protocol involved carrying out 53 *pick-and-place* trials, using a sample of objects with regular geometry (50 mm side cubes) placed on the robot's driving plane.

OMX-F Pick-Place Performance Summary

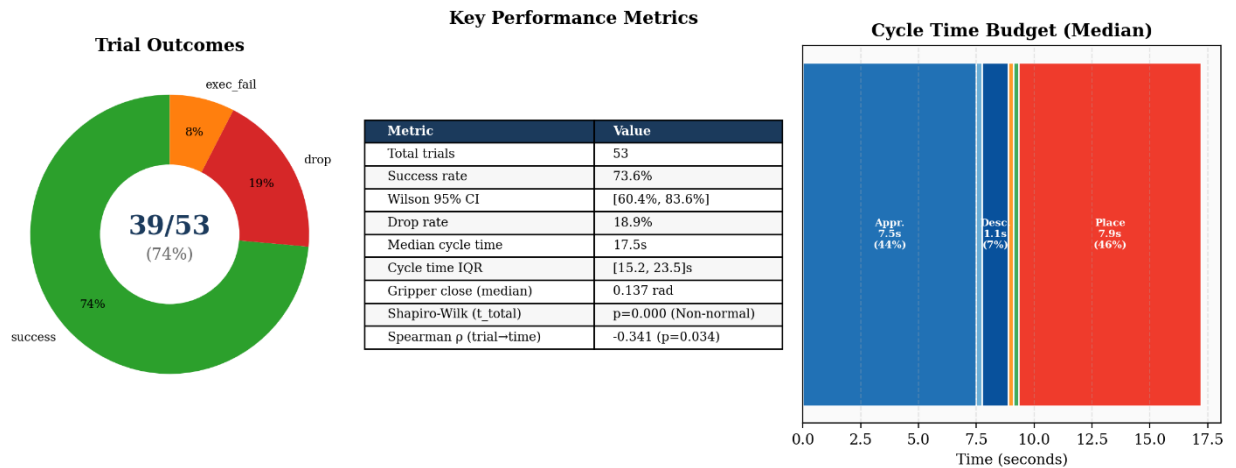


Fig. 17 Performance indicators and cycle-time distribution (Pick-and-Place)

4.3. Data limitations

Only 45% of the trials (24 out of 53) benefited from a complete six-phase decomposition. Due to automatic-detection errors in the initial sessions (subsequently corrected), the statistics for the close, ascent and place stages were computed on a reduced sample of $n=21$.

4.4. Conclusions from the experimental results

In contrast to the Cartesian motions, which are fast and deterministic, OMPL planning takes up 92% of the time budget. For this reason, efficiency optimisation must target the level of the planning algorithms, since the control system already has a minimal temporal impact.

5. Implementation of artificial-intelligence systems within the project

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This section presents a complementary direction of the paper, representing a proof-of-concept for a "touchless" teleoperation interface of the Xplorer Mini platform. The proposed system uses the MediaPipe Hands library to extract 21 biomechanical points of the hand, which are then processed by an MLP neural network to classify the fundamental control gestures (Fig. 6). The model was trained on an original dataset of 9,000 observations, using a stratified split (80% training, 20% testing) and obtaining an F1 score of 0.89 under controlled laboratory conditions with a single user. Operational safety is supported by implementing asymmetric decision thresholds (0.60 for the critical "STOP" command and 0.85 for motion) to reduce the risk of accidental actions. The main limitations identified include the dependence on the hand morphology of a single subject, sensitivity to lighting variations and the need for processing on external hardware, defining the future directions for migrating the algorithms towards edge computing.

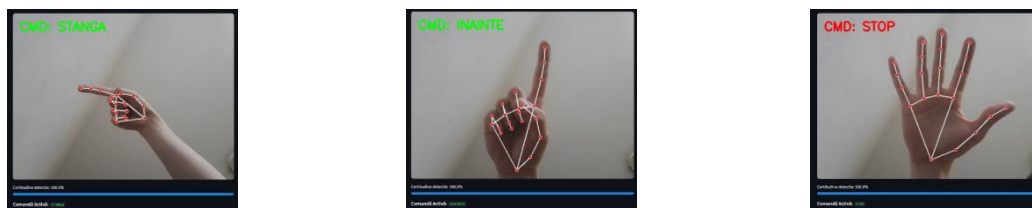


Fig. 18 Gesture-based teleoperation interface

6. Conclusions

This paper has detailed the design and validation of the Xplorer Mini platform, a modular ROS 2-based architecture that integrates a robust chassis, Raspberry Pi 5 processing and a sensor suite. The central contribution targeted the implementation of a mobile manipulation system using MoveIt 2, validated by correlating Gazebo simulations with physical tests. The experimental results indicated a success rate of 73,6% in pick-and-place. Future research directions target the integration of feedback for the automatic correction of grasping and the complete migration of processing to Edge Computing architectures. These optimisations will provide the technological foundation required for the transition to the advanced SAIM Modular Pro system, conceived as an autonomous robotic platform dedicated to urban spaces. The emphasis will be on local execution of the algorithms to minimise response latency and guarantee operational independence from external infrastructures. Through the use of computer vision and advanced sensor fusion, the system will allow real-time interpretation of the surrounding environment.

7. References

- [1] B. F. Abaza, "AI-Driven Dynamic Covariance for ROS 2 Mobile Robot Localization," *Sensors*, vol. 25, no. 10, Art. no. 3026, May 2025.
- [2] Open Source Robotics Foundation, "ROS 2 Jazzy Jalisco Documentation", 2024. [Online]. Available at: <https://docs.ros.org/en/jazzy/index.html>. [Accessed: 15-May-2026].
- [3] PickNik Robotics, "MoveIt 2 Documentation", 2024. [Online]. Available at: <https://moveit.picknik.ai/main/index.html>. [Accessed: 15-May-2026].
- [4] ROBOTIS, "cyclo: Open-source cycloid drive design tool", 2021. [Online]. Available at: <https://github.com/ROBOTIS-GIT/cyclo>. [Accessed: 15-May-2026].
- [5]. S. Macenski, T. Foote, B. Gerkey, C. Lalancette, W. Woodall, "Robot Operating System 2: Design, architecture, and uses in the wild," *Science Robotics* vol. 7, May 2022.
- [6]. S. Macenski, A. Soragna, M. Carroll, Z. Ge, "Impact of ROS 2 Node Composition in Robotic Systems", *IEEE Robotics and Autonomous Letters (RA-L)*, 2023.

DEVELOPMENT AND EXPERIMENTAL EVALUATION OF A MODULAR MOBILE MANIPULATION PLATFORM USING ROS 2, GAZEBO AND MOVEIT 2

- [7]. S. Macenski, F. Martín, R. White, J. Clavero. The Marathon 2: A Navigation System. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2020.
- [8]. B. Felbrich, "onshape-to-robot documentation", 2021. [Online]. Available at: <https://onshape-to-robot.readthedocs.io/en/latest/>. [Accessed: 15-May-2026]
- [9]. A. Merzlyakov, S. Macenski. A Comparison of Modern General-Purpose Visual SLAM Approaches. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2021.
- [10]. F. Zhang, V. Bazarevsky, A. Vakunov, et al. *MediaPipe Hands: On-device Real-time Hand Tracking*. arXiv preprint arXiv:2006.10214, 2020.

DESIGN AND DEVELOPMENT OF A PROTOTYPE VEHICLE CONTROLLED BY OPERATOR GESTURES

DIMA Matei-Andrei

Scientific Advisor: Assoc. Dr. Eng. BIGAN Cristin

Faculty: F.I.I.R., Specialization: Informatică Industrială, Year of study: Licență IV, email: matei_andrei.dima@stud.fir.upb.ro

ABSTRACT:

The robot presented in this paper is a remotely controlled vehicle designed to demonstrate aircraft marshalling maneuvers, applicable to any type of ground or aerial vehicle. This model was chosen for demonstration purposes, in order to illustrate how visual gestures can be effectively used for vehicle control and guidance.

The system is composed of two main components: a single-board computer responsible for capturing and interpreting the operator's gestures, and a microcontroller responsible for controlling the movement of the vehicle.

1. Introduction

The development of image processing technologies and artificial intelligence algorithms has enabled the creation of modern methods for human-vehicle interaction, without the use of classic controls such as remote controls or joysticks. Gesture recognition represents an intuitive and fast solution, used in fields such as robotics, industrial automation, autonomous transport, and vehicle guidance [1].

The objective pursued in this paper consists in designing and developing a prototype vehicle controlled through visual signs performed by an operator, using artificial intelligence and image processing techniques. The system must be capable of detecting and recognizing different gestures in real time, interpreting them as movement instructions, and transmitting the corresponding commands to the vehicle [2]. Furthermore, it aims to demonstrate the viability of using YOLO-type detection algorithms in a practical application for the control and guidance of a mobile robotic system [3].

This is achieved through the three important components of the vehicle: the "Raspberry Pi Camera Module 3 Wide" camera, which captures gestures from the live stream, the "Raspberry Pi 5" board, which identifies and interprets the gestures via a neural network, and the "Arduino UNO WiFi" board, responsible for the movement of the car.

2. Current state

Robotic vehicles, also known as autonomous vehicles or robotic cars, play a crucial role in the modern robotics industry, having diverse applications: industrial (automated transport in factories, smart logistics), civil (urban autonomous transport, deliveries, public services), military (reconnaissance, patrolling, logistics transport), and research (space exploration, mapping, data collection). The rapid development of sensors, positioning systems, and artificial intelligence algorithms has significantly increased the autonomy and safety of these vehicles.

Interest in autonomous road transport has grown significantly in recent years, as companies and research centers attempt to develop cars capable of moving autonomously, recognizing their environment, and making decisions in real time. In this context, computer vision plays an essential role in enabling vehicles to "perceive" the road, identify obstacles, pedestrians, and traffic signs, and react appropriately to any encountered situation [4].

Traditional control of robotic vehicles is usually achieved through remote controls, joysticks, or special software interfaces, requiring human operation. However, current research focuses on developing natural language control interfaces that allow the control of robots through gestures, visual signs, or voice commands. This type of interaction offers high intuitiveness and accessibility, allowing users to communicate directly with robots without

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auxiliary equipment.

Consequently, the integration of visual gesture recognition systems into robot control represents the new trend, lying at the intersection of mobile robotics, computer vision, and artificial intelligence. This solution has the potential to contribute to the development of smarter vehicles, capable of responding efficiently to users' commands and environments, by significantly improving safety, flexibility, and human-machine interaction [5].

3. Implementation

To train the neural network, around 200 pictures were captured with 4 types of signs ("forward", "backward", "left", "right"), made from painted containers in order to facilitate their detection.



(1. Representation of the "forward" sign)



(2. Representation of the "backward" sign)



(3. Representation of the "left" sign)



(4. Representation of the "right" sign)

Capturing the live stream is done via the "Raspberry Pi Camera Module 3 Wide" camera, chosen for its high field of view (102° horizontal, 67° vertical, 120° diagonal).

The neural network model is implemented on the Raspberry Pi 5 board. The two boards communicate via the serial port (USB/UART) at 115200 bits. Based on the detected gesture, mapping to a system command is performed. The generated signal is encoded in a simple format and sent to the control system (0-"stop", 1-"forward", 2-"backward", 3-"right", 4-"left"). Arduino Uno WiFi generates the command signals for controlling the vehicle's movement, these being transmitted to the L289N motor driver, which powers and controls the four DC motors. For obstacle detection and collision avoidance, the system uses an ultrasonic sensor,

DESIGN AND DEVELOPMENT OF A PROTOTYPE VEHICLE CONTROLLED BY OPERATOR GESTURES

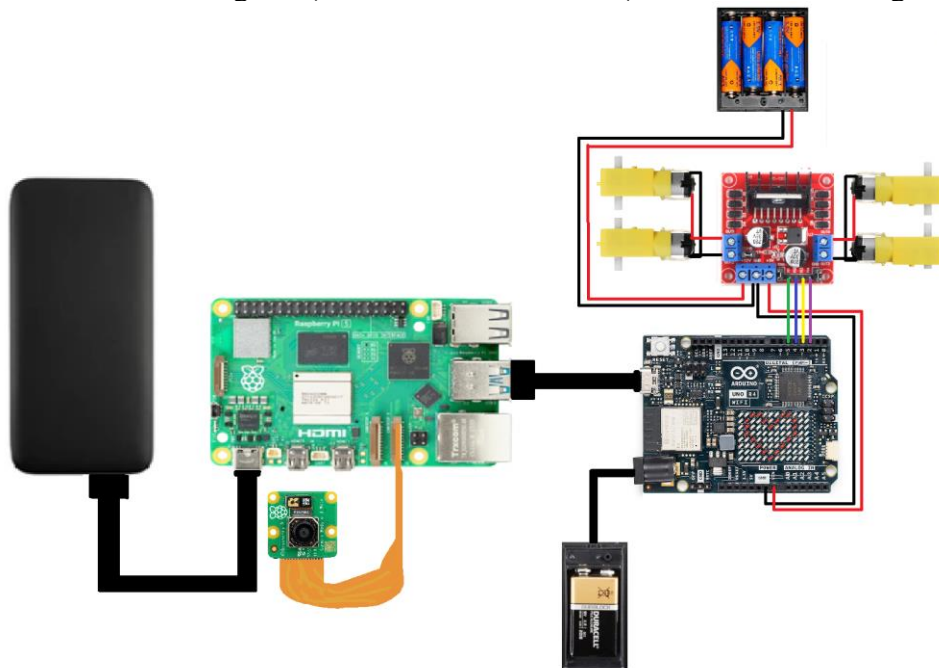
integrated for measuring the distance to nearby objects.

```
switch (c) {  
  case '0': //STOP  
    digitalWrite(in1, LOW);  
    digitalWrite(in2, LOW);  
    digitalWrite(in3, LOW);  
    digitalWrite(in4, LOW);  
    break;  
  case '1': //INAINTE  
    digitalWrite(in1, LOW);  
    digitalWrite(in2, HIGH);  
    digitalWrite(in3, HIGH);  
    digitalWrite(in4, LOW);  
    break;  
  case '2': //INAIPOI  
    digitalWrite(in1, HIGH);  
    digitalWrite(in2, LOW);  
    digitalWrite(in3, LOW);  
    digitalWrite(in4, HIGH);  
    break;  
  case '3': //DREAPTA  
    digitalWrite(in1, LOW);  
    digitalWrite(in2, HIGH);  
    digitalWrite(in3, LOW);  
    digitalWrite(in4, HIGH);  
    break;  
  case '4': //STANGA  
    digitalWrite(in1, HIGH);  
    digitalWrite(in2, LOW);  
    digitalWrite(in3, HIGH);  
    digitalWrite(in4, LOW);  
    break;  
}
```

(5. Movement code segment)

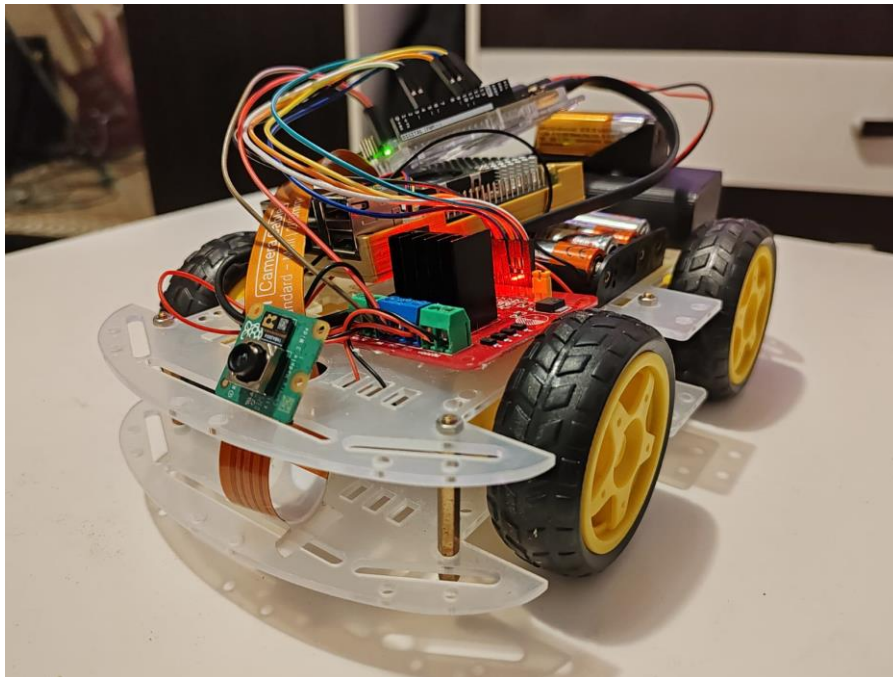
```
cmd = b'0' #se trimite constant bitul 0 pentru STOP  
  
if results[0].boxes is not None and len(results[0].boxes) > 0:  
  cls_ids = results[0].boxes.cls.cpu().numpy()  
  detected = [names[int(c)] for c in cls_ids]  
  
  if "inainte" in detected:  
    cmd = b'1'  
  elif "inapoi" in detected:  
    cmd = b'2'  
  elif "dreapta" in detected:  
    cmd = b'3'  
  elif "stanga" in detected:  
    cmd = b'4'
```

(6. Detection code segment)



(7. Electrical diagram)

DESIGN AND DEVELOPMENT OF A PROTOTYPE VEHICLE CONTROLLED BY OPERATOR GESTURES



(8. Assembled vehicle)

4. Conclusions

In this paper, a prototype vehicle controlled through gestures captured and processed in real time was designed, developed, and tested. The main objective was to demonstrate the feasibility of human-machine interaction using computer vision techniques and artificial intelligence algorithms, eliminating the need for traditional control devices.

Testing the prototype in a controlled environment validated the system's performance, confirming that the Raspberry Pi 5 board can process the video stream and run the YOLO model with low latency, while the Arduino Uno WiFi board ensures fast and precise control of the electric motors.

In conclusion, this project illustrates the significant potential of visual gesture control interfaces in modern robotics, with direct applications in fields that require natural, accessible, and intuitive interaction between operators and mobile systems, such as autonomous transport or industrial automation..

5. Bibliography

- [1] C. Choi, J.-H. Ahn and H. Byun, "Visual Recognition of Aircraft Marshalling Signals Using Gesture Phase Analysis," in *Intelligent Vehicles Symposium*, Eindhoven, 2008.
- [2] G. Angelidis and L. Bampis, "Gesture-Controlled Robotic Arm for Small Assembly Lines," 2025.
- [3] Ultralytics, "Explore Ultralytics YOLOv8," [Online]. Available: <https://docs.ultralytics.com/models/yolov8#overview>.
- [4] S. Estable, J. Schick, F. Stein, R. Janssen, R. Ott et W. Ritter, «A real-time traffic sign recognition system,» chez *Proceedings of the Intelligent Vehicles '94 Symposium*, Paris, 1994.
- [5] S. David-Christian, C. Andrei-Cosmin and P. Constantin-Adrian, "STUDY ON AGV ROUTE OPTIMIZATION," *Journal of Industrial Engineering and Robotics*, pp. 108-111, 2024.

AUTOMATED CARGO LOADING SYSTEM USING A ROBOTIC ARM AND QR CODE IDENTIFICATION

MATEI Raul-Ovidiu, TĂBĂCARU Florina - Cristina, CODREANU Irina, ULMEANU Mihaela-Elena

Faculty of Industrial Engineering and Robotics, Specialization: Industrial Informatics, Year IV, email: raul.matei@student.upb.ro

ABSTRACT: *This paper describes an automated cargo loading system that combines mechanical, electrical and software components into a single working prototype. The core of the system is a robotic arm fixed to a single-axis overhead crane. Two PLA storage cabinets, a QR code reader and an Arduino board handle package identification and motion control. A dashboard built in PySide6 monitors warehouse inventory and logs operational data in real time. Overall, the project shows that a functional smart warehouse unit can be built at low cost using off-the-shelf parts and open-source tools.*

KEYWORDS: *automated loading, robotic arm, Arduino, QR code, smart warehouse*

1. Introduction

Warehouse automation has grown considerably over the last decade. Factories and distribution centers now handle far larger volumes of goods than before, and manual sorting methods can no longer keep up with the required speed and accuracy. As a result, robotic handling systems, barcode and QR-based tracking, and custom software interfaces have become standard tools in modern logistics operations. The system presented here was built around a robotic arm that moves along a single-axis overhead crane.

It works together with two storage cabinets, a QR code scanner for box identification, and an Arduino board that controls the motors. A PySide6 interface provides live monitoring of stock levels and system activity.

The motivation behind this project was straightforward: reduce human intervention in repetitive box-handling operations and cut down error rates. Many large-scale smart warehouse systems already exist commercially, but small implementations using low-cost hardware and opensource code are rarely described in the literature. This gap was one of the main reasons for undertaking the project. Looking at existing solutions, systems like AGVs and cobot platforms are effective but expensive to buy and integrate. Recent studies confirm that small embedded platforms like Arduino can handle light automation tasks adequately [1]. QR codes are widely used in warehouses, but they are rarely paired with full closed-loop motor control and a dedicated monitoring interface in the same system [2]. This project aims to demonstrate that such a combined system is feasible, with an emphasis on keeping the design modular and easy to replicate.

2. Methods and Resources

2.1 Resource Management

Building the system required planning across several months. The resources involved included physical hardware, software tools and the working time of the team members. From the start, activities were defined clearly, durations were estimated and dependencies between tasks were mapped out to avoid bottlenecks.

On the hardware side, the main components were a custom robotic arm, a single-axis overhead crane, two 3D-printed PLA cabinets and an Arduino microcontroller. QR code scanners were added to identify packages and feed that information directly into the control flow.

Several software tools were used across the project. SolidWorks handled the 3D design work. The firmware was written in Arduino C++. The supervisory interface was coded in Python with PySide6. Microsoft Project was used for scheduling, and the documentation was written in Word. Resources were allocated so that no tool or team member was assigned to two competing tasks at the same time. Each phase began only after the previous one was confirmed complete, which kept the workflow orderly and

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reduced rework.

The diagrams in this chapter were generated with AI assistance, used to structure and render the project planning data visually.

2.2 Work Breakdown Structure (WBS)

The WBS splits the project into three subsystems. The mechanical subsystem includes the storage cabinet, the robotic arm and the overhead crane. The arm has three segments base, middle link and gripper bolted together with M3x6 fasteners and stiffened by an oval aluminum bar. The crane uses a wheeled cart running along a transverse rail. The electrical subsystem is centered on the Arduino board, which drives five motors, controls the gripper, distributes power and reads QR code signals. The software subsystem covers the Arduino firmware divided into serial communication, motor control and gripper control and the PySide6 Dashboard, which handles data, analytics and display. Figure 1 shows the full WBS.

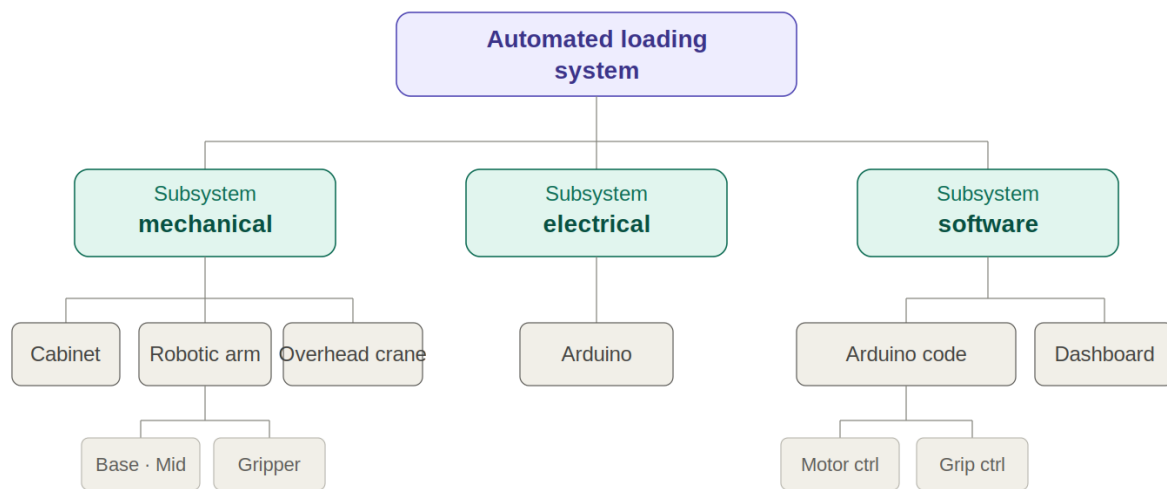


Fig. 1. Work Breakdown Structure (WBS)

3. Functional Analysis

The system moves QR-coded boxes between two storage cabinets and a loading area. An Arduino microcontroller handles the five drive motors and the gripper, reads QR input and triggers the corresponding movement steps. A PySide6 dashboard runs alongside the hardware, showing current stock, package deadlines and activity logs in real time.

Figure 2a shows the block diagram of the system the main components and how signals pass between them. Figure 2b shows the operational flow diagram, which traces the step-by-step logic of a standard loading or unloading cycle.

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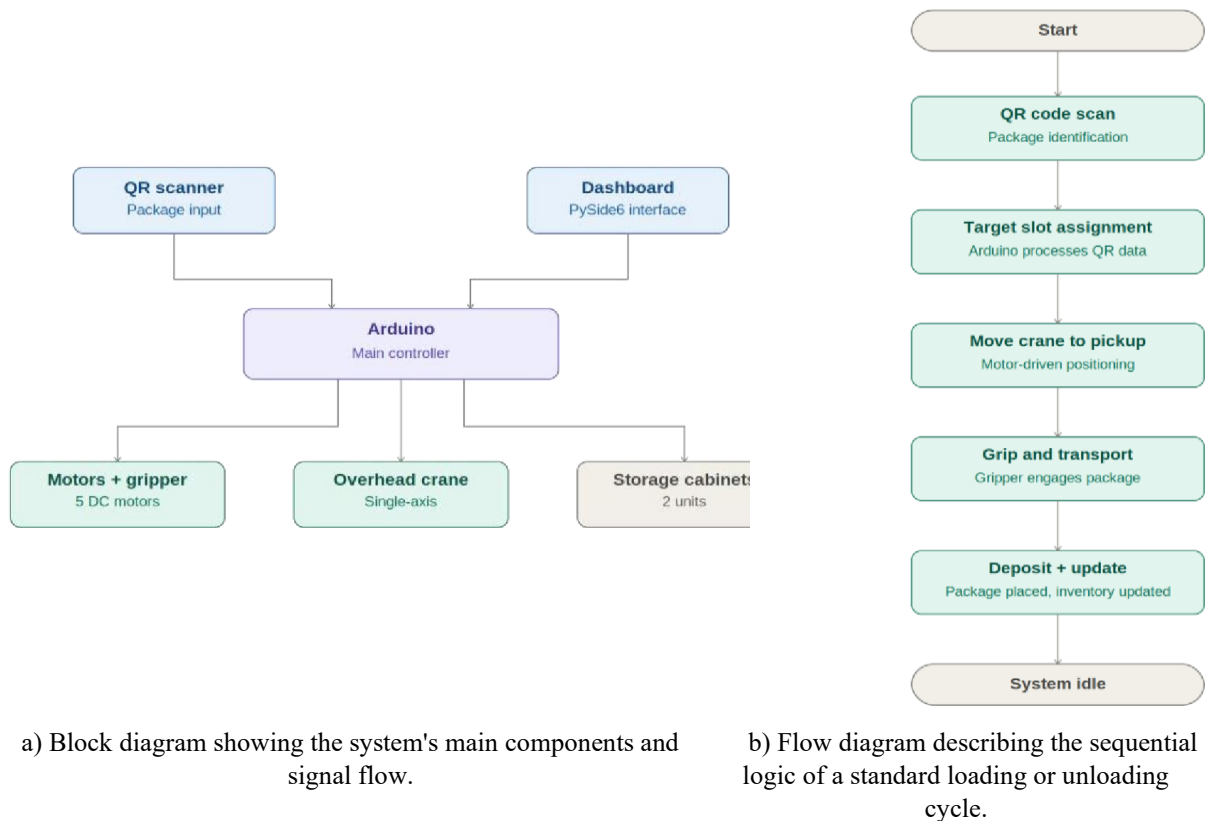


Fig. 2. Automated cargo loading system: a) System block diagram; b) Operational flow diagram

4. 3D Modeling

All 3D design work was done in SolidWorks. Each component was modelled and checked for geometric errors independently before being added to the full assembly. This modular approach made it easier to catch problems early.

The mechanical structure has three sub-assemblies: the storage cabinet, the robotic arm and the overhead crane. Design choices in each case were driven by functional requirements, with manufacturing simplicity and part compatibility kept as priorities throughout.

The storage cabinet is a box-shaped enclosure made of walls, covers and threaded inserts, held together by slot joints. Wall thickness is 5 mm throughout enough to withstand handling forces without adding unnecessary weight. No bolts or screws are used; parts are press-fit to tight tolerances. Everything is printed from PLA using FDM.

The robotic arm has three parts: base, middle link and gripper. Motors are bolted directly to the structural members using M3x6 fasteners, and an oval aluminum bar stiffens the translation axis. The gripper was designed to pick up and release QR-labelled boxes reliably, driven by a dedicated servo motor.

The overhead crane moves the arm along the horizontal axis. Like the cabinet, its parts are press-fit together with no additional fasteners needed. A stepper motor drives the cart along the rails. The guide rails were sized to eliminate side play and keep the trajectory consistent across repeated cycles. Before printing, the full assembly was run through SolidWorks interference detection to confirm that all parts fit together without conflicts. Figure 4 shows the model in closed configuration. Figure 5 is the exploded view, which makes the assembly order and part relationships easier to follow.

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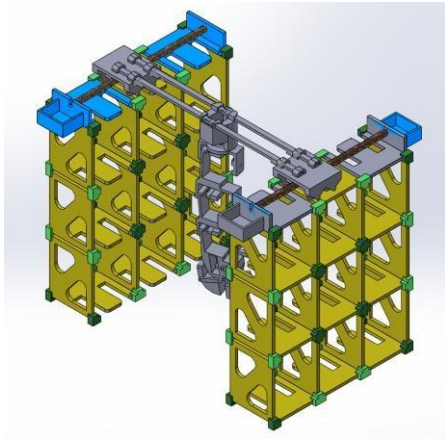


Fig. 4. 3D assembly model

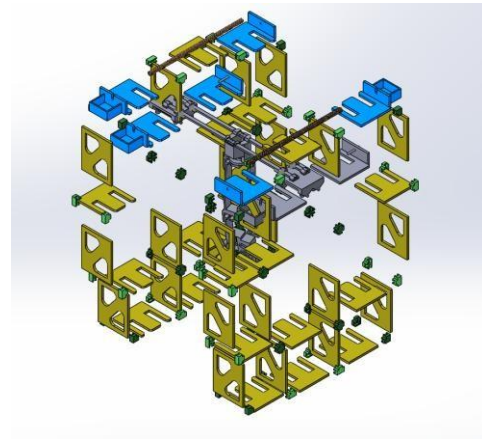


Fig. 5. Exploded assembly model

5. Prototyping and Testing

5.1 Prototyping Stages

Prototyping was done in stages. The first was a purely digital check models were inspected in SolidWorks using interference analysis and assembly simulation. Any dimensional conflicts found at this point were corrected before printing began, which saved time and material.

In the second stage, parts were physically printed. STL files were exported from SolidWorks and sliced before being sent to the printer. Print settings layer height, infill, and speed were adjusted repeatedly based on results. The press-fit joints needed especially tight tolerances, so those parts went through several iterations.

The third stage was physical assembly and testing. Each sub-assembly was put together and checked: the press-fit joints in the cabinet and crane, motor mounts on the arm, and cart travel along the rails. When something did not fit or move as expected, the CAD model was revised locally, and the affected part was reprinted. The rest of the assembly was left untouched.

5.2 3D Printing Process

All structural parts were printed from PLA using an FDM printer. PLA was chosen because it is cheap, easy to print and strong enough for this application. Wall thickness was set to 5 mm for all components to keep the mechanical behavior consistent. The cabinet and crane use slottype press-fit joints without screws required. The arm is assembled differently: motors are mounted on the structural members first, then the members are bolted together with M3x6 fasteners.

In summary: all parts are PLA, printed at 5 mm wall thickness. Two joining methods were used press-fit for the cabinet and crane, bolts for the arm. Because each component is independent, any part that came out of tolerance could be reprinted on its own without affecting the rest of the build. Figure 6 shows the finished storage cabinet and Figure 7 shows the robotic arm in its initial assembled state.

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Fig. 6. Printed PLA storage cabinet assembled prototype



Fig. 7. Robotic arm prototype initial assembly configuration

6. Software Implementation

The control software is split into two layers. Firmware running on the Arduino handles the hardware directly, while a supervisory dashboard on the host PC manages inventory and monitoring. The two communicate over a USB serial link, with the Arduino acting as the executor and the dashboard as the operator interface. This separation keeps the timing-critical motor routines on the microcontroller and the heavier data handling on the PC.

6.1 Arduino Firmware

The firmware was written in Arduino C++ as a single sketch. After initialisation, the program enters its main loop and waits for commands on the serial port. Commands follow a compact text protocol that names a single storage cell. The format is L<cabinet><column><row>, where the cabinet index selects one of the two cabinets and the column and row select a cell in its 3×3 grid. For example, L213 targets cabinet 2, column 1, row 3. Keeping the protocol short reduces parsing overhead and makes the serial traffic easy to follow during testing.

When a valid command arrives, the firmware decodes the target cell and converts it into motion. The crane stepper moves the cart to the correct horizontal position, the arm servos rotate to reach the selected row, and the gripper servo opens or closes to pick up or release the box. Each motion stage runs in sequence, with short settling delays so the structure stops vibrating before the next step begins. Once the cycle finishes, the firmware sends an acknowledgement back over serial, which the dashboard uses to confirm the move and update its logs. Malformed commands are rejected and reported rather than executed, so a typing error cannot drive the arm to an undefined position.

Package identification is tied into the same flow. The QR scanner reads the label on each box and passes the decoded identifier to the host, which maps it to a target cell and issues the corresponding command. In this way the QR data drives the firmware indirectly: the microcontroller never interprets the label itself, only the resulting cell command. Table 1 summarises the command structure.

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Field	Values	Meaning
L	fixed prefix	load / move instruction
cabinet	1 – 2	target storage cabinet
column	1 – 3	grid column within the cabinet
row	1 – 3	grid row within the cabinet

Table 1. Serial command protocol

```
// ----- loop: asteapta comanda L<dulap><col><rand> -----
void loop() {
  if (Serial.available()) {
    char c = Serial.read();
    if (c == '\n') {
      comanda.trim();
      if (comanda.length() == 4 && comanda.charAt(0) == 'L') {
        int dulap = comanda.charAt(1) - '0';
        int col = comanda.charAt(2) - '0';
        int row = comanda.charAt(3) - '0';
        if (dulap>=0 && dulap<2 && col>=0 && col<3 && row>=0 && row<3) {
          pickAndPlace(dulap, col, row);
          Serial.println("OK");
        }
      }
      comanda = "";
    } else {
      comanda += c;
    }
  }
}
```

Fig. 8. Firmware command-handling routine: serial parsing followed by the motion sequence.

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6.2 Monitoring Dashboard (PySide6)

The supervisory interface was built in Python with PySide6, the official Qt binding for Python. It uses a dark theme and is organised into tabs so that the different functions stay separated. The main warehouse tab shows both cabinets side by side as 3×3 grids, with each cell reflecting whether it is occupied and by which package. Packages can be moved with drag-and-drop, and the corresponding serial command is generated automatically from the source and target cells.

Serial communication runs in a dedicated worker thread rather than in the main GUI thread. The worker talks to the Arduino in the background and reports back through Qt signals and slots, so the interface stays responsive and never freezes while waiting for a reply from the hardware. Inventory state is stored in a local SQLite database, which means stock levels, package identifiers and deadlines persist between sessions and are restored automatically when the program starts.

A separate analytics tab presents the logged data occupancy, package deadlines and activity history and allows the records to be exported to CSV for reporting. Together, the firmware and the dashboard form a closed loop: the operator issues or confirms a move on the PC, the Arduino executes it, and the result is written back and displayed. Figure 9 shows the dashboard during operation.

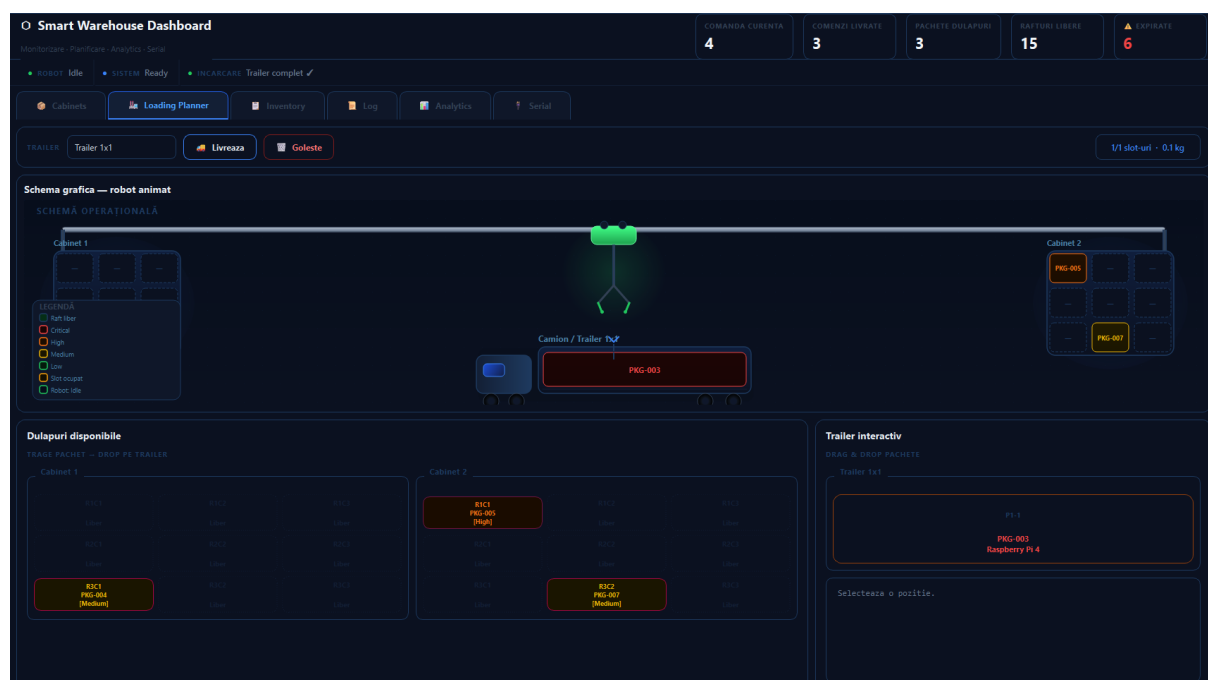


Fig. 9. PySide6 monitoring dashboard showing the dual-cabinet warehouse view.

6. Conclusions

This paper presented a working automated cargo loading system that brings together mechanical, electrical and software components into one functional prototype. The project addresses a practical need automating repetitive box-handling operations since commercial systems such as AS/RS cube storage or large industrial robots are too costly for small-scale use [1], [2]. The mechanical parts, designed in SolidWorks and printed in PLA, proved that a solid, repeatable structure can be achieved with limited resources. The electrical side Arduino plus QR scanners controlled the motors in real time and identified packages reliably.

The PySide6 interface provided inventory tracking, data export and basic analytics, which is comparable to what dedicated industrial systems offer at a much higher price.

The results confirm that a low-cost smart warehouse system is viable. This is consistent with the direction the industry is moving companies like Boston Dynamics and DHL are already investing heavily in large-scale automated cargo handling [3], [4]. The system also follows cargo securing

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principles in line with European transport guidelines [5]. Future work could expand storage capacity, add autonomous navigation and connect the system to an ERP platform for live inventory management.

7. Bibliography

- [1]. Azadeh, K., De Koster, R. and Roy, D. (2019), "Robotized and Automated Warehouse Systems: Review and Recent Developments", *Transportation Science*, 53(4), 917-945, DOI: [10.1287/trsc.2018.0873](https://doi.org/10.1287/trsc.2018.0873), also available at: <https://repub.eur.nl/pub/121281/>.
- [2]. *** AutoStore System (2024), Why AutoStore - Reliability, available at: <https://www.autostoresystem.com/why-autostore/reliability>, accessed 2025.
- [3]. Boston Dynamics (2024), Stretch - Warehouse Robot, available at: <https://bostondynamics.com/products/stretch/>, accessed 2025.
- [4]. DHL Group (2025), DHL Group Expands Strategic Partnership with Boston Dynamics, available at: <https://group.dhl.com/en/media-relations/press-releases/2025>, accessed 2025.
- [5]. European Commission (2014), European Best Practice Guidelines on Cargo Securing for Road Transport, Publications Office of the EU, available at: https://transport.ec.europa.eu/transport-modes/road/road-safety/cargo-securing-andabnormal-loads_en, accessed 2025.
- [6]. *** AutoStore System (2024), Why AutoStore - Advantages, available at: <https://www.autostoresystem.com/why-autostore>, accessed 2025.
- [7]. Boston Dynamics (2024), Automated Trailer Unloading, available at: <https://bostondynamics.com/solutions/truck-unloading/>, accessed 2025.
- [8]. *** Publications Office of the EU (2014), European Best Practice Guidelines on Cargo Securing for Road Transport [PDF], available at: <https://op.europa.eu/en/publicationdetail/-/publication/4a7f0f8e-2573-4c2f-b3f5-0a79e39b1d2d>, accessed 2025.
- [9]. *** The Robot Report (2022), DHL buying 1,000 Stretch robots from Boston Dynamics, available at: <https://www.therobotreport.com/dhl-buying-1000-stretch-robots-fromboston-dynamics/>, accessed 2025.
- [10]. *** DC Velocity (2022), DHL to buy 1,000 container unloading robots, available at: <https://www.dcvelocity.com/articles/62412-dhl-to-buy-1000-container-unloading-robots>, accessed 2025.
- [11]. *** Ocado Intelligent Automation (2024), available at: <https://www.ocadointelligentautomation.com/>, accessed 2025.
- [12]. *** Exotec (2024), Skypod System, available at: <https://www.exotec.com/>, accessed 2025.
- [13]. *** Hai Robotics (2024), available at: <https://www.hairobotics.com/>, accessed 2025.
- [14]. *** SSI Schaefer (2024), available at: <https://www.ssi-schaefer.com/>, accessed 2025.
- [15]. *** Vanderlande (2024), available at: <https://www.vanderlande.com/>, accessed 2025.

DEVELOPMENT OF A LOW-COST MES PROTOTYPE FOR PRODUCTION MONITORING, TRACEABILITY, AND AUTOMATIC DEFECT DETECTION

Eugen Adrian TAMAȘ, Ion-Edi NĂFLIU-JOÎȚA and Prof. dr. ing. ec. DOICIN Vasile Cristian

Faculty: Industrial Engineering and Robotics, Specialization: Computer Applications in Industrial Engineering, Year of study: 2, e-mail: tamas.eugen.adrian@gmail.com

ABSTRACT: *The paper presents the development of a modular Manufacturing Execution System (MES) intended for SMEs, designed using the MBSE (ARCADIA) methodology. The paper evaluates the performance of several database engines in massive industrial telemetry data insertion scenarios, using a test set of 100,000 records. The results indicate the efficiency of using message queues to reduce insertion latencies and improve processing capacity in near-real time. For quality control, the system experimentally integrates a YOLO module, critically analyzing the limits of automatic detection in an industrial context.*

KEYWORDS: *manufacturing execution system, cyber-physical architecture, model-based systems engineering, industrial interoperability, real-time data processing.*

1. Introduction

The transition from the rigid hierarchical Purdue model (ISA-95) [1] toward Industry 4.0 demands cyber-physical systems (CPS) [2] capable of ensuring seamless collaboration between physical equipment, MES, and ERP platforms. This research addresses the need for SME digitalization through a "Low-Cost High-Tech" system that eliminates information asymmetry and operational capacity losses of 15–20%. For a rigorous foundation, the design utilizes Model-Based Systems Engineering (MBSE) via the Eclipse Capella tool, structuring requirements across four essential architectural layers. The main contributions of this work consist of: designing a modular MES architecture for production monitoring and traceability, modeling the architecture through the MBSE/ARCADIA methodology using Eclipse Capella, developing a web prototype for production management, planning, quality, and shop floor operations, designing a relational database for the integration of orders, machines, operators, downtimes, scrap, and PLC data, conducting a comparative evaluation of MariaDB, MySQL, and MS SQL Server engines for massive industrial data insertion, and experimentally integrating a YOLO module for the visual detection of parts and defects.

2. Cyber-Physical Architecture and MBSE Design Methodology

Implementing a complex industrial system requires a rigorous approach, such as Model-Based Systems Engineering (MBSE), which centralizes requirements into a single source of truth. The ARCADIA methodology, utilized through the Eclipse Capella tool [3], structures the design into four essential layers:

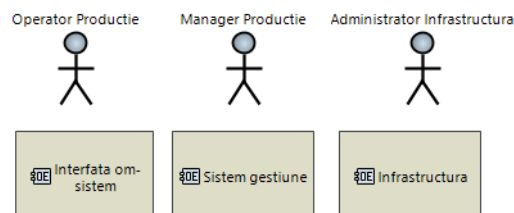


Fig. 1. Operational Entities Blank Diagram (OEBD)

In industry, workstation operators interact with information systems to obtain a list of activities to be performed during their shift, start an activity and obtain the steps to follow and equipment configuration parameters (for equipment without a stored program), load production equipment with raw materials using transport equipment, monitor industrial processes, and properly label semi-finished/finished

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products resulting from industrial processes.

Operational Analysis: defines the business processes and actors (operators, engineers) without specifying the system. The operational actors are: production operators at each workstation, production managers, and infrastructure administrators. The operational entities are human-system interfaces, generally representing the management system and the infrastructure with which the actors interact.

System Needs Analysis: identifies the MES functions without detailing them, along with its external interfaces. Operational activities (according to the ISA-95 standard) can be simplified into the following categories: Production Resource Management (resource status monitoring, resource allocation, resource management), Product Definition Management (manufacturing bill of materials mBOM management, standard operating procedure SOP management, production order distribution), Production Execution and Control (work order dispatching, production flow control, operational activity management), Production Data Collection (process data acquisition, product genealogy management, event logging), and Production Quality Management (in-line inspection execution, statistical process control monitoring, non-conformance management). Figure 2 presents a portion of the Operational Activity Blank Diagram (OABD) within the Eclipse Capella software tool.

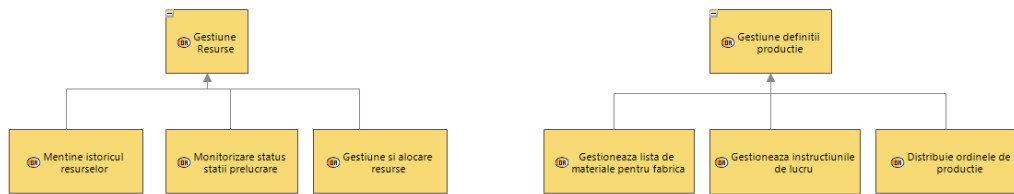


Fig. 2. Operational Activity Blank Diagram (OABD)

Logical Architecture: Decomposes functions into conceptual components, independent of the final technology (e.g., a data collection engine for PLCs and sensors). **Physical Architecture:** Represents the final implementation plan, where software components are allocated to hardware nodes and Docker containers.

Table 1. ARCADIA levels and modeled elements within each level

ARCADIA Level	Element modeled in the work	Result used in the design
Operational analysis	operator, engineer, machine, production order	definition of work scenarios
System needs analysis	data collection, reporting, traceability, scrap	MES functions
Logical architecture	modules: production, quality, inventory, API	separation of software components
Physical architecture	local server, Docker, database, ERP, terminals	prototype implementation

At the control level, the architecture evolves from synchronous request-response protocols (Modbus TCP) toward semantic standards (OPC UA) and publish-subscribe protocols (MQTT). This shift enables the offloading of critical networks through IIoT sensors that can transmit data directly to the MES or ERP.

3. Economic Analysis, Strategic Product Marketing, and Market Research

The proposed system aims to lower the barrier to entry for MES solutions among SMEs [4]. This solution minimizes information loss and reduces management times, thereby also lowering the relevant costs associated with specialized personnel in planning, production, and logistics departments. Through the transition to a "Paperless Shopfloor", reporting becomes an embedded part of the process, ensuring full traceability via QR codes and compliance with the IATF 16949 standard [5].

The system is designed to run primarily locally, with the possibility of data synchronization to the cloud and with open-source ERP systems; it facilitates production continuity on affordable hardware (e.g., Raspberry Pi) by reducing resource consumption and offering the ability to be used within a standard internet browser (such as Mozilla Firefox), lowering the cost per workstation.

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The design, based on the Genchi Genbutsu principle [6], has compressed reporting time to just 2–15 seconds according to the database performance comparison conducted in the next section. The use of visual signals improves the rapid adoption of this low-cost yet useful technology in simplifying processes within competitive sectors such as the automotive industry [7].

Table 2. Economic analysis

Cost Category	Breakdown and Rationale	Value (EUR)
Cloud Infrastructure & Security	Development environments, databases, SSL certificates, encryption	450
Testing & Edge Hardware	Industrial tablets, IoT Gateways, scanning terminals	1.100
Software Engineering (Labor)	UX/UI Design, Backend, Frontend, Testing, Tool installation	3.000
Licenses, Tools & Documentation	Operating system, runtimes, and tools are open-source and free	0
TOTAL		4.550

The validation of the prototype demonstrates an extremely efficient investment model, with a total cost of 4,550 EUR. This amount is distributed between software labor at 3,000 EUR, which constitutes the core of the intellectual property and the premise for future replicability, and the hardware infrastructure at 1,550 EUR. The efficiency of the financial model is consolidated through the exclusive use of open-source solutions, a fact that eliminates recurring financial barriers related to licensing and ensures long-term sustainability for production facilities operating on limited budgets.

4. Training the Computer Vision Model for Scrap Identification

In modern manufacturing, integrating artificial intelligence models like YOLO into a custom Manufacturing Execution System (MES) [8] revolutionizes quality control on the assembly line. This system enables real-time visual identification of defective parts, instantly transmitting the data to the ERP system. Consequently, the ERP automatically records scrap, adjusts inventory, and calculates yield without human intervention.

The data structure for training and validation was as follows: the root folder training_data which contains the data.yml file (responsible for specifying the directories of images to be labeled, the labels themselves, and the list of available labels), a subdirectory for training data (train), and another subdirectory for evaluation data (val).

The data was preprocessed locally using Label Studio installed via Docker. The labeling process took place in two stages: the first consisted of labeling the training data (train), and the second involved labeling the evaluation data (val). The training data is used directly for the actual training of the model, whereas the evaluation data is used solely for inference after training to validate the model and generate statistical data.

Table 3. YOLO training parameters

Parametru	Valoare
YOLO Model	YOLOv11 (yolo11n.pt variant)
Training platform	Local (Python, Ultralytics)
Number of classes	5 (2 part types, 3 defect types)
Number of training images (train)	10
Number of evaluation images (val)	5
Image resolution (imgsz)	640x640 pixeli

Ten labeled images were used for training the model, and another five distinct images were used for its evaluation, on which inference was automatically tested by the training script included in YOLO. For a quality control application, recall is the critical indicator, as an undetected defect can advance further into the production flow. Therefore, while the current model is promising as an experimental prototype, it remains insufficient for industrial deployment without dataset expansion, augmentation, and confidence threshold tuning.

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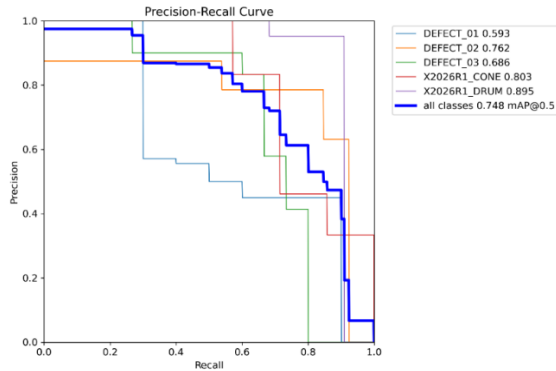


Fig. 3. Precision-recall curve graph of the trained model

Precision vs. Recall: The model is "cautious". With a Precision of ~91.2% [9], false alarms are rare. In contrast, a Recall of ~37.9% [10] means that the system misses a significant portion of the defects, letting them pass down the line.

Accuracy (mAP): An mAP50 of ~75% shows that the system distinguishes defects well, but the stricter mAP50-95 score (~46.4%) [10] suggests that the bounding boxes are not always perfectly fitted around the defect shapes.

Overfitting: Training errors (loss) decrease steadily, but validation errors stagnate after 40–50 epochs. The model has begun to memorize the test images rather than learning general detection rules.

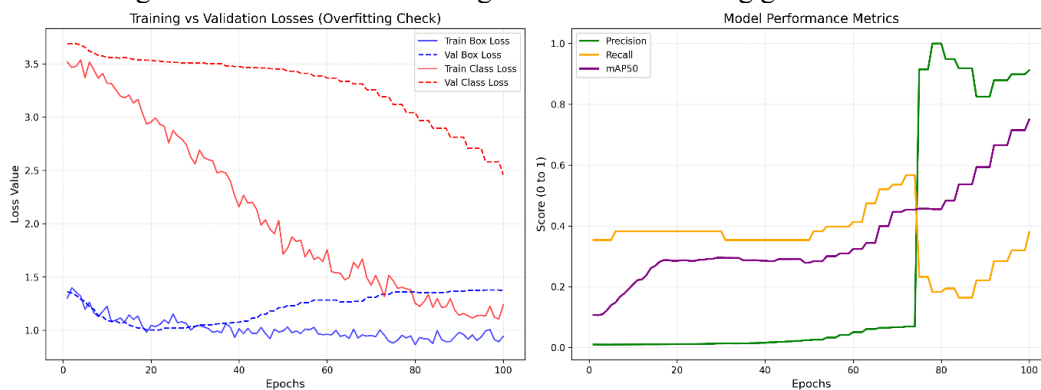


Fig. 4. Overfitting and model performance graph

5. Development of the Production Management System Application (PHP)

Choosing PHP [11] and XAMPP [12] for the development of this prototype targets the "next billion users" business segment—small factories that require rapid digitalization with low infrastructure costs. In a low-connectivity environment, the system runs on a local central server to eliminate the risk of downtime caused by the cloud. Synchronization with the cloud is occasional, allowing continuous operation on low-end hardware and inexpensive thin-client terminals, thereby providing a robust and accessible solution for custom software production digitalization. PHP is preferred for its ease of running on hardware-constrained devices due to its small number of files (compared to NodeJS, whose node_modules can reach tens of thousands of small, fragmented files, reducing performance on conventional hard drives). Subsequently, the minimum viable prototype will also be implemented in Python (using Flask and PyQt/Tkinter) and Java (using Spring or Swing), as they can offer lower RAM consumption compared to integrating an entire modern internet browser. Users authenticate using a username and password, with RFID-based solutions to be introduced later.

According to the specifications, the model recognizes 5 distinct classes: 2 Classes for Parts: X2026R1_CONE (simulated with a disposable cup) and X2026R1_DRUM (simulated with a plate), and 3 Classes for Defects: DEFECT_01 (rectangle), DEFECT_02 (triangle), and DEFECT_03 (circle).

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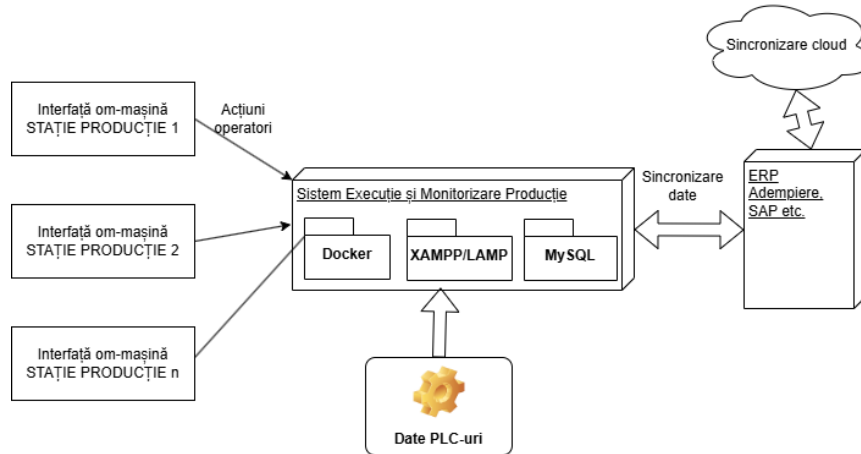


Fig. 5. General architecture of the system

The architecture was designed for interoperability with open-source ERPs such as ADempiere via REST/SOAP APIs, with the full validation of bidirectional synchronization to be carried out in a subsequent phase. This application features APIs for all key functions to allow the interface to be rewritten in other web technologies or even as native applications for platforms like Windows, Linux, and Android, thereby enabling the reuse of existing factory equipment or cheap refurbished hardware.

☐	Name	Container ID	Image	Port(s)
☐	dissertation_project	-	-	-
☐	erp_postgres	a935cf3fc4ea	postgres:1	5432:5432
☐	mes_mysql	543a7e6d0852	mysql:8.0	3303:3306
☐	mes_backoffice_php_apache	9162ffbb44be	dissertatio	8080:80
☐	mes_totem_php_apache	bb0771982163	dissertatio	8081:80
☐	erp_adempiere	a2b746e07662	erpya/ader	8274:8888

Fig. 6. Production planning interface example

The application utilizes the Manager-View model, separating the processing logic (Manager) from the data presentation (View). This structure facilitates rapid maintenance and scalability. The sidebar-content interface ensures intuitive navigation between the inventory, planning, and quality modules, and is optimized for factory terminal screens. The sidebar-content interface is not just an aesthetic choice, but a functional one. It allows users—whether production managers or logistics personnel—to navigate quickly between essential modules (Inventory, Orders, Quality Reports) without losing visual context. On the shop floor, time is a critical resource; an intuitive interface reduces the learning curve and minimizes operating errors.

Although the prototype initially runs on XAMPP for simplicity, the final architecture is migrated to Docker using a docker-compose.yml file [13]. A local on-premise central server runs separate containers for: the MySQL/MariaDB/MS SQL/PostgreSQL service (the database), the LAMP server (the PHP application), and the integrated local ERP (Adempiere).

Operators access these services via thin clients (e.g., Raspberry Pi or old mini-PCs), reducing hardware costs per workstation.

The system is functionally segmented to serve two distinct needs: Back-Office: Complex modules for logistics, planning, and production, accessible to administrative personnel; and Shop Floor: A Totem-type interface (industry-specific layout) for operators. This is simplified, offering large buttons and critical information regarding machine status and shift objectives, optimized for rapid use in processing departments.

DEVELOPMENT OF A LOW-COST MES PROTOTYPE FOR PRODUCTION MONITORING, TRACEABILITY, AND AUTOMATIC DEFECT DETECTION

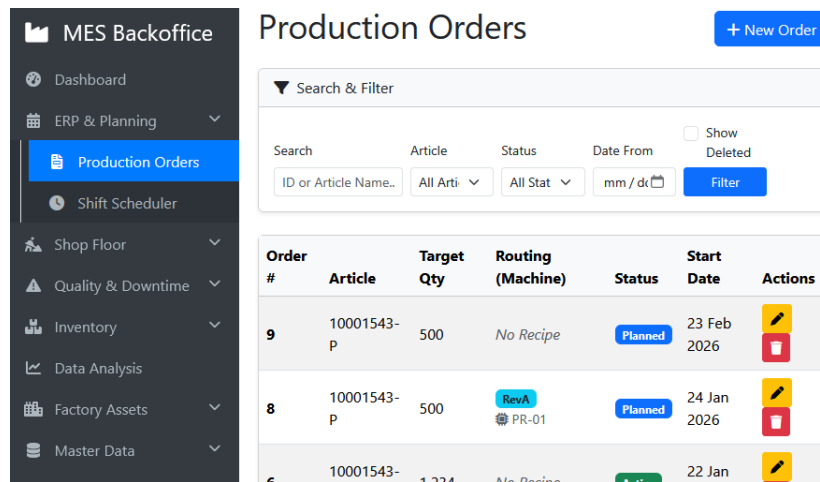


Fig. 7. Production planning interface example

6. Database Development and Performance Measurement of the System

In this chapter, the performances of the MySQL, MariaDB, and MS SQL Server database engines were analyzed within the context of MES systems under Docker, evaluating the insertion of 100,000 telemetry (PLC) records into a table named "wago". The benchmark results are: MariaDB 10.11 (setup: 0.04s; insertion: 1.91s), MySQL 8.0 (setup: 1.58s; insertion: 3.40s), and MS SQL Server 2022 (setup: 0.14s; insertion: 12.04s). The study highlights MariaDB as the efficiency leader for massive real-time data writing in containerized environments.

The database structure was designed to be used by a minimum viable prototype for the MES system and is divided as follows: master data: defines the core entities. The article table stores the catalog of materials and products. The hierarchy of production units is modeled by city, country, and plant, while the technical infrastructure is represented by the machine and section tables.

Table 4. Methodology and configuration for the database performance test

Test Element	Configuration / Value	Test Element	Configuration / Value
Platform / Environment	Docker Containers (Localhost)	MySQL/MariaDB Insertion Method	Bulk insert (executemany), 5,000-row batch
Tested Table	wago	MS SQL Insertion Method	Optimized bulk insert (manual T-SQL), 1,000-row batch
Total Records	100000	Evaluated Indicators	Connection setup/cleanup time (s) and Effective insertion time (s)
Tested Engines (Ports)	MySQL 8.0 (3303), MariaDB 10.11 (3304), MS SQL Server 2022 (1433)		

Production Engineering (Routing/Recipe): Manages the manufacturing flow. production_recipes defines the required times, sequences, and equipment. The input/output components of the recipes are detailed in recipe_inputs and recipe_outputs.

DEVELOPMENT OF A LOW-COST MES PROTOTYPE FOR PRODUCTION MONITORING, TRACEABILITY, AND AUTOMATIC DEFECT DETECTION

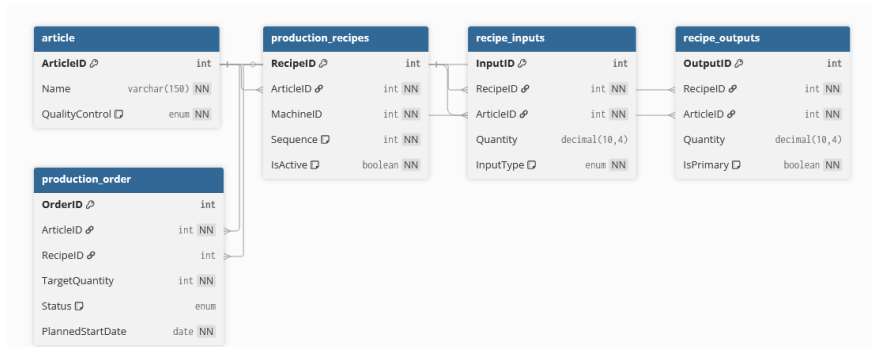


Fig. 8. Database tables regarding production management – synchronizes with ERP

Planning and Management: The `production_order` table tracks order execution (targets compared to achievements). Shift allocation to equipment is handled via `machine_planning`, while manual quantity corrections are recorded in `adjustment`.

Traceability and Operations: `batch_log` and `raw_material_log` ensure the traceability of raw materials and processed lots. Complementarily, `production_log` logs production per equipment (times, start/stop, operators).

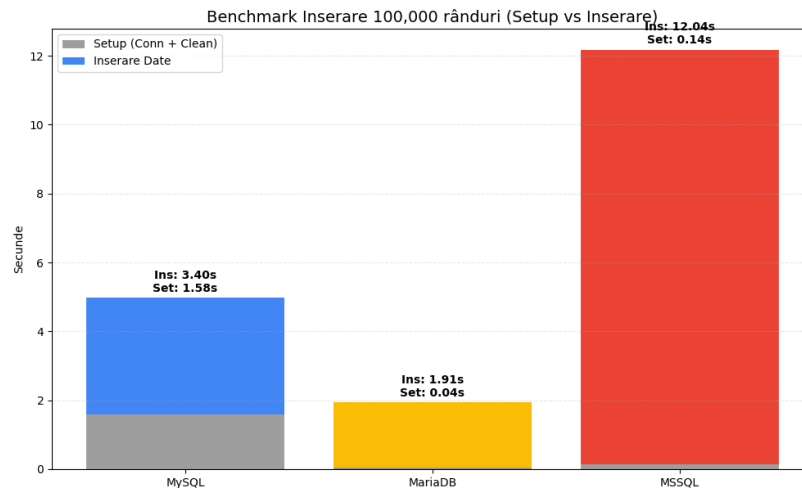


Fig. 9. Performance when inserting 100,000 records across different relational database containers

Telemetry and Data Acquisition: The `wago` table stores raw data automatically collected from PLCs regarding production volumes. This telemetry data is subsequently correlated with active orders through the `processed_production` table. **Performance and Quality:** Evaluates quality and OEE indicators. The `reject`, `reject_category`, and `reject_reason` tables classify and quantify scrap. Efficiency is diagnosed by `machine_stop_log`, which records downtime causes and durations in detail. **Administration and Security:** Identities, permissions, and time-tracking are managed centrally through `user`, `operator_log`, and `shifts`. The security and auditing of API interactions are ensured by `api_audit_log` and `api_keys`.

7. Conclusions

This work presented the design and development of a modular MES prototype oriented toward production execution monitoring, traceability, and real-time industrial data integration. The proposed system combines a cyber-physical architecture modeled through the MBSE/ARCADIA methodology, a local-first web application for shop floor operations, a relational database for managing orders, machines, operators, and scrap, as well as an experimental Computer Vision module for automated defect detection. The obtained results highlight the feasibility of a low-cost MES solution based on open-source technologies. The benchmark conducted for the insertion of 100,000 telemetry records indicates superior performance for MariaDB in the tested scenario, which supports its use for rapid industrial data collection. The YOLO module demonstrates potential for visual quality control, but requires expanding the dataset and optimizing recall before deployment in production.

8. References

DEVELOPMENT OF A LOW-COST MES PROTOTYPE FOR PRODUCTION MONITORING, TRACEABILITY, AND AUTOMATIC DEFECT DETECTION

[1] International Society of Automation (ISA). „ISA-95 Standard”. ISA Standards. Available: <https://www.isa.org/standards-and-publications/isa-standards/isa-95-standard> (accessed May 15, 2026).

[2] Y. Lu, F. Riddick and N. Ivezic. „The Paradigm Shift in Smart Manufacturing System Architecture”. IFIP Advances in Information and Communication Technology, 2016. Available: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=920863 (accessed May 15, 2026).

[3] Getting Design Right. „Introduction to Arcadia with Capella”. Capella Tutorial. Available: https://gettingdesignright.com/GDR-Educate/Capella_Tutorial_v6_0/OperationalAnalysis.html#EntityBreakdown (accessed May 15, 2026).

[4] World Economic Forum (WEF) & McKinsey & Company. „Capturing the true value of Industry 4.0”. WEF, 2022. Available: <https://www.mckinsey.com/capabilities/operations/our-insights/capturing-the-true-value-of-industry-four-point-zero> (accessed May 15, 2026).

[5] Ostadi Bakhtiar, Mohammad Aghdasi, Reza Baradaran Kazemzadeh. The impact of ISO/TS 16949 on automotive industries and created organizational capabilities from its implementation. Available: https://www.researchgate.net/publication/307660592_The_impact_of_ISOTS_16949_on_automotive_industries_and_created_organizational_capabilities_from_its_implementation (accessed May 15, 2026).

[6] Lean Enterprise Institute. „Genchi Genbutsu”. Lean Lexicon. Available: <https://www.lean.org/lexicon-terms/genchi-genbutsu/> (accessed May 15, 2026).

[7] United Nations Industrial Development Organization (UNIDO). „The Future of Industrialization - Building Future-ready Industries to Turn Challenges into Sustainable Solutions”. 2024. Available: <https://www.unido.org/sites/default/files/unido-publications/2024-11/The%20Future%20of%20Industrialization%20-%20Building%20Future-ready%20Industries%20to%20Turn%20Challenges%20into%20Sustainable%20Solutions.pdf> (accessed May 15, 2026).

[8] Queris. „Sistem MES” [MES System]. Queris Polska. Available: <https://queris.pl/ro/mes-system-ro/> (accessed May 15, 2026).

[9] A. Bochkovskiy, C.-Y. Wang and H.-Y. M. Liao. „YOLOv4: Optimal Speed and Accuracy of Object Detection”. arXiv preprint arXiv:2004.10934, 2020. Available: https://www.researchgate.net/publication/340883401_YOLOv4_Optimal_Speed_and_Accuracy_of_Object_Detection (accessed May 15, 2026).

[10] N. Hütten, M. A. Gomes, F. Hölken, K. Andricevic, R. Meyes and T. Meisen. „Deep Learning for Automated Visual Inspection in Manufacturing and Maintenance: A Survey of Open-Access Papers”. Applied System Innovation, vol. 7, no. 1, p. 11, 2024. Available: <https://www.mdpi.com/2571-5577/7/1/11> (accessed May 15, 2026).

[11] The PHP Group. „History of PHP and Related Projects”. PHP Manual. Available: <https://www.php.net/manual/phpfi2.php#history> (accessed May 15, 2026).

[12] Apache Friends. „XAMPP Installers and Downloads for Apache Friends”. Apache Friends. Available: <https://www.apachefriends.org/index.html> (accessed May 15, 2026).

[13] Docker Inc. „Getting started with Docker Compose”. Docker Documentation. Available: <https://docs.docker.com/compose/gettingstarted/> (accessed May 15, 2026).

DESIGN, FABRICATION, AND TESTING OF A GUIDE DEVICE FOR WIRE-SHAPED/TUBULAR TOOL ELECTRODES USED IN ELECTROCHEMICAL MICRO-DRILLING

Ing. CONSTANTIN Paul-Andrei, Ing. BUNEA Ionuț-Alexandru, Ing. PĂUN Albert-Georgian, Ing. SANDU Constantin-Andrei, Prof. Dr. Ing. GHICULESCU Liviu Daniel, Prof. Dr. Ing. IONESCU Nicolae, drd. ing. Maria-Miruna UNGUROIU, drd. ing. Elena ENE

Faculty of Industrial Engineering and Robotics, Specialization: Engineering of Nanostructures and Unconventional Processes, Year of study: II, e-mail: paul.constantin@upb.ro

ABSTRACT: This paper presents the development of a tool-guiding device for conventional machines used in micro-ECM processes, driven by the lack of dedicated solutions on the market. Following a market analysis and the establishment of technical specifications, several design concepts were generated and evaluated, and the one with the highest technical potential was selected. The selected concept was developed through detailed design, followed by the manufacture of a functional prototype and its validation through usage tests. The results confirm that the adopted solution meets the required specifications and improves the precision and repeatability of micro-ECM processes.

KEYWORDS: microECM, tubular/wire electrode, guiding.

1. Introduction

The tool-electrode guiding device is an essential component in electrochemical micro-drilling (microECM) processes, ensuring precise positioning, maintaining coaxiality, and reducing vibrations during machining, with a direct impact on the quality and repeatability of the obtained microstructures. Existing models do not allow the direct adaptation of a conventional ECM machine for producing small diameters. In this context, this paper aims to develop an auxiliary guiding device compatible with conventional ECM machines, designed with an emphasis on constructive simplicity, reduced cost, and meeting the fundamental requirements of the process through the guiding of tubular or wire-shaped tool electrodes with micrometric dimensions.

2. Strategic Marketing and Project Management

The first step in the project development was conducting a market study to determine the equipment's market viability. Various potential customers from different fields of activity were identified and responded to questions regarding various issues encountered in micro-drilling processes.

For a clearer interpretation, the results were processed and then displayed in pie charts, which highlight the importance of the specifications and facilitate understanding.

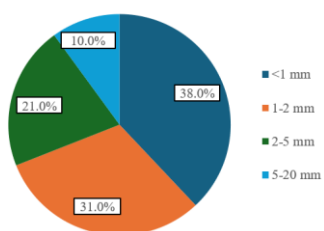


Fig. 1. Machining diameter

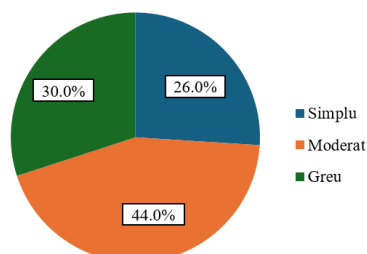


Fig. 2. Complexity of use

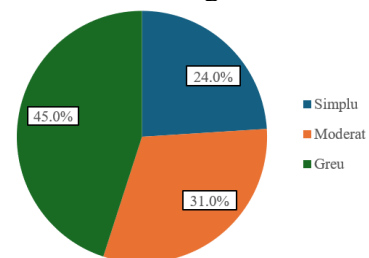


Fig. 3. Maintenance difficulty

From the charts presented in Figures 1, 2, and 3, a preference for holes with small diameters emerges, the highest share being up to 2 mm. The moderate ease of use results from

DESIGN, FABRICATION, AND TESTING OF A GUIDE DEVICE FOR WIRE-SHAPED/TUBULAR TOOL ELECTRODES USED IN ELECTROCHEMICAL MICRO-DRILLIN

the high number of component parts in existing devices. The difficult maintenance stems from the special material used for long-term corrosion prevention and part replacement, which have higher costs due to the required precision.

In order to ensure an efficient and structured development of activities, the project was organized based on a clear division of tasks according to the chapters of the paper. Each activity was assigned to team members according to their individual specializations and competencies, thereby ensuring a balanced coverage of all development stages.

A central element of project management is the identification and management of risks. The main risks that could affect the project's progress, both from a technical and organizational perspective, were identified, and measures to reduce their impact on the deadlines and expected outcomes were proposed. Two major risks are presented in Table 1.

Table 1. Risk Management

No.	Risk description	Triggering factor	Affected activity	Responsibility	Proposed strategy
1.	Delay in component delivery	Supplier/transport issues	Manufacturing	Manufacturing	Building up stocks Establishing alternative suppliers
2.	Technical failures	Design or testing errors	Design and manufacturing	Design / manufacturing / assembly / testing	Testing and simulating operation throughout development

From a financial-administrative perspective, a detailed analysis of the cost structure was carried out, including production costs, profit margin, and the estimated price of the final product. This was illustrated through a graphical representation intended to provide a clear picture of the project's economic viability, shown in Figure 4.



Fig. 4. Product manufacturing costs

To establish material costs, technological sheets are used, which accurately indicate material consumption. Initially, the production costs for a prototype will be calculated; its role is to verify the precision of the main guiding prism. The prototype is manufactured by additive manufacturing, namely the SLA (Stereolithography) technique, and a special material called "White Resin V4.1" [1] was used to achieve the specific geometry.

For the initial calculation of the prototype's production cost, design applications were used to determine the volume of the parts. This was followed by accounting for the removal of interior material specific to additive manufacturing to save time, the cost of material (specified in Table 2), the operating cost of the production equipment, and labor costs.

Table 2. Cost of manufactured parts

No.	Part	Manufacturing time	Mass	Mass final	Material	Material cost
1.	Body	≈ 2 h	53 g	≈ 26 g	Resin V4.1	19 lei
2.	Support	≈ 20 min	2 g	2	Resin V4.1	1,5 lei
3.	Force application	≈ 15 min	0,7 g	0,7 g	Resin V4.1	0,5 lei

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4.	Insert	≈ 20 min	0,7 g	0,7 g	Resin V4.1	0,5 lei
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Additionally, the price of commercially purchased parts was added:

- Spring – 1 piece – 0.5 lei
- Threaded insert – 1 piece – 2 lei
- Screw M4x25 – 1 piece – 2 lei

Thus, the total product cost with raw materials alone amounts to approximately 26 lei.

Finally, the feasibility analysis of the project integrated both the financial dimension and the estimation of potential market demand, providing a reasoned basis for initiating the design and manufacturing process of the device.

3. Establishing Specifications

As a continuation of the product development process, it is necessary to establish the equipment's characteristics in order to compare it with various competing products or existing patents. These characteristics are closely linked to the requirements of potential customers. In this regard, a requirements–quality characteristics correlation matrix was developed, allowing the identification of how each requirement is supported by the product's characteristics and their impact on the performance and satisfaction of the end user [3]. Some of the quality characteristics correlated with customer requirements are: minimal tool-electrode wear – efficient clamping and guiding system; lowest possible surface roughness – vibration reduction and efficient guiding.

The integration of quality characteristics into the design and manufacturing process contributes to meeting customer requirements and increasing market competitiveness. International standards, such as ISO 9001:2015, underline the importance of identifying and managing quality characteristics throughout the product life cycle [2], [4].

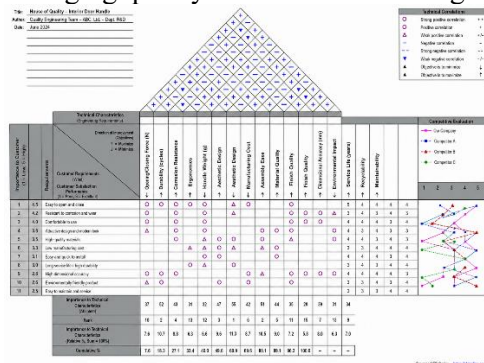


Fig. 5. House of Quality

Subsequently, the QFD (Quality Function Deployment) method is applied for the final product. The method allows the translation of user requirements into quantifiable technical-functional characteristics. The House of Quality is presented in Figure 5.

The use of the QFD method for the ECM electrode guiding device enabled the coherent and justified establishment of technical specifications, ensuring a direct correlation between market requirements and the

design solutions adopted. This helps compare it with various competing products or patents that largely satisfy the same requirements. For comparison, four ECM/EDM machines with integrated tool guiding devices and four patents were used. Some of these are specified in Figures 6–9.



Fig. 6.
PEMTec
PEMCenter



Fig. 7. EMAG PO
100 SF [6]

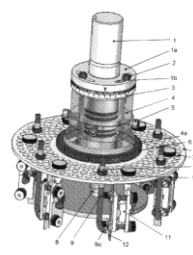


Fig. 8.
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[7]

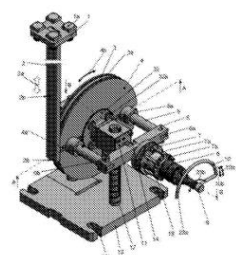


Fig. 9.
RO131489A0 [8]

DESIGN, FABRICATION, AND TESTING OF A GUIDE DEVICE FOR WIRE-SHAPED/TUBULAR TOOL ELECTRODES USED IN ELECTROCHEMICAL MICRO-DRILLIN

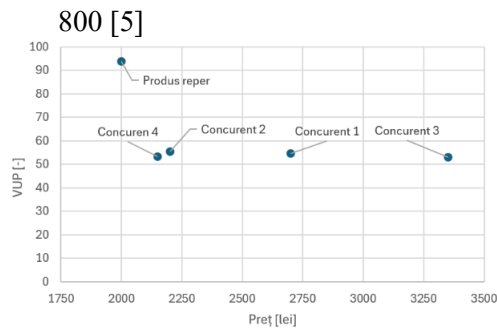


Figure 10. Competitive product matrix

4. Conceptual Design

After establishing the specifications, the concept generation stage follows. Patents, existing equipment, and ideas were studied, and based on these, the functional tree was developed in which the main functions are distinguished.

Ø = Micro-hole machining

Ø₁₁ = Allows adaptation to a machine tool

Ø₁₂ = Permite orientarea si fixarea piesei

Ø₁₃ = Allows orientation and fixation of the TE

Ø₁₄ = Ensures adequate electrical power supply

Ø₁₅ = Allows polarization P(+)/TE(-)

Ø₁₆ = Ensures the presence of a working medium (Electrolyte)

Ø₁₇ = Ensures the flow of the working medium

Ø₁₈ = Ensures relative movement between TE and workpiece

Ø₁₉ = Ensures easy maintenance at low cost

Ø₁₁₀ = Prezintă ergonomicie

Ø₁₁₁ = Ensures user safety

Ø₁₁₂ = Ensures high precision in micro-hole machining

From among the main functions established above, a list of critical functions was compiled (Table 3), which determine the commercial success of the product.

Table 3. List of critical functions

Function No.	Critical product function
Ø ₁₃	Allows orientation and fixation of the TE
Ø ₁₅	Allows polarization P(+)/TE(-)
Ø ₁₈	Ensures relative movement between TE and workpiece
Ø ₁₁₂	Ensures high precision in micro-hole machining

For selecting the optimal concept to be further developed, a two-step methodology is generally used, namely:

Pasul 1. Concept screening

Pasul 2. Concept evaluation

Based on concept screening, the main concepts retained for improvement or combination are presented.

A

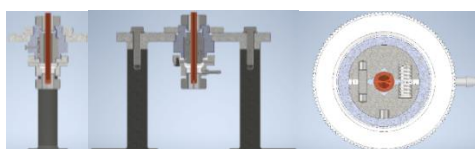
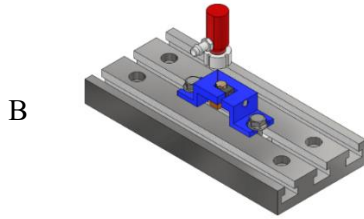


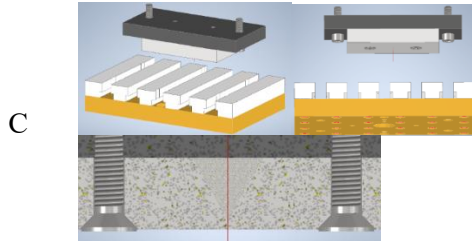
Table 4. Presentation of concepts

The tool electrode is clamped to the machine tool via a collet chuck, with table fixation achieved using clamps and screws in T-slots. Tool orientation is ensured by two prisms — one fixed and one adjustable via screw and spring.

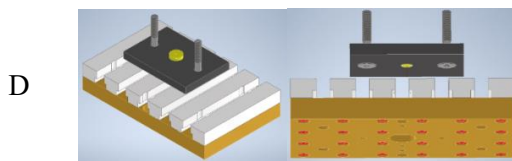
DESIGN, FABRICATION, AND TESTING OF A GUIDE DEVICE FOR WIRE-SHAPED/TUBULAR TOOL ELECTRODES USED IN ELECTROCHEMICAL MICRO-DRILLIN



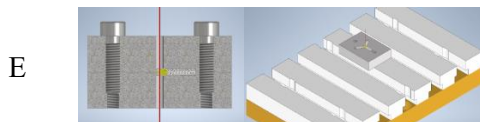
The electrode is assembled on the machine tool via a collet chuck, with table fixation achieved using screws in T-slots. Tool orientation is ensured by a hexagonal part with multiple prisms, compatible with electrodes of different diameters.



The device is clamped to the machine tool via screws, and the tool electrode is assembled by bonding with silver paste. The guiding channel has a conical profile, facilitating both electrode insertion and the application of silver paste.



The device is fixed to the machine tool using long screws with spacers, facilitating the connection of the tool to the negative pole. Electrode orientation is ensured by a precision bushing, assembled by press fit.



The device is fixed to the machine tool via screws, with tool electrode orientation ensured by three balls with compression springs, a system that allows self-centering and an ergonomic design.

For the selection of the optimal concept, selection criteria must be established; these must characterize the general function of the product and are set based on customer requirements and product characteristics. The most important selection criteria for concept screening are ease of operation, reliability, cost, and manufacturability. The conclusion is to develop Concept B, which has the highest score in the decision matrix.

After choosing the concept, the definitive specifications of the product are established. Starting from the target specifications and taking into account the results obtained from the modeling (the technical and cost models presented earlier), as well as the competitive product maps, the definitive specifications of the product will be established.

5. Detailed Design

Detailed design involves a thorough analysis of each choice made that influences the final result of the product through its characteristics. Each option must be justified, whether economically, technologically, or aesthetically.

For each part, analyses and calculations were carried out to establish the optimal specifications of the components, with the aim of obtaining a functional and easy-to-use product.

Electrode guiding is achieved using a hexagonal insert (4) with "V" grooves on each face, similar to a guiding prism in contact with the electrode (Figure 10). The hexagonal shape ensures both efficient positioning in the assembly and access to multiple faces for creating the grooves, allowing the guiding of diameters ranging from 0.125 mm to 2.66 mm (Table 14).

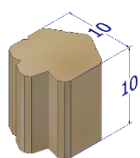


Fig. 10. Hexagonal insert [9]

The electrode is in contact both with the "V" groove surface of the insert and with the semi-cylindrical surface of the clamping force element. Element number 1 represents the equipment body, serving multiple roles: mounting on the machine table and linking all assembly components. Number 7 denotes the electrode; in this case it is a tubular electrode with an outer diameter of 0.5 mm and an inner diameter

of 0.2 mm. Number 4 represents the hexagonal insert, which was used with its 3rd face, the one that allows guiding of the electrode diameter. Keeping the electrode (7) in contact with

DESIGN, FABRICATION, AND TESTING OF A GUIDE DEVICE FOR WIRE-SHAPED/TUBULAR TOOL ELECTRODES USED IN ELECTROCHEMICAL MICRO-DRILLIN

both parts (contact piece 6 and hexagonal insert 4) is achieved by applying a horizontal force perpendicular to the electrode through a spring (5) shown in Figures 11 and 12. This exerts a force on the insert support (4). Two screws (M4x25) are used for pre-tensioning the force so as not to deform the electrode.

To allow the electrode to pass through, a cutout was made at the base of the insert support (2).

In Figures 11 and 12, the electrode clamping system is presented. One screw is used to pre-tension the spring that

Face	D _{min} [mm]	D _{max} [mm]
1	0,125	0,240
2	0,147	0,333
3	0,300	0,666
4	0,600	1,333
5	1,200	2,660

Table 4. Guiding diameter range on each face of the hexagonal insert [10]

pushes the support to the “open” position, while the right screw tightens it.

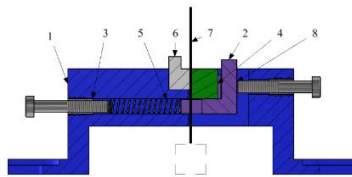


Fig. 11. Clamping system

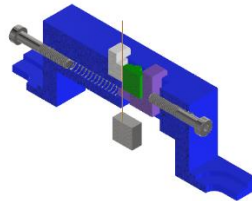


Fig. 12. Isometric view

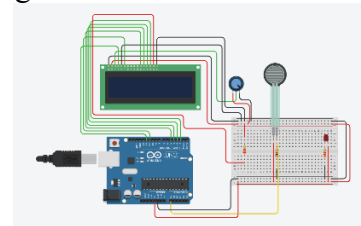


Fig. 13. Force calculation system

To prevent the clamping from deforming the electrode, a real-time force measurement system was devised (Figure 13) using a resistive force sensor attached to element 6 that reads the applied pressure and provides real-time force values on an LCD screen. For this application, an Arduino Uno base board was used to connect all components, a breadboard, and an LED that lights up as long as the detected force is greater than 0 and starts blinking when a force K that could deform the electrode is exceeded, in order to alert the user.

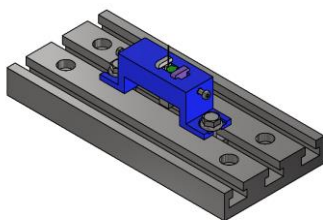


Fig. 14. Equipment mounting on the machine table

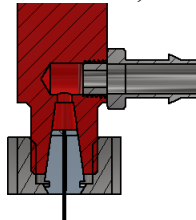


Fig. 15. Electrolyte supply

The requirements to be easily mounted on the machine table (Figure 14) and to allow electrolyte supply directly through the interior of the tool in the case of tubular electrodes (Figure 15) are also satisfied. For the electrolyte supply, channels and a threaded hose fitting were designed to be mounted in the tool holder equipment

6. Manufacturing – Testing of the Product Prototype

The prototype was manufactured through additive manufacturing processes and the acquisition of commercially available components. During the manufacturing process, two main criteria were primarily considered: the economic one (cost as low as possible) and the technological one (parts must satisfy geometries and materials compatible with the ECM process). Figures 16, 17, and 18 show the manufacturing stages of the main parts produced by FDM (Fused Deposition Modeling). The remaining commercially acquired parts are shown in Figure 19.

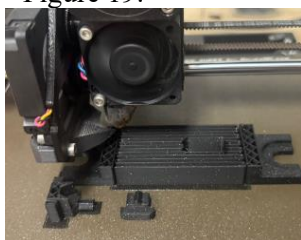


Fig. 16. Manufacturing

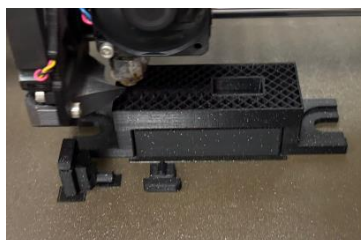


Fig. 16. Manufacturing 60%

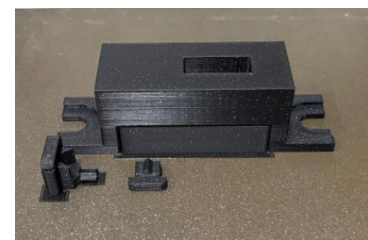


Fig. 18. Manufacturing

DESIGN, FABRICATION, AND TESTING OF A GUIDE DEVICE FOR WIRE-SHAPED/TUBULAR TOOL ELECTRODES USED IN ELECTROCHEMICAL MICRO-DRILLIN

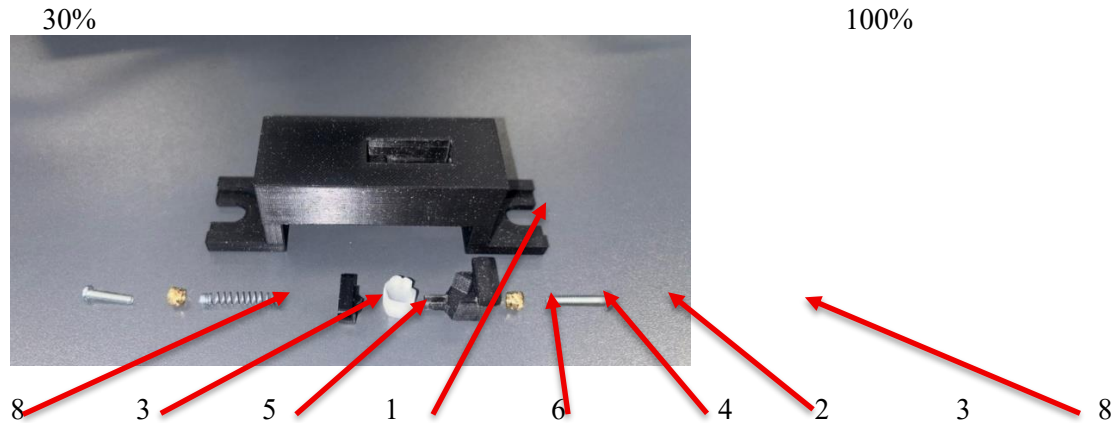


Fig. 19. Assembly parts correlated with CAD design

7. Use and Commercialization

The device is intended to be used in a wide range of application fields, satisfying multiple market demands. Some of these fields are specified in Figure 20. For efficient commercialization, potential users who could utilize this product were identified. These are either research institutes (red), educational institutions (blue), or manufacturing companies (green).



Fig. 20. Examples of applications of electrochemical micro-drilling

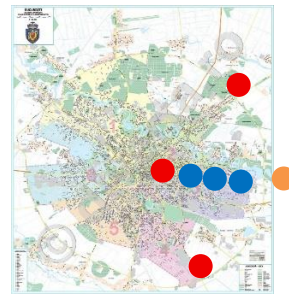


Fig. 21. Map of Bucharest city [11]

The identified potential customers are marked in Figure 21. These are: the National Institute for Research and Development in Materials Physics, the Elie Carafoli National Institute for Aerospace Research and Development, the National Institute for Research and Development in Microtechnology (red), Politehnica University of Bucharest, Ferdinand I Military Technical Academy, TPS Company Srl (blue), and Romanian Optical Enterprise Bucharest (green).

8. Conclusions and Future Directions

The project followed a complete path, from identifying the need for a tool-guiding device for conventional micro-ECM machines, to the manufacturing and testing of a functional prototype. Through market analysis, specification definition, concept screening, and detailed design, the optimal solution was selected and developed. Usage tests validated the device's functionality and confirmed its potential to improve the precision and repeatability of micro-ECM processes.

Two main development directions are being considered. The first concerns the redesign of the device's clamping system to the machine head, so that it allows controlled rotation and its use for producing inclined holes at various angles, significantly expanding the range of applicability. The second direction consists of integrating a concrete clamping force measurement system with real-time warning when the optimal value is reached, thus eliminating the risk of tool damage.

9. Bibliography

- [1]. <https://formlabs.com/store/materials/white-resin-v4-1/> (Accessed on 10.05.2026)
- [2]. A. Spieser, A. Ivanov, (2015), "Design of an Electrochemical Micromachining Machine", *The International Journal of Advanced Manufacturing Technology*,

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- Volume 78, pages 737–752, Brunel University, School of Engineering & Design, Advanced Manufacturing and Enterprise Engineering, print ISSN 0268-3768;
- [3]. Drăghici, G. (1999). Integrated Product Engineering. Eurobit Publishing House, ISBN 973-96065-7-1, Timișoara;
- [4]. L.D. Ghiculescu (2024). “Electrochemical Manufacturing Technologies”, course at Politehnica University of Bucharest. Available at: curs.upb.ro/2023, (Accessed on: 28.03.2024)
- [5]. <https://pemtec.de/en/machines/pem-800/> (Accessed on 22.05.2025)
- [6]. https://cdn.emag.com/fileadmin/user_upload/content/machines/ecm-pecm-machines/ECM_machines_summary_bros_en.pdf (Accessed on 22.05.2025)
- [7]. N.-I. Marinescu, L.-D. Ghiculescu, A. M. Țițu, and A.-S. Nanu, Equipment for simultaneous machining of micro-slot structures by ultrasound-assisted electroerosion, RO Patent 127948 B1, 30 May 2017.
- [8]. N.-I. Marinescu, L.-D. Ghiculescu, and A.-S. Nanu, Technology and equipment for finishing micro holes by ultrasound-assisted electroerosion, RO Patent 126381 A0, 30 June 2011.
- [9]. Thorlabs, “HFF001 – Fiber Ferrule Fixture,” Thorlabs Inc. Disponibil la: <https://www.thorlabs.com/item/HFF001>. (Accessed on: 21.01.2026).
- [10]. Thorlabs, “Fiber Holders and Force Sensors for Multi-Axis Flexure Stages,” Thorlabs Inc. Disponibil la: <https://www.thorlabs.com/fiber-holders-and-force-sensors-for-multi-axis-flexure-stages?tabName=Overview>. (Accessed on: 21.01.2026).
- [11]. <https://diverta.ro/bucuresti-si-zone-limitrofe-harta-plan-de-perete-rutiera-administrativa-230x250cm-scara-1-10-000-laminata-baghete.html> (Accessed on 15.05.2026)

MOBILE UNIT FOR ELECTROLYTE SUPPLY AND ULTRASONIC RECONDITIONING IN ELECTROCHEMICAL MICROMACHINING

BIDICĂ Ana-Mihaela, PETRACHE Dănuț-Mădălin, SINDILE Emil-Mădălin, VOICU Mihai-Alexandru și Conducători Științifici Prof.dr.ing. GHICULESCU Liviu-Daniel și Prof.dr.ing. IONESCU Nicolae
Facultatea de Inginerie Industrială și Robotică, Specializarea: INPN, Anul de studii: II, e-mail: bidica_anamihaela@yahoo.com

ABSTRACT: This paper addresses the development of a mobile unit for the filtration, recirculation, and ultrasonic reconditioning of electrolytic liquids used in electrochemical micromachining. It presents the analysis of market opportunities, the establishment of technical specifications, and the analysis of competing products. The main components of the installation are also described, such as the reservoir, centrifugal pump, filtration system, and ultrasonic module, together with the general architecture of the assembly and explanatory sketches.

KEYWORDS: *mobile unit, electrolytic liquid, filtration, ultrasonic reconditioning.*

1. Introduction

The paper presents research on the development of a mobile unit for the filtration, ultrasonic reconditioning, and supply of electrolytic liquid, which can be attached to any machine tool adapted for electrochemical machining.

2. Strategic marketing of the product

Identification of market opportunities

This approach aims to highlight the needs of potential customers, so that the product positioning and development directions are based on concrete data. For this purpose, a questionnaire was applied to a sample of respondents, and the results were centralized in Table 1. The questionnaire includes the questions asked, the answer options, and the percentage corresponding to each option.

Table 1. Questionnaire

No.	Question	Answer	Percent [%]
1	What types of materials are the most difficult to machine in modern industrial applications?	Conductive materials with high hardness, such as alloys or superalloys	45
		Nickel- and cobalt-based superalloys, such as Inconel-type alloys	30
		Titanium alloys and austenitic stainless steels	15
		Hardened / heat-treated steels, such as tool steels and bearing steels	10
2	What difficulties occur during the mechanical machining of these materials?	Mechanical cutting processes are slow and expensive for hard materials	40
		Accelerated tool wear	50
		Heat generation, risk of deformation, and damage to surface integrity	10
3	How important is surface quality in precision applications?	It is essential, especially in fields such as medicine, microelectronics, and aeronautics	35
		It is critical for the proper functioning of assemblies	40
		It directly influences reliability: crack	25

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		initiation, material fatigue, corrosion resistance, and service life	
4	In what situations is advanced surface cleaning necessary?	In laboratories, the food industry, or the medical industry	20
		For microcomponents, such as microchannels and fine holes	65
		In maintenance and reconditioning operations	15
5	How is surface cleaning approached in cases of radioactive contamination?	Non-invasive, precise, and efficient methods are sought, such as the use of ultrasound	70
		Controlled procedures are applied in closed or isolated systems	15
		The working steps are standardized	15
6	What happens to electrolytic liquids after several uses?	They lose efficiency, chemically degrade, and may require reconditioning in order to be reused	65
		Variations in conductivity occur	20
		The risk of deposits, foaming/gas formation, and clogging increases	15

Following this study, the primary customer needs could be identified.

N1. The need to efficiently machine conductive and difficult-to-machine materials, such as alloys, superalloys, and treated steels, used in demanding industrial applications.

N2. The need to increase productivity and reduce the total machining cost, while maintaining process stability for difficult-to-machine materials.

N3. The need to obtain superior surface quality, with high functionality and integrity, for precision applications and long-term reliability.

N4. The need for advanced, controlled, and efficient cleaning of surfaces and micro-geometries, in order to remove contaminants and ensure process quality.

N5. The need for safe, controlled, and repeatable radioactive decontamination, with traceability and minimization of exposure and contaminant dispersion.

N6. The need to maintain and restore electrolyte performance through reconditioning/conditioning, including ultrasonic treatment, contamination control, and stabilization of process parameters.

3. Establishing the specifications

Performance of competing products

In order to determine these specifications, an analysis of competing products will be carried out to identify the values of the parameters corresponding to those established by the product development team. This identification is necessary in order to create a common basis for comparison and to set the limits of the target specifications within a range as close as possible to these values. The competing products analyzed are presented in Figures 1–4.



Figure 1. PowerBurr420 [1]



Figure 2.



Figure 3.



Figure 4.

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AMAFILTER Alfie 500 [3] RoseDale
AFK24 [2] Filter [4]

The perceived use value data for the customer segment are centralized in Table 2.

Table 2. VUP Evaluation

Characteristic	<i>A-</i>		<i>B-</i>		<i>C-</i>		<i>D-</i>		<i>P_{imed}</i>
	<i>ECD POWER-BURR 480</i>		<i>AMAFILTER AFK24</i>		<i>ALFIE 500</i>		<i>ROSEDAL E</i>		
	<i>X_i</i>	<i>X_{ir}</i>	<i>X_i</i>	<i>X_{ir}</i>	<i>X_i</i>	<i>X_{ir}</i>	<i>X_i</i>	<i>X_{ir}</i>	[%]
<i>Gf</i> [L]	5	0.83	25	0	4	0.87	1	1	8
<i>Qf</i> [l/h]	750	0.14	2000	0.88	500	0	2200	1	8
<i>Dr</i> [mm]	1220x610x500		219x210x1540		1000x700x1200		218x207		6
<i>Cr</i> [l]	227	1	47	0.11	30	0.03	25	0	8
<i>Ph</i>	7	1	5	0.33	6	0.67	4	0	7
<i>C_e</i> [NTU]	10	1	5	0	9	0.8	9	0.8	7
<i>Q</i> [l/min]	5	0	150	0.38	10	0.01	378	1	8
<i>K</i> [ms/cm]	100-150	1	100-150	1	100-150	1	100-150	1	8
<i>Ve</i> [m/s]	1.8	0.8	1	0	1.2	0.2	2	1	8
<i>p</i> [bar]	5	0.5	6	1	4	0	5	0.5	5
<i>Ef</i> [%]	96	0.25	95	0	98	0.75	99	1	8
<i>C_{eg}</i> [kW]	1	1	3	0.33	4	0	2	0.67	5
<i>DCF</i> [s]	30	0.6	20	1	45	0	25	0.8	6
<i>C_{NaCl}</i> [%]	10	1	10	1	10	1	10	1	8

Vup1=65.26

Vup2=40.92

Vup3=41.84

Vup4=72.25

Based on the VUP dimensions and the assigned weights, the VUP is determined for both the developed product and the competing organizations' products, using the following equations:

$$VUP = \sum_{i=1}^n p_i \cdot X_{ir} \qquad \sum_{i=1}^n p_i = 100\%$$

Figure 5 presents the comparison of the offers according to price and VUP, highlighting the positioning of each supplier.

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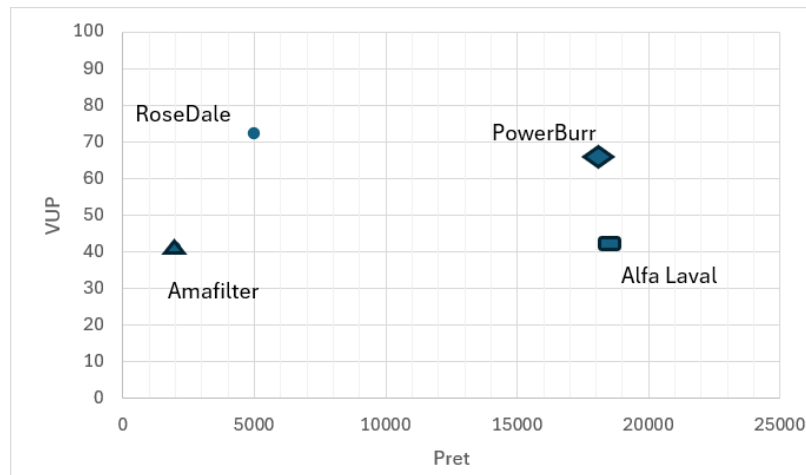


Figure 5. Price comparison chart

4. Conceptual Design

4.1 General Function and Component Functions

The general functions of the mobile unit include ensuring the mounting and operation of the ultrasonic chain inside the reservoir, in order to homogenize the electrolytic liquid; carrying out the residue filtration process, which involves the maintenance of the filtering elements, the separation of large solid residues before fine filtration, as well as the filtration of ferromagnetic metallic particles, together with the adjustment of flow rate and pressure in the filtration circuit; and the recirculation of the electrolytic liquid.

4.2 Internal Research for New Constructive Solutions

The need to identify suitable technological and constructive solutions required greater involvement of the creative component of the design process. In this context, special attention was given to the study and application of methods for stimulating technical creativity, both individually and within the team.

Following this process, the main components of the electrolytic liquid circuit were established and are summarized in Table 3.

Table 3. Components selected following the internal research

No.	Component	Constructive solution	Illustration
1	Reservoir	Mobile polypropylene container	
2	Pipes	PVC pipes	
3	Pump	Diaphragm pump	
4	Fine filter	Double filter with polypropylene cartridge	
5	Pressure sensors	Pressure gauge	
6	Shut-off element	Plastic valve, made of polypropylene	

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7	Ultrasonic generator	Transducer	
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4.3 Product Architecture

Product architecture represents the way in which the functional elements of a product are arranged into a physical structure. It begins to take shape during the concept development stage, often through sketches, functional diagrams, and concept development drawings. One of the initial 2D sketches is presented below. Starting from a functional sketch, in which the main components were represented, the 3D assembly concept was then developed in order to integrate all components efficiently into a compact and functional volume.

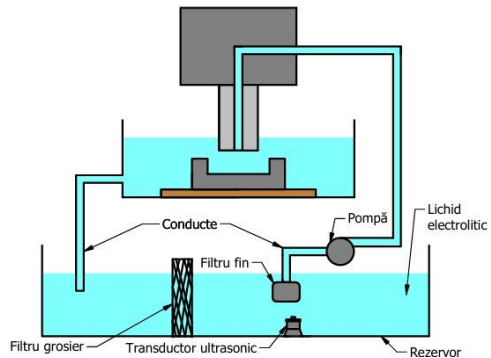


Figure 5. Initial sketch of the assembly

Figure 5 shows the basic layout of the installation assembly, illustrating the path of the electrolytic liquid and the main components of the recirculation and filtration circuit.

The installation is equipped with a double-cartridge filtration system, consisting of a coarse filter and a fine filter, mounted successively on the recirculation circuit. These filters have the role of retaining both large particles and fine impurities, contributing to the protection of the installation and to maintaining the properties of the electrolyte.

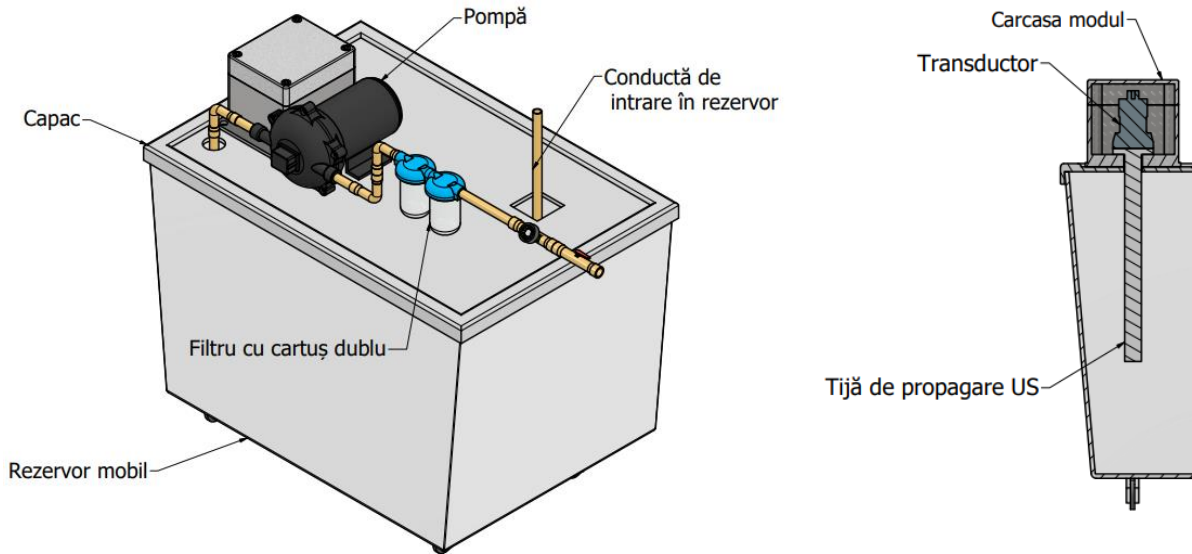


Figure 6. 3D representation of the product concept in isometric and sectional view

Compared to the initial sketch, the project was improved by introducing a two-cartridge filtration system and by designing a dedicated housing for the ultrasonic module. The ultrasonic transducer is mounted on the container lid, while the energy is transmitted to the liquid through a metal rod. This solution protects the electrical components and contributes to liquid homogenization and reduction of deposits.

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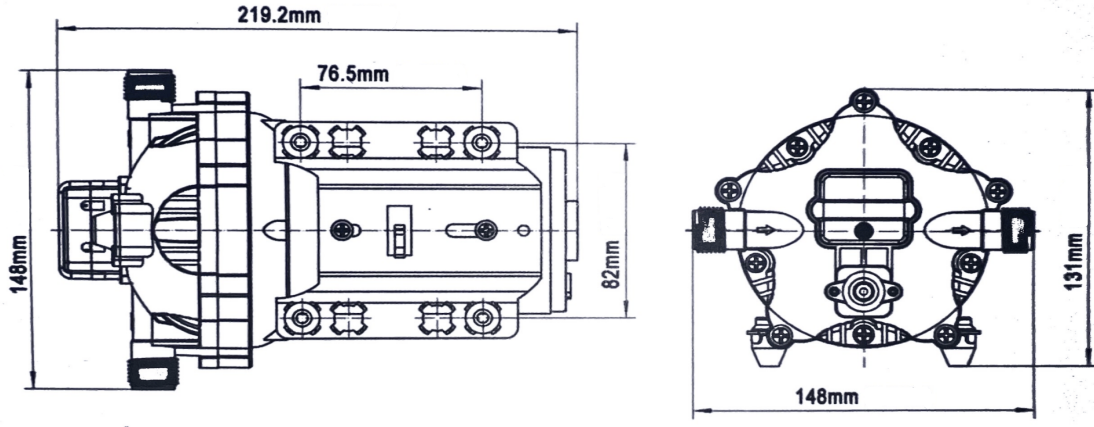


Figure.7 Diaphragm pump

5. Product Approval and Commercialization

5.1. Product Approval

Technical File for Product Approval

Unit: Technical / Production Department

Registration number: DTO – 2026/001

Date of issue: 27.04.2026

Document status: Approved

Equipment Identification and Purpose

Identification data

- Equipment name: Mobile unit for the supply and ultrasonic reconditioning of electrolyte in electrochemical micromachining
- Model code: AF-US-120 (Series 01)
- Beneficiary: Non-Conventional Machining Department
- Manufacturer / Designer: Internal — Technical Team

Technical Verification Sheet

Table 4 presents the comparison between the imposed values and the target values from the project with the values measured on the unit. For each parameter, the compliance conclusion is indicated as ACCEPTED, confirming that the equipment meets the required specifications.

Table 4. Validation of compliance between the imposed values and the values achieved

No.	Technical Parameter	Unit	Imposed Limit (min/max)	Target / Measured Value	Conclusion
1	Equipment mass	kg	Max. 3,5	3	ACCEPTED
2	Transducer frequency	kHz	20 – 45	30	ACCEPTED
3	Power consumption	W	100 - 180	100	ACCEPTED

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4	Machining speed	mm³/min	300 - 700	500	ACCEPTED
5	Electrolytic liquid concentration	[%]	5-20%	10%	ACCEPTED
6	Reservoir capacity	litri	Min. 25	120	ACCEPTED
7	Supply pressure	bar	Min. 4	4	ACCEPTED
8	Machining current	[A]	50-100	50	ACCEPTED
9	Ultrasonic amplitude	[μm]	10-30	15	ACCEPTED
10	Operating autonomy	Hours	2-6	4	ACCEPTED
11	Best roughness of the machined surface	[μm]	1-2	1	ACCEPTED
12	M. T. B. F.	hours	5000-10000	6000	ACCEPTED
13	Safety	YES/NO	YES	YES	ACCEPTED
14	Material conductivity	[Ms/m]	1-60	40	ACCEPTED
15	Operating noise	[dB]	60-90	80	ACCEPTED
16	Reconditioning efficiency	%	95	99	ACCEPTED
17	Production cost	RON	10.000 – 20.000	15.000	ACCEPTED

Analysis of the risks associated with the mobile unit

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Electrical risks → faults, overheating

Measures: overcurrent protection, protective housings.

Chemical risks → leaks, splashes, contact with corrosive substances

Measures: proper sealing, chemically resistant materials, handling rules.

Mechanical risks → tipping over, tensioning of cables and hoses

Measures: stable structure, lockable wheels, safe operation.

Ultrasonic risks → noise, vibrations, heating of the electrolyte.

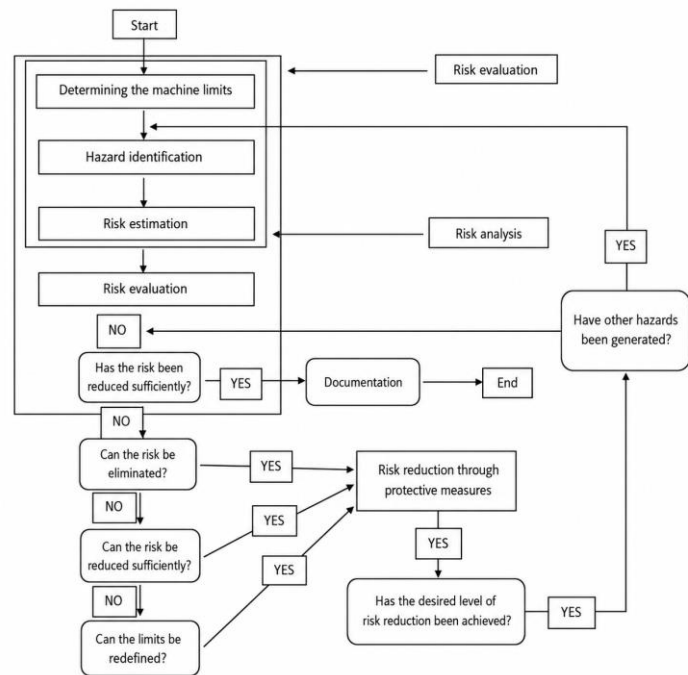


Fig. 8. Schematic representation of the risk reduction process [6]

Measures: temperature monitoring, access limitation.

Conclusion → protective measures and operator training ensure the safe use of the mobile unit.

5.2. Commercialization

Electrochemical machining technology is essential for manufacturing components that require microscopic precision, durability under extreme conditions, and superior surface finishes, without thermal wear.

Figure 8 shows the potential buyers located around Bucharest on the map.

In the aerospace industry, it is used for critical aircraft and helicopter components, ensuring maximum performance and safety.

MOBILE UNIT FOR ELECTROLYTE SUPPLY AND ULTRASONIC RECONDITIONING IN ELECTROCHEMICAL MICROMACHINING

- **Components:** Turbine rotors and stators, compressor disks and blades, printed circuit boards (PCBs) for flight control, structural fuselage panels, and door frames.
- **Potential buyers:** Turbomecanica, INCAS, Romaero, Honeywell Aerospace România, Airbus Helicopters România.
- In the automotive industry, ECM enables the production of complex systems required for new generations of vehicles and devices.
- **Components:** Injection systems, braking systems, electronic control systems, and electric propulsion systems. It is also used for phone housings and precision electronic components.

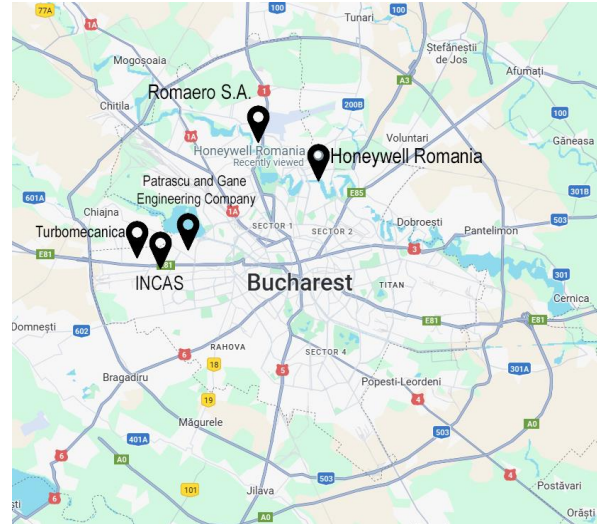


Figure 9. Map representation of potential buyers

- **Potential buyers:** CNC Tech SRL, Eastman Metal Work, Continental Automotive România.
- In the medical industry, the technology ensures smooth edges and biocompatibility for implantable devices and surgical instruments.
- **Components:** Orthopedic implants, such as titanium screws and rods, dental implants, vascular stents made of nitinol, heart valves, and surgical instruments, such as forceps and blades.
- **Potential buyers:** Patrașcu & Gane Engineering Company SRL.

6. Conclusion

The contributions of this paper consist in the development of a mobile unit designed for the filtration, recirculation, and ultrasonic reconditioning of the electrolytic liquid used in electrochemical micromachining. The proposed constructive solutions were validated through checks and tests, and the system contributes to liquid homogenization, reduction of deposits, and maintenance of stable operating conditions. The obtained results demonstrated the proper technical and functional operation of the mobile unit.

7. Bibliografie

[1]. *** Disponibil la: <https://www.flowgrinding.com/products-services/electrochemical-deburring-systems/> accesat la 22.04.2026;

[2]. *** Disponibil la: <https://www.amafiltration.com/products/filter-housings/cartridge-filter-housings/> accesat la 30.04.2026;

[3]. *** Disponibil la: <https://shop.alfalaval.com/en-us/water-based-fluids--2267428/alfie-500--1327572-> accesat la 02.05.2026;

[4]. *** Disponibil la: https://www.rosedaleproducts.com/700-series-cartridge-filter-housings-c-47_51_378.html accesat la 21.04.2026;

MOBILE UNIT FOR ELECTROLYTE SUPPLY AND ULTRASONIC RECONDITIONING IN ELECTROCHEMICAL MICROMACHINING

[5]. Ewa Szatylowicz, Iwona Skoczko; “Magnetic Field Usage Supported Filtration Through Different Filter Materials”, 11(8), Iulie, 2019. (Accesat la data de 20.01.2026: <https://www.mdpi.com/2073-4441/11/8/1584>)

[6] International Organization for Standardization. (2010). *Safety of machinery — General principles for design — Risk assessment and risk reduction* (BS EN ISO 12100:2010). (Accesat la data de 28.04.2026)

PRESCRIBING ASSEMBLY PRECISION BASED ON DIMENSION-DEPENDENT TOLERANCES

CODREANU Irina-Maria, GHEORGHE Ștefania-Adriana and **IONESCU Nicolae**

Faculty of Industrial Engineering and Robotics, Specialization: Master Industrial Engineering, 2nd year, e-mail: irina.codreanu01@gmail.com

***ABSTRACT:** The paper presents the development of a computational model for the graphical representation of ISO fits and geometric boundaries associated to the Maximum and Least Material Conditions, as well as the Virtual and Resultant Condition Boundaries. The proposed model integrates both dimensional and geometric tolerances for calculations and plotting. The application is implemented in Python and uses basic libraries to produce an end product that is simple but effective in its intended purpose. The system allows for the representation of clearance, transition and interference fits, as well as the influence of the position tolerances on the effective functional behaviour of the assembly. The developed model contributes to improving the interpretation of the link between boundaries and functional conditions and represents a basis for future developments dedicated to additive manufacturing.*

***KEY WORDS:** ISO fits, GD&T, MMC, VCB, geometric tolerances.*

1. Introduction

Dimensional and geometric tolerances represent a fundamental component in the design and manufacturing of mechanical assemblies, ensuring functionality, modularity, and reliability. In industrial manufacturing processes, parts cannot be manufactured at their exact measurements due to limitations of machining processes, tool wear, process instability, and environmental influences [1], [2].

This situation is why standardized tolerancing systems are needed to define the allowed dimensional variations, keeping intact the functionality of the assemblies. International standards like ISO 286, ISO 1101, and ASME Y14.5 for geometric tolerances offer the necessary means for dimensional and geometric variation control in different applications [2], [3]. ISO 286 establishes a standardized system of fits for holes and shafts by using tolerance and fundamental deviation classes. These systems allow the specification of dimensional requirements in a recurrent and internationally known manner, making possible the compatibility of components that are fabricated in different production environments [1], [2].

The representation of ISO fits remains a numerical and tabular one. It requires supplementary interpretations and clarifications to understand the real functional behavior of the assembly. Although the dimensional compatibility can be mathematically proven by the calculus of the maximum and minimum fits (J_{max} and J_{min}), the tabular representations offer limited information on the influence of geometric variations that affect the effective assembly conditions [1], [4].

In modern designing, dimensional tolerances are frequently linked with Geometric Dimensioning and Tolerancing (GD&T) principles. The purpose is not only to control the dimension of features but also the orientation, shape, and their positioning [5]. Concepts such as Maximum Material Condition (MMC), Least Material Condition (LMC), the position tolerance, the Virtual Condition Boundary (VCB), and the Resultant Condition Boundary (RCB) allow for the assessment of the functional behavior of assemblies in limit-case scenarios [6], [7].

Unlike the simple dimensional tolerances, the geometric tolerances directly influence the components that are in contact in the assembly. This is why a fit that is considered a clearance fit could become restrictive when position variations are introduced [8], [9]. The

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interpretation of these concepts becomes more complex in additive manufacturing environments. Here, the dimensional deviations are influenced directly by the parameters of the process, thermal deformations, nozzle wear, material shrinkage, and the calibration of the equipment [10].

For this reason, this paper proposes the development of a computational model for the functional representation of ISO fits and GD&T boundaries, implemented as a Python application. The developed system allows for the simultaneous representation of nominal diameters, dimensional boundaries, position tolerances, and functional boundaries, highlighting both dimensional clearances and the resulting functional conditions [9], [11].

2. Research gap and paper motivation

Current methods for representing ISO fits are based mostly on numerical tables and analytical calculus. Although these models ensure the dimensional standardization and the repeatability of the manufacturing processes, they offer limited support in understanding the combined influence of dimensional and geometric tolerances upon the functionality of assemblies [1], [3]. Fig. 1 illustrates a typical online ISO fit calculator for numerical evaluation of hole-shaft assemblies. Such tools normally indicate the dimensional limits of the selected tolerances and the corresponding maximum clearance and maximum interference values, calculated from the ISO 286 tables [12]. While useful for checking dimensional compatibility, analysis of these calculators is generally limited to nominal dimensional conditions and tabular interpretations of the fit.

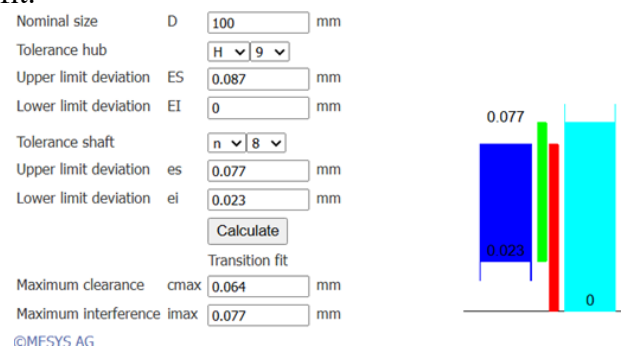


Fig. 1 Online calculation of fits application [12]

Most of the existing online calculators do not incorporate any GD&T related concepts such as position tolerances, Maximum Material Condition (MMC), Least Material Condition (LMC), Virtual Condition Boundaries (VCB) or Resultant Condition Boundaries (RCB). So they provide little insight into the actual functional behavior of assemblies under conditions of geometric variation. The effect of positional deviations on effective assembly clearances is usually not visualized and the interpretation of functional fit behaviour, therefore, depends on supplementary computations and engineering analysis.

In practical engineering applications, designers and students need to interpret separately the effects of dimensional tolerances, geometric deviations and material modifying conditions to get a better understanding of the real functional behaviour of a mechanical assembly [6], [8]. International standards define the mathematical framework for the tolerance analysis, but do not provide a common methodology for the simultaneous representation of the nominal dimensions, the tolerance zones, the geometric deviations and the functional boundaries [9], [13].

That is why ISO fits are often presented and explained with the help of graphics as well as with numerical tolerance tables. The diagrams are a clearer way to visualize the relative positions of the hole and shaft tolerance zones with respect to the zero line, enabling users to better understand the concepts of clearance, transition and interference fits. A classical graphical representation of an ISO fit is shown in fig. 2 which shows the dimensional limits

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and tolerance zones for the hole and shaft features.

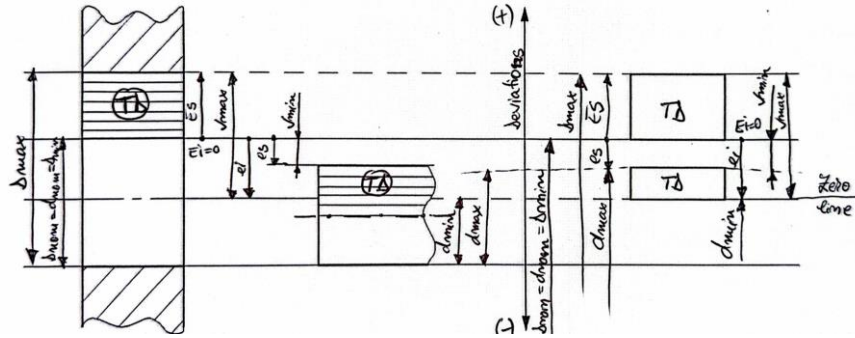


Fig. 2 Graphical representation of clearance fit

The ASME Y14.5 standard recommends graphical representation for application of Maximum Material Condition (MMC), Least Material Condition (LMC) and Regardless of Feature Size (RFS) to illustrate the effect of geometric tolerances on functional assembly behavior [9], [11]. These representations are used to visualize the relation between feature size, positional variation and the associated functional boundaries that result from geometric controls.

The graphical models in ASME Y14.5 focus on the effect of geometric deviations in different material conditions using concepts such as Virtual Condition Boundaries (VCB) and Resultant Condition Boundaries (RCB), unlike typical ISO fit diagrams which mainly show the dimensional tolerance zones. However, these representations are mostly aimed at the theoretical interpretation of single GD&T cases, instead of the integrated analysis of complete dimensional and functional fit behavior.

Fig. 3 presents examples of MMC- and LMC-based graphical representations adapted from the ASME Y14.5-2018 standard, highlighting the influence of positional tolerances on the resulting functional boundaries of internal features [9].

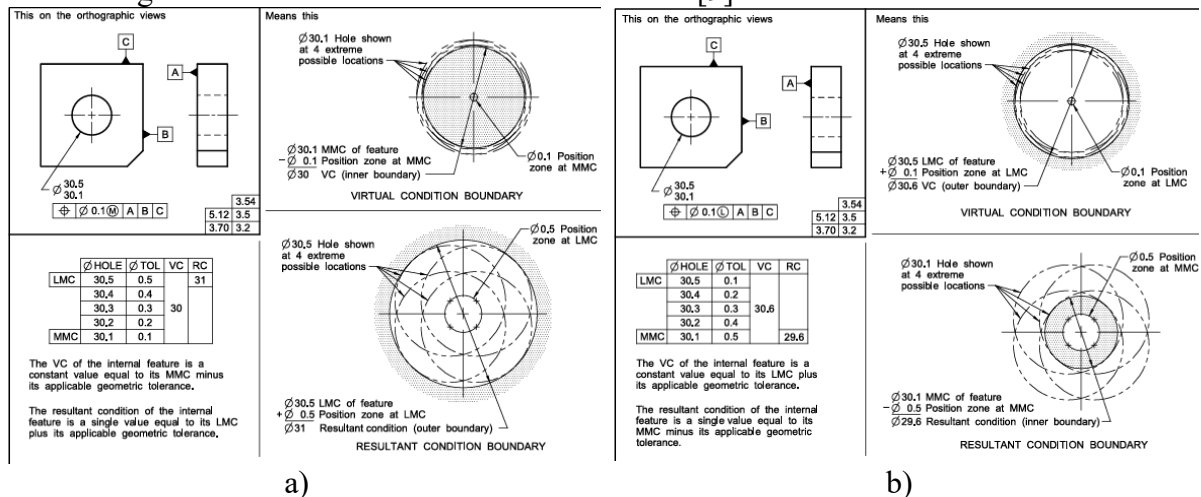


Fig. 3 a) VCB using MMC on internal feature and b) VCB using LMC on internal feature

These representations do not provide a unique framework to integrate ISO fits, maximum and minimum clearances or interferences and GD&T functional boundaries, in the same analysis environment and simultaneously. Moreover, they provide limited support for the interactive evaluation of the effect of dimensional and geometric tolerances on the effective assembly behavior under different material conditions [9], [11].

The relationship of the dimensional fits defined by ISO 286 and the functional behavior imposed by geometric tolerances is still difficult to interpret, especially in manufacturing environments with increasing dimensional variability, e.g. additive manufacturing processes [10].

This paper addresses this limitation through the development of a computational model

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capable of simultaneously visualizing ISO fits, positional tolerance zones, MMC and LMC conditions, as well as Virtual and Resultant Condition Boundaries within a unified functional analysis system.

3. Methodology

3.1. Architecture of application

The developed application was implemented in Python due to its support for scientific calculus, visualization and rapid development of graphical interfaces. The software architecture has been designed adopting a modular structure that separates the ISO tolerance databases, the engineering calculations and the graphical representation layer. The approach separates the numerical interpretation of ISO 286 fits and GD&T concepts from the visualization logic which improves the readability, maintainability and future scalability of the application.

The computational model is structured into multiple functional modules. The first module obtains the ISO tolerance data for holes and shafts, through the use of structured lookup tables with the standard deviations associated with the tolerance classes and the intervals of the nominal diameters. The second module performs the engineering calculations for the determination of MMC, LMC, Virtual Condition Boundaries (VCB), Resultant Condition Boundaries (RCB) and the dimensional and functional clearances. The third module translates these numerical values to graphical representations using circular geometries, positional tolerance zones and shaded functional regions. Such separation of data, calculations and visualization makes the link between the theoretical tolerancing model and the resulting functional behavior more evident.

The graphical user interface was developed using the Tkinter library that has standard interface elements like buttons, labels, text fields, and selection menus. Tkinter was selected due to the lightweight nature of desktop application development and the ease of integration with Python-based scientific tools [14], [15]. The graphical representation of the fits and boundaries was realized using the Matplotlib library, which supports the generation of customizable engineering visualizations and geometric plots [16], [17]. For the plotting of the figures of Matplotlib, the FigureCanvasTkAgg component was used for embedding the figures directly into the Tkinter interface, so that the calculation modules and the graphical visualization environment could interact simultaneously.

3.2. Implementation of ISO tolerances and calculations

The values of the ISO tolerances for holes and shafts were introduced in the application using Python dictionaries, which contain dimensional ranges and the associated upper and lower boundaries. Each tolerance class is represented with a dedicated key which is associated with several nominal diameter ranges. The structure allows an automated extraction of the required deviations for a user-defined nominal diameter and offers a direct link of the standardized ISO data to the used functional analysis model in the application.

The hole and shaft systems were used to enable the analysis of clearance, interference and transition fits on the same graphical representation. The modular structure of the tolerance data also facilitates the extension of the application to further tolerance classes and nominal diameter intervals.

The application employs calculations that use the principles of Maximum Material Condition (MMC), Least Material Condition (LMC), Virtual Condition Boundary (VCB), and Resultant Condition Boundary (RCB) [6], [7]. Separate calculation procedures were developed for internal and external features because of the inverse material behaviour of holes and shafts. The following relationships, seen in table 1, were used in the dimensional model:

Table 1. Formulas and code for feature conditions

Feature	Condition	Formula	Code
Hole	MMC	$MMC_{hole} = D_{nominal} + EI$	<code>mmc = nominal + min(lower_dev, upper_dev)</code>

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	LMC	$LMC_{hole} = D_{nominal} + ES$	$lmc = nominal + \max(lower_dev, upper_dev)$
Shaft	MMC	$MMC_{shaft} = D_{nominal} + es$	$mmc = nominal + \max(lower_dev, upper_dev)$
	LMC	$LMC_{shaft} = D_{nominal} + ei$	$lmc = nominal + \min(lower_dev, upper_dev)$

Based on these limit conditions, the minimum and maximum dimensional fits are determined as follows in table 2:

Table 2. Formulas and code for fit calculations

Description	Formula	Code
Minimum fit	$J_{min} = MMC_{hole} - MMC_{shaft}$	<code>jmin = mmc_hole - mmc_shaft</code>
Maximum fit	$J_{max} = LMC_{hole} - LMC_{shaft}$	<code>jmax = lmc_hole - lmc_shaft</code>

The fit classification logic implemented in the computational model is based on the minimum and maximum dimensional fits calculated. The minimum clearance is obtained by applying the MMC conditions for the hole and the shaft, and the maximum clearance is obtained by applying the LMC conditions. The fit is a clearance fit if the minimum clearance is positive. If the maximum clearance is negative, the fit is said to be interference fit. All intermediate cases are counted as transition fits as both clearance and interference may be obtained depending on the effective dimensions of the manufactured parts.

A model based on the VCB and RCB conditions was used to integrate the influence of geometric tolerances on the functional behavior of the assembly, as shown in table 3:

Table 3. Formulas and code for geometric relationships

Description	Formula	Code
Functional tolerance	$T_{func} = T_{pos} + d_{actual} - d_{ref} $	<code>t_func = t_pos + abs(d_actual - d_ref)</code>
VCB – Hole	$VCB_{hole} = MMC_{hole} - (T_{pos} + d_{actual} - MMC_{hole})$	<code>vcb_hole = mmc_hole - (t_pos + abs(d_actual - mmc_hole))</code>
VCB – Shaft	$VCB_{shaft} = LMC_{shaft} + (T_{pos} + d_{actual} - LMC_{shaft})$	<code>vcb_shaft = lmc_shaft + (t_pos + abs(d_actual - lmc_shaft))</code>
RCB – Hole	$RCB_{hole} = LMC_{hole} + (T_{pos} + d_{actual} - MMC_{hole})$	<code>rcb_hole = lmc_hole + (t_pos + abs(d_actual - mmc_hole))</code>
RCB – Shaft	$RCB_{shaft} = MMC_{shaft} - (T_{pos} + d_{actual} - LMC_{shaft})$	<code>rcb_shaft = mmc_shaft - (t_pos + abs(d_actual - lmc_shaft))</code>

The minimum functional clearance is determined from the difference between the Virtual Condition Boundaries of the hole and shaft, while the maximum functional clearance is determined from the difference between the corresponding Resultant Condition Boundaries. Unlike the classical ISO clearances, these values also include the influence of positional tolerances and therefore provide a more representative evaluation of the effective assembly behavior under geometric variation conditions. Thus, the developed computational model allows both the verification of dimensional compatibility and the evaluation of the functional behavior of assemblies under geometric variation conditions. The theoretical relationships defined by ISO and GD&T standards were directly integrated into the engineering calculations implemented within the Python application.

3.3. User interface and representation of the fits

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The developed application has an interactive graphical user interface to simplify the input, calculation and visualization of ISO fits and GD&T parameters. In the input section the user defines the nominal diameter, chooses the hole and shaft tolerance classes, enters the positional tolerance value and selects the material condition concept used in the analysis, such as MMC or LMC, as seen in fig. 4.

The input data panel contains the following fields and values:

- Nominal Ø (mm): 20
- Hole fit: H12
- Shaft fit: c11
- Position ØT (mm): 0.20
- Concept: MMC

Fig. 4 Input data panel

The calculations panel displays the following information:

Clearance fit | Jmin=-0.290 mm | Jmax=1.190 mm | Concept: MMC
 Ø 20.0 mm | H12/c11 | t = 0.2 mm | Concept = MMC

SIZE LIMITS (from ISO tables)
 Hole MMC = Ø + EI = 20.000 mm
 Hole LMC = Ø + ES = 20.210 mm
 Shaft MMC = Ø + es = 19.890 mm
 Shaft LMC = Ø + ei = 19.760 mm

BOUNDARIES (concept = MMC)
 General formula:
 VCB = d_{actual} - (t + |d_{actual} - d_{MMC}|)
 RCB = d_{actual} + (t + |d_{actual} - d_{MMC}|)

HOLE VCB (d_{actual} = MMC = 20.000)
 = 20.000 - (0.2 + |20.000 - 20.000|)
 = 20.000 - (0.2 + 0.000)
 = 20.000 - 0.200 = 19.800 mm

HOLE RCB (d_{actual} = LMC = 20.210)
 = 20.210 + (0.2 + |20.210 - 20.000|)
 = 20.210 + (0.2 + 0.210)
 = 20.210 + 0.410 = 20.620 mm

SHAFT VCB (d_{actual} = MMC = 19.890)
 = 19.890 + (0.2 + |19.890 - 19.890|)
 = 19.890 + (0.2 + 0.000)
 = 19.890 + 0.200 = 20.090 mm

SHAFT RCB (d_{actual} = LMC = 19.760)
 = 19.760 - (0.2 + |19.760 - 19.890|)

Plot fit

Fig. 5 Calculations panel

The interface also provides a numerical information panel that displays the calculated values of MMC, LMC, VCB and RCB and the associated dimensional and functional clearances for the selected fit. Besides the final values the application shows the used formulas and intermediate steps of the calculations so that the user can better follow the relation between the dimensional tolerances, the positional tolerances and the functional behavior of the assembly, shown in fig. 5. This approach makes the application a visualization tool in the field of tolerance analysis and an educational support tool as well.

The graphical representation of the fits was obtained by using concentric circular plots, which were developed to show the relationship between dimensional boundaries, position tolerances, material conditions and functional boundaries of mechanical assemblies. The VCB- and RCB-based conditions are each represented graphically, providing the possibility to compare dimensional limits and functional boundaries simultaneously for different material conditions.

For the dimensional variations specific to ISO fits, a radial exaggeration factor was used to increase the visibility of the differences between dimensional and functional boundaries, as they are very small with respect to the nominal size of the components. For the conversion of dimensional values into the radii of graphical representation the following relationship was used:

$$R_{\text{plot}} = R_{\text{base}} + [(d - D_{\text{nominal}}) / 2] \cdot E \rightarrow \text{return BASE_RADIUS} + ((d - \text{nom}) / 2) * \text{exaggeration}$$

Position tolerances are represented as circular zones associated with the permissible displacement of geometric features:

$$R_{\text{pos}} = [(T_{\text{pos}}) / 2] \cdot E \rightarrow \text{return (pt / 2) * exaggeration}$$

The graphical interface also has an interactive legend system that allows activation/deactivation of individual graphical layers. The mechanism allows the user to selectively display dimensional boundaries, VCB and RCB conditions, positional tolerance zones, nominal diameters, and the shaded Jmin and Jmax functional regions. This feature

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enhances the readability of the graphical representation, in particular when more than one overlapping boundary and tolerance zone are displayed simultaneously. The model makes it possible to identify situations where a fit, which is dimensionally classified as a clearance, transition or interference fit, can behave functionally differently under geometrical variation conditions, by comparing dimensional and functional clearances within the same graphical environment. Fig. 6 shows the graphical interface of the developed application, where the simultaneous display of ISO dimensional limits, positional tolerance zones, functional boundaries and the interactive layer management system related to the analyzed fit are shown.

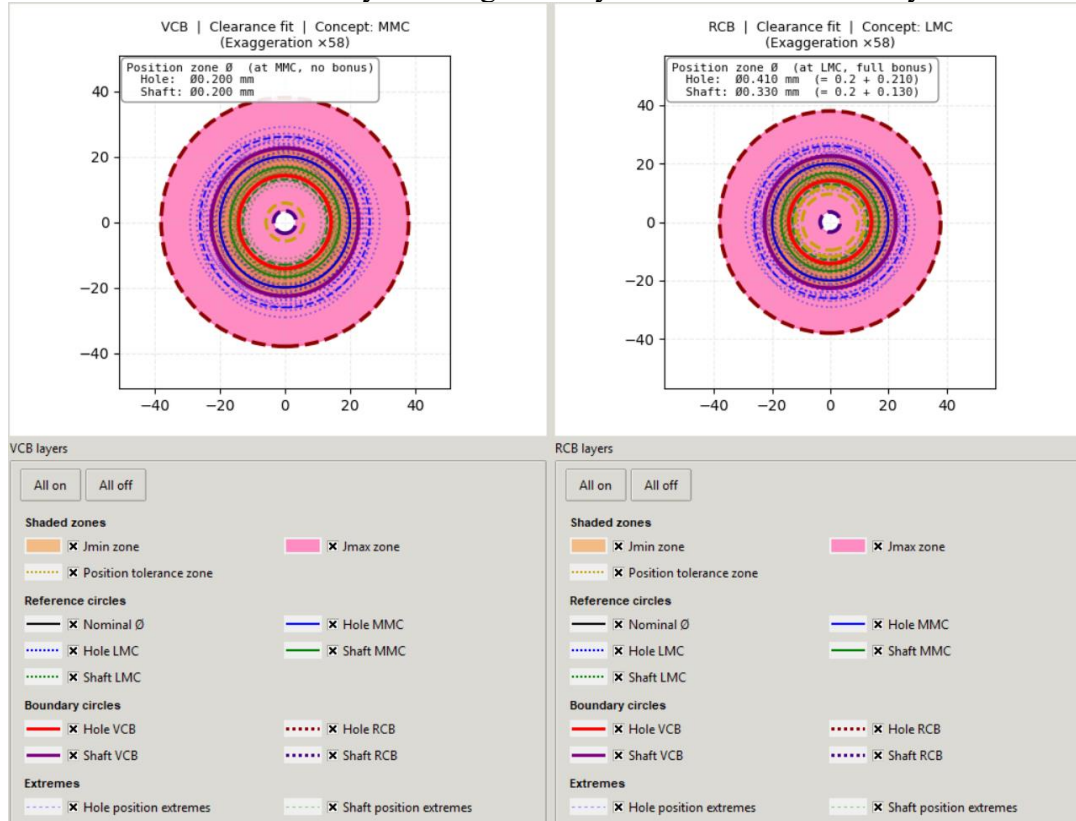


Fig. 6 Graphical representation panel

The developed graphical model highlights the differences between classical dimensional analysis and functional analysis based on geometric tolerances. By simultaneously representing the VCB and RCB boundaries, the application allows a clearer evaluation of the influence of positional tolerances on the effective assembly behavior and functional clearances. Compared to conventional approaches based only on ISO tables and numerical calculations, the proposed model improves the interpretation of the relationship between dimensional limits and functional behavior by integrating ISO fits and GD&T concepts within the same graphical environment.

4. Conclusions and future developments

The obtained results show that classical dimensional fit analysis is not always sufficient for evaluating the effective functional behavior of mechanical assemblies. Even in situations where a fit is dimensionally classified as a clearance, transition, or interference fit, geometric tolerances can significantly influence the resulting assembly conditions.

By combining ISO 286 dimensional relationships with the functional boundary concepts defined in ISO 1101 and ASME Y14.5-2018, the developed model provides a clearer interpretation of assembly behavior under geometric variation conditions. The graphical representation of VCB and RCB boundaries also improves the understanding of the relationship between dimensional limits, positional tolerances, and functional clearances.

The proposed system provides a foundation for future engineering and educational tools focused on functional fit analysis and the integration of dimensional and geometric tolerancing concepts in mechanical assembly evaluation.

Future developments of the proposed model include the integration of additive manufacturing process

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analysis, where dimensional and geometric deviations are strongly influenced by process parameters, thermal deformation, material shrinkage, and machine calibration. Such an extension could allow the prediction of functional assembly behavior directly from manufacturing conditions and improve the evaluation of fit performance in additive manufacturing environments.

5. Bibliography

- [1] ISO 286 vs GD&T: Mechanical Fits and Tolerance Standards. (2025, June 9). ALEKVS. <https://www.alekvs.com/iso-286-vs-gdt-mechanical-fits-and-tolerance-standards/>, accessed November 2025
- [2] ISO 286-1:2010
- [3] ISO 286-2:2010
- [4] Willson D. Types of fit in engineering: clearance, transition, and interference [Internet]. Fictiv. 2025. Available from: <https://www.fictiv.com/articles/engineering-fits-clearance-transition-interference>, accessed November 2025
- [5] Bemis C, Bemis C. ISO vs ASME Position Tolerance | GD&T Basics. GD&T Basics. <https://www.gdandtbasics.com/iso-vs-asm-position-tolerance/>, accessed November 2025
- [6] Basics G. Maximum Material Condition (MMC) | GD&T Basics. GD&T Basics. <https://www.gdandtbasics.com/maximum-material-condition/>, accessed November 2025
- [7] Basics G. Least Material Condition (LMC) | GD&T Basics. GD&T Basics. <https://www.gdandtbasics.com/least-material-condition/>, accessed November 2025
- [8] Basics G. True Position – Position tolerance | GD&T Basics. GD&T Basics. <https://www.gdandtbasics.com/true-position/>, accessed November 2025
- [9] ASME Y14.5-2018, Dimensioning and Tolerancing, Engineering Product Definition and Related Documentation Practices, International Standard
- [10] Tolerances for 3D printing: accuracy, clearance & design tips - Sinterit – Professional SLS 3D Printers & Accessories. Sinterit – Professional SLS 3D Printers & Accessories. <https://sinterit.com/3d-printing-guide/design-for-3d-printing/tolerances-3d-printing/>, accessed April 2026
- [11] Basics, G. (2022, December 14). Regardless of feature size | GD&T Basics. GD&T Basics. <https://www.gdandtbasics.com/regardless-of-feature-size/>, accessed November 2025
- [12] Online calculation of fits, <https://www.mesys.ch/calc/tolerances.fcgi?lang=en>, accessed April 2026
- [13] Bemis, C., & Bemis, C. (2024, May 20). Designing to MMC and LMC | GD&T Basics. GD&T Basics. <https://www.gdandtbasics.com/designing-to-mmc-and-lmc/>, accessed November 2025
- [14] tkinter — Python interface to Tcl/Tk. (n.d.). Python Documentation. <https://docs.python.org/3/library/tkinter.html>, accessed May 2026
- [15] GeeksforGeeks. (2025, July 12). What is Tkinter for Python? GeeksforGeeks. <https://www.geeksforgeeks.org/python/introduction-to-tkinter/>, accessed May 2026
- [16] Quick start guide — Matplotlib 3.10.3 documentation, https://matplotlib.org/stable/users/explain/quick_start.html, accessed May 2026
- [17] Why every data scientist should know Matplotlib | Noble Desktop. (2025, July 15). <https://www.nobledesktop.com/blog/why-learn-matplotlib-for-data-science>, accessed May 2026

**RESEARCH REGARDING THE DESIGN AND DEVELOPMENT OF AN EXPERIMENTAL
MOBILE PLATFORM FOR SOIL SAMPLE COLLECTION**

**SIMION Andrei, VOICU Daniel, CHIRVASIU Cosmin-Mihai, SIMUT Alexandru and SAVU Tom,
TARBĂ Ioan Cristian**

Faculty: Industrial Engineering and Robotics, Specialization: Computer Applications in Industrial
Engineering, Year of study: Master 1, e-mail: andrei.simion2211@stud.fiir.upb.ro

ABSTRACT

The current research stage of the design and development of an experimental mobile platform for soil sample collection is presented in this study. The proposed system aims to automate the sampling process, coordinate navigation and temporary storage of collected samples. The study analyzes the soil sampling method, the storage capacity of the samples, the navigation strategy based on zig-zag movement between predefined coordinates and the energetic consumption of the system. The paper also presents the selected power supply solution and several aspects regarding the future user interface. The proposed experimental model represents a preliminary step toward the development of a semi-autonomous platform for agricultural and environmental applications.

KEYWORDS: soil sampling, mobile platform, zig-zag navigation, energetic consumption, autonomous system

1. Introduction

Soil sampling is one of the most important steps in the analysis of agricultural land quality and in the monitoring of environmental parameters. In modern agriculture, the information obtained from soil analysis is used to establish the optimal amounts of fertilizers, assess moisture, determine pH and analyze the composition of the soil. In most cases, sampling is carried out manually, a process that is time-consuming and involves a high consumption of human resources.

According to recommendations on the correct sampling of soil samples, the routes used for harvesting should allow obtaining representative samples for the entire analyzed area [1]. Several modern methods of movement and sampling are presented in the specialized literature, including zigzag routes, grid methods and autonomous systems based on GPS coordinates and navigation algorithms [2], [3]. Among them, the zigzag movement method is one of the most used due to its uniform coverage of the land and simplicity of implementation.

The paper presents the current status of the team project on the development of a mobile experimental platform for soil sampling. At this stage of the project, the sampling and storage method of the samples, the movement of the platform to predetermined coordinates using a zigzag path and the energy consumption of the system together with the power supply method were analyzed. Also, some directions regarding the development of a user interface are presented.

The main objective of the project is to develop a mobile system capable of moving autonomously or semi-autonomously to certain coordinates and taking soil samples under controlled conditions, reducing the time required for the process and the errors associated with manual sampling.

2. Needs analysis

The development of a mobile platform for soil sampling is driven by the need to automate the sampling process in the field of precision agriculture and environmental monitoring.

Currently, manual sampling involves a high consumption of time and human resources, and the results can be influenced by the operator's experience and the uneven distribution of sampling points [1]. In addition, extensive agricultural lands require moving over large areas and repeating sampling operations at several points.

The needs analysis highlights several main requirements for the proposed system:

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- reducing the time required for sampling;
- increasing the uniformity and repeatability of the process;
- the possibility of moving to preset GPS coordinates;
- separate storage of samples to avoid contamination;
- reducing direct human intervention;
- ensuring sufficient energy autonomy for field operation.

From a functional point of view, the system must allow both manual control and semi-autonomous operation. The use of a mobile robotic platform offers the possibility of later integration of additional sensors for monitoring environmental parameters and soil analysis.

3. Functional analysis

The functional analysis of the system highlights the main functions necessary to carry out the automated soil sampling process.

The main function of the system is the sampling and transport of soil samples from predetermined points to the storage area.

To achieve this main function, the system must perform the following secondary functions:

- autonomous or semi-autonomous movement in the field;
- identification of GPS coordinates;
- stopping at sampling points;
- activation of the sampling mechanism;
- collection and storage of samples;
- power supply of electronic and mechanical components;
- transmission of information to the user.

From a structural point of view, the system is made up of several interdependent subsystems:

- movement, navigation and GPS subsystem;
- sampling and storage subsystem;
- control and communication subsystem;
- energy subsystem

Figures 1.1, 1.2 present the conceptual diagram of the general functioning of the system.

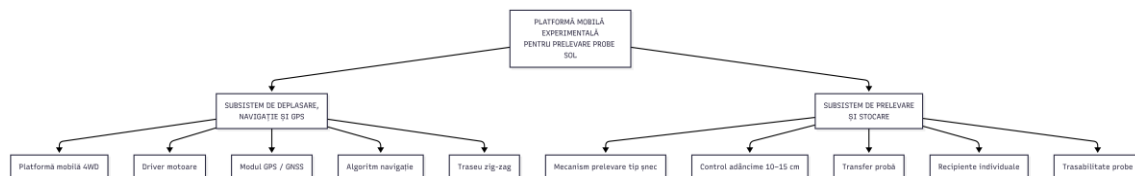


Figure 1.1 General functional diagram of the platform

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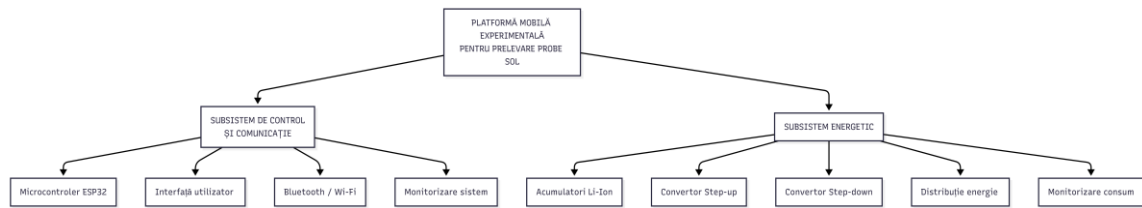


Figure 1.2 General functional diagram of the platform

4. Current status

In recent years, the development of autonomous systems used in agriculture has experienced a significant increase due to the need to automate agricultural processes and reduce resource consumption. UGV (Unmanned Ground Vehicle) systems are increasingly used in precision agriculture for monitoring, mapping and automatic soil sampling [2], [3]. Mobile platforms used for monitoring agricultural land are increasingly integrated into precision agriculture concepts.

Several modern commercial systems use GPS sensors, GNSS modules and autonomous navigation algorithms to move to pre-set coordinates. Relevant examples are the Agrobot Lala systems [2] and the automated platforms from AMS [3] and Wintex Agro [4], used for sampling and analyzing soil parameters in real time [3]. In the case of soil sampling systems, the emphasis is on positioning accuracy, mechanical stability of the platform and the storage of the harvested samples.

According to the information presented in modern soil sampling guidelines, the collection should be carried out at several points evenly distributed over the analyzed area, and the samples should be stored separately to avoid contamination and to ensure their traceability [1]. In practice, the number of samples depends on the area of the land and its uniformity.

5. Sampling method and sampling quality

One of the most important components of the project is the soil sampling mechanism. In this stage of the project, the use of a helical auger-based system for controlled soil extraction was analyzed.

Auger-type mechanisms are frequently used in sampling systems because they allow relatively uniform extraction of material and reduce losses during transfer [3]. In addition, the system allows for control of the sampling depth and sample evacuation to a storage container.

In the case of precision agriculture, the sampling depth frequently used for soil analysis is between 0 and 20 cm [1]. For the experimental model analyzed within the project, a depth of approximately 10–15 cm was considered, a sufficient value for testing the functionality of the mechanism.

Figure 1 shows an example of a commercial system used for mechanized soil sampling [3].



Figure 1.3 Automated soil sampling system [3]

The amount of soil sampled for each sample must be sufficient for subsequent analyses. In practice, a sample can have a mass between 200 g and 500 g, depending on the type of analyses performed [2]. For the experimental model, it was aimed to create containers capable of storing approximately 250–300 g of material.

The total number of samples collected depends on the land surface and the distribution of sampling

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points. In the case of extensive or uneven land, it is necessary to increase the number of sampling points to obtain representative results [1]. Within the experimental model, it was aimed to achieve a compromise between storage capacity, transported mass and the autonomy of the mobile platform. The experimental platform is designed to store several samples collected successively during the field trip. At this stage of the project, the possibility of using a storage system with 4–6 individual containers was analyzed. The use of separate containers allows for the avoidance of contamination between samples and facilitates subsequent identification of the coordinates from which they were taken. In the conceptual figure of the system, the sampling mechanism is centrally located to maintain the stability of the platform during operation. Mass distribution is an important aspect because the center of gravity influences the stability of the vehicle on uneven terrain. To determine the estimated maximum mass of the stored samples, the relationship can be used:

$$m_{total} = n * m_p \quad (1)$$

- m_{total} = total mass of stored samples [kg]
- n = number of containers
- m_p = mass of an individual sample [kg]

For a system with 6 containers and an average mass of 0.25 kg for each sample:

$$m_{total} = 6 * 0.25$$

$$m_{total} = 1.5 \text{ kg}$$

6. Coordinates travel method

Figure 2 shows an example of a zigzag sampling method used to evenly distribute sampling points across the field [1].

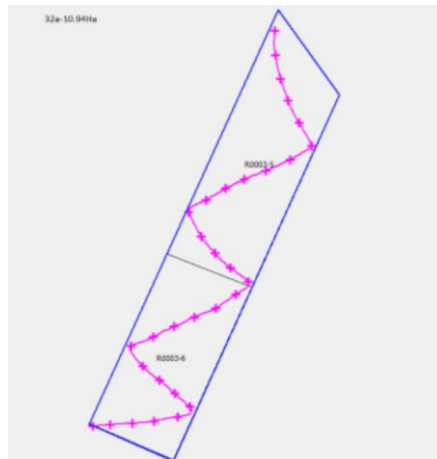


Figure 1.4 Sample route example [1]

The movement of the platform to the coordinates of interest is an essential step in the automation process. In the specialized literature, the movement paths for taking soil samples are chosen in such a way as to ensure a uniform coverage of the analyzed terrain [1], [2]. The use of a zigzag path was analyzed in the project because this method allows for efficient surface coverage and reduces the possibility of concentrating samples in a single area. The zigzag path [2] is also frequently used in manual soil sampling.

The platform moves between preset coordinates using GPS information obtained through a GNSS module connected to the robot control system. In the case of the experimental model, the coordinates can be entered manually by the user or generated automatically based on a delimited surface.

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To move to the GPS coordinates, the platform uses a simple navigation algorithm based on comparing the current position with the target position. The GPS module transmits the robot's coordinates to the main microcontroller in real time, and the system calculates the direction and distance to the next sampling point.

During movement, the platform's motors are controlled differentially to make turns and correct the trajectory. If the robot deviates from the established path, the system changes the speed of the motors to return the platform to the desired direction.

In the current project, the use of an ESP32 microcontroller together with a standard GPS module was analyzed to test the system's operation. Communication between the components allows for continuous position updating and execution of the zigzag path between the sampling points.

For professional applications, the accuracy of the system can be improved by using RTK-GPS systems, capable of reducing positioning errors down to the centimeter level [2], [3]. The main advantages of zigzag movement are:

- uniform distribution of sampling points;
- reduction of the time required to cover the terrain;
- relatively simple implementation at the software level;
- possibility of adapting the route depending on the size of the terrain.

In the case of a small experimental terrain, the route can be established so that the platform makes stops at regular intervals. At each stop point, the sampling mechanism is activated.

For the orientation of the platform and the control of the direction of movement, direct current electric motors are used together with a motor driver. At this stage of the project, the use of a 4WD mobile platform was analyzed due to its low cost and simplicity of implementation.

Positioning accuracy is an important factor in the project. Standard GPS systems can have errors of the order of meters, which is why RTK-GPS systems are used in professional applications. For the current experimental model, it was considered sufficient to use a standard GPS module intended for functional testing.

7. Energy consumption and power supply

Energy consumption is an essential parameter in the design of an autonomous mobile platform, as it directly influences the autonomy, operational stability and total mass of the system. In the case of a platform used for soil sampling, the power supply must be sized to support both the movement on the ground and the operation of the sampling mechanism [5].

Figure 1.3 shows an example of an autonomous robotic platform used for sampling and analyzing soil parameters.



Fig.1.5. Autonomous robot for soil sampling and analysis – Agrobot Lala [2]

Within the project, the main energy-consuming components are:

- electric motors used to move the platform;
- sampling mechanism motor;
- ESP32 microcontroller;

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- GPS/GNSS module;
- sensors and auxiliary modules;
- motor drivers and voltage converters.

Most of the energy consumption is generated by the travel motors and sampling mechanism, as they require higher currents during start-up, movement on uneven terrain or penetration into the ground. Electronic components, such as the ESP32 microcontroller and sensors, have lower consumption, but require a stabilized voltage for correct operation.

The energy consumption of a component can be estimated with the relationship:

$$P = U * I \quad (2)$$

Where: P represents the power consumed [W], U represents the supply voltage [V], and I represents the electric current intensity [A].

8. User interface

Figures 1.4, 1.5 show an example of a software interface used for monitoring and controlling an autonomous precision agriculture platform. The project also analyzed the development of a simple interface for monitoring platform parameters and controlling the main functions [2].

The interface can allow:

- Entering travel coordinates;
- Monitoring the battery level;
- Displaying the number of samples collected;
- Manual control of travel;
- Starting and stopping the sampling mechanism.

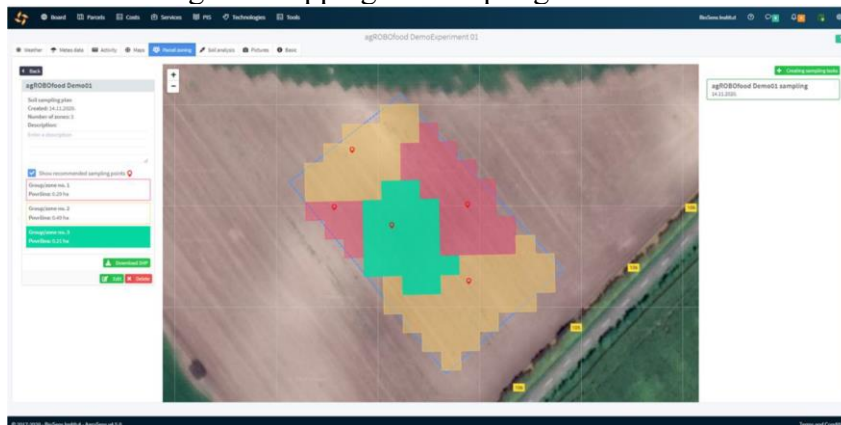


Figure 1.6 Software user interface [2]



Figure 1.7 User interface [2]

RESEARCH REGARDING THE DESIGN AND DEVELOPMENT OF AN EXPERIMENTAL MOBILE PLATFORM FOR SOIL SAMPLE COLLECTION

9. Conclusions

The paper presents the current status of the project on the development of a mobile experimental platform for soil sampling. At this stage, the main components of the system and the technical solutions used for the operation of the platform were analyzed.

The sampling and storage method of samples, the zigzag movement strategy to preset coordinates and the preliminary analysis of energy consumption and the power supply system were presented.

The results obtained to date indicate that the use of a mobile platform to automate the sampling process can reduce the time required for sample collection and improve their uniformity.

Also, the use of an autonomous mobile platform can contribute to reducing errors associated with manual sampling and increasing the repeatability of the sampling process. The integration of GPS coordinates and an individual sample storage system allows for better data traceability and facilitates subsequent analysis of the investigated terrain.

In the future stages of the project, the development of a more advanced navigation system, the integration of additional sensors and the performance of experimental field tests are aimed at.

10. Bibliography

[1] <https://www.naturevo.ro/blog/prelevarea-probelor-de-sol> [accessed on 13.05.2026, 21:00]

[2]. Kitić, G., Krklješ, D., Panić, M. et al. (2022), “Agrobot Lala—An Autonomous Robotic System for Real-Time, In-Field Soil Sampling and Analysis of Nitrates”, *Sensors*, vol. 22, nr. 11 <https://www.mdpi.com/1424-8220/22/11/4207> [accessed on 13.05.2026, 21:15]

[3] <https://www.ams-samplers.com/powerprobes> [accessed on 13.05.2026, 21:30]

[4] <https://www.wintexagrousa.com> [accessed on 13.05.2026, 22:00]

[accessed on 13.05.2026, 22:00]

[5] <https://batteryuniversity.com/article/bu-204-how-do-lithium-batteries-work> [accessed on 13.05.2026, 22:00]

SCOUTING ROBOT FOR SMALL ENCLOSED SPACES

GHEORGHE Ștefania -Adriana, CODREANU Irina-Maria, DUGĂEȘESCU Ileana

Faculty of Industrial Engineering and Robotics, Specialization: Master - Industrial Engineering, 2nd study year, e-mail: adriana.gheorghe59@yahoo.ro

Faculty of Industrial Engineering and Robotics, Manufacturing Engineering Department
POLITEHNICA BUCHAREST

Abstract: Taking into consideration the continuous technology development and the need of continuous maintenance of small enclosed spaces, it has become necessary to develop a system which can aid in the preventive maintenance process. The system integrates a mobile robot, multiple types of sensors, such as infrared sensors, temperature and humidity sensors and a camera), and a web application which aids in real time monitoring. The data is collected in a Node.js server where it is processed and further sent to be showed in a dashboard for continuous real time analysis. The proposed solution allows for remote control and data collection, therefore creating a modular platform with a reduced cost for smart maintenance and remote inspection.

KEY WORDS: robot, small, spaces, Arduino, dashboard

1. Introduction

Robotics has become one of the most dynamic domains in modern engineering by combining mechanics, electronics, informatics and artificial intelligence for creating systems capable of finishing tasks autonomously or semi-autonomously [1]. Since the first development of mobile robotic systems, the development of technology has caused the robotic system to raise their autonomy level, mobility and analysis ability of the environment, thus allowing many engineers to implement them in various industrial contexts [2].

As technology advances, mobile robots have taken over numerous industries and applications. They are engineered to function independently across multiple settings, including industrial spaces and outdoor landscapes. Wheel robots have become quite popular in the recent years due to their adaptive nature. This type of robots is engineered to traverse various challenging paths, including slippery routes and those with obstacles. They can adapt their wheel movements to different surface conditions and enhance their flexibility with the aid of mechanisms attached to their actuators. Typically, their primary objective is to efficiently track and follow a specific target or individual [2, 3].

Restricted environments, such as underground man made channels, are environments difficult to work in and periodically monitor and maintain them. Those spaces are characterized by limited visibility, small spaces, and restricted human access. In those situations, the direct intervention of people is restricted. Additionally, European standards tightly enforce the periodical verification and maintenance of those spaces [4].

The periodical maintenance of such environments is needed for preventing possible structural defects, infiltrations, deterioration and corrosion which can lead to higher maintenance and servicing costs [5]. Currently, the conventional methods for verification are based on manual inspection or through fixed sensors placed at different points of the environment. Through this, many limitations are identified such as high operation costs, high inspection time and limited data collection time and space [3].

In this case, the purpose of this project is to create a smart wheel robot for scouting confined spaces. The main objective of using smart wheel robots is to conduct thorough inspections of such environments, identifying potential problems like cracks or corrosion [6].

This ensures the environment remains intact and prevents failures that could pose environmental risks or lead to expensive repairs. These robots are designed to navigate complex networks independently, accessing areas that are hard or unsafe for humans. This autonomy enables comprehensive inspections without manual involvement, making the process more cost-effective by reducing labour needs and accident risks. The integration of advanced technologies such as cameras and sensors improves the robots' ability to accurately detect and analyse pipe conditions. This technology also supports real-time

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data collection and analysis, allowing for quicker maintenance decisions [6].

2. State of the art

Scouting robots for small enclosed spaces have become diversified in offering many commercial and academic solutions with many advantages and disadvantages. Studies regarding such robots have shown that integrating multiple sensors in analysis systems have increased the efficiency of preventive maintenance [6, 7].

By using infrared sensors for detecting thermal issues in small spaces has been documented as an efficient and low cost solution compared with commercial thermal cameras. Studies have shown that thermal mapping sensors can detect heat points efficient enough, even for low resolutions, and, in combination with the visual information collected by a camera, improve collected data quality [8].

On the other hand, IoT technologies and embedded systems have triggered the apparition of many real time monitoring platforms. The integration of microcontrollers, sensors and software applications have allowed for continuous data collection and transfer collected from environments [3].

IoT architectures for real time monitoring have been continuously improving due to the reducing manufacturing cost of components and accelerated improvement of open source software platforms. Systems based on microcontrollers with data transmission through serial or wireless communication have been repetitively used for varied industrial and academic applications involving engineering skills and the rapid emergence of AI [9, 10].

By using an event driven approach integrated with Node.js, an open source application used for creating servers or different software applications, an optimal academic solution for real time monitoring is confirmed. The asynchronous data collection allows for a simultaneous data flux management, thus, ensuring an efficient continuous transfer of information. Studies have shown that REST API architectures based on Node.js offer a better performance compared to traditional IoT solutions [10, 11].

Following the technology development, IoT connectivity has transformed the way robots work in industrial settings by creating systems in which many units work as one. IoT connected robots send real time environment data to monitoring platforms, thus, allowing a smooth transition between reactive maintenance to preventive maintenance. Those type of applications allow for local processing of low latency data, important to inspection tasks and technical monitoring. In this project, the IoT architecture implemented follows a separation principle between the data collection, transfer and analysis. The Node.js server has an edge node role through which the sensor data is processed before being sent and showed in the web monitoring dashboard [10, 12].

The significance of the project comes from the practical necessity of preventive maintenance of such small spaces where manual methods present higher risks for human operators and high intervention risks. The software architecture developed, which is based on direct serial transfer through Node.js with REST API, changes the robot from a simple data collector to a predictive maintenance analysis platform capable of reducing maintenance time and lowering the rate of error apparitions. Thus, the robot becomes relevant for current technology trends keeping it relevant to not only technical industries but to technology enthusiasts who want to keep up with the engineering community [7, 10].

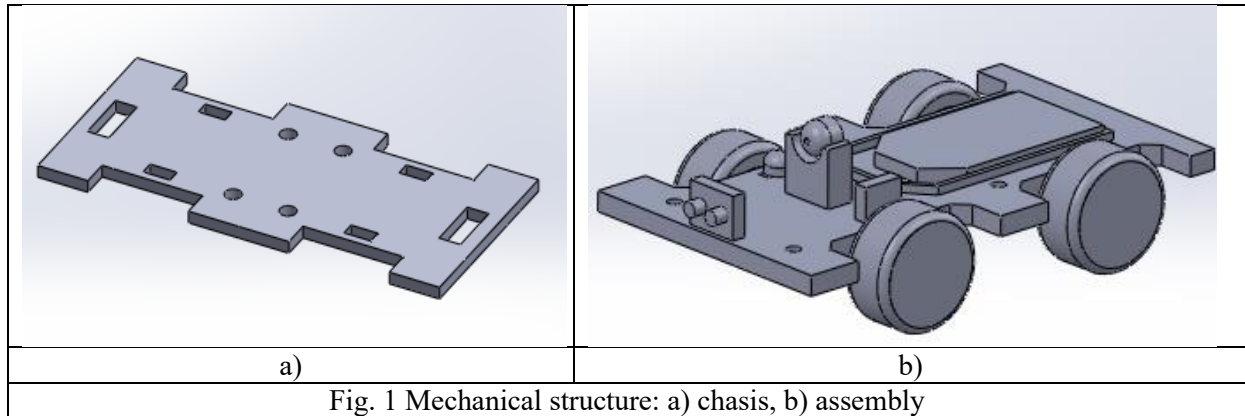
3. Code and implementation

In this chapter it will be discussed the integration between the hardware and software parts by detailing each step of the development and the thought behind it.

3.1 Mechanical structure

The chasis of the robot was designed to fit small spaces and to fit all sensors and motors of the robot, thus, folloing a modular concept which allows for sensors to be replaced easily. The movement system consisting of two DC motors was chosen due to its simple and effcient design. The chasis and the assembly can be seen in Figures 1.a) and 1.b).

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3.2 Electronic architecture

The electronic architecture is based on the Arduino UNO microcontroller. The microcontroller controls the sensors, motors and data transmissin through serial communication [13]. The pin conexions, system role and component list can be seen in Table 1.

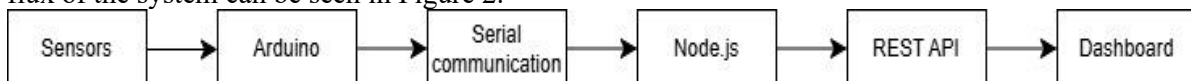
Table 1 System conexions, components role and list

Component	Arduino pin	System role
DHT11	D8	Measures ambiantal humidity and temperature
HC-SR04 Trig	D9	Emits the ultrasonic impulse
HC-SR04 Echo	D10	Receives the ultasonic echo
LED RGB Red	D11	Visually shows the state of the environment. Yellow=balanced, Red=bad status, Green=good status
LED RGB Green	D12	Visually shows the state of the environment. Yellow=balanced, Red=bad status, Green=good status
LED RGB Blue	D13	Visually shows the state of the environment. Yellow=balanced, Red=bad status, Green=good status
L298N enA	D3	Controls the speed of motor A
L298N in1	D2	Controlls the direction of motor A
L298N in2	D4	Controls the direction of motor A
L298N enB	D6	Controls the speed of motor B
L298N in3	D5	Controlls the direction of motor B
L298N in4	D7	Controls the direction of motor B
MLX90614 SDA	A4	Collects thermal environent data
MLX90614 SCL	A5	I2C clock
MLX90614 VIN	5V	Provides electric supply
ESP32-CAM	WiFi	Provides live footage

The ESP32-CAM functions independently from the Arduino UNO and is connected directly to the local WiFi. After the programming of the module, it automatically starts a video stream accessible on the dashboard through an IP address shown in the serial monitor in Arduino IDE [8].

3.3 Software architecture

The software architecture is the main component of the proposed preventive maintenance system due to its effect on the scouting robot which allows it to become a mobile real time monitoring platform. The software architecture is made of 3 main components: Arduino firmware, server backend made with Node.js, and monitoring web dashboard. This leveled approach allows for a more logical separation between the data collection, data transmission, and the software application [9, 10, 11]. The general flux of the system can be seen in Figure 2.



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Fig. 2 Flux diagram

The Node.js server reads the data directly from the serial port of Arduino by using the serial port library, thus, reducing the data transmission latency and simplifying the general flux of the system [10].

3.4 Arduino structure

The Arduino code functions on a polling cycle in which the sensors are periodically read. In each cycle the following steps are done: reading of the ambient temperature and humidity, distance measurement, determining the status and outputting the LED signal color, transmitting the JSON object to the serial port. The validation of the values collected by the DHT sensor is made by the returned values in case of a failed communication. The failed reading is restarted after some time [9]. The movement of the robot which is caused by the DC motors is controlled with the help of an ultrasonic sensor. The ultrasonic sensor functions by stopping the robot if it comes in proximity of an external object or entity smaller than 16 cm. Otherwise the robot continues its movement at nominal speed PWM 155. The stopping of the motors functions at PWM 0 for a full stop [2]. The complete Arduino hardware structure can be seen in Figure 3.

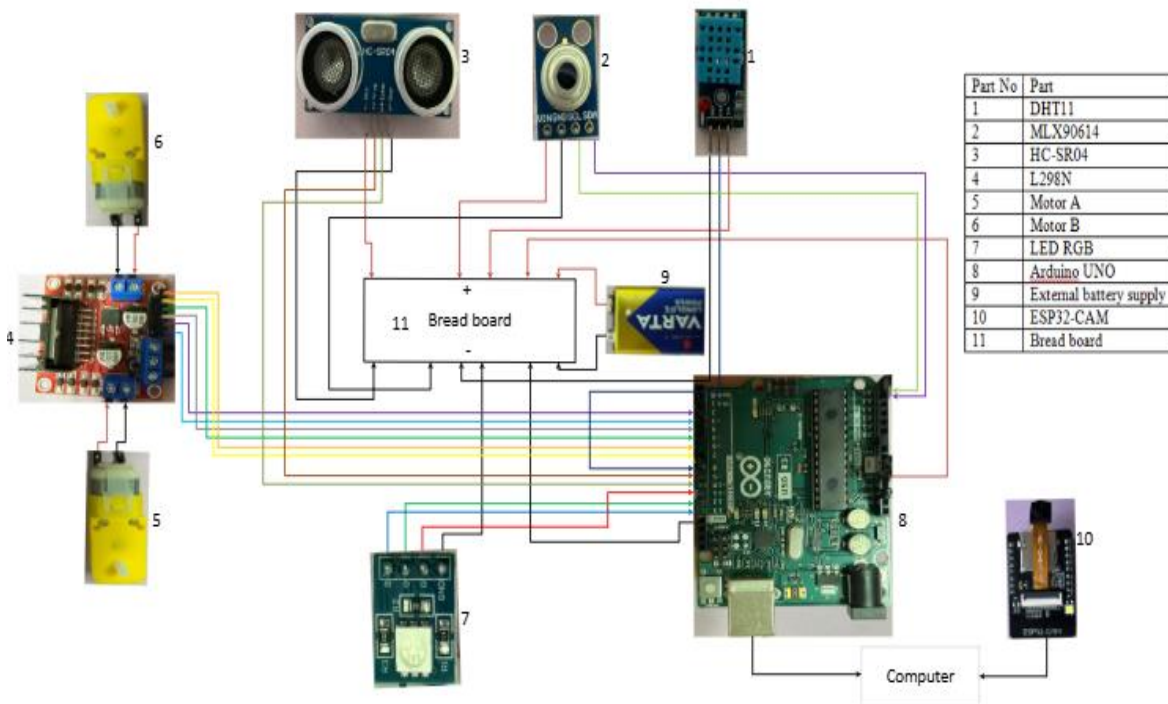


Fig. 3 Hardware structure

3.5 Serial communication

The serial communication between Arduino and the software application is done through the USB connection. The system uses a 9600 baud speed for data transmission in JSON text format. The Node.js server is used as a data base for the *SerialPort* [14] and the *ReadlineParser* [14] for data flux interpretation. The delimitation of packets is done through newline the character where each line represents an individual measurement [11].

The system supports the *key:value* and JSON formats. The JSON format is used for complex data transmission such as the temperature data. The Node.js parser is used for standardizing the parameter's names through key mapping functions, thus, ensuring server compatibility no matter the written variable used in Arduino [11, 15].

Each JSON message received is processed in 3 steps:

- Key normalizing;
- Validation and filtration of useless values (e.g. ultrasonic distances bigger than 300 cm caused by reflection and refraction);
- Simultaneous update of the general buffer through measurements [14, 15].

This type of real time processing architecture in combination with the data exposure through REST API makes the Node.js to become a processing edge node taking into consideration the IoT architectures

[16].

3.6 Node.js server

The backend server was created using the open source platform Node.js and the open source framework Express.js. The server has the role of reading, processing, and transmitting the data. The server is built in order to allow simultaneous management of the serial communication, HTTP signals, and data processing without blocking the execution of the application [10, 16].

The serial communication is managed through the npm serialport [17] library which simplifies the access to the serial port of the operating system and shows an asynchronous API JavaScript compatible with the execution mode of Node.js. The data receives from Arduino is parsed line by line through the *ReadlineParser* library [14] which detects the line end character and triggers the processing of each JSON message individually, thus reducing the resource consumption of the server [15, 16].

The backend uses REST API with eight endpoints. Using such an approach allows for smoother future improvement process [15]. The endpoints used can be found in Table 2.

Table 2 API used in Node.js [15]

Endpoint	Method	Function
/api/data	GET	Getting sensor data and the measurement history
/api/thermal	GET	Getting the thermal information
/api/ports	GET	Getting the serial port list available on the computer
/api/connect	POST	Connecting to the serial port of Arduino
/api/disconnect	POST	Disconnecting the serial connection
/api/clear	POST	Resetting the data
/api/export	GET	Exporting the data
/api/camera/set	POST	Configuring the IP of ESP32-CAM

Using the selected method of REST API with 8 endpoints, logically organized taking into account the standard convention of REST architecture, with HTTP methods ensures a flexible working mode for the server while enhancing the functionality of future upgrades [11, 15].

3.7 Web dashboard

The web dashboard is the main monitoring interface of the system and it was developed using HTML5 [18], CSS3 [19], Bootstrap5 [20], and Chart.js [11, 21]. The interface is structured in five sections: the header with the serial port selection and action buttons, the statistical windows with current values, the web camera, the graph section, and the table section.

The header allows a direct connection to the serial port of Arduino from the browser, the selection of the baud rate, and the starting of a new inspection session. The statistical section is showing the latest data value collected. The Web camera section is connecting the video stream in MJPEG format directly from the ESP32-CAM through the IP searching section. The stream is in proxy through the Node.js server and is making it accessible on the static IP coded in Arduino [8].

Lastly, the graph section together with the table section allow for a direct analysis of the data collected while ensuring data history to be visualized. The graph section includes six line charts which shows the evolution of all measured parameters which are updated incrementally every 3 seconds. The table shows the last 20 registered data with their respective timestamp. The CVS button present in the heather will transfer the table data for further analysis [15]. The web dashboard can be seen in Figure 4 a), b), and c).

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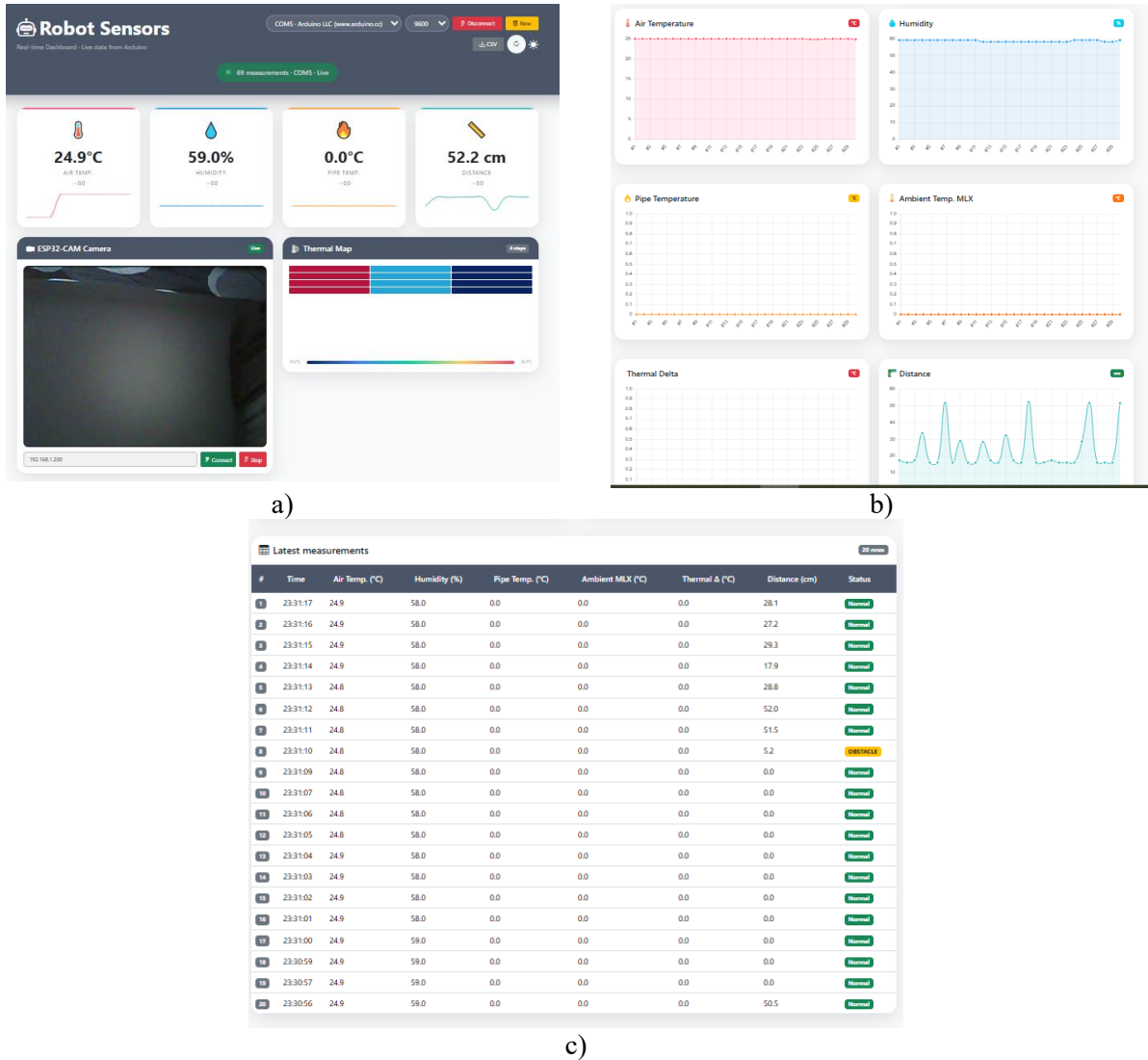


Fig. 4 Dashboard structure a) the header and the most recent data collected, b)graphs of temperature, humidity and obstacle history, c) data history table

4. Results and limitations

The tests have showed that the sensors are functioning properly. Their values have been received and showed in real time in the dashboard. The data was automatically updated without the need of refreshing the page and all graphs generated with Chart.js have allowed a complex analysis of sensor collected data. The CSV export button has successfully generated an excel file with all the collected data, thus allowing for further data comparison and history collection.

The main limitation of the system is the MLX sensor which has a single point measurement. While the MLX sensors detect major anomalies, for better event detection, it is recommended on using other sensors. Another limitation would be the battery which can offer easy replacement but limited usage life. A future plan for the robot is replacing the existing MLX sensor with an AMG8833 sensor which offers a more detailed thermal mapping of the environment, thus, improving the event detection.

5. Conclusions

This study has presented a possible development of a mobile scouting robot for preventive maintenance of small enclosed spaces. The system uses temperature and humidity sensors, proximity sensors, infrared sensors, and a camera for live video streaming.

The main contribution is represented by the Arduino structure and the software architecture. By using such a complex system, data is collected and analyzed in real time, thus ensuring a proper monitoring of the environment.

The solution proposed represents a modular platform with a low cost for inspection maintenance

applications, ensuring that advanced inspections can be obtained through accessible hardware and open source software.

6. Bibliografy

[1] Diana Popescu, *Robotics, Facultatea de Inginerie Industrială și Robotică*,

Universitatea POLITEHNICA din București, 2023.

[2] M.H. Korayem, H.R. Adriani, *Pursuing a target by wheel-legged mobile robot using NMPC while optimizing obstacles passing*, *ISA Transactions*, 2024, <https://doi.org/10.1016/j.isatra.2024.12.035>.

[3] Ali M. Sadeghioon, Nicole Metje, David N. Chapman, Carl J. Anthony, *SmartPipes: Smart Wireless Sensor Networks for Leak Detection in Water Pipelines*, *Journal of Sensor and Actuator Networks*, 2014, 3(1), 64-78, <https://doi.org/10.3390/jsan3010064>.

[4] *NORMATIV NORMATIV privind proiectarea, executia si exploatarea instalatiilor electrice aferente cladirilor - Indicativ I 7 – 2011*, [efaidnbmnnnibpcajpcglclefindmkaj/https://www.mdlpa.ro/userfiles/reglementari/Domeniul_XII/12_6_I_7_2011.pdf](https://www.mdlpa.ro/userfiles/reglementari/Domeniul_XII/12_6_I_7_2011.pdf)

[5] Giovanni de Feo, Antoniou George, Franz Fardin et al., *The Historical Development of Sewers Worldwide*, *Sustainability*, 2014, 6(6), pp. 3936-3974, <https://doi.org/10.3390/su6063936>.

[6] M. A. Viraj J. Muthugala, Povendhan Palanisamy, S. M. Bhagya P. Samarakoon, Saurav Ghante Anantha Padmanabha, Mohan Rajesh Elara and Dylan Ng Terntzer, *Raptor: A Design of a Drain Inspection Robot*, *Sensors* 2021, 21(17), 5742; <https://doi.org/10.3390/s21175742>

[7] Peng Jin, Xinyan Qin, Jin Lei et al., *Design and stability performance optimization of a novel hybrid inspection robot walking device for smart grid applications*, *Alexandria Engineering Journal*, Vol. 109, 2024, pp. 970-988, <https://doi.org/10.1016/j.aej.2024.09.067>.

[8] Zhaxalikov, A., Mombekov, A., Sotsial, Z., *Surveillance Camera Using Wi-Fi Connection*, *Procedia Computer Science*, Vol. 231, 2024, pp. 721-726, <https://doi.org/10.1016/j.procs.2023.12.147>.

[9] Goyal, D., Patra, S., Sapre, A. et al., *Design and Development of Arduino-Based Four-Channel Data Acquisition System with Digital Temperature Control for Chemiresistive Sensors*, *Sensing and Imaging*, Vol. 25, 30, 2024, <https://doi.org/10.1007/s11220-024-00477-2>.

[10] *Exploring Dynamic RESTful API Implementation in IoT Environments Using Docker*, *Scientific Reports*, Nature, 2025, <https://doi.org/10.1038/s41598-025-16460-0>.

[11] Ancona, M. et al., *Towards Runtime Monitoring of Node.js and Its Application to the Internet of Things*, *arXiv:1802.01790*, 2018, <https://arxiv.org/pdf/1802.01790>.

SCOUTING ROBOT FOR SMALL ENCLOSED SPACES

[12] Manoj Kumar, Piyush Kumar Singh, *IoT-based real-time robot monitoring*

and control system using cloud computing, Journal of King Saud University

Computer and Information Sciences, Vol. 34, Issue 9, 2022, pp. 7610-7618,

<https://doi.org/10.1016/j.jksuci.2021.09.014>

[13] Arduino UNO, <https://docs.arduino.cc/hardware/uno-rev3/>, last accessed 14.05.2025

[14] SerialPort Contributors, Node SerialPort — ReadlineParser Documentation, GitHub / serialport.io, available at <https://serialport.io/docs/api-parser-readline>,

Last accessed 15.5. 2026.

[15] Chandrasekar Rajagopalan, Rajeswari Sridhar, *Design and Implementation*

of RESTful API Architecture for IoT Data Management Using Node.js and Express, Computers and Electrical Engineering, Vol. 108, 2023, <https://doi.org/10.1016/j.compeleceng.2023.108652>

[16] Usman Ullah Sheikh, Mohd Norzali Haji Mohd, *Real-Time Serial Data Acquisition and Monitoring Framework Using Arduino and Node.js for IoT Applications, IEEE Access, 2023, <https://doi.org/10.1109/ACCESS.2023.3269087>*

[17] npm, Inc., @serialport/parser-readline — Official Package Documentation, npm Registry, available at <https://www.npmjs.com/package/@serialport/parser-readline>,

Last accessed 15.05.2026.

[18] W3C, HTML5 — A vocabulary and associated APIs for HTML and XHTML, W3C Recommendation, available at <https://www.w3.org/TR/html5/>, last accessed at 15.05.2026.

[19] W3C, CSS Snapshot 2023, W3C Working Group Note, available at <https://www.w3.org/TR/css-2023/>, last accessed at 15.05.2026.

[20] Otto, M., Thornton, J., Bootstrap — The most popular HTML, CSS, and JS library, v5.3, Bootstrap Core Team, 2023, available at <https://getbootstrap.com/docs/5.3/>, last accessed 15.05.2026.

[21] Chart.js Contributors, Chart.js — Simple yet flexible JavaScript charting library, v4.0, 2023, available at <https://www.chartjs.org/docs/latest/>, last accessed at 15.05.2026.

RESEARCH ON THE DEVELOPMENT OF AN INTELLIGENT SORTING SYSTEM FOR POLYMERIC PARTS

MIROIU Ana-Maria, NIȚU Maria-Luiza, CHIVU Carmen-Alexandra,
Prof. dr. ing Nicolae IONESCU, Conf. dr. ing. Bogdan Felician ABAZA

Faculty: Industrial Engineering and Robotics, Specialization: INPN/IEMA, Year of study: I, e-mail:
maria_luiza.nitu@stud.fiir.upb.ro

SUMMARY: This paper presents the conceptual development of a fully integrated intelligent sorting system for polymeric parts, designed for small and medium enterprises. The system combines a modular conveyor, AI-based visual inspection using MobileNetV2, embedded control via Arduino, and an automatic sorting mechanism. Functional and non-functional requirements, detailed specifications, system architecture, and complete operation scenarios are defined. An economic analysis demonstrates feasibility with a prototype cost of 380–480 EUR, accuracy above 95%, and throughput of 10-20 parts/min. The work provides a solid technical and economic foundation for future physical implementation, integrating additive manufacturing, artificial intelligence, and embedded systems in a scalable, low-cost solution.

KEYWORDS: intelligent sorting system, computer vision, polymer components, additive manufacturing, economic analysis

1. Introduction

In the polymer industry, ensuring quality control during component assembly (e.g., bases, covers, housings) is critical for minimizing defect rates and maintaining market competitiveness. Manual inspection methods are inherently slow—limited to throughputs of 10–20 parts per minute—and are prone to human error rates of 10–20%. Conversely, existing automated industrial solutions carry prohibitive capital expenditures, often exceeding EUR 5,000–15,000, and lack the flexibility required for rapid adaptation to small-batch production [7].

To address these limitations, this paper presents the conceptual, ground-up development of an intelligent sorting system that synergistically integrates additive manufacturing, artificial intelligence, and embedded control systems [1][3]. The primary objective of this study is to define the functional and non-functional requirements, comprehensively detail system functions and technical specifications, outline the operational workflow, conduct a rigorous economic analysis, and establish the foundational architecture for a physical prototype. The proposed system is designed to be modular, scalable, and low-cost (under EUR 500), while achieving a minimum sorting accuracy of 95% and a minimum throughput of 50 parts per minute.

2. State of the Art

The sorting of polymer components is currently achieved through three primary approaches: manual inspection, which features low initial costs but suffers from poor throughput and high error rates; high-end industrial systems (e.g., Keyence, Cognex) that deliver high accuracies exceeding 98% but incur prohibitive capital costs; or research frameworks based on Convolutional Neural Networks (CNNs), the majority of which remain confined to the simulation level [7].

Several critical gaps have been identified in the literature: a lack of comprehensive mechanical-AI hardware integration, prohibitive deployment costs for Small and Medium-sized Enterprises (SMEs), and a general absence of well-defined functional requirement specifications. This paper addresses these deficiencies by proposing a mature, economically viable conceptual architecture [2].

3. System Requirements, Functions, Specifications, and Characteristics

3.1 Needs and Requirements

The proposed system addresses key operational needs, including controlled transport, automated defect detection (covering geometry, alignment, color, and structural integrity), rapid OK/NOK sorting, real-time feedback, and low-cost implementation.

RESEARCH ON THE DEVELOPMENT OF AN INTELLIGENT SORTING SYSTEM FOR POLYMERIC PARTS

Functional Requirements (FR):

- FR1: Component transport at a linear velocity of 0.2–0.5 m/s.
- FR2: Image acquisition at a frame rate of ≥ 30 fps.
- FR3: OK/NOK classification with an accuracy of $\geq 95\%$.
- FR4: Sorting mechanism actuation time of less than 0.3 s.
- FR5: Real-time statistical data display.

Non-Functional Requirements (NFR):

- NFR1: Total prototype development cost $\leq$ EUR 500.
- NFR2: New component reconfiguration time ≤ 30 min.
- NFR3: Continuous operational capacity of ≥ 8 hours/day.
- NFR4: Intuitive and user-friendly user interface.

3.2 Primary functions and technical specifications

Function 1 – Mechanical transport and component positioning

The component transport system consists of a modular belt conveyor featuring an effective width of approximately 200 mm and an overall length ranging between 0.5 and 1.0 m. These dimensions are optimized to ensure the controlled transport of polymer components toward the visual inspection and automated sorting zones.

The structural frame of the conveyor is designed for additive manufacturing technologies, specifically Fused Deposition Modeling (FDM), by 3D printing the structural components from advanced composite materials, such as carbon-fiber-reinforced polylactic acid (PLA-CF) with a 1–2% carbon fiber mass fraction. Additionally, polymeric nanocomposites are integrated to enhance structural stiffness, vibration damping, and dimensional stability.

The utilization of advanced composite materials significantly reduces the total weight of the assembly, maximizes the stiffness-to-weight ratio, and minimizes mechanical deformations under load. Furthermore, this approach aims to dampen operational vibrations and extend the fatigue life of components subjected to cyclic loading.

The conveyor belt is driven by a direct current (DC) electric motor regulated via a Pulse Width Modulation (PWM) signal. This setup enables precise velocity tuning based on the cycle times required for image acquisition and processing.

This adaptive velocity control yields several key advantages, including:

- Seamless synchronization of component transport with the AI inference pipeline;
- Reduction of motion blur and image capture artifacts;
- Repeatable component positioning within the specified Region of Interest (ROI);
- Optimization of the overall cycle time.

To mitigate vibration-induced noise and eliminate unwanted structural oscillations during image capture, the frame incorporates dedicated stiffening elements and integrated anti-vibration mounts.

Function 2 – Image procurement and preprocessing

The visual inspection subsystem utilizes a Full HD 1080p industrial USB camera with a capture rate of 60 FPS, positioned at an optimal standoff distance of approximately 25–30 cm from the surface of the inspected component.

To ensure the repeatability and stability of the acquisition process, the system integrates an artificial LED illumination subsystem with a colour temperature of approximately 5000 K, which closely approximates neutral daylight. Selecting this specific colour temperature minimizes chromatic variations, eliminates harsh shadows, enhances defect contrast, and improves the overall classification accuracy of the AI model.

Image preprocessing represents a critical stage in maximizing the performance of the intelligent model. It encompasses the following sequential operations:

RESEARCH ON THE DEVELOPMENT OF AN INTELLIGENT SORTING SYSTEM FOR POLYMERIC PARTS

- Resizing raw images to a standardized 224 × 224 pixel format;
- Dynamic contrast and brightness adjustment;
- Digital image noise filtering.

Furthermore, standardizing the images prior to inference significantly reduces computational overhead, increases the stability of the classification architecture, and enhances the generalization capabilities of the AI algorithm.

Function 3 – Intelligent component classification

The automated classification process is executed via a hybrid model based on the MobileNetV2 Convolutional Neural Network (CNN) architecture, which is optimized through fine-tuning techniques specifically tailored for resource-constrained embedded systems [5].

This deep learning architecture is combined with a deterministic colour-space analysis in the Hue-Saturation-Value (HSV) domain, which is utilized to validate chromatic features and identify specific surface defects inherent to polymer components.

The model was trained on a comprehensive dataset comprising over 2,000 images, which were artificially augmented using techniques such as: controlled rotations, translations, illumination variations, scaling (zooming), specular reflections, and contrast adjustments [6]. These augmentation techniques enhance model robustness under real-world industrial operating conditions.

To minimize false classifications caused by transient fluctuations or visual noise, the system implements a majority-voting algorithm across an interval of 5–7 consecutive frames. The final sorting decision is determined by the dominant class detected within the analysed sequence [5].

The projected performance characteristics of this intelligent subsystem include seamless compatibility with ESP32-based embedded platforms or edge computing hardware, deterministic real-time operation, and ultra-low inference latency.

Currently, the system classifies components into two primary categories: conforming (OK) or non-conforming (NOK). In subsequent development stages, the software architecture can be scaled to support multi-class classification and discrete defect type identification.

Function 4 – Automated component sorting

Upon completion of the intelligent classification routine, components are automatically routed to their respective destinations via an electromechanical sorting mechanism.

The sorting system consists of a structurally reinforced, 3D-printed mechanical arm driven by a digitally controlled SG90 servomotor. The mechanism supports two primary actuation positions:

- Routing conforming (OK) components down the main production line;
- Deflecting non-conforming (NOK) components into a dedicated scrap bin.

The geometry of the robotic arm is optimized for low mass and low rotational inertia, thereby ensuring a rapid transient response and minimized power consumption.

The total response time of the sorting mechanism is estimated to be under 0.3 s, enabling its seamless integration into low-footprint automated production lines. To maximize system reliability, the angular positioning of the arm is programmatically synchronized with both the conveyor velocity and the AI inference telemetry.

Function 5 – Human-Machine Interface and Process Monitoring

The Human-Machine Interface (HMI) enables real-time monitoring of the system status and provides the operator with critical telemetry regarding the production workflow.

The hardware architecture includes an OLED display for visualizing primary operational parameters, dual-colour LEDs for rapid status signalling, an acoustic buzzer for critical alarms, and an automated data-logging module that exports telemetry in a CSV format.

The logged dataset includes the total number of inspected components, individual counts of OK and NOK parts, cycle times, defect rates, alarm histories, and various internal system variables.

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By archiving these metrics, the system guarantees process traceability and facilitates downstream statistical production analysis, workflow optimization, and full compliance with Industry 4.0 and Smart Manufacturing paradigms.

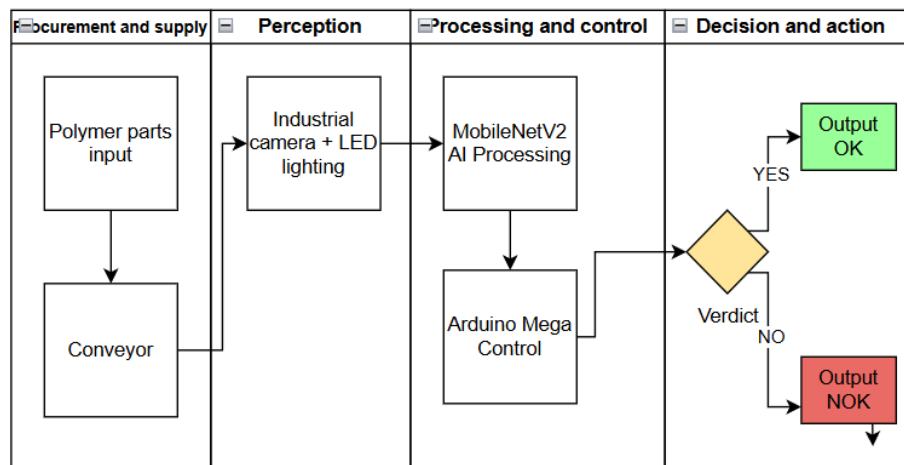


Image 1. Conceptual architecture of the intelligent polymer component sorting system.

Table 1. Main technical specifications.

Parameter	Target value	Unit
Belt speed	0,5-1,0	m
Belt speed	0,2 – 0,5	m/s
Classification accuracy	≥ 95	%
Total cycle time	$< 3,5$	S
Maximum throughput	15-20	Parts/min.
Prototype cost	380 – 480	EUR

4. Detailed operational scenario

The operator places the polymer components onto the conveyor belt at the feeding inlet. The belt advances at a constant linear velocity of 0.3 m/s. Upon entering the visual inspection zone, the industrial camera captures a sequence of 5–7 frames. The processing software detects the presence of the component, extracts its HSV color-space features, executes the MobileNetV2 inference pipeline, and applies a majority-voting algorithm to determine the final classification.

If the verdict is OK (conforming), the component continues its trajectory along the main conveyor belt. Conversely, if the verdict is NOK (non-conforming), the system waits for a calculated delay of 0.2 s, after which the servomotor actuates the sorting arm to deflect the defective component into a dedicated scrap chute.

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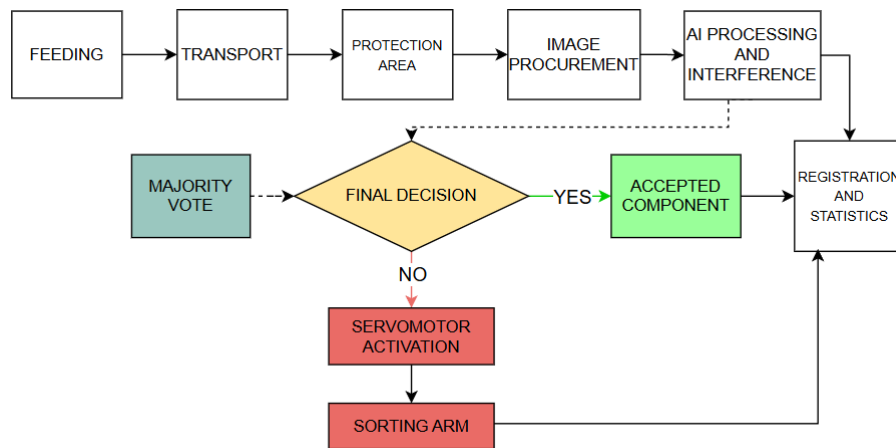


Image 2. Operational Flow

5. Economic analysis and feasibility

5.1. Cost estimation methodology

Component and development costs were estimated based on actual market rates from the 2025–2026 period, sourced from major distributors and e-commerce platforms (including Amazon.de, eMAG, AliExpress, and specialized 3D printing and electronics vendors). A standard procurement margin of 10–15% was integrated into the budgetary model to account for supplier pricing fluctuations and shipping variations. All selected hardware and structural components strictly comply with the functional requirements defined in Chapter 3 [2][4].

5.2. Detailed prototype cost structure

Table 2. Detailed breakdown of estimated costs

Category	Main components	Cost (EUR)
Mechanical components + 3D printing	PLA-CF filament (2.2–2.5 kg), 3D printing services, profiles, belt	110 – 140
Electronics	Arduino Mega, 1080p camera, servomotors, OLED, sensors	140 – 170
Support structure + miscellaneous	Frame, cables, fasteners	50 – 70
Software development and testing	Programming, AI model optimization	40 – 60
TOTAL		380 – 480

5.3. Economic benefits

Reduction of defect rates from 12–18% to below 5% brings cost savings of 15–25%. The productivity is increased by a factor of 3.0–3.5. The operating cost is EUR 0.015/part. At a production volume of 3,200 parts/month: a payback period of 6–8 months, yielding a monthly net profit of EUR 150–220 post-ROI [2].

Table 3. Comparative economic analysis

Indicator	Manual	Proposed system	Industrial
Initial cost	EUR 0	EUR 380–480	EUR 4.000–12.000
Productivity	15–20/min	50–70/min	80–150/min
Error rate	10–20 %	< 5 %	< 2 %
Payback period	–	6–8 months	18–30 months

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The solution delivers the optimal cost-performance ratio for SMEs operating within the polymer industry.

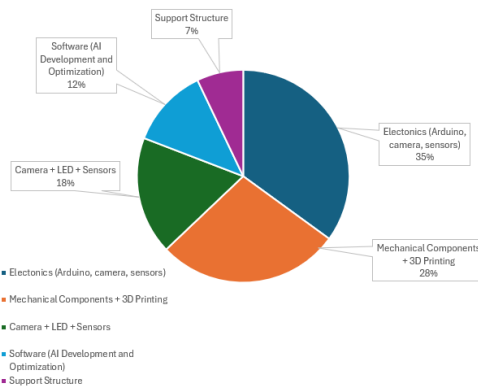


Image 3.1. Cost structure

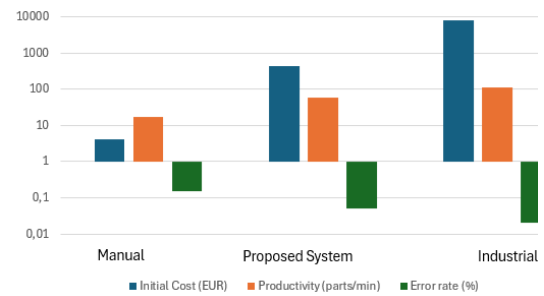


Image 3.2. Economic Comparison

6. Conclusion

This paper has presented the conceptual development of a fully integrated intelligent sorting system designed to address real-world industrial needs. The main contributions of this study include: a modular and scalable architecture, an optimal integration of additive manufacturing with accessible AI, and a rigorous economic analysis that demonstrates technological and financial feasibility for SMEs.

The proposed system establishes a robust foundational framework for the development of a physical prototype. Future research directions will focus on the optimization of nanostructured materials and the migration of the inference pipeline onto dedicated edge-computing devices.

7. Future Research Directions

The proposed system serves as a robust and accessible foundational framework for quality control in SMEs, featuring a modular architecture designed to facilitate the integration of Industry 4.0 technologies. Transitioning from a prototype to a scalable industrial solution requires further developments that can be successfully implemented within a 12–18 month timeframe [2][3].

7.1 Expanding macroscopic defect detection capabilities

Currently, the system focuses on major assembly defects (such as misalignment, missing components, and chromatic anomalies). Future iterations will expand this scope to encompass the detection of fractures, superficial cracks, localized deformations, and surface scratches that compromise both structural integrity and component assembly tolerances. This objective will be pursued by:

- Deploying multi-spectral illumination subsystems;
- Training advanced object detection models;
- Combining convolutional neural networks (CNNs) with texture descriptors [7].

7.2 Advancing AI algorithms and continuous learning integration

Another critical development path involves upgrading the artificial intelligence pipeline through the deployment of state-of-the-art CNN architectures or deep learning models,

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such as EfficientNet, YOLO, or Vision Transformers. These architectures are capable of delivering higher precision in isolating complex defects and enabling robust multi-class classification of polymer components. In a subsequent stage, the system will integrate continuous learning frameworks. This will allow the AI model to automatically retrain using novel data streams harvested during real-world operations, thereby enhancing system robustness and adaptability to manufacturing process variations [5][7].

7.3 Migration to edge computing and industrial IoT architectures

A third major milestone consists of migrating the complete AI inference workload onto edge devices. Replacing the personal computer with a high-performance embedded system—such as a Raspberry Pi 5 equipped with a Coral USB accelerator, or an NVIDIA Jetson Orin Nano—will enable fully autonomous system operation. This architectural shift minimizes overall capital costs, enhances hardware reliability in harsh industrial environments prone to dust, vibrations, and thermal fluctuations, and facilitates seamless integration into legacy production lines. Furthermore, the system can evolve toward a distributed edge computing or Industrial IoT (IIoT) architecture, leveraging a dedicated web interface for remote monitoring and control [2].

7.4 Optimization and modernization of mechanical components

The fourth direction aims to improve mechanical performance through the integration of advanced materials. Utilizing polymer filaments enhanced with nanoparticles (such as graphene or carbon nanotubes at a 1–2% wt. fraction) for drive rollers, structural supports, and the conveyor frame can significantly reduce mechanical wear, structural vibrations, and component slippage [4].

Additionally, engineering the contact surfaces via laser surface texturing or two-photon polymerization techniques can optimize controlled adhesion characteristics, thereby improving image capture stability and extending the operational lifespan of the system. For heavy-duty industrial applications, the mechanical frame can be redesigned using advanced engineering plastics and CNC-machined components to maximize structural rigidity, reliability, and continuous duty-cycle resilience.

7.5 Integration of Industry 4.0 concepts: digital traceability, digital twins, and predictive maintenance

Implementing full Industry 4.0 compliance entails deploying a cloud-based digital traceability framework for real-time telemetry tracking, statistical analytics, and predictive maintenance. This deployment includes developing a high-fidelity Digital Twin (utilizing software platforms such as Unity or Factory I/O) to conduct simulations and optimizations without physical operational risks, alongside adaptive control loops that automatically modulate operational parameters based on real-time defect telemetry [7].

7.6 Hardware and Software scalability for industrial deployments

The platform's hardware can be scaled by incorporating ultra-high-resolution cameras, auxiliary sensor arrays, and advanced automation actuators, transforming the setup into a comprehensive intelligent inspection cell for polymer products. The progressive implementation of these upgrades—achievable via resource-accessible workflows suitable for SMEs or research laboratories—will elevate sorting accuracy beyond 97%, providing a high-performance, cost-effective alternative to cost-prohibitive commercial solutions.

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8. References

- [1] Miroiu, A. M. et al. (2025). *Bachelor's Thesis*, National University of Science and Technology POLITEHNICA Bucharest.
- [2] Nitu, M. L. (2025). *Product Development Project – Intelligent Sorting System for Polymeric Parts*, National University of Science and Technology POLITEHNICA Bucharest, Faculty of Industrial Engineering and Robotics, Master's Degree Program: Engineering of Nanostructures and Unconventional Processes.
- [3] Chivu, C. A. (2025). *Product Development Project – Intelligent Sorting System for Polymeric Parts*, National University of Science and Technology POLITEHNICA Bucharest, Faculty of Industrial Engineering and Robotics.
- [4] Howard A.G. et al. (2017), "MobileNets: Efficient Convolutional Neural Networks for Mobile Vision Applications", *arXiv preprint arXiv:1704.04861*.
- [5] Sandler M. et al. (2018), "MobileNetV2: Inverted Residuals and Linear Bottlenecks", *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pp. 4510-4520.
- [6] Goodfellow I., Bengio Y., Courville A. (2016), *Deep Learning*, MIT Press, Cambridge, Massachusetts.
- [7] Bangre S. (2020), *Development of Deep Learning method for unsupervised screening of visual defects on Injection Moulded Plastics*, Master Thesis, Technical University of Denmark (DTU Compute).

DESIGN AND DEVELOPMENT OF AN EXPERIMENTAL DIGITAL TWIN SYSTEM FOR DEFECTIVE PARTS SORTING

PENELEA-DIMA Sebastian, DUMITRU Melania, ENACHE Robert, VIERU Andrei and
IONESCU Nicolae (Scientific Coordinator)

Faculty of Industrial Engineering and Robotics, Applied Informatics in Industrial Engineering, Master
1, e-mail: sebastian.penelea@stud.fiir.upb.ro

ABSTRACT: This paper presents the design and development of an experimental Digital Twin system for automated defective parts sorting. The proposed system integrates a conveyor-based transport mechanism, a visual recognition module and an electronically controlled sorting mechanism capable of separating defective components from compliant parts. The Digital Twin model provides real-time synchronization between the physical process and its virtual representation, supporting process monitoring, flow analysis and operational optimization. The experimental concept combines controlled part feeding, image-based defect detection and automated decision-making in order to improve sorting accuracy, reduce manual intervention and create a scalable basis for Industry 4.0 applications.

KEYWORDS: Digital Twin, automated sorting system, computer vision, conveyor system, defect detection.

1. Introduction

The automation and digitalization of production lines represent important directions for improving productivity, flexibility and quality in modern manufacturing systems. Automatic sorting systems are widely used for material handling, quality control and product classification, especially in industrial environments where repetitive manual inspection can lead to errors and inconsistent results. Conveyor-based solutions are suitable for such applications because they provide continuous transport, predictable part movement and compatibility with automated inspection modules [1], [7].

The development of Industry 4.0 technologies has increased the interest in Digital Twin solutions. A Digital Twin can be described as a virtual representation of a physical system that receives data from the real process and uses this data for monitoring, simulation and optimization [3]. In an automated sorting application, the Digital Twin is useful because it can synchronize the position and status of each part with the physical conveyor, allowing the system to estimate the correct sorting moment and to visualize the process in real time.

The objective of this paper is to present the current stage of the design and development of an experimental Digital Twin system for defective parts sorting. The proposed system combines a conveyor subsystem, a computer vision subsystem and an automatic sorting mechanism. The work focuses on a laboratory-scale model, intended to demonstrate the basic principles of visual inspection, real-time synchronization and automatic decision-making for sorting defective parts.

2. Current State

Automated sortation conveyors are currently used in industrial plants, warehouses, airports and distribution centers. Systems such as crossbelt sorters, tilt-tray sorters and belt conveyor sorters can transport and divert a large number of products with high repeatability. These solutions usually combine mechanical transport, sensors, software control and discharge mechanisms in order to increase throughput and reduce manual handling [1].

In the field of industrial automation, large companies develop Digital Twin platforms for the simulation, monitoring and optimization of production processes. Siemens Tecnomatix is

used for modelling and analyzing manufacturing lines before physical implementation, while ABB RobotStudio supports simulation and programming of robotic and automated processes [4], [5]. Such platforms are important because they allow engineers to test scenarios, identify bottlenecks and reduce commissioning time.

Recent research also combines Digital Twin concepts, computer vision and artificial intelligence for improving industrial sorting. Experimental environments such as SortingEnv have been proposed for the simulation and optimization of sorting processes using reinforcement learning methods [2]. At the

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same time, computer vision libraries such as OpenCV make it possible to detect contours, measure geometrical features and identify colour differences in real time [6].

However, many industrial solutions are complex and expensive, while educational or experimental platforms often focus on only one component of the process. The system proposed in this paper is designed as a compact experimental model that integrates the physical conveyor, visual recognition, sorting actuator and Digital Twin monitoring in a single coherent architecture.

3. Equations

The operation of the conveyor subsystem is mainly influenced by the belt speed, because this parameter determines both the travelling time of each part and the available time for visual inspection and sorting. In the proposed experimental system, the travelling time of a part between the inspection area and the sorting mechanism can be estimated using the ratio between the travelled distance and the conveyor speed:

$$t = \frac{d}{v} \quad (1)$$

t – travelling time [s];

d – travelled distance [m];

v – conveyor belt speed [m/s];

The transport flow of the system can also be estimated according to the number of parts moved during a specific time interval:

$$Q = \frac{n}{t} \quad (2)$$

Q – part flow rate [parts/s];

n – number of transported parts;

t – travelling time [s];

For the experimental model, the conveyor speed is considered in the range of 0.05–0.15 m/s, which provides enough time for image acquisition, defect detection and activation of the sorting actuator. The detection accuracy can be generally expressed as:

$$A = \frac{N_c}{N_t} * 100 \quad (3)$$

A – detection accuracy [%];

N_c – number of correctly classified parts;

N_t – total number of analysed parts.

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4. Needs Analysis and System Requirements

In modern industrial processes, the identification and separation of defective parts are essential for maintaining product quality and reducing waste. Manual inspection can be slow and subjective, especially when parts move continuously or when operators must verify large batches. An automated system is therefore required to detect visible defects, classify parts and remove non-compliant components from the production flow.

The proposed experimental system is focused on defects that can be observed from the top view of the part. This limitation makes the concept feasible for a laboratory model, because it avoids the need for multiple cameras or complex orientation devices. Examples of detectable defects include incorrect outer diameter, missing material on the contour, geometric deformation, colour difference and eccentric position of the central hole.

The main needs identified for the system are:

- automatic detection of visible defects;
- monitoring of part position on the conveyor;
- real-time synchronization between the physical system and the virtual model;
- adjustment of transport speed according to the flow of parts;
- reduction of human intervention during the sorting process;
- improvement of sorting accuracy and repeatability.

Table 1. Main subsystems and roles of the proposed experimental system

Subsystem	Main role	Representative data
Feeding and transport	Introduces parts individually and moves them to the inspection and sorting areas.	Conveyor speed, part spacing, motor state
Visual recognition	Captures images and extracts visual/geometrical features for defect detection.	Contours, colour values, diameter, hole position
Digital Twin and control	Synchronizes the physical process with the virtual model and stores process states.	Part ID, position, classification, system status
Sorting mechanism	Separates defective parts from compliant parts according to the classification result.	Actuator command, rejection moment, collection bin

5. Functional Analysis and Proposed Architecture

The main function of the system is the automatic identification and separation of defective parts from compliant parts while they are transported on a conveyor. In order to achieve this function, the system must feed the parts, move them through the inspection area, capture images, classify each part, update the Digital Twin model and activate the sorting mechanism at the correct time.

From a structural point of view, the experimental model is divided into several interdependent subsystems: the feeding subsystem, the conveyor transport subsystem, the visual recognition and analysis subsystem, the sorting subsystem, and the Digital Twin and control subsystem. Each subsystem has a specific role, but the performance of the complete system depends on the synchronization between them.

The feeding subsystem introduces the parts onto the conveyor in a controlled manner and prevents overlapping. The transport subsystem moves the parts at a controlled speed through the inspection area. The recognition subsystem uses a camera and image-processing algorithms to extract features from the parts. The Digital Twin receives the detected attributes, position and classification result, while the sorting subsystem uses this information to divert defective parts to a separate collection area.

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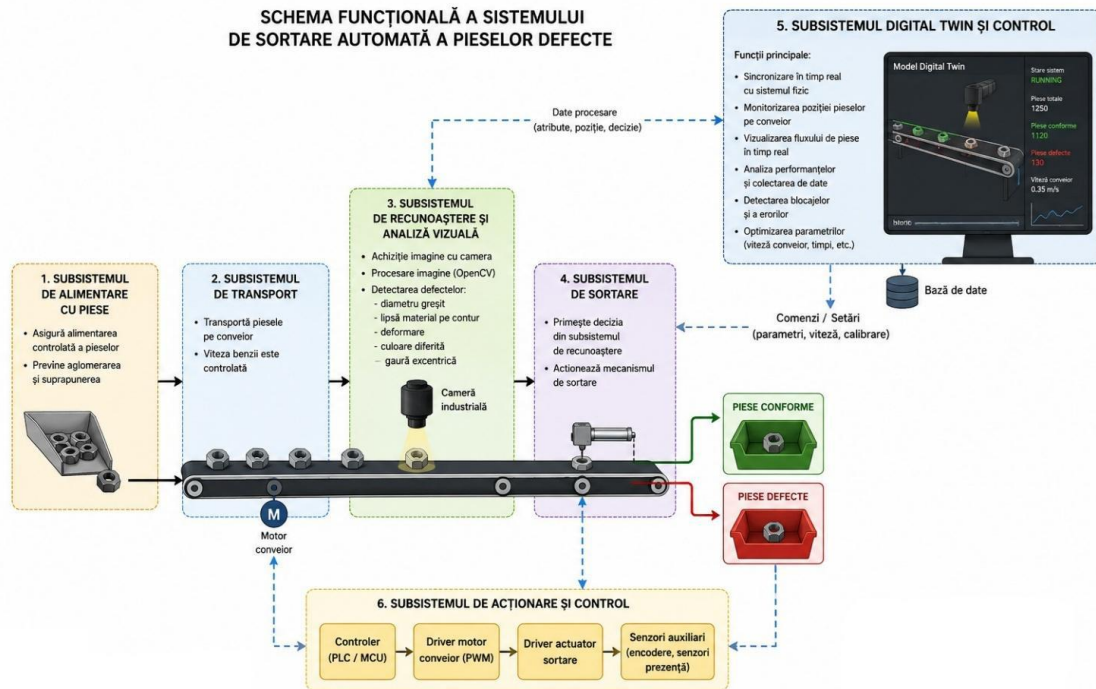


Fig. 1. General functional architecture of the automated defective parts sorting system [9]

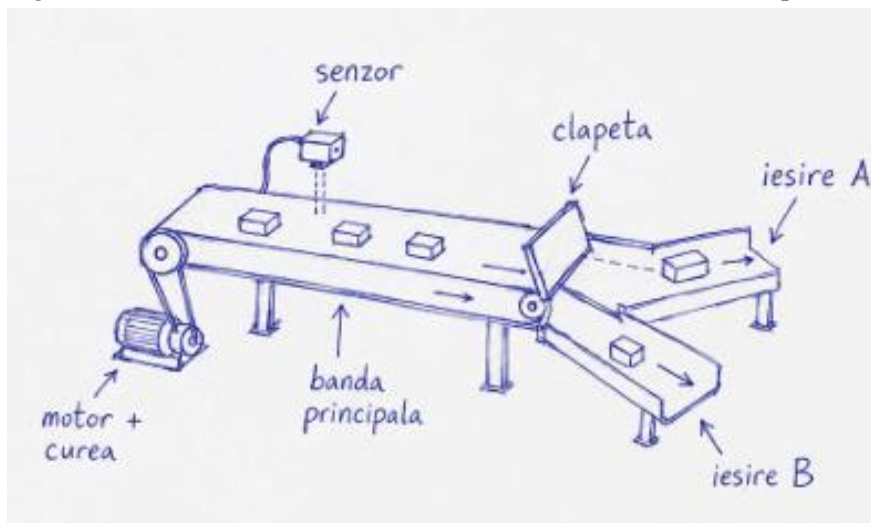


Fig. 2. Diverter flap conveyor for defective parts sorting

6. Feeding and Conveyor Transport Subsystem

The feeding and transport subsystem ensures the controlled introduction of parts onto the conveyor and their movement toward the visual inspection area. A stable flow of parts is important because the camera must capture individual components without overlap. If the feeding is irregular, the recognition algorithm may process two parts as a single object or may miss a defective part.

For the proposed experimental model, the parts can be introduced individually by using a simple mechanical guide. The minimum distance between two consecutive parts was estimated at approximately 50-70 mm, allowing enough time for image acquisition and processing. The conveyor can be driven by a 12 V DC motor controlled through PWM, which allows the transport speed to be adjusted according to the needs of the recognition subsystem [7].

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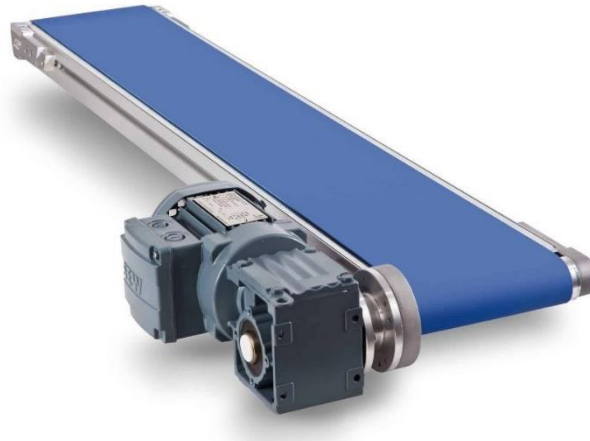


Fig. 3. Example of belt conveyor used for part transport [8]

The conveyor speed has a direct influence on the available processing time. For the experimental model, a speed between 0.05 m/s and 0.15 m/s is considered suitable for using a standard camera and OpenCV image-processing algorithms.

7. Visual Recognition and Defect Detection Subsystem

The visual recognition subsystem identifies and analyzes the parts transported by the conveyor. The inspection process is performed using a camera mounted above the belt and image-processing algorithms implemented in Python with the OpenCV library [6]. The camera position is chosen so that the top surface of each part is visible when it enters the inspection area.

The experimental system can use simple geometrical components such as washers, 3D-printed parts or circular plastic elements. These parts are appropriate for a laboratory model because their defects can be detected through classical computer vision methods. The system focuses on defects visible from the upper plane, which reduces the complexity of the mechanical design and the calibration process.

The recognition process follows several steps: image acquisition, conversion to grayscale, noise reduction using a Gaussian Blur filter, contour detection, feature extraction and part classification. For colour-related defects, the image can also be converted to the HSV colour space, which is frequently used in industrial inspection tasks because it separates colour information from brightness variations [6].



Fig. 3. Recognition subsystem used for image-based inspection [9]

Contour analysis j is higher than the accepted tolerance, the part is classified as defective. The same principle can be applied for detecting missing material on the contour or an eccentric central hole.

After classification, the recognition subsystem transmits the result to the Digital Twin. The transmitted data may include the part identifier, current position, extracted geometrical attributes, colour information and classification result. This communication is essential for maintaining synchronization between the physical part and its virtual representation.

8. Digital Twin Synchronization and Automatic Sorting

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9. User Interface and Control Concept

A graphical user interface is necessary for monitoring and controlling the experimental sorting system. The interface allows the operator to visualize the main process parameters and to interact with the Digital Twin model. It also improves the clarity of the experimental platform, because the physical process and its virtual representation can be observed at the same time.

The proposed interface should display the conveyor speed, the total number of inspected parts, the number of compliant parts, the number of defective parts, the current system state and the active alarms. It may also show the image captured by the camera and the virtual position of the part in the Digital Twin model.

The operator should be able to start and stop the system, modify the conveyor speed, reset counters and calibrate the inspection parameters. In a future implementation, the interface can be developed using Python Tkinter, PyQt or industrial dashboards integrated with RobotStudio. The purpose is not only to control the system, but also to create a clear experimental tool for analyzing the relation between physical data, virtual synchronization and sorting performance.

For safety and reliability, the interface should also include warning messages for possible errors, such as camera disconnection, conveyor blockage, incorrect actuator response or synchronization loss between the real and virtual models. These alerts can help the operator identify problems faster and reduce downtime during experimental testing.

The experimental validation of the system can be performed by preparing several batches of compliant and defective parts. Each batch should contain known defects, so that the classification result generated by the computer vision algorithm can be compared with the real status of the part. This approach allows the accuracy of the recognition subsystem and the efficiency of the sorting mechanism to be evaluated in a controlled manner.

The validation process should also analyze the influence of conveyor speed on detection and sorting. At lower speeds, the camera has more time to acquire clear images, while at higher speeds the throughput increases but the risk of recognition or actuation errors may also increase. For this reason, the Digital Twin can be used to compare different operating scenarios before choosing the final experimental parameters.

The collected data can be stored in a simple database or log file and later used for graphical analysis.

The most relevant indicators are:

- sorting accuracy, calculated as correct classifications divided by total inspected parts [%];
- throughput, calculated as the number of processed parts per second [parts/s];
- defect rate, calculated as defective parts divided by total inspected parts [%];
- response time between defect detection and actuator command [s];
- downtime generated by errors, blockage or synchronization loss [s].

These indicators provide a quantitative basis for demonstrating that the experimental system is not only functional, but also useful for process monitoring and optimization.

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10. Conclusions

This paper presented the current stage of the design and development of an experimental Digital Twin system for automated defective parts sorting. The proposed solution integrates controlled part feeding, conveyor transport, image-based defect detection, Digital Twin synchronization and automatic sorting actuation into a coherent laboratory-scale architecture.

The system is designed to detect visible defects such as incorrect diameter, missing contour material, geometrical deformation, colour differences and eccentric hole position. OpenCV-based image processing is proposed for extracting relevant geometrical and visual features, while the Digital Twin model stores and updates the status and position of each inspected part in real time.

The use of a Digital Twin can improve the monitoring capacity of the experimental system, support process visualization and allow the estimation of the correct sorting moment. The integration of ABB RobotStudio as a virtual modelling environment provides a useful basis for testing the sorting process before the complete physical implementation.

Future work will focus on the practical development of the experimental model, the implementation of the graphical user interface, the calibration of the computer vision algorithm and the complete synchronization between the physical system and its virtual representation. Additional improvements may include performance indicators, energy monitoring and economic analysis of the sorting process.

11. Bibliography

- [1]. Boysen, N., Briskorn, D., Fedtke, S. and Schmickerath, M. (2018), Automated Sortation Conveyors: A Survey from an Operational Research Perspective, Friedrich-Schiller-Universität Jena and Bergische Universität Wuppertal.
- [2]. Maus, T., Zengeler, N. and Glasmachers, T. (2024), SortingEnv: An Extendable RL-Environment for an Industrial Sorting Process, Ruhr-University Bochum.
- [3]. Tao, F., Zhang, H., Liu, A. and Nee, A.Y.C. (2019), Digital Twin in Industry: State-of-the-Art, IEEE Transactions on Industrial Informatics, Vol. 15, No. 4.
- [4]. Wang, S., Wan, J., Li, D. and Zhang, C. (2016), Implementing Smart Factory of Industrie 4.0: An Outlook, International Journal of Distributed Sensor Networks.
- [5]. Lee, J., Bagheri, B. and Kao, H.A. (2015), A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems, Manufacturing Letters.
- [6]. Szeliski, R. (2022), Computer Vision: Algorithms and Applications, Springer.
- [7]. Groover, M.P. (2020), Automation, Production Systems, and Computer-Integrated Manufacturing, Pearson.
- [8]. Easy Conveyors, Belt conveyors, <https://easy-conveyors.com/belt-conveyors/>, accessed on 02.05.2026.
- [9]. Image generated with the support of artificial intelligence for the proposed experimental concept.
- [10]. ABB RobotStudio example interface, <https://www.youtube.com/watch?v=ulbMsWrEz3g>, accessed on 03.05.2026.

RESEARCH CONCERNING THE DEVELOPMENT OF SENSORS FOR MONITORING POLLUTION IN INDUSTRIAL WORKING ENVIRONMENTS

Ulieru Oana-Maria, Ionescu Nicolae

Faculty: FIIR, Specialization: INPN, Year of study: I, email: oana_maria.ulieru@stud.faima.upb.ro,
sitex45@gmail.com

ABSTRACT: The paper presents the development of a numerical model for a multi-pollutant electrochemical sensor designed for the simultaneous monitoring of Pb^{2+} , PFOA/PFOS (including emerging PFAS) and nitrates in industrial waters. The model was developed in COMSOL Multiphysics 5.5 using 2D Axisymmetric geometry, the Tertiary Current Distribution, Nernst-Planck (Supporting Electrolyte) interface, Electrode Surface with Butler-Volmer kinetics, Surface Accumulation and Surface Reactions, together with Time-Dependent and Frequency Domain studies. The techniques of Anodic Stripping Voltammetry (ASV) for Pb^{2+} , Electrochemical Impedance Spectroscopy (EIS) for PFAS and amperometry for nitrates were configured and optimized. The work demonstrates the efficiency of advanced numerical simulation.

KEYWORDS: multi-pollutant electrochemical sensor, COMSOL Multiphysics 5.5, industrial water monitoring, amperometry, PFAS

1. Introduction

The quality of industrial waters is a major environmental and public health issue, with uncontrolled wastewater discharges leading to contamination of water resources by toxic pollutants such as heavy metals (e.g., Pb^{2+}), perfluorinated compounds (PFOA, PFOS), and excess nutrients (nitrates) [1, 2]. These pollutants are highly toxic, causing carcinogenic effects and endocrine disruptions even at low concentrations [3, 4]. Traditional analytical methods, although precise, are costly and require specialized laboratories, being incapable of real-time monitoring [5, 6].

In this context, electrochemical sensors offer a promising alternative [5, 7]. This study proposes the development of a multi-pollutant electrochemical sensor capable of simultaneously detecting Pb^{2+} , PFOA, PFOS, and nitrates in industrial waters, developed exclusively through numerical simulation in COMSOL Multiphysics 5.5 [8, 9]. The modeling was performed in a 2D axisymmetric geometry, allowing optimization of parameters such as deposition time and electrode modification.

The study also includes a strategic marketing analysis, highlighting a clear competitive advantage and an estimated commercial price below €300 per unit, substantially lower than laboratory solutions [10]. The impact of this solution is significant both socially, contributing to public health protection, and economically, by reducing monitoring costs. Technologically, the proposal involves transitioning to an integrated multi-pollutant device, with potential extensions to 3D and IoT integration, while considering the PFMEA methodology from the design phase to identify and reduce quality risks in the future production flow [11]. Various electrochemical techniques have been compared for efficiency, including Anodic Stripping Voltammetry for Pb^{2+} and Electrochemical Impedance Spectroscopy for perfluorinated compounds. The main objectives are numerical modeling, comparison of electrochemical techniques, strategic positioning, and feasibility assessment of the solution.

2. State of the Art

Monitoring the quality of industrial waters is a global priority, regulated by European directives such as the Water Framework Directive 2000/60/EC [12] and Directive 2013/39/EU on priority pollutants. Major pollutants, such as lead (Pb^{2+}), perfluorinated compounds (PFOA, PFOS), and nitrates, are highly toxic even at minimal concentrations, causing carcinogenic effects and disruptions to the nervous system [3, 4]. These pollutants are classified by authorities as priority substances due to their toxicity, persistence, and bioaccumulation potential [1, 13].

Traditional detection methods, such as ICP-MS or HPLC-MS, are precise but expensive

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and slow, lacking real-time monitoring capability [5, 6]. While there are single-pollutant sensors available, multi-pollutant sensors remain experimental [5, 7]. The European Union enforces strict regulations for PFAS, including a limit of 0.1 µg/L for the sum of 20 PFAS, effective from 2026 [14], as well as the universal REACH restriction (Annex XVII) [15]. In Romania, pollution cases include high Pb^{2+} concentrations in specific areas, and PFAS have been detected in wastewater treatment plants as well as industrial zones [2, 16].

Commercial sensors face limitations regarding selectivity and costs [5, 7, 6], but the numerical model in COMSOL Multiphysics 5.5 offers zero-cost development solutions and rapid optimization [8, 9]. The main obstacle remains the complexity of the real aquatic matrix, which introduces interferences. This situation highlights the need for more efficient solutions and strict regulations to protect the quality of industrial waters.

3. Numerical modeling of the electrochemical sensor

The model was developed in COMSOL Multiphysics 5.5 (Electrochemistry Module) using a 2D Axisymmetric geometry [8, 9]. The Tertiary Current Distribution, Nernst-Planck (Supporting Electrolyte), and Electrode Surface interfaces with Butler-Volmer kinetics were utilized. Anodic Stripping Voltammetry (ASV) was configured for Pb^{2+} , Electrochemical Impedance Spectroscopy (EIS) for PFOA/PFOS, and the amperometric technique for nitrates. Numerical parameters and settings (Extremely Fine mesh, relative tolerance of 10^{-6}) were defined and prepared for running complete simulations [8, 9].

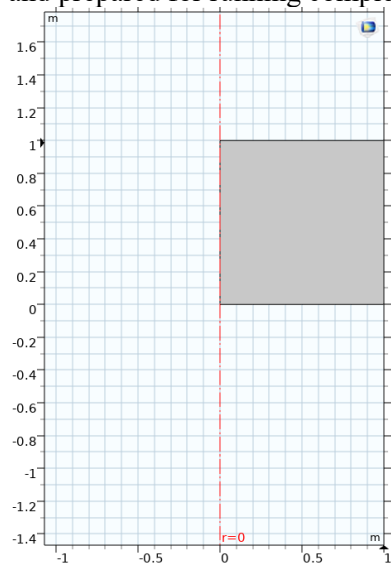


Fig. 1. Geometry of the multi-pollutant

Pb^{2+}

electrochemical sensor in COMSOL Multiphysics 5.5 (2D Axisymmetric)

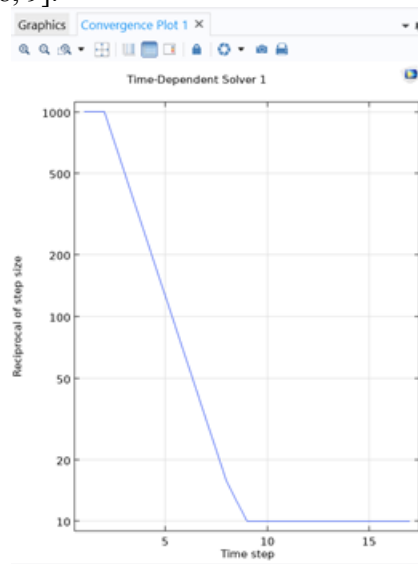


Fig. 2. Solver convergence curve for the

detection model (ASV)

The computational domain consists of a rectangular electrolyte with axial symmetry along the axis $r = 0$. The working electrode is located on the upper surface. The graph in Figure 2 shows the solver convergence over time. The decreasing curve indicates that the numerical error was rapidly reduced, confirming a stable mathematical model for the lead sensor.

4. Results and Discussions

The simulation results in COMSOL Multiphysics 5.5 confirm the efficiency of the multi-pollutant electrochemical sensor in simultaneously detecting Pb^{2+} , PFOA/PFOS, and nitrates.

Table 1. Simulated performances of the multi-pollutant electrochemical sensor

Technique	Pollutant	Calculated LOD	Sensitivity	Response Time	Selectivity
ASV	Pb^{2+}	0,032 ppb	0,85 µA/ppb	3–5 min	Very good
EIS	PFOA /	8–12 ppt	R_{ct}	2–3 min	Excellent

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	PFOS		variation		
Amperometric	Nitratēs	0,18 mg/L	1,45 $\mu\text{A} \cdot \text{L}/\text{mg}$	< 1 min	Good

Table 2. Comparison of the Simulated Electrochemical Techniques

Characteristic	ASV (Pb^{2+})	EIS (PFOA/PFOS)	Amperometric (Nitrates)
Concentration Range	0,1–100 ppb	1 ppt–100 ppb	0,1–50 mg/L
Detection Principle	Anodic Stripping	Impedance Variation	Limiting Current
Modified Electrode	Graphene and Bismuth	MIP / Oxidized Graphene	Copper Nanoparticles
Main Advantage	Preconcentration	High Selectivity	Rapid Response

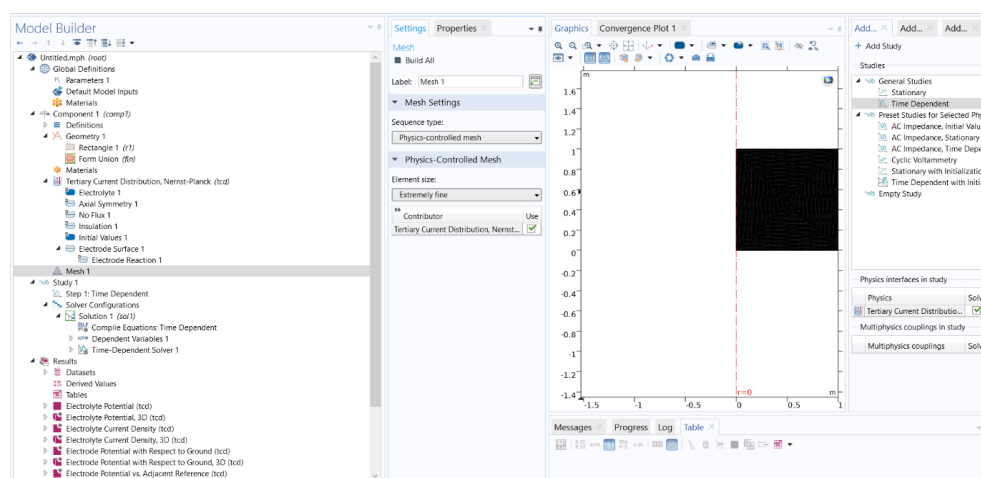


Fig. 3. Computational domain discretization using an “Extremely Fine” mesh

To achieve superior precision at the electrode–electrolyte interface — the region with the steepest concentration gradients — an Extremely Fine mesh discretization was employed. This configuration, visible in the Settings panel, produces a high density of finite elements, which minimizes truncation errors and guarantees solution convergence under tight tolerances on the order of 10^{-6} .

RESEARCH CONCERNING THE DEVELOPMENT OF SENSORS FOR MONITORING POLLUTION IN INDUSTRIAL WORKING ENVIRONMENTS

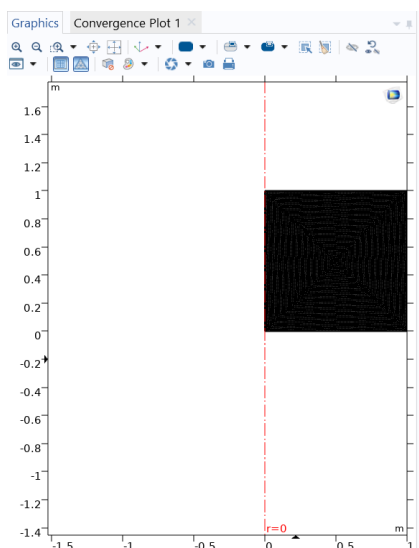


Fig. 4. Detaliu al mesh-ului la interfața electrod–electrolit

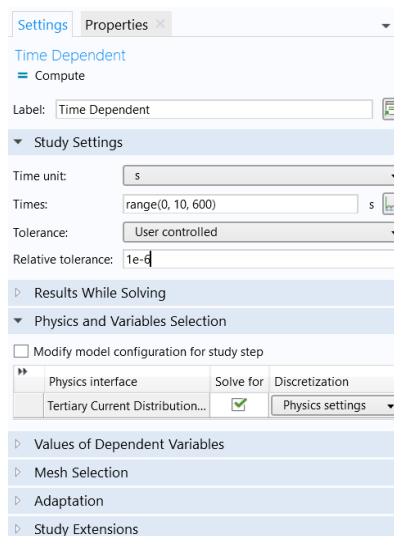


Fig. 5. Setările studiului Time-Dependent pentru ASV

Sursă: Simulări efectuate în COMSOL Multiphysics 5.5 (elaborare proprie).

The image in Figure 4 illustrates the mesh element distribution, emphasizing the high element density needed for precise resolution of mass transport phenomena and electrochemical kinetics at the electrode surface. In accordance with the technical settings, the time-dependent study was configured with a total simulation time of 600 s, providing adequate resolution during the lead ion deposition phase. For ensuring result accuracy, the relative tolerance was set to 10^{-6} (Figura 5).

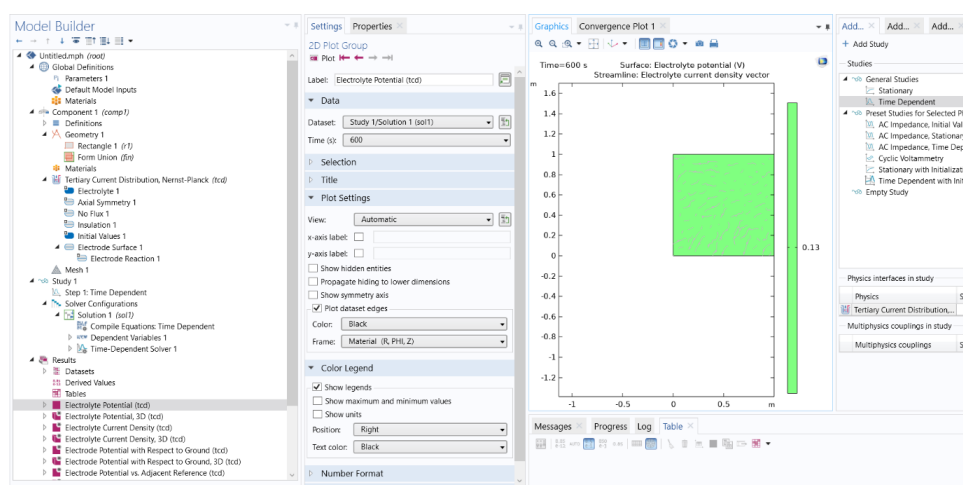


Fig. 6. Electrolyte potential distribution at the end of the deposition step ($t = 600$ s)

Figure 6 depicts the system state after 600 seconds of simulation. A stable potential distribution and the achievement of steady-state conditions are evident, thus confirming the validity of the numerical setup for the lead ion accumulation phase at the electrode surface.

The frequency interval was set from 0.01 Hz to 100 kHz, employing a logarithmic sweep with a resolution of 60 points per decade. This configuration enables accurate resolution of charge transfer processes and double-layer capacitance, which is essential for the sensitive detection of PFAS pollutants (PFOA/PFOS).

RESEARCH CONCERNING THE DEVELOPMENT OF SENSORS FOR MONITORING POLLUTION IN INDUSTRIAL WORKING ENVIRONMENTS

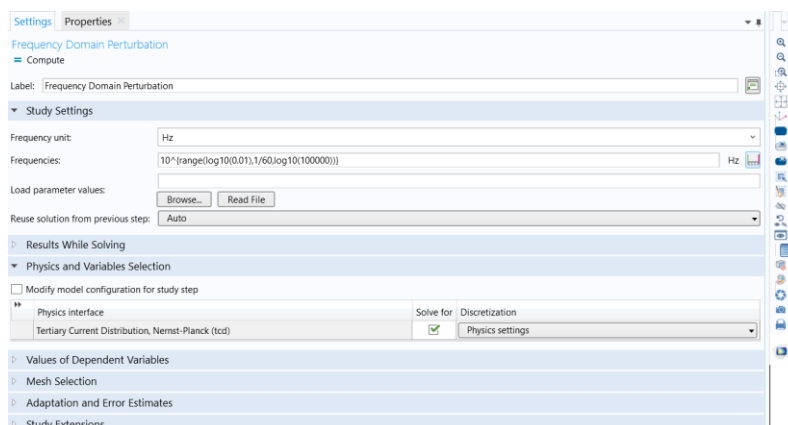


Fig. 7. Frequency Domain Study Settings for EIS (PFOA/PFOS)

Table 3. LOD Comparison: Proposed Sensor versus Classical Methods [5, 7]

Method / Sensor	Pb ²⁺	PFOA/PFOS	Nitrates
Proposed Sensor (COMSOL)	0,032 ppb	8–12 ppt	0,18 mg/L
ICP-MS / HPLC-MS	< 0,01 ppb	< 1 ppt	0,05 mg/L
Commercial Single-Pollutant Sensors	0,1–1 ppb	50–500 ppt	1–5 mg/L

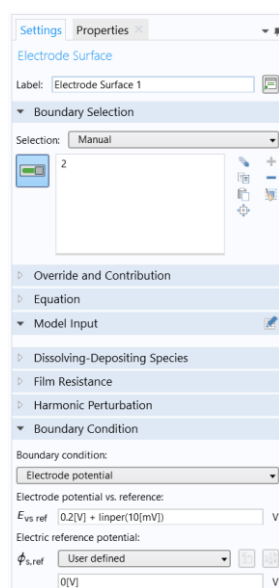


Fig. 8. Bias and Harmonic Perturbation Settings (10 mV)

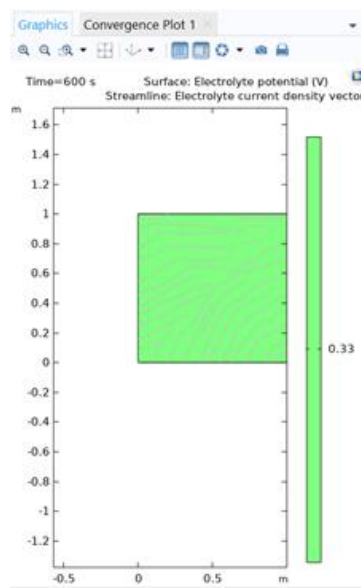


Fig. 9. Electrolyte potential distribution and current flow lines in the EIS simulation

Figure 8 presents the application of a DC polarization potential of +0.2 V, deemed optimal for PFAS-specific adsorption. A small-amplitude sinusoidal perturbation (linper) of 10 mV was superimposed to acquire the system's impedance response. Figure 9 illustrates the steady-state condition after 300 seconds of polarization at -0.8 V. The uniform potential distribution and the alignment of current vectors confirm the stabilization of the nitrate reduction process, thereby validating the model for the extraction of the diffusion-limited current.

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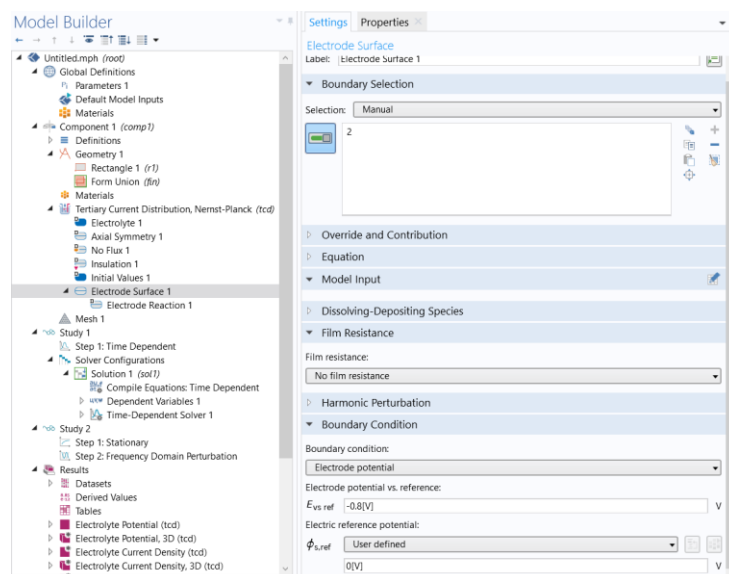


Fig. 10. Fixed Potential Settings for the Amperometric Detection of Nitrates

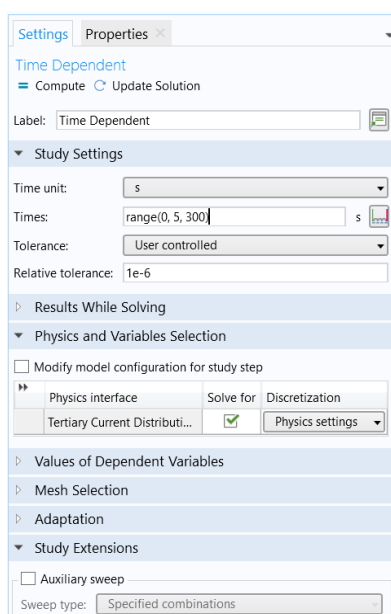


Fig. 11. Time Interval of 300 s for Limiting density

Current Stabilization

The obtained simulation results show that the multi-pollutant electrochemical sensor developed in COMSOL Multiphysics 5.5 satisfies the sensitivity and selectivity criteria required by EU regulations.

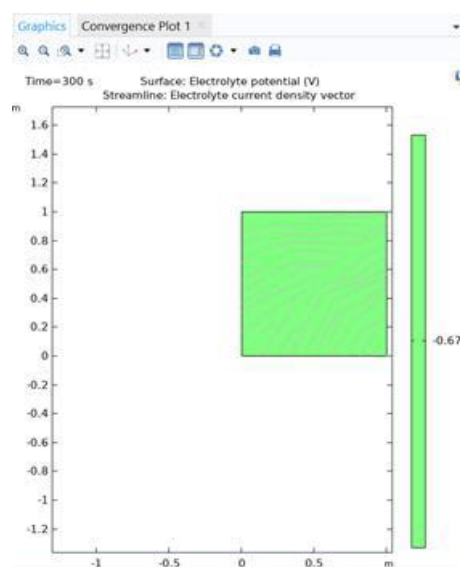


Fig. 12. Potential distribution and current

at the end of the amperometric simulation

Table 4. Electrochemical Parameters Employed in the Simulations [5, 8]

Parameter	Common Value	ASV (Pb ²⁺)	EIS (PFOA/PFOS)	Amperometric (Nitrates)	Observations
Temperature	298 K	—	—	—	Standard conditions
Supporting Electrolyte	NaCl 0,1 M sau PBS pH 7,0	—	—	—	Realistic ionic strength
Fluid Velocity	0 m/s	—	—	—	Static model
Diffusion Coefficient Pb ²⁺	$7,2 \times 10^{-10}$ m ² /s	—	—	—	Literature standard
Diffusion Coefficient NO ₃ ⁻	$1,9 \times 10^{-9}$ m ² /s	—	—	—	Literature standard
Diffusion Coefficient PFAS	$5,0 \times 10^{-10}$ m ² /s	—	—	—	Average value
Working Potential	—	-1,2 V (depozitare)	+0,2 V (polarizare)	-0,8 V (constant)	vs. Ag/AgCl
Main Step Duration	—	120 s	—	300 s	Stabilization / preconcentration time
Scan Rate / Frequency	—	50 mV/s	0,01 Hz – 100 kHz	—	Parametric domain
Concentration Range	—	0,1 – 100 ppb	1 ppt – 100 ppb	0,1 – 50 mg/L	Industrially relevant range
Exchange Current Density (i ₀)	—	$1,5 \times 10^{-4}$ A/m ²	—	$2,0 \times 10^{-5}$ A/m ²	Modified electrode

6. Conclusions

The integrated numerical model exhibits competitive performances and a distinct competitive edge, placing it in the NW quadrant of the Customer Matrix. This study validates the effectiveness of advanced numerical simulation using COMSOL Multiphysics 5.5 in the design of modern electrochemical sensors, substantially lowering both costs and development time. Future research directions involve the physical manufacturing of the sensor, experimental validation using real samples collected from polluted sites in Romania (Copșa Mică, Baia Mare, the Danube Delta, and intensive agricultural areas), as well as extending the numerical model to a complete three-dimensional geometry. Implementing the PFMEA methodology within the sensor manufacturing process, in line with current quality management standards [11], will ensure a smooth and reliable transition from the numerical model to the final industrial product. Extending the model to a complete 3D geometry, incorporating convection, temperature, and biofouling effects, along with integration into an IoT system with wireless communication, constitute the subsequent development stages. The results obtained in this dissertation contribute to the advancement of state-of-the-art electrochemical sensors [4] designed for the protection of aquatic ecosystems and public health. These findings are aligned

with the provisions of the Water Framework Directive [12], the Drinking Water Directive (2020/2184) [14], and the REACH regulatory restrictions concerning PFAS [15].

7. Bibliography

[1] *** World Health Organization (WHO). (2022), *Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda*, Geneva: World Health Organization. <https://www.who.int/publications/i/item/9789240045064> [Accessed 12 May 2026].

[2] *** European Environment Agency (EEA). (2023), *Industrial pollution in Europe – Country fact sheets: Romania*. Copenhagen: EEA. <https://www.eea.europa.eu/en> [Accessed 13 May 2026].

[3] *** Agency for Toxic Substances and Disease Registry (ATSDR). (2022), *Toxicological Profile for Lead*. Atlanta: ATSDR. <https://wwwn.cdc.gov/Tsp/ToxProfiles/ToxProfiles.aspx?id=96&tid=22> [Accessed 13 May 2026].

[4] Grandjean, P. & Clapp, R. (2021). PFAS and human health: A review of the evidence. *Environmental Health Perspectives*, 129(5), pp. 1–12.

[5] Wang, J. et al. (2023). Recent advances in electrochemical sensors for heavy metal ions detection. *Electrochimica Acta*, 456, pp. 142–155.

[6] Brett, C.M.A. & Oliveira Brett, A.M. (2018). *Electrochemistry: Principles, Methods and Applications*. Oxford University Press.

[7] Li, M. et al. (2024). Molecularly imprinted polymer-based electrochemical sensors for PFAS detection: A review. *Talanta*, 267, pp. 125–138.

[8] *** COMSOL Multiphysics. (2019). *Electrochemistry Module User's Guide, Version 5.5*. COMSOL AB, Stockholm. [comsol.com](https://www.comsol.com) [Accessed 10 May 2026].

[9] Ghiculescu, L.D. et al. (2023). Numerical modeling of electrochemical sensors using COMSOL Multiphysics. *Journal of Electroanalytical Chemistry*, 912, pp. 117–129.

[10] Drăghici, G. (1999). *Integrated Product Engineering*. Editura Eurobit, Timișoara, ISBN 973-96065-7-1

[11] Țițu, A.M., Doicin, C.V., Ionescu, N., Gusan, V. (2023), *Application of the PFMEA Methodology in a Production Flow with Collaborative Robots*. In: Karabegovic, I., Kovačević, A., Mandzuka, S. (eds) *New Technologies, Development and Application VI. NT 2023. Lecture Notes in Networks and Systems*, vol 687. Springer, Cham. https://doi.org/10.1007/978-3-031-31066-9_3

[12] European Parliament and Council. (2000), *Directive 2000/60/EC establishing a framework for Community action in the field of water policy*. *Official Journal of the European Union*, L327, pp. 1-73. [europa.eu](https://eur-lex.europa.eu/eli/dir/2000/60/oj) [Accessed 13 May 2026].

[13] *** U.S. Environmental Protection Agency (EPA). (2024), *Final National Primary Drinking Water Regulation for PFAS*. Washington, D.C.: EPA. [epa.gov](https://www.epa.gov) [Accessed 11 May 2026].

[14] *** European Parliament and Council. (2020), *Directive (EU) 2020/2184 on the quality of water intended for human consumption*. *Official Journal of the European Union*, L435, pp. 1-62. [europa.eu](https://eur-lex.europa.eu/eli/dir/2020/2184/oj) [Accessed 10 May 2026].

[15] *** European Chemicals Agency (ECHA). (2023), *Universal PFAS restriction proposal – Annex XVII REACH*. Helsinki. [europa.eu](https://echa.europa.eu) [Accessed 10 May 2026].

[16] *** ANAR – Administrația Națională „Apele Române” (2024). *Report on the Water Quality in the Danube River Basin*. Bucharest. Available at: rowater.ro [Accessed 10 May 2026].

COMPARATIVE STUDY OF NONDESTRUCTIVE INSPECTION TECHNIQUES APPLIED TO ADDITIVE MANUFACTURED PARTS

PAVEL Gabriel¹, GROȘANU Darius-Marian², Ș.I. DUMITRAȘCU Constantin și Conf.dr.ing. MARINESCU Marinela-Nicoleta (Scientific Supervisors)

Faculty: Faculty of Robotics and Industrial Engineering, Specialization: Mechatronics and Robotics, Year of study: I, e-mail:pavelgabriel345@gmail.com

ABSTRACT: The paper comparatively evaluates ultrasonic testing (UT) and infrared thermography (IRT) applied to 3D printed PLA and PETG reference specimens. The UT method precisely locates depth defects, being marginally favored by the rigidity of PLA, which reduces mechanical wave attenuation. However, in parts with a 0° infill angle, acoustic anisotropy completely blocks UT detection. Here, thermography intervenes as a rapid method immune to filament orientation. IRT excels on PETG specimens, whose thermal conductivity prevents lateral diffusion, clearly delineating anomalies. Conversely, the reduced conductivity of PLA degrades thermogram clarity. Thus, the methods are complementary, and PETG represents the optimal material for combined NDT inspection.

KEYWORDS: 3D Printing, 3D, thermography, ultrasonics, defectoscopy,

1. Introduction

3D printing technologies have revolutionized materials processing, finding applicability from hobby projects to precision industrial production. Although additive manufacturing allows the creation of highly complex geometries, it raises a fundamental problem: the integrity of the internal structure of the part.

Because materials exhibit varied behavior, rigorous control of printing parameters is essential to minimize internal defects, such as microporosities. This necessity becomes critical in high-technology sectors (e.g., aerospace, medical industry), where additive manufacturing (including metal powder-based) must comply with strict quality standards.

Therefore, non-destructive testing (NDT) methods become indispensable, offering the possibility to evaluate reliability and operational safety without destroying or compromising the inspected part. This paper analyzes the behavior of PLA (Polylactic Acid) and PETG (Glycol-modified Polyethylene Terephthalate) materials in the context of NDT inspection, using ultrasonic flaw detection and infrared thermography. The central objective is to highlight the advantages, limitations, and optimal application scenarios for each testing technique.

2. Experimental Section

2.1. Materials

The materials chosen for testing are PLA and PETG, versatile and easily accessible materials for prototyping and production. In order to analyze the proposed materials under optimal conditions using both testing methods, we designed a series of reference specimens

represented in Onshape software in Fig.1a and Fig.1b.

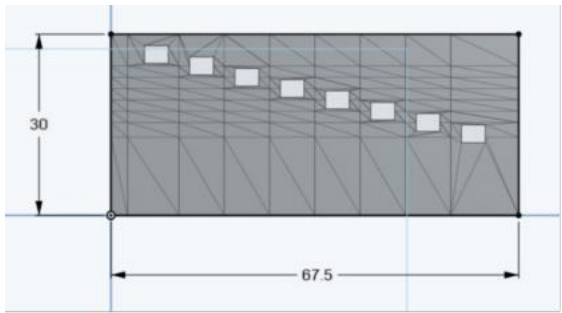


Fig.1a: First version of reference specimen

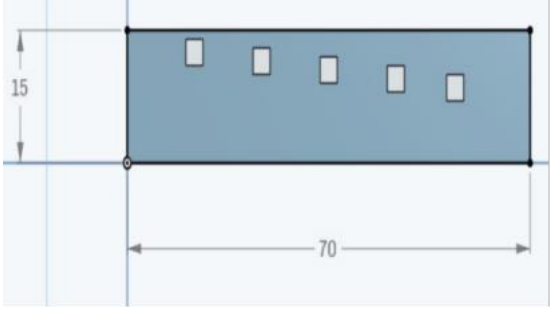


Fig.1b: Second version of reference specimen

The reference specimen corresponding to figure (1a) was 3D printed twice with PETG and once with PLA. The parts were printed with the same settings differing only in printing temperature, except for the second PETG piece.

Table 1: Printing Parameters

Layer Height	Infill Density	Infill Pattern	Extrusion Factor	Infill Angle	Printing Temperature
0.24 [mm]	100%	Rectilinear	0.95 (95%)	45°	265[°C] PETG 220[°C]PLA

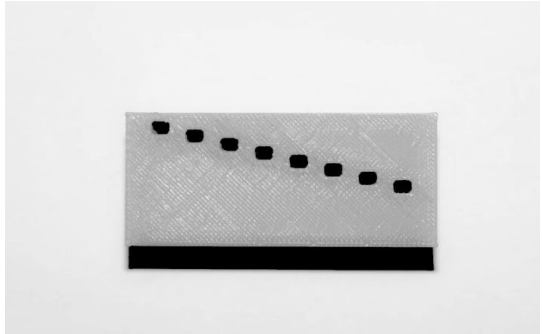


Fig.2a: PETG Reference Specimen

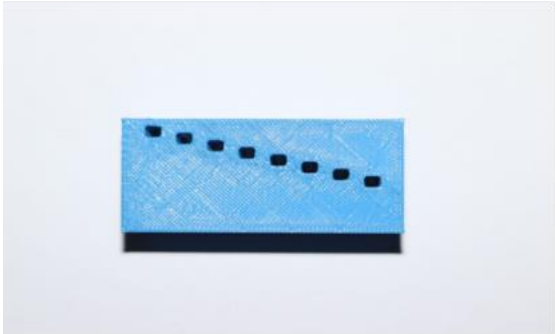


Fig.2b: PLA Reference Specimen

As with specimen (1a), for specimen (1b) three test pieces were printed, one from PLA and two from PETG, with one PETG specimen printed with different settings compared to the other two pieces.

Table 2: Printing Parameters

Layer Height	Infill Density	Infill Pattern	Extrusion Factor	Infill Angle	Printing Temperature
0.16 [mm]	100%	Rectilinear	0.98 (98%)	45°	265[°C] PETG 220[°C]PLA





Fig.3b: PLA Reference Specimen

Fig.3a: PETG Reference Specimen

We chose to make two additional PETG reference specimens with different printing settings due to a previous test on this type of thermoplastic with the ultrasonic flaw detector. The following tables record the major changes we made to the pieces.

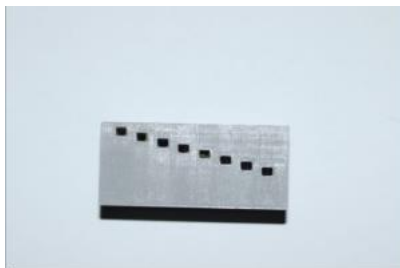


Fig.4: PETG Reference Specimen with dimensions (1a)



Fig.5: PETG Reference Specimen with dimensions (1b)

Table 3: Printing Parameters

Unghiul Umpluturii	Factor de extrudare
0°	1.01 (101%)

Table 4: Printing Parameters

Layer Height	Printing
Temperature	
0.28 [mm]	270[°C] PETG

2.2. Equipment

Ultrasonic system: Flaw Detector "GE Inspection Technologies USM35", digital with high-frequency transducer, facilitating the emission of longitudinal waves. Coupling gel is used to adapt the acoustic impedance between the probe and the surface of the printed part.

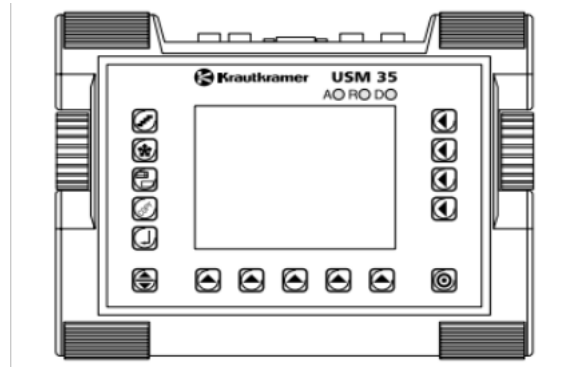
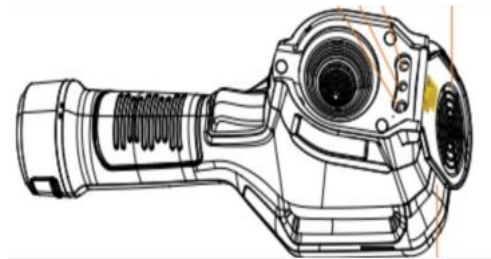


Fig.6: Flaw Detector "GE Inspection Technologies USM35"

Thermographic system: Thermal imaging camera "HIKMICRO M60", coupled to a thermal excitation system using lamps for applying a uniform thermal pulse. Subsequent data are saved and analyzed in the "HIKMICRO Analyzer" software.



2.3. Working Methods

For ultrasonic analysis, the flaw detector was calibrated to a sound propagation speed of 2101 [m/s], specific to PLA and PETG. Coupling gel is applied and the surfaces of the reference specimens are scanned. Signals are recorded for the identification of defect echoes.



Fig.8: Flaw detector settings

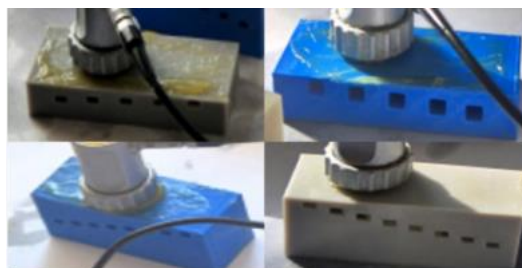


Fig.9: Applying the couplant



Fig.10: Echo signals

For the thermographic procedure, the active thermography technique is used, with the reference specimens subjected to a controlled thermal pulse. The thermal imaging camera records the surface cooling gradient in real time, with internal defects generating thermal anomalies on the thermogram, which are captured and stored for subsequent analysis.

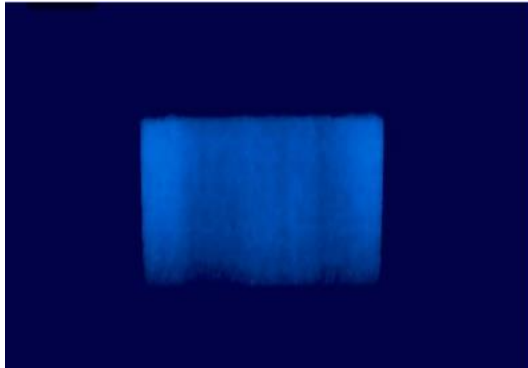


Fig.11: Initial specimen

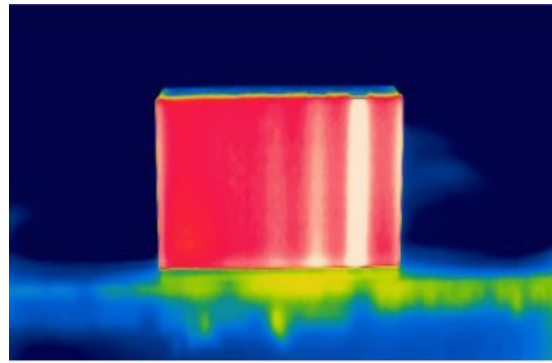


Fig.12: Applying the thermal pulse

3. Results Interpretation

3.1. Comparative Analysis of specimens 2a and 2b relative to Specimen 4

The analysis of experimental data extracted from the ultrasonic flaw detector for specimens printed with a layer height of 0.24 mm and infill angle of 45° demonstrates the capability of the method to isolate internal discontinuities. On the flaw detector screens, the clear presence of defect echoes distinct from the structural background noise is observed. The 45° angle of the internal structure cross-sections the direction of propagation of longitudinal ultrasonic waves, providing an adequate reflection surface at the artificial defect interface. Although the under-extrusion parameter (flow 95%) generates microporosities distributed throughout the part volume, increasing attenuation, detection of macro-differences remains feasible. Based on physical properties, specimen 2b (PLA) shows marginally superior acoustic transmissibility (Fig.13). The higher elastic modulus and more rigid character of PLA, compared to the molecular flexibility of PETG (specimen 2a), reduces mechanical wave attenuation, generating echoes with theoretically larger and more well-defined amplitude.

The experimental data for specimen 4 reveal a total inability of the flaw detector to monitor internal defects (Fig.14). The displays show only the initial pulse followed by constant baseline noise, without useful echoes. This inability stems directly from the 0° infill angle setting. This orientation aligns the extrusion lines perpendicular to the scanning direction, inducing extreme acoustic anisotropy. Ultrasonic energy undergoes multiple reflections and refractions between the parallel printing lines, generating a wave-guiding effect along the filaments and massive diffraction. Although the 101% extrusion factor should ensure greater material densification, the 0° grid geometry nullifies UT testing efficiency.

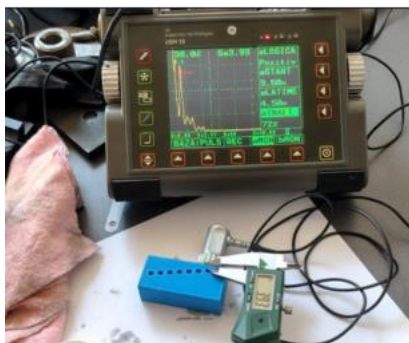


Fig.13: Correlation of flaw detector indication with physical dimension (3.93 mm)



Fig.14: Inability to monitor defects

3.2. Comparative Analysis of specimens 3a and 3b relative to Specimen 5

The ultrasonic response indicates maintained defect detectability, but the structural noise level is influenced by printing resolution. A layer height of 0.16 mm results in a significantly higher number of fusion lines between layers per millimeter, compared to the 0.24 mm specimens. Each additional interface acts as a micro-reflector, increasing the material's dispersion coefficient. The acoustic response of specimen 3b (PLA) remains more well-defined (Fig.15) due to rigidity that partially compensates for interface dispersion, while specimen 3a (PETG) shows slightly higher energy absorption at these multiple deposition planes, resulting in a more attenuated signal (Fig.16).

The evaluation of specimen 5, characterized by a layer height of 0.28 mm and a printing temperature of 270°C, highlights the optimal ultrasonic monitoring conditions for PETG parts. The high detection capability is due to the thermal fusion phenomenon. The temperature of 270°C reduces the polymer viscosity during extrusion, facilitating near-complete bonding. This advanced thermal fusion eliminates most micro-voids at the boundary between layers. Additionally, the layer thickness of 0.28 mm minimizes the total number of acoustic interfaces along the propagation axis. Consequently, specimen 5 approaches physically the behavior of a homogeneous, isotropic polymer. Structural attenuation drops to a minimum, allowing the ultrasonic wave to penetrate the volume with minimal energy loss, resulting in the precise identification of defects (Fig.17).



Fig.15: More attenuated signal than in the previous specimen

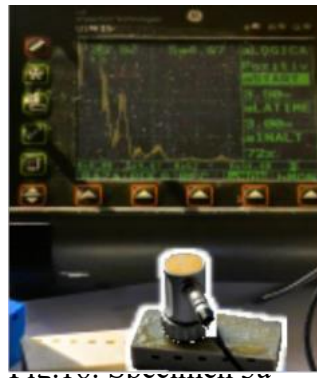


Fig.16: Specimen 3a

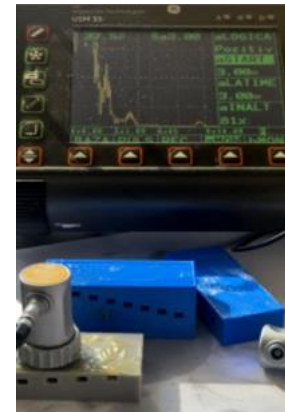


Fig.17: Specimen 5, with better results than 3a

3.3. Comparative Analysis of thermograms

The analysis of the cooling gradient extracted from the thermographic video recordings confirms the superior detection efficiency for PETG material, highlighting clear differences in thermal contrast compared to PLA.

The thermograms demonstrate a delineation of internal defects, which appear as distinct vertical bands with thermal anomalies during the cooling phase. A high contrast and well-defined geometric boundaries between the massive polymer zones and the zones containing artificial voids are observed. This superior definition is a direct consequence of the higher thermal conductivity of PETG material. The heat front propagates more efficiently in depth; upon encountering the polymer-air interface, the defect acts as an insulator, blocking dissipation, resulting in thermal accumulation that generates a gradient in the internal geometry.

Fig.18: PETG specimen at the thermal
imaging camera

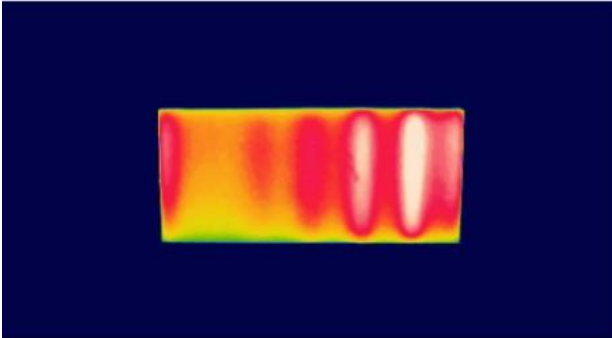
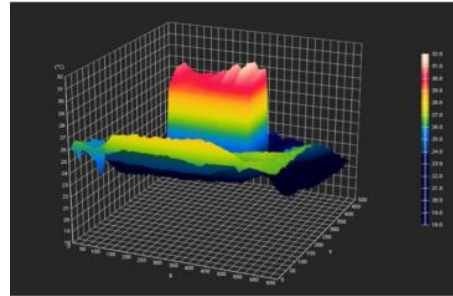


Fig.19: 3D graph from HIKMICRO
Analyzer



The thermal response recorded for the PLA specimen exhibits a diffusion phenomenon. Although the presence of volumetric defects is detectable, the local thermal contrast is lower compared to the PETG specimen. The physical cause is the lower thermal conductivity of PLA material. The higher thermal resistance of the material volume promotes energy retention in the superficial layers and accentuates lateral heat dissipation to the detriment of in-depth propagation.

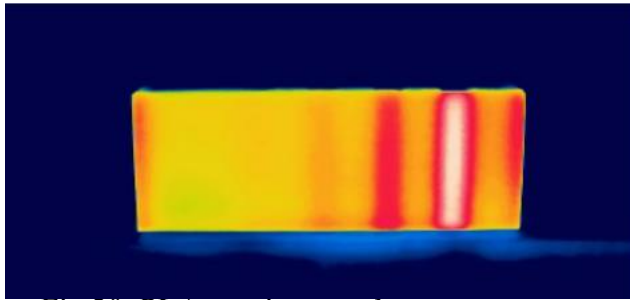


Fig.20: PLA specimen at the thermal imaging camera

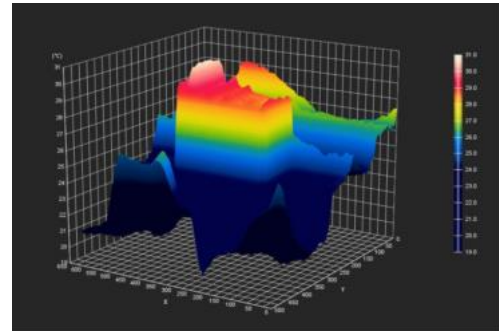


Fig.21: 3D graph from HIKMICRO Analyzer

4. Conclusions

Ultrasonic flaw detection is distinguished by its capacity to provide high spatial resolution on the depth axis, allowing precise localization of anomalies in the part volume. This method is optimal for detecting point defects or isolated microporosities. The favorable use scenario involves inspection of high-density components with internal geometries specifically designed to facilitate acoustic propagation, such as 45° infill patterns. The application of ultrasonics is preferred in situations requiring rigorous certification of deep structural integrity of the material.

Infrared thermography represents a non-contact inspection technique characterized by speed, with the capacity to simultaneously evaluate large surfaces in a single capture. Its main quality lies in its immunity to the directional anisotropy of printing filaments, not being affected by infill angles that block acoustic propagation. The favorable scenario for this method includes real-time monitoring of the manufacturing process, being the ideal tool for detecting delaminations and discontinuities located near the surface.

The ultrasonic flaw detector becomes inoperable in the presence of extreme acoustic anisotropy, a phenomenon generated by infill structures oriented at 0° or by the formation of internal wave guides. Under these conditions, multiple reflections generate structural noise that masks defect echoes, blocking detection capability. At this critical operational point, infrared thermography intervenes. Because the propagation of thermal flux through molecular conduction is not limited by the mechanical orientation of the filaments to the same extent as sound waves, this method allows visualization of defects that the ultrasonic beam misses.

The efficiency of the thermal camera is restricted by lateral thermal diffusion and the limitation of thermal flux penetration depth. As a defect is positioned deeper in the material, the thermal gradient dissipates before reaching the monitored surface, resulting in a diffuse image or complete absence of thermal signal. In this situation, ultrasonic testing intervenes. Ultrasonic equipment has the capacity to penetrate significant thicknesses of polymer to confirm the presence, exact depth, and size of deep volumetric anomalies that thermography signaled imprecisely or could not detect.

The nature of the thermoplastic material directly influences the performance of inspection equipment. PETG polymer favors both methods due to its thermal stability, which allows a stronger thermal pulse without deforming the part, and superior inter-layer fusion at high temperatures, which reduces structural attenuation of ultrasound. In contrast, PLA polymer marginally favors ultrasonic testing due to its rigidity which minimizes mechanical wave attenuation. However, its reduced thermal conductivity severely penalizes thermography, favoring lateral heat diffusion and considerably degrading the clarity of contours for sub-surface defects.

5. Bibliography

- [1]. ISO 16810:2014 Non-destructive testing - Ultrasonic testing - General principles
- [2]. ISO 18251-1:2017 Non-destructive testing— Infrared thermographyPart 1: Characteristics of system and equipment
- [3]. Îndrumar de laborator – Tehnologia materialelor 1
- [4].Manual USM 35 - <https://www.jwjndt.com/wp-content/uploads/2016/04/USM-35X-Operating-Manual.pdf>
- [5].Manual HIKMICRO M-series - <https://webassets.hikmicrotech.com/global/asset/79659298ab83425a9da25eb58031e8b5.pdf>
- [6].The Mechanical Properties of 3D-Printed Polylactic Acid/Polyethylene Terephthalate Glycol Multi-Material Structures Manufactured by Material Extrusion - <https://pmc.ncbi.nlm.nih.gov/articles/PMC10880662/>

IMPROVING ORGANIZATIONAL COMMUNICATION IN THE CONTEXT OF THE TRANSITION TO INDUSTRY 4.0

NICULESCU Miruna-Andreea, CARAMAN Marina-Izabela

Supervisor: Assistant Professor PhD Eng. Bogdan DUMITRU

Faculty: Faculty of Industrial Engineering and Robotics, Specialization: Intelligent Industrial Technologies, Year of study:
IV, e-mail: niculescu_miruna@yahoo.com

ABSTRACT:

This research analyzes the optimization of organizational communication in the context of the transition to Industry 4.0, highlighting the strategic role of emerging technologies (AI, IoT, Big Data) in streamlining managerial processes. The paper emphasizes the need to develop employees' digital skills and adopt collaborative platforms, such as Slack or Microsoft Teams, to support hybrid work and decision-making transparency. Strategies based on digital planning, ethics, and cybersecurity are proposed to prevent information overload. The case studies demonstrate concrete benefits, such as a 50% increase in active participation within the educational environment and a 30% reduction in approval times for technical documentation in engineering. Ultimately, the authors conclude that digitalization transforms the manager into an "architecture of communication," which is essential for the adaptability and performance of the modern organization.

1. Introduction

1.1 General context of the research

In an economic and social context marked by accelerated changes, organizational communication becomes an essential element for the success and adaptability of any organization. In the digital era, characterized by rapid technological advancement and the emergence of the Industry 4.0 concept, the way organizations communicate—both internally and externally—is undergoing a profound transformation. Industry 4.0 represents both a technological revolution and a challenge for managerial thinking, organizational structure, and employee work behaviors. The transition to Industry 4.0 involves integrating advanced digital technologies, such as artificial intelligence, the Internet of Things (IoT), data analytics (Big Data), automation, and intelligent robotics, into all production and management processes. In this context, communication is no longer just a process of transmitting information, but a strategic mechanism that facilitates collaboration between people and technologies.

1.2 Objectives and methodology of the paper

This paper aims to analyze how organizational communication can be improved in the context of the transition to Industry 4.0, focusing on the adaptation of processes, channels, and organizational culture to new digital realities. The main objective is to identify effective communication management strategies that support performance, innovation, and technological integration in the contemporary organizational environment.

2. Theoretical foundations of organizational communication

2.1 The concept of organizational communication

Organizational communication represents the process through which information is transmitted, received, and interpreted within an organization to achieve common objectives. This involves both formal flows (reports, meetings, emails) and informal flows (spontaneous conversations, unofficial feedback).

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Effective communication contributes to team cohesion, increases decision-making transparency, and reduces uncertainty. In the digital era, organizational communication is no longer just an internal process, but a complex system of technologically mediated interactions.

2.2 Types and models of communication in organizations

Several types of communication are recognized in the specialized literature: Vertical communication between hierarchical levels (manager-employee); Horizontal communication between colleagues or departments; Diagonal communication between individuals at different levels but in distinct functional areas; External communication between the organization and partners, clients, or the public.

2.3 The role of communication in organizational management

Communication represents the foundation of all managerial processes. Without a clear, coherent, and bidirectional communication system, no plan, objective, or strategy can be implemented effectively. Managers do not just transmit information; they also create meaning, direction, and motivation among employees.

In modern management, communication fulfills several essential functions: The informational function, which ensures the transmission of data necessary for decision-making; The motivational function, which encourages and actively involves employees in achieving goals; The control function, which allows verifying the conformity of actions with established plans; The integration function, which consolidates team cohesion and promotes organizational values.

In the context of the transition to Industry 4.0, the role of communication expands. The manager becomes a digital leader, capable of managing hybrid teams (physical + virtual), utilizing online collaboration platforms, and promoting transparency through digital channels. Tools like Slack, Microsoft Teams, Zoom, or Trello are no longer just communication channels, but true collaborative management ecosystems that centralize information, documents, and processes.

3. Industry 4.0 – The digital transformation of the organizational environment

3.1. Defining the Concept of Industry 4.0

Industry 4.0 refers to the integration of advanced digital technologies into industrial and organizational processes. The concept emerged in Germany as part of a government strategy launched in 2011 and represents the fourth industrial revolution, succeeding traditional automation.

The main characteristics are: Interconnectivity of cyber-physical systems; Intelligent process automation; Real-time data analysis; Human-machine collaboration.

3.2. Emerging technologies: Automation, Artificial Intelligence, IoT, Big Data

Emerging technologies facilitate a new form of organizational communication based on data, algorithms, and digital assistants.

- Artificial Intelligence (AI) allows for employee sentiment analysis, message personalization, and the automation of repetitive communication..
- IoT connects equipment and sensors, generating continuous streams of relevant data for rapid decision-making.
- Big Data provides a vast informational foundation for evaluating performance and identifying trends.
- Automation reduces temporal and spatial barriers, enabling global collaboration in real time.

3.3. Employees' digital skills in the 4.0 era

The transition to Industry 4.0 has profoundly redefined the profile of the modern employee. While in the past technical skills were sufficient, today the labor market demands a combination of technological, cognitive, and interpersonal abilities. Digital skills no longer represent a competitive advantage, but a strategic necessity for the survival and development of organizations.

A. Definition of Digital Skills

According to the European Commission (2020), digital skills represent the "safe, critical, and creative use of information and communication technologies for work, learning, and participation in society". In an organizational context, these involve the ability to use digital tools for communication, analysis, collaboration, and innovation.

B. Categories of Digital Skills

1. Technical skills: using collaborative platforms (Teams, Slack, Asana), analysis tools (Excel, Power BI), and ERP systems..
2. Cognitive skills: critical analysis of information, filtering relevant data, and the ability to make decisions based on digital insights.
3. Virtual collaboration skills: working effectively in geographically distributed teams using digital channels.
4. Digital security and ethics skills: complying with GDPR regulations, protecting personal data, and responsible online behavior.

C. Impact on Organizational Performance

Developing digital skills increases productivity, stimulates innovation, and improves internal communication. Employees become more autonomous, and decision-making processes become faster and more transparent.

Organizations that invest in digital training (workshops, e-learning, technological mentoring) succeed in creating a culture of continuous learning, prepared for the future.

3.4. Digitalization of communication processes. Digital platforms and collaborative tools (Slack, Teams, etc.)

The digitalization of organizational communication has become an essential pillar of digital transformation. In a context where hybrid work and distributed teams are increasingly widespread, collaborative platforms ensure efficient coordination, transparency, and speed in transmitting information.

A. The Concept of Communication Digitalization

Digitalizing communication involves using technologies and digital tools to manage internal and external information flows. This does not mean simply replacing traditional channels (physical meetings, paper reports) with online alternatives, but a profound reconfiguration of how the organization communicates, collaborates, and makes decisions.

B. Platforms and Collaborative Tools

1. Slack: allows the creation of thematic channels, the integration of applications (Google Drive, Trello, Asana), and instant communication. It is ideal for dynamic teams and agile projects.
2. Microsoft Teams: offers integrated features for chat, video calls, file sharing, and document collaboration. It is widely used in the corporate environment.

3. Zoom and Google Meet: provide remote video communication, with options for recording and automatic transcription.
4. Trello / Asana / Monday.com: project management platforms that offer transparency regarding the status of tasks and responsibilities.
5. Miro / Notion / ClickUp: creative tools for brainstorming, documentation, and visual coordination of teams.

C. Advantages of Communication Digitalization: Increases the speed of information transmission; facilitates real-time collaboration between remote teams; reduces logistical and travel costs; offers traceability and automatic archiving of conversations; contributes to the development of a digital organizational culture.

D. Challenges and Limitations: Information overload; loss of human contact and empathy in virtual communication; risks related to data security; difficulties in maintaining employee attention and engagement.

To avoid these problems, organizations must adopt balanced digital communication strategies that combine online channels with direct interactions, thereby promoting a culture of authentic connection.

3.5. Ethics and information security in digital communication

With the digitalization of communication, aspects of ethics and information security acquire major importance. In an environment dominated by data, algorithms, and artificial intelligence, organizations must ensure that information flows responsibly, securely, and transparently.

A. Ethics in Digital Communication

Digital ethics refers to the moral behaviors and principles that govern online interactions. In an organizational context, this implies:

- Respecting the confidentiality of employee and partner data;
- Using digital platforms responsibly (without online discrimination, abuse, or harassment);
- Transparency in communicating decisions and internal changes;
- Avoiding information manipulation and disinformation.

Managers have an obligation to create clear digital ethics policies, and employees must be trained to realize the impact of their online actions on the organization's image.

B. Information Security

The security of digital communication involves protecting data and information transmitted through electronic means. The main risks include:

- Cyberattacks (phishing, malware, ransomware);
- Unauthorized access to files and conversations;
- Loss of sensitive data due to human negligence.

To prevent these risks, organizations must implement:

- Cybersecurity policies (complex passwords, multi-factor authentication, data encryption);
- Periodic training for employees on recognizing digital threats;
- Incident response plans in case of security breaches;
- Compliance with GDPR and ISO/IEC 27001 regulations regarding data protection.

C. The Balance Between Ethics and Efficiency

In a hyperconnected digital environment, the major challenge is balancing communication efficiency with the protection of sensitive information. An organizational culture based on

trust, respect, and digital responsibility becomes a key factor for the sustainability and reputation of the organization.

4. Strategies and best practices for improving organizational communication

4.1. Strategic planning of communication in the digital environment

Strategic planning in the digital environment involves establishing clear objectives, choosing the right channels, and structuring an efficient communication flow adapted to the organization's needs and the specifics of the employees.

A well-built strategy includes:

Analysis of communication needs:

- Identifying existing problems: information bottlenecks, delays, lack of transparency.
- Evaluating current channels (email, intranet, digital platforms) and their efficiency.
- Consulting employees through questionnaires or interviews.

Establishing strategic objectives:

- Improving internal vertical and horizontal communication.
- Increasing the speed of information transmission.
- Reducing operational errors caused by a lack of communication.
- Increasing the level of employee engagement through digital interactions.

Choosing the right digital channels:

- Collaborative platforms (MS Teams, Slack) for synchronous and asynchronous communication.
- Intranet and document management systems for centralizing information.
- Project management tools (Asana, Trello, Jira) for tracking tasks.
- Internal newsletter for important communications or official announcements.

Defining responsibilities:

- Clarifying roles: who communicates, who approves, who forwards.
- Establishing standard procedures: templates, communication guides, tone of messages.

Continuous monitoring and optimization:

- Using key performance indicators (KPIs): response time, platform utilization level, employee feedback.
- Adapting the strategy according to technological evolution and organizational changes.

4.2. Training and development programs for communication skills

Developing employees' communication skills is vital in a digitalized work environment because technology changes how people interact, present information, and collaborate.

Training for effective digital communication:

- Professional use of platforms like Teams, Slack, Zoom.
- Asynchronous communication techniques (clear, concise, structured messages).
- Written communication: wording of messages, digital etiquette, appropriate tone.

Developing presentation skills in the online environment:

- How to structure a digital presentation.
- Using visual tools (Canva, advanced PowerPoint).
- Managing emotions and maintaining attention in video calls.

Training for collaboration and remote teamwork:

- Conflict management in the virtual environment.
- Working on shared documents and version control systems.
- Online brainstorming techniques.

Specialized programs for middle and top management:

- Digital leadership.
- Strategic communication in crisis situations.
- Coordinating geographically distributed teams.

Skills assessment and follow-up:

- Periodic testing to check progress.
- Correcting weaknesses through micro-learning or personalized sessions.

4.3. Promoting a collaborative culture and trust in the digital environment

A strong collaborative culture is essential for organizational performance, especially in the context of digitalization and remote or hybrid work.

Creating a climate of trust:

- Transparency in communicating decisions and objectives.
- Leadership's availability to answer questions and provide clarifications.
- Promoting an environment where employees can express ideas without fear of consequences.

Stimulating collaboration:

- Using shared platforms for documents, projects, and communication.
- Sharing responsibilities fairly among members.
- Promoting interdepartmental projects.

Rewarding collaborative initiatives:

- Recognizing employees who actively contribute to communication and collaboration.
- Implementing "Employee of the Month" programs or non-financial bonuses.

Ethics and professional behavior in the digital environment:

- Internal regulations regarding the use of digital platforms.
- Clear norms regarding respect, confidentiality, and data protection.
- Internal awareness campaigns regarding cybersecurity (phishing, passwords, data access).

Activities that consolidate the organizational community:

- Online events (digital team building, coffee talks).
- Internal discussion groups on various topics (wellbeing, hobbies).
- Social projects and digital volunteering to increase the sense of belonging.

5. Case study (within the internship companies)

5.1. Case Study 1: Trainer within the Young Engineers Robotics Workshops

Organizational Context: Robotics workshops for children represent a modern educational environment oriented toward using advanced technologies—educational robots, sensors, microcontrollers, software platforms—which directly reflects the principles of Industry 4.0. The trainer's activity involves coordinating groups of children, facilitating learning through exploration, and effectively communicating with parents and the organization's team.

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Identified Problem: Within the workshops, communication between trainers, coordinators, and parents was carried out predominantly through traditional methods (phone messages, short discussions before/after classes). This generated:

- Incomplete transmission of technical information about the children's progress;
- Lack of a centralized digital support system for organizing lessons;
- Difficulties in team coordination when schedule changes occurred;
- Impossibility of tracking educational objectives in real time.

Implementation of Industry 4.0 Specific Communication:

To modernize the process, digital tools were introduced that changed the communication flow:

1. Collaborative platform (Google Classroom / Teams): Materials for children, worksheets, exercise results, and tutorials were uploaded online; parents could track their children's progress in real time.
2. Applications for robotics design and simulation (e.g., Tinkercad, Blockly): Allowed students to test programs before working on the physical robot; facilitated the visual communication of technical concepts.
3. Internal communication channel between trainers (Slack / Discord): Rapid exchange of educational resources, lesson plans, and solutions for technical problems; increased coherence among team members.

Results:

- A 40-50% increase in children's active participation due to interactive materials;
- Informarea părinților a devenit completă și predictibilă;
- Informing parents became complete and predictable;
- Decrease in organizational errors related to the schedule;
- A higher level of uniformity among trainers in teaching robotics modules;
- Development of digital skills for both trainers and students, in the spirit of Industry 4.0.

Conclusion: The digitalization of communication led to the efficiency of the educational act and the improvement of organizational coordination. The study shows that the principles of Industry 4.0 are applicable not only in the industrial environment but also in education, where digital communication becomes essential for coherence and performance.

5.2. Case study 2: Design engineer within austing insurance company

Organizational Context: Austing Insurance is a company that integrates modern technologies for risk assessment, design of technical systems related to insurance policies, and automation of workflows. The design engineer's role is to elaborate technical documentation for assessments, digital models, and technical solutions used in the insurance industry.

Identified Problem: Internal communication between the technical department, the underwriting department, and the claims assessment department was carried out through:

- Multiple emails without a clear tracking system;
- Technical documents in different formats, hard to integrate;
- Delays in approvals due to the lack of a digitalized flow;
- Difficulties in updating technical documentation in real time.

This affected design efficiency and the synchronization of information between departments.

Implementation of Industry 4.0 Specific Communication:

To solve the problems, modern digital tools were integrated:

1. PLM (Product Lifecycle Management) Platform / Document Management System: All technical documents were uploaded into a unified system; controlled versions and differentiated access for each department.

2. Use of 3D Digital Models (Digital Twin) for technical assessments: The design engineer can quickly transmit digital models to colleagues in underwriting; communication becomes visual, clear, and complete.
3. Automated Approval Workflow (e.g., Jira / Monday): Each stage of the design is tracked digitally; response times are shortened; document loss is avoided.
4. Hybrid meetings integrated with live model-sharing systems: Allow simultaneous discussion of technical solutions with all colleagues involved.

Results:

- Reduction of technical documentation approval time by up to 30%;
- Elimination of errors caused by using wrong versions of documents;
- Increased transparency between departments;
- Optimization of collaboration between engineers, assessors, and analysts;
- Modernization of the operational flow towards Industry 4.0.

Conclusion: The implementation of advanced digital tools significantly improved internal communication, reducing working times and increasing the accuracy of technical processes. The transition to Industry 4.0 brought about an organizational culture based on digital collaboration, transparency, and efficiency.

6. Conclusions

The digitalization of communication in the era of Industry 4.0 represents not just a change of tools, but a profound reconfiguration of organizational culture. The research demonstrates that the success of the transition depends on the balance between advanced technologies and the development of human skills, transforming information flows into interactive and transparent systems. Implementing these digital strategies ensures not only operational efficiency but also increased adaptability, essential for sustainable performance in the contemporary economic environment.

7. Bibliography

- [1]. Argenti, P. (2021), Organizational Communication: A Managerial Perspective, McGraw-Hill Education.
- [2]. Robbins, S. și Judge, T. (2020), Organizational Behavior, Pearson Education.
- [3]. Daft, R. (2018), Management: Communication and Collaboration in a Digital World, Cengage Learning.
- [4]. Heath, R. L. și O'Hair, H. (2020), Handbook of Strategic Communication, Routledge.
- [5]. Lind, P. (2022), Digital Communication in the Workplace: Tools, Trends, and Strategies, Springer.
- [6]. Men, L. R. și Qin, Y. (2021), Public Relations and Strategic Communication in the Digital Age, Wiley.
- [7]. Leonardi, P. (2020), Technology Choices: Why Occupations Differ in Their Embrace of Digital Tools, MIT Press.
- [8]. Bălăceanu, A. și Ionescu, M. (2021), Comunicare organizațională în era digitală, Editura ASE.

THE USE OF ARTIFICIAL INTELLIGENCE IN THE EDUCATIONAL PROCESS IN A REGULATED CONTEXT

CODREANU Irina-Maria, GHEORGHE Stefania-Adriana,

*scientific coordinator **prof. Irina SEVERIN**

Faculty of Industrial Engineering and Robotics, Specialization: Master Industrial Engineering, 2nd year, e-mail: irina.codreanu@upb.ro

*Faculty of Industrial Engineering and Robotics, Quality Engineering and Industrial Technologies

***ABSTRACT:** Fast artificial intelligence integration in higher level education has changed the way students access information, write academic articles and interact with the educational process. This study analyses the difference between real use of AI by students and the existing institutional regulatory framework. The study combines a survey targeting students, an analysis conducted on the existing academic regulations on AI usage, a matrix comparative evaluation, a Pareto analysis, and a Fishbone diagram. The results will highlight less-defined statements and issues which could be interpreted in multiple ways leading to confusion for students and professors.*

***KEY WORDS:** AI, Regulations, Improvements, Pareto, Fishbone*

1. Introduction

The integration of artificial intelligence in the education process is one of the most important aspects of technology transformations in modern times. The accelerated development of generative AI models such as Chat GPT, Gemini or Grammarly, have changed the way students get access to information, write academic articles and interact with the educational process [1], [2].

In specialized literature, artificial intelligence is defined as the ability of information systems to reproduce cognitive functions such as learning, data analysis, and problem solving. In education, this is used for personalized learning, autonomous evaluation, education recommendation, and aiding administrative processes. Many authors highlight the fact that AI can improve the efficiency of the educational process and can facilitate a faster access to information [2], [3].

Despite all, using artificial intelligence raises ethical, equity, academic, and data protection problems. It has been highlighted that excessive enthusiasm regarding AI can lead to insufficiently analyzed implementation, without a clear understanding of the impact on education and on the relationship between students and professors [4].

Rapid development of AI tools utilization in the university level environments determines educational institutions to reevaluate their learning and teaching processes. Studies show that students use artificial intelligence to generate ideas, writing, grammar verifications, and for organizing information [5], [6].

In a study made by ETH Zurich [7] on approximately 4800 students, most of the students have confirmed that they wish to integrate AI in the educational process and consider that universities should offer tools based on validated academic sources. The study has showcased differences between study domains as well. Students from technical domains have shown a higher synergy with AI technologies [7].

Recently, it has been highlighted the relationship between AI utilization and development of competencies of learning autonomy. Tools based on artificial intelligence can offer instant feedback and personalized recommendations thus, contributing to the improvement of the learning process [8], [9].

In a study based on the usage of artificial intelligence in the higher education environment, it has been illustrated that auto-efficiency and curiosity enhances the usage level of AI among students. Those who trust their own skills of using technology and who have a higher curiosity level tend to frequently integrate AI tools in their academic activities [9].

On the other hand, using artificial intelligence can lead to important academic integrity problems. The apparition of generative models which can create relevant academic texts have caused many to question the plagiarism degree of articles and the level of implication of students in the learning process [10].

ChatGPT's disponibility has raised some question marks when it comes to the future of evaluations based on essays, due to AI capabilities. Similarly, it has been shown that many students choose to use AI for choosing the theme and the methodology and for developing the main ideas for formulating academic articles [5], [10].

Despite all, studies suggest that AI usage does not automatically lead to high academic performance. More likely, the use of artificial intelligence changes the way students organize and handle academic activities, thus becoming a complementary tool in the educational process [5].

Recently, it has been observed the psychological and social effects caused by excessive use of AI in the academic environment. Artificial intelligence can contribute to the enhancement of accessibility and to the lowering of necessary time in finishing academic activities, despite the cons such as: technological stress, digital fatigue, and lower social interactions [11].

Excessive addiction of AI instruments can affect the development of interpersonal skills and of emotional intelligence, therefore creating social isolation and anxiety. All this can lead to risks caused by the recent reorganization of the educational domain caused by the excessive dependency on algorithms and autonomous systems [4], [11].

In this case, it becomes necessary to elaborate some clear regulations and institutional politics for using artificial intelligence in education. AI integration should not be exclusively from a technological perspective, but from an ethical, transparent and academic responsible perspective as well [3], [12].

Studies show that students perceive AI usage differently based on the activity conducted. There is a high level of acceptance when it comes to artificial intelligence tools usage for the teaching-learning process and administrative activities. On the other hand, there is a high level of reluctance when it comes to autonomous evaluation, admissions and other examination processes. Thus, AI implementation in a higher educational environment needs a regulated framework in which it is defined the usage limitations and the academic integrity mechanisms [12].

2. Research context and methodology

Despite all the benefits, artificial intelligence integration in universities raises significant challenges based on responsible usage and academic integrity. Although educational institutions have begun to implement AI usage regulations, it is hard for those institutions to keep up with the supply and demand of those tools.

In this context, a comparative analysis between the real way in which artificial intelligence is used by the students and the existent regulatory framework becomes relevant. This analysis aims to identify potential discrepancies and aspects which could use additional regulations.

In order to analyse the way in which artificial intelligence is used and perceived in the academic environment, research was conducted in two complementary directions: the application of a questionnaire addressed to students and the analysis of the institutional regulation on the use of AI tools in academic work. The purpose of this comparative approach

The use of Artificial Intelligence in the educational process in a regulated context

was to identify the differences between the actual use of artificial intelligence by students and the level of clarity, applicability and adaptability of the existing regulatory framework.

The questionnaire was distributed online and addressed to students from multiple academic domains, including technical, economic, medical and social sciences fields. The target group included bachelor, master and doctoral students, aiming to obtain a broader perspective regarding the integration of artificial intelligence in higher education activities. All collected responses were considered valid and included in the analysis, without excluding incomplete perspectives related to AI usage patterns, in order to preserve the diversity of opinions and experiences associated with AI integration in education.

The questionnaire follows the identification of the way in which students use artificial intelligence tools in academic activities, the perceptions on the advantages and risks of AI usage, as well as the degree of AI literacy of students and the clarity of the existing rules and regulations. The analysis of the answers highlights problems of efficiency in using artificial intelligence tools, as well as the impact on the educational process, academic integrity and the connection between practical use of AI and academic expectations. The identified issues were grouped into four main categories: AI usage issues, educational and learning issues, academic integrity and evaluation issues, and regulatory and guidance issues. In Annex 1, some of the essential questions for this study and the distribution of responses can be seen.

In parallel, the academic regulatory framework was analyzed from the perspective of the degree of operationalization and its capacity in answering to challenges generated by accelerated usage of artificial intelligence in the academic environment. The analysis follows the identification of ambiguities, applicability limitations and insufficiently developed elements at the procedural and pedagogical level. The issues identified in the regulation were grouped into four categories: clarity and applicability issues, pedagogical guidance and AI literacy issues, academic integrity and assessment issues, and technological adaptation and operationalization issues.

3. Comparative analysis

To compare the results obtained from the questionnaire and the regulation analysis, two multi-criteria matrices were constructed, adapted to the context of the use of artificial intelligence in education.

The identified problems were evaluated through a multi-criteria scoring approach based on seven dimensions: Quality, Delivery, Integrity, Clarity, Adaptability, Guidance and Sustainability. Each criterion was evaluated on a scale from 1 to 5, where:

- 1 represented a low impact or low relevance level;
- 3 represented a moderate impact level;
- 5 represented a critical impact or a highly relevant issue requiring institutional attention.

These dimensions allowed the assessment of the impact of the problems on the quality of the educational process, the pace of AI adoption, academic integrity, regulatory clarity, institutional adaptability, the need for pedagogical guidance and the sustainability of the development of academic skills in the long term.

Table 1 identifies the problems within the questionnaire in the academic environment.

Table 1. Matrix of survey identified problems in an academic environment

Problem classification	Problems identified	Q	D	I	C	A	G	S	Total
Problems caused by AI usage	Frequent usage of AI without verification and validation of generated information	5	5	4	5	5	5	4	33
	AI usage as a final result, not as a guiding tool	5	5	5	5	5	5	4	33
	AI usage for writing academic texts	4	5	4	4	3	5	3	28
	AI usage for solving homework and projects	4	5	4	4	3	5	3	28

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	AI usage without explicit awareness of its integration	3	5	4	5	5	5	5	32
Educational and learning problems	Excessive addiction of AI in academic activity	5	5	5	5	2	5	5	32
	Less personal effort through AI usage	5	5	4	5	2	5	5	31
	Superficial learning process	5	4	4	5	2	5	5	30
	Possible decrease of critical thinking through AI usage	4	4	4	4	4	5	5	30
	Lack of efficient prompt formulation skills	4	5	5	5	5	5	5	34
	Lack of critical validation skills for AI generated information	5	5	4	5	5	5	4	33
Academic integrity and evaluation problems	AI usage without a complete understanding of generated content	4	4	5	5	3	5	5	31
	Difficulties in evaluating the fairness of AI generated information	5	3	5	5	4	5	5	32
	Lack of verifiable references in AI generated responses	4	3	5	5	2	5	3	27
	Risk of affecting the fairness of academic evaluation	5	4	5	4	4	5	5	32
	Risks involving the academic ethic associated with AI usage (plagiarism, no self-contribution)	5	5	5	5	4	5	5	34
Regulatory and guidance problems	Differences between students AI usage and professors expectations	4	5	4	5	5	5	5	33
	Unclear AI utilization boundaries	4	5	5	5	5	5	5	34
	Lack of perception of AI regulations	4	5	5	5	5	5	5	34
	Necessity of well-structured rules for AI usage	5	5	5	5	5	5	5	35

The analysis of the results obtained after the application of matrix shows that the highest scores are given to problems regarding AI usage without verification of the generated information, shallowness of the learning process, and difficulty in understanding AI usage limitations. Those results suggest the existence of an extensive and fast usage of AI tools in parallel with lack of validation of information and lack of understanding regarding responsible usage limits.

Table 2 identifies the problems within the regulation.

Table 2 Matrix of survey identified problems in the regulation

Problem classification	Problems identified	Q	D	I	C	A	G	S	Total
Clarity and applicability issues	Low degree of clarification regarding allowed and restricted use of AI	3	5	5	5	5	5	3	32
	General formulations which could be interpreted differently by students and professors	5	4	5	5	5	5	5	34
	Insufficiently clear demarcation between using AI as support and using AI as a substitute for one's own contribution	5	4	5	4	5	5	3	34
	Ambiguity regarding AI usage in activities such as brainstorming, structuring or rephrasing	3	4	4	5	5	5	4	30
	Lack of clear mechanisms for the declaration of AI usage	4	5	5	5	5	5	5	34
	Lack of a standardized model for AI citation	3	3	4	5	4	4	3	26

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	Lack of examples for clear academic situations	5	4	5	4	5	5	5	33
	Possible non-uniform application between faculties and professors	4	3	5	5	5	4	5	31
Pedagogical guidance and AI literacy issues	Low level of emphasis on AI literacy for students	5	4	4	4	5	5	5	32
	Lack of clear measures for developing critical thinking	5	4	4	4	5	5	5	33
	Lack of practical recommendations on validating information generated by AI	5	5	5	5	5	5	4	34
	Limited focus on constructive pedagogical use of AI	4	4	4	4	5	5	4	30
	Lack of clear mechanisms for awareness and periodic information of students	4	4	4	4	5	5	5	31
Academic integrity and assessment issues	Predominant focus on integrity and sanctions compared to practical guidance	4	4	4	4	4	5	5	30
	Lack of standardized procedures for verifying the use of AI	4	4	4	5	5	5	4	31
	Lack of clear criteria for assessing human contribution	5	5	5	5	5	5	4	34
	Low level of differentiation between assessment and learning activities	5	5	4	4	5	5	5	33
Technological adaptation and operationalization issues	Lack of differentiation between types of AI tools	4	5	4	4	5	4	3	29
	Low level of clarification on AI integrated into common applications	4	5	3	5	5	5	4	31
	Difficult adaptation to the rapid evolution of AI technologies	4	5	5	5	5	5	5	34

Although the numerical differences between some scores are relatively small (for

example 33 versus 34 points), the purpose of the matrix was not to establish strict quantitative separations between problems, but rather to identify recurring critical tendencies. The highest-ranked issues were selected based not only on the final score, but also on their recurrence across multiple evaluation dimensions and their potential systemic impact on the educational process.

The comparative analysis between the two matrixes presented in tables 1 and 2 has showcased a gap between the fast rhythm of acceptance of AI usage among students and the degree of institutional implementation of relevant regulations regarding AI. While students largely use AI in a varied academic context, the present regulations are more focused on general aspects of academic integrity and less on practical guidance in responsible and sustainable AI usage.

The given scores had a highlighting role for the critical problems considering both the students perspective and the regulations. The problems with the highest scores, showcased as the highlighted rows in the tables, represent the highest priority for furthering the analysis and for formulating the conclusions. The results obtained suggest a gap between the speed at which students adopt and integrate AI in their academic activity and the level of actual clarity

and implementation of institutional regulations. Particularly, problems associated with AI information validation, human contribution evaluation, clear AI usage boundaries and the adaptability degree of regulations to the evolution speed of AI technologies have obtained the highest scores in the analysis matrixes.

The analysis highlights the fact that the most important challenge is not only the AI usage among university students, but the necessity of developing an education and regulatory framework which can

The use of Artificial Intelligence in the educational process in a regulated context

offer practical guidance, clarity and AI literacy in a technological context in continuous improvement.

To support the prioritization process, the analysis followed a Pareto-oriented interpretation approach, focusing on the limited number of issues that generated the highest cumulative impact regarding academic integrity, AI literacy, critical thinking and institutional adaptability. This approach allowed the identification of the most influential problems requiring priority institutional intervention. The Pareto chart can be seen in figure 1.

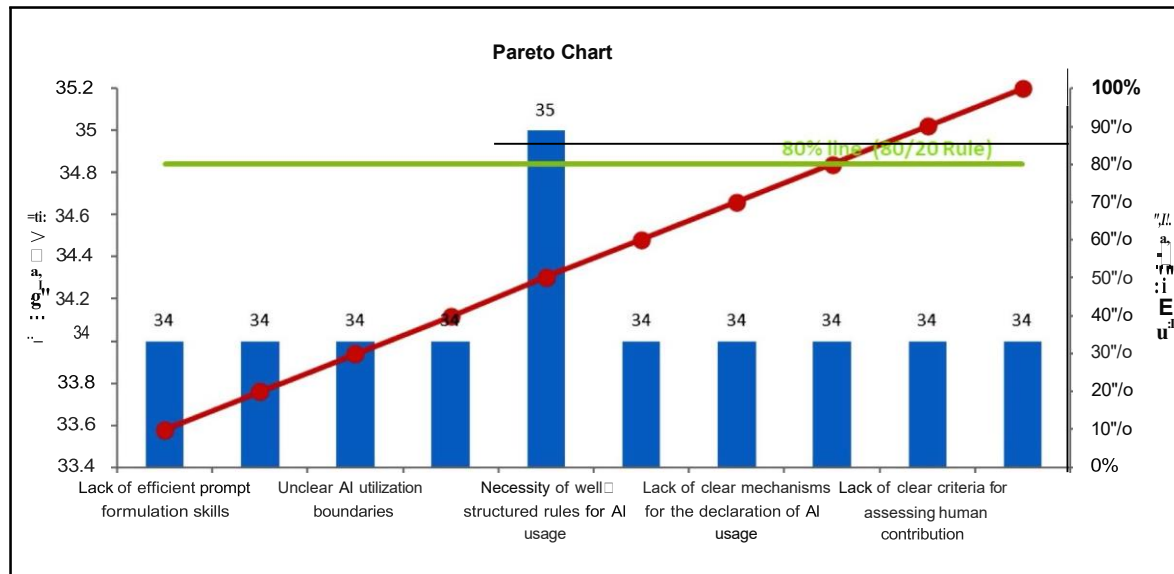


Fig. 1 Pareto Chart [13]

The Pareto analysis highlighted that the identified problems present relatively similar impact levels, suggesting that the challenges associated with AI integration are systemic rather than isolated.

4. Fishbone analysis

For identifying the main causes which contribute to widening the gap between real usage of AI by students and the present institutional framework it has been used a Fishbone diagram

(Ishikawa). This method is used for highlighting the cause-effect relationships and for classifying the problems in main causality categories.

The diagram was built starting from the top ten problems identified from the matrix analysis: five associated with the gaps present in the regulation and five associated with the gaps identified from the survey. Those problems were classified in six main categories: students' AI usage, skills and AI literacy, academic integrity, regulation clarity, evaluation and procedures, and institutional adaptability.

Through this method, the diagram allows for a systemic analysis of factors which influence AI integration in universities and highlights that the main difficulties are generated by a fast implementation and usage of AI and by current limitations of educational institutions. The Fishbone analysis can be seen in figure 2.

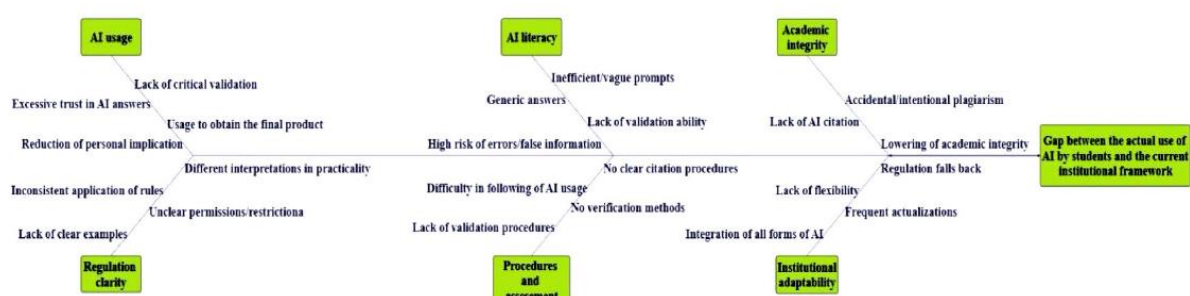


Fig. 2 Cause = effect analysis

5. Proposed improvements

The analysis conducted through the Ishikawa diagram highlights the necessity for an integrated approach regarding the use of artificial intelligence in the academic environment. The results suggest that the main difficulties are not exclusively generated by the students' usage of AI, but also by the lack of guiding, validation and adaptation mechanisms.

A first direction for improvement could be the development of several practical guides and clear examples regarding the allowed usage of artificial intelligence in academic work. These could reduce differing interpretations of the regulation and would facilitate the application of the rules in a more unified matter.

The results also highlight the need to develop AI literacy skills. Universities should introduce activities dedicated to validating AI-generated information, prompt engineering, and responsibly using generative tools in academic work.

It is necessary to develop clearer procedures for declaring the use of AI and assessing human contribution in academic works. Implementing standardized citation and verification models could help reduce risks associated with academic integrity.

Finally, educational institutions need to develop more flexible mechanisms for updating regulations that can keep pace with the rapid evolution of AI technologies and their integration into the applications used by students every day.

6. Conclusions

The introduction of artificial intelligence in the university environment is a process that is developing very fast and has a huge impact on the way students learn, write and use academic information. The analysis carried out with the help of a questionnaire, multicriteria matrices, and the Ishikawa diagram reveals a gap between the real use of AI by students and the current

level of adaptation of the institutional framework.

The analysis highlights that the major challenge associated with artificial intelligence in higher education is not represented exclusively by the existence or usage of AI tools, but by the ability of students and educators to critically interpret and validate AI-generated information. Domain-specific knowledge remains essential in order to identify inaccuracies, limitations and contextual errors generated by artificial intelligence systems.

The results suggest that critical thinking, analytical reasoning and synthesis capabilities should become central elements continuously exercised during educational activities. Artificial intelligence should therefore be integrated as a complementary support instrument rather than as a substitute for the learning and reasoning process.

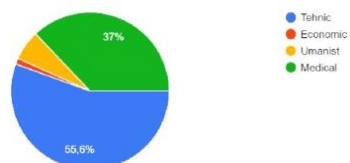
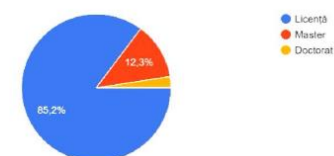
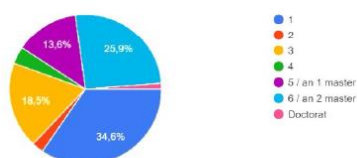
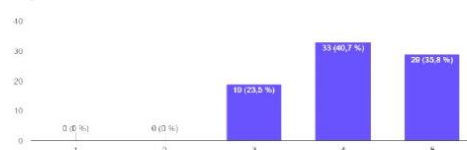
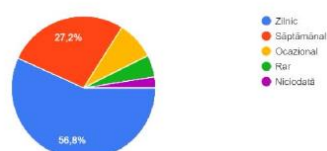
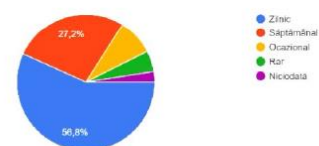
At the same time, the development of AI literacy competencies becomes necessary for all actors involved in the educational process. Both students and academic staff need the capability to responsibly use, evaluate and supervise AI-generated content in order to maintain academic integrity, educational quality and the long-term sustainability of higher education.

7. Resources

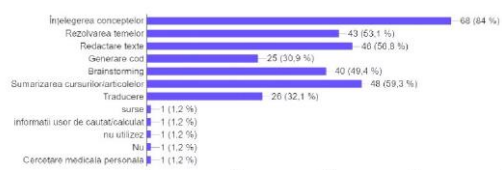
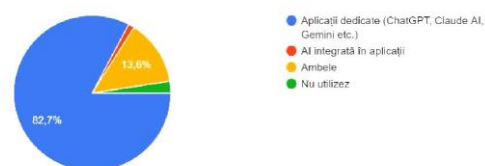
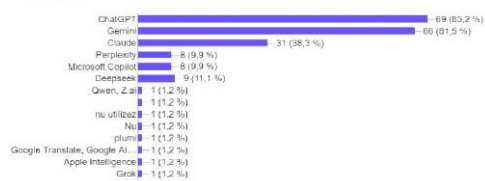
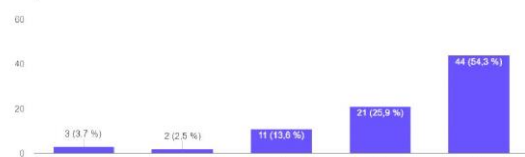
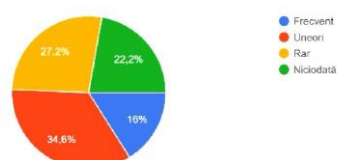
- [1] Holmes, W., & Tuomi, I. (2022). State of the art and practice in AI in education. *European Journal of Education*, 57(4), 542-570. <https://doi.org/10.1111/ejed.12533>
- [2] Nguyen, N. D. (2023). Exploring the role of AI in education. *London Journal of Social Sciences*, 6, 84-95. <https://doi.org/10.31039/ljss.2023.6.108>
- [3] Harry, A., & Sayudin. (2023). Role of AI in education. *Injuruty: Interdisciplinary Journal and Humanity*, 2(3), 260-271.
- [4] Selwyn, N. (2024). On the limits of artificial intelligence (AI) in education. *Nordisk tidsskrift for pedagogikk og kritikk*, 10, 3-14. <https://doi.org/10.23865/ntpk.v10.6062>
- [5] Smerdon, D. (2024). AI in essay-based assessment: Student adoption, usage, and performance. *Computers and Education: Artificial Intelligence*, 7, 100288. <https://doi.org/10.1016/j.caeai.2024.100288>
- [6] Dai, Y. (2025). Why students use or not use generative AI: Student conceptions, concerns, and implications for engineering education. *Digital Engineering*, 4, 100019. <https://doi.org/10.1016/j.dte.2024.100019>
- [7] Balabdaoui, F., Dittmann-Domenichini, N., Grosse, H., Schlienger, C., & Kortemeyer, G. (2024). A survey on students' use of AI at a technical university. *Discover Education*, 3(51). <https://doi.org/10.1007/s44217-024-00136-4>
- [8] Wise, A. F. (2014). Designing pedagogical interventions to support student use of learning analytics. In *Proceedings of the Fourth International Conference on Learning Analytics and Knowledge* (pp. 203-211). ACM. <https://doi.org/10.1145/2567574.2567588>
- [9] Schutte, N. S., & Li, H. (2025). The role of self-efficacy and curiosity in student use of artificial intelligence (AI). *International Journal of Educational Technology in Higher Education*, 22(73). <https://doi.org/10.1186/s41239-025-00574-6>
- [10] Playfoot, D., Quigley, M., & Thomas, A.G. (2024). Hey ChatGPT, give me a title for a paper about degree apathy and student use of AI for assignment writing. *The Internet and Higher Education*, 62, 100950. <https://doi.org/10.1016/j.iheduc.2024.100950>
- [11] Klimova, B., & Pikhart, M. (2025). Exploring the effects of artificial intelligence on student and academic well-being in higher education: A mini-review. *Frontiers in Psychology*, 16, Article 1498132. <https://doi.org/10.3389/fpsyg.2025.1498132>
- [12] Kumar, R. V. V., & Raman, R. (2023). Student perceptions on artificial intelligence (AI) in higher education. In *Proceedings on higher education and AI integration* (pp. 1-5).
- [13] Pareto template, Template developed by Wendy Jamieson - April, 2001. Updated July 2020.

Annex 1

Data about study participants

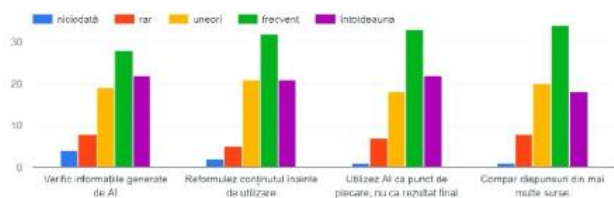
Domeniul general de studiu
81 de răspunsuriCiclul de studiu
81 de răspunsuriAn de studiu
81 de răspunsuriCum vă evaluați competențele digitale? (1 = foarte scăzute, 5 = foarte ridicate)
81 de răspunsuriCât de des utilizați instrumente de inteligență artificială?
81 de răspunsuriCât de des utilizați instrumente de inteligență artificială?
81 de răspunsuri

Data on the instruments used

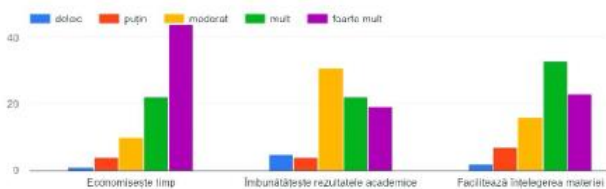
În ce scopuri utilizați AI? (selectați toate variantele aplicabile)
81 de răspunsuriCe tip de AI utilizați cel mai frecvent?
81 de răspunsuriCe aplicații AI utilizați? (selectați toate variantele aplicabile)
81 de răspunsuriCe aplicație sau platforme, care au funcționalități AI integrate, utilizați? (selectați toate variantele aplicabile)
81 de răspunsuriÎn ce măsură sunteți conștient(ă) că aceste aplicații utilizează AI?
81 de răspunsuriCât de des utilizați funcționalitățile AI din aceste aplicații fără a le considera explicit ca fiind „AI”?
81 de răspunsuri

Data on usage

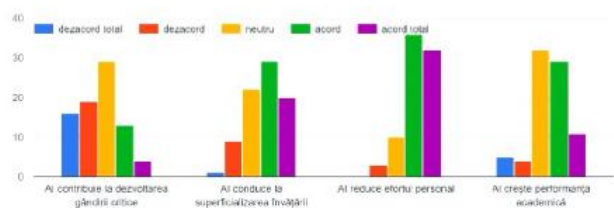
Indicați în ce măsură sunteți de acord cu următoarele afirmații



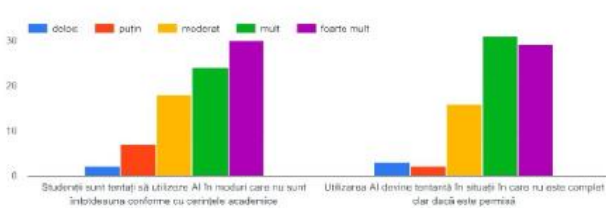
În ce măsură considerați că AI



În ce măsură sunteți de acord cu următoarele afirmații

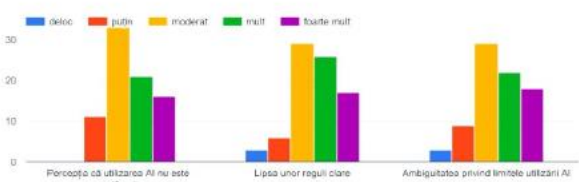


În ce măsură sunteți de acord cu următoarele afirmații

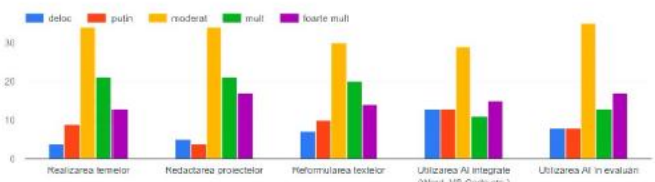


Data on knowledge of regulations

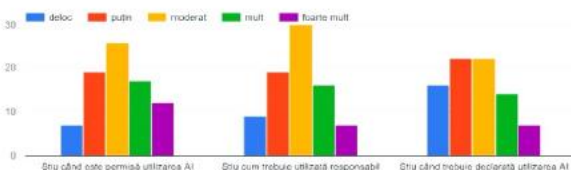
În ce măsură considerați că utilizarea AI este influențată de următorii factori



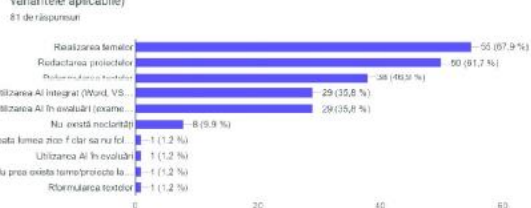
În ce măsură considerați că există situații neclare privind utilizarea AI în activitățile academice



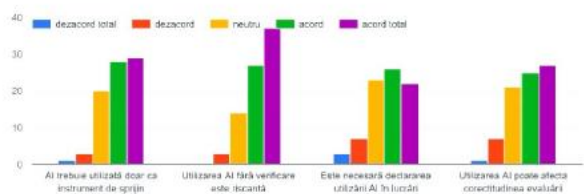
În ce măsură considerați că studenții cunosc limitele acceptabile ale utilizării AI



În ce situații considerați că utilizarea AI este mai puțin clar reglementată? (selecționați toate variantele aplicabile)



În ce măsură sunteți de acord



În ce măsură sunteți de acord cu următoarele afirmații

